METHODOLOGIES FOR ASSESSING SUSTAINABILITY IN MARITIME TRANSPORT

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Acknowledgments

I was fortunate to start my career as an engineer from research, back in 2005. It was Prof. H. Psaraftis who offered me the opportunity to be actively involved in the research agenda of the School of Naval Architecture and Marine Engineering of NTUA, for which I am really grateful. In NTUA, I teamed up with Ass. Professor N. Ventikos, my dear friend Nikos, with whom I had the pleasure to cooperate for ten consecutive years. I prefer the term work because I am viewing this period more as a working period rather than a studying period. This PhD thesis, is the outcome of work during the last five years of my presence in NTUA, as Nikos finally purchased me to serve not only as research assistant but also as doctoral student of the School. Overall, Nikos has largely contributed to my doctoral studies and to my professional development, as supervisor, teammate and tutor, and most importantly as a real friend. I have no words to thank him for this.

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LIST OF SYMBOLS ABBREVIATIONS AND ACRONYMS

AE: Auxiliary Engine
CH_4: Methane
CO: Carbon Monoxide
CO_2: Carbon Dioxide
DALY: Disability Adjusted Life Years
DCS: Data Collection Scheme of IMO
DWT: Deadweight of the ship
EC: European Commission
ECA: Emission Control Area
EEA: European Environment Agency
EEDI: Energy Efficiency Design Index
ESA: Environmental Systems Analysis
ESPO: European Sea Ports Organisation
EU: European Union
GHG: Green House Gas
GRI: Global Reporting Initiative
HFO: Heavy Fuel Oil
ILCD: International Reference Life Cycle Data System
IMO: International Maritime Organisation
IOPC International Oil Pollution Compensation
IPA: Impact Pathway Approach
ISM: International Safety Management Code
ISO: International Organization of Standardization
IS: Impact Score
JRC: Joint Research Centre
KPI: Key Performance Indicator
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment

LIME:	Life Cycle Impact Assessment Method based on Endpoints
LNG:	Liquefied Natural Gas
MARPOL:	International Convention for the Prevention of Pollution from Ships
MCR:	Maximum Continuous Rating
MC:	Monte Carlo Simulation
MDO:	Marine Diesel Oil
ME:	Main Engine
MGO:	Marine Gas Oil
MRV:	Monitoring Reporting and Verification
NG:	Natural Gas
NOx:	Nitrogen Oxide Emissions
NTUA:	National Technical University of Athens
O_3:	Ozone
PM:	Particulate Matter
RF:	Radiating Forcing
SDG:	Sustainable Development Goal
SEEMP:	Ship Energy Efficiency Management Plan
SETAC:	The Society of Environmental Toxicology and Chemistry
SFOC:	Specific Fuel Consumption
SLCA:	Social Life Cycle Assessment
SO_2:	Sulphur Dioxide
SOx:	Sulphur Oxide Emissions
SSI:	Sustainable Shipping Initiative
TERM:	Transport and Environment Reporting Mechanism
TEU:	Twenty feet Equivalent Unit
UNEP:	United Nations Environmental Programme
VOC:	Volatile Organic Compounds
WHO:	World Health Organisation

To my father

1. EXECUTIVE SUMMARY

The main goal of this thesis is to examine the main drivers affecting the sustainability of ships in a life cycle perspective. Therefore, the work concerned the development of methodologies, software and the conduction of case studies that produce inventories of the main environmental drivers of ships but more importantly can perform impact assessments of these drivers in a life cycle context.

A review of selected sustainability issues and challenges of international shipping is first presented. Then, a literature review in sustainability and in particular in transportation sustainability is carried out in order to select information on the interpretation of sustainability in the broader transport sector. This review has identified three principles that the sustainable transport system should always observe namely:

1. Accessibility: the ability to obtain or have access to desired goods, services, activities and destinations
2. Resource constrains: the acceptance of natural (e.g. for fossil fuels) and social limits (e.g. in safety)
3. Equity: the balanced distribution of transport benefits and costs among people and between generations

Following the aforementioned principles the author presents his own definition for a maritime transport sustainability which states that: *'A Maritime Transport System is sustainable when it has the capability to offer and maintain non-declining and efficient accessibility by observing the principles of equity and resource constrains'.*

It is noted that at the time (2011) during the author launched the above definition there was no official definition for what means a sustainable transport system. It was only two years later (2013) that the IMO launched its official view.

Life Cycle Thinking is the conceptual basis on the road to sustainability assessments since it considers the full life cycle of the product/process and aims at the holistic evaluation of environmental aspects included in the life cycle stages. The link between sustainability and life cycle thinking is first emphasised and a literature review with applications of the LCA method in ships follows. In the context of this doctoral thesis the standard LCA method has been utilised to perform holistic assessment of important environmental drivers of ships. However, the review demonstrated that the LCA method as proposed in the relevant ISO standard, has not been particularly developed for the case of ships and most of its features match better to land based products and services. It is therefore essential to adapt the LCA before conducting an LCA study for ships. Hence, this thesis proposes a unique framework for studying specific environmental drivers (i.e. ship emissions) in a life cycle perspective. The proposed ship- LCA framework considers the ship as a system that may be detailed into sub-systems and further into system elements for which: (a) inputs, (b) processes, and (c) outputs, are identified and elaborated. Important ship life cycle stages taken into account in this model are: the shipbuilding stage, the ship operation including major maintenance activities, and the stage of ship dismantling/recycling.

At the process level, the emissions are calculated using theoretical or empirical mathematical modelling. Therefore, the ship-LCA framework comprises a series of algorithms which calculate air emissions in the different life cycle stages of the ship. These calculations lead to the development of the Life Cycle Inventory (LCI) of ship air emissions. The Framework can produce various useful outputs namely: a. inventory of air emissions from any identified process, b. air emissions per life cycle stage, per process, system element, subsystem, and total, c. annual air emissions analysis, and d. emissions comparisons between different operational ship profiles and operational scenarios (i.e. slow steaming, speed limit, fleet distribution, etc.). Case studies with the use of the ship-LCA Framework were conducted to test and evaluate the framework. Moreover, in the process of conducting the case studies, the framework has been reviewed and updated with new features such as the algorithm for the added hull resistance due to marine growth, or the updated algorithm for the process of hull coatings using real shipyard data.

The thesis elaborated on the important parameters that can drastically affect the emissions inventories produced by the LCA framework; namely the speed parameter, and the parameter of fuel consumption and the uncertainty in relation to its monitoring and reporting. A novel probabilistic model has been developed for this analysis that can also serve as an evaluation tool in the reporting of fuel consumption and emissions data that are used to comply with EU regulations (namely the MRV Regulation).

A software (in the MATLAB environment) has been developed which models all elaborated processes of the ship LCA framework, with their equations and algorithms. This software is suitable for producing emissions reports (per trip and year), and can support decisions in the long-term since it can produce projections for air emissions during the life cycle of the ship.

A comparative Life Cycle Assessment study for two marine fuel alternatives was conducted (namely LNG vs. low sulphur HFO). The fuel supply chain formulating the life cycle included: extraction, crude product processing and transport of fuels by sea, storage in import terminals and finally bunkering and combustion in an engine of a car/passenger ferry. The comparison of LNG and low sulphur HFO has been made in the same boundary conditions.

The study has demonstrated that the benefits of LNG as fuel, are clear for the case of ship air pollutants (SOx, NOx, and PM) and marginal for the case of greenhouse gas emissions (CO2 and CH4). Therefore, the option of LNG as a future marine fuel in the specific scenario examined is a promising solution with respect to the reduction of air pollution which might be more favourable if the Mediterranean Sea falls in the ECA regime in the future. From a strict environmental point of view, LNG will be more attractive as marine fuel in the future, if climate change impacts are reduced along the supply chain. In this respect, life cycle analysis will have to be applied in order to justify and evaluate the possible environmental benefits of such selections.

Two different approaches have been used for examining the environmental impacts of ship drivers. The first approach is the assessment in the context of the LCA methodology, the so called Life Cycle Impact Assessment step of LCA. The second approach is the one using the external cost concept.

The study identified that the impact of GHGs is not easily measurable which is basically due to the wide range of monetary values used in the literature. However, the health and environmental impacts of air pollutants are subject to the proximity of the emission source to the receptors and therefore can vary significantly.

Ship air emissions may have local and global effects to human health and ecosystems and these were handled in the impact assessment work. Two separate approaches were used in the ship impact assessment namely: the Life Cycle Impact Assessment (LCIA), a standardized method through the ISO framework for LCA and the external cost approach.

This thesis proposes a life cycle impact tool for ships based on principles of the ISO standards for LCA, and validated damage models (namely the EcoIndicator and the Recipe 2008 damage models). The main objectives of the tool are:

1. To record all pollutants (oil and non-oil liquid wastes, garbage, air emissions), generated by the various ship related processes and
2. To assess their environmental impact throughout the ship's life cycle.

The results of the case studies in the external cost approach reveal also the wide range of uncertainty in the estimation of emissions impact and associated costs. The total external cost of CO_2 over the life cycle of the ship ranges between 16 and 65 million Euros. It is noted that this is the result for the whole ship system (hull and machinery life cycle emissions are included). For the case study of the Panamax oil tanker, the external cost per year has been estimated that it can double over the years of the ship's life, starting from (an average of) one million Euros to account for two million Euros (in year twenty-five of her life cycle).

Health impacts of ship air emissions in port areas have been examined using the impact pathway approach. Meteo data were applied for modelling the dispersion of air pollutants together with population data and exposure response functions to assess the external cost in human health. Open-source software has been used for modelling the dispersion of air pollutants. The results are given in monetary values of the annual impact of ships to human health. One important finding of the port emissions study (conducted for Piraeus port) is that the health impacts of ship emissions and specifically of those related to particulate matter are not negligible. The ship air pollutant with the biggest mortality external cost as well as the biggest morbidity external cost is PM_2.

International shipping has seen its environmental agenda growing rapidly in recent years and ships are forced to comply with expensive retrofits or by using more expensive fuels, or even changing their operating profile. This "greening" process needs to be better supported from sound evidence about the real pressures posed by ships to the environment and human health throughout their life cycle. In this direction, substantial support can be offered from life cycle assessment studies similar to those conducted in this thesis. Finally, the timeline of enforcement of new regulations would be probably more justifiable if a prioritisation of the importance of ship environmental drivers would be made feasible. The above illustrate the necessity for additional emphasis on ship environmental impact assessments in the future.

2. INTRODUCTION

2.1 Motivation

The work presented in this thesis started in 2010 and concluded in 2016. Editing was concluded in 2018. During this period, the international shipping industry has seen a number of important actions targeting the environmental performance and the energy efficiency of ships.

In 2013 (1st January), the first international regulation covering the greenhouse gas emissions of ships entered into force. The regulation consists of two parts: the Energy Efficiency Design Index, EEDI, which regulates the carbon dioxide emissions in the design face and the Ship Energy Efficiency Management Plan, the SEEMP, which covers the operational face. It was the first time that the international shipping industry, through its main regulatory body, the International Maritime Organisation, IMO, put forward rules for greenhouse gases. This makes shipping one of the last industrial sectors to take regulatory action for climate change. The EEDI however, as a global standard for designing ships, is receiving a great amount of criticism for its robustness and effectiveness. The author had the pleasure to work near the team lead by Prof. Psaraftis, which represented Greece in the discussions within IMO, prior the entry into force of the EEDI. The Greek delegation, with the supervision of Prof. Psaraftis, presented in IMO, its own calculations on the EEDI and proposed some alternative formulae to tackle the issue of speed (i.e. the great influence of ship's speed in the index) (Psaraftis, 2018). Part of this work was carried out by the author and can be found in Chapter 8, and Appendix I of this thesis.

In 2013, in an IMO symposium held during the World Maritime Day (26 September), the Secretary General of IMO, introduced on a global agenda a formal definition of the sustainable maritime transportation system. This was the first time that an official statement was made for what actually sustainability means for the shipping industry. Defining maritime transport sustainability was the first research question of this thesis. The author published his view on the subject in 2011, in the International Congress of International Maritime Association of the Mediterranean (IMAM), held in Genoa.

During the period of research, other initiatives that highlight the relevance of this work were introduced. The ISO 14001, which calls for the establishment of environmental management systems, was updated in 2015. One of the important new requirements is the introduction of the life cycle approach in the management of environmental aspects within an organisation.

Life Cycle Analysis was also the topic of the EU funfed research framework, namely the HORIZON 2020, in the area of waterborne transport (MG-4.3-2015). The topic in this call is entitled: "System modelling and life-cycle cost optimization for waterborne assets".

Specifically, the text of the call highlighted that research projects of this topic should focus on "*New design and mathematical modelling tools and paradigms supporting the full understanding of operational practices and situations covering the entire useful* *economic life of a vessel or maritime structure (including material recovery, "from cradle to cradle") in terms of costs and performance*”.

The life cycle thinking approach corresponds to one important goal of this thesis. Large part of the work focused in identifying and assessing the main environmental drivers’ in the ship’s life cycle. One of the main results of this thesis is a life cycle framework (a methodology), explicitly developed for the estimation of ship air emissions in a life cycle perspective, together with a software tool that performs the relevant calculations for different ship types and operational profiles, and a number of case studies with life cycle emission results.

The thesis after identifying the important environmental drivers of shipping, has concentrated more in the study of ship air emissions. Ship air emissions is the highest priority for shipping nowadays. This is clearly depicted in the activities of operators and regulators and overall has a great impact in the industry’s everyday practice. In 2014, IMO published the Third IMO Greenhouse gas study, which concluded that international shipping is responsible for about 2.4 percent of the global anthropogenic greenhouse gases. Despite this very low contribution of shipping in greenhouse gases, the European Commission proceeded without IMO and adopted a European regulation on the monitoring, reporting and verification (MRV) system of ship emissions, based on the fuel consumption, as a necessary starting point to other mitigation strategies, such as the development of market-based instruments. Ships have begun complying with, the so-called MRV Regulation of EC, and starting from 1/1/2018, the first reporting period is on. Recently, IMO also granted that a global performance standard for fuel consumption measurement for ships is missing, and has also put forward the implementation of a scheme similar to MRV on a global level, the so called Data Collection System (DCS). DCS reporting will start from 2019, with a one-year delay compared to the MRV.

Air pollution has major effects on ecosystems and human health. According to the World Health Organization (WHO), exposure to air pollution is the world’s largest single environmental health risk, causing one in eight of total global deaths, or seven million deaths in year 2012 (WHO, 2014). In Europe, climate change is perceived as the biggest environmental threat followed by air pollution (EC, 2017).

Air pollution from shipping is not negligible, and there is strong activity worldwide to tackle its impacts. One of the main concerns in this respect is the quality of marine fuels, which for the case of shipping, remains low compared to other transport modes. Regulators put regional and global limits in the sulphur content of marine fuels and set nitrogen emission standards for new engines. In response, the shipping industry considers the use of alternative fuels that eliminate air pollutants (i.e. the Liquefied Natural Gas, LNG) or retrofit the ships with scrubber technology to capture harmful exhaust gases.

The European Environment Agency in its 2018 report on air quality in Europe, states that “*effective action to reduce air pollution and its impacts requires a good understanding of its causes…., ……and how pollutants impact humans, ecosystems, the climate and subsequently society and the economy*” (EEA, 2018). However, for the case of ship air emissions, the scientific literature is focusing mainly on the development of emissions inventories; hence, studies examining the impact of these emissions are scarce. This motivated the author to put under the spotlight the impact of ship emissions, devoting three chapters (Chapter 9, 10, and 11) and implementing two different approaches (i.e. the life cycle impact assessment and the external cost concept) for that purpose.

Overall, the environmental agenda of shipping is constantly expanded over the years with new regulations, industry standards and initiatives as response of the global societal demand for effective but “clean” transportation systems. This doctoral thesis aims to contribute to this discussion, with the submission of theoretical concepts, algorithms, methodologies, tools and illustrated case studies for assessing the main environmental drivers of ships and their impacts to the environment and the human health.

2.2 Research Questions

a. How is sustainability understood in the maritime transport sector?
b. What are the main elements of this concept?
c. What are the main drivers affecting the sustainability of ships?
d. What is the impact of these drivers?
e. Are there available methods and tools to examine the impact of these drivers in a life cycle context?

2.3 Goals

The main goal of this thesis is to examine the main drivers affecting the sustainability of ships in a life cycle perspective. The work is focusing on the development of methodologies for examining the main environmental drivers of ships and their impact in a life cycle context. Specific goals of the work are shown below:

a. Propose a definition for a sustainable maritime transport system
b. Identify the main parameters affecting the sustainability of a ship
c. Examine the applicability of the Life Cycle Assessment method for the case of ships
d. Implement methodologies for assessing the environmental impact of ships in a life cycle perspective

2.4 Thesis structure – work development

2.4.1 Structure

The work starts with the literature review on the sustainability of maritime transport. It became apparent during this review (which was conducted in 2011), that there was no definition for the sustainable maritime transport system. The author identifies the main aspects affecting the sustainability of maritime transport systems and proposes a definition for maritime sustainability in Chapter 2.

Chapter 3 discusses the life cycle approach in the study of environmental drivers of shipping. A comprehensive literature review in the field of life cycle assessment is made which identifies existing methods and their applications with particular focus on the maritime transport area.

In Chapter 4, the author proposes a framework suitable for studying the main environmental drivers of ships in a life cycle perspective. In the context of this framework, the study proposes a mathematical model for calculating these drivers for the different systems and sub-systems of a ship.

In Chapter 5, and in the context of the framework and the mathematical modelling performed previously, a novel software for studying ship air emissions in a life cycle perspective is presented.

Chapter 6 includes the results of four case studies which concerned the development of ship emissions life cycle inventories. The first one of these case studies presents the results of an emissions inventory for a panamax tanker and has made use of the mathematical model of this thesis. The second one is a life cycle inventory of air emissions using ship activity data. The third one, examines various scenarios of operation and their effect in the results of the life cycle inventory of ship air emissions. The fourth case study is dealing with emissions from coating operations in a life cycle perspective, a joint work between the author and researchers from the Yildiz Technical University of Istanbul.

In Chapter 7, a comparative life cycle assessment study is performed that examines the life cycle environmental performance of two marine fuel alternatives, namely the liquefied natural gas and the low sulphur fuel oil, in the same operating scenario.

Chapter 8 discusses the uncertainty in fuel consumption estimates and consequently in air emissions results. The impact of speed as a crucial parameter in the assessment of air emissions is highlighted and a probabilistic model using real field data is presented for the estimation of fuel consumption and subsequent air emissions.

The different categories of impacts from shipping are identified and discussed in Chapter 9. The origin and impact of ship emissions are presented and the methodologies for studying the impact of ships in a life cycle perspective are evaluated. Two approaches for studying the impact of ships are followed; the first one is the life cycle impact assessment in the context of the life cycle assessment method (LCA), and the second one is the impact assessment in the context of the external cost approach.

Chapter 10 presents case studies with the application of the life cycle impact assessment in ships, following the two different approaches discussed in the previous chapter.

In Chapter 11, focus is made to the health impacts of ship air emissions in port areas. A case study of the Piraeus passenger port is presented where the impacts of emissions causing health effects are examined. The study follows the impact pathway approach in which meteo data for modelling of the dispersion of air pollutants are used together with exposure response functions. The work used open-source software for modelling the dispersion of air pollutants and the allocation of impacts and the results are monetary values of the annual impact of ships to human health.

Chapter 12, is the discussion chapter. The main contributions of this thesis are presented and discussed. Additionally, an update on the most recent developments at the policy level that are relevant to the subject of this thesis are presented in order to demonstrate the relevance of the work.

Chapter 13, concludes the thesis presenting the most illustrating results, commenting on the methodological approach and proposing areas of possible future research.

2.4.2 Work Development - Research projects

Large part of the work included in this thesis has been carried out in the context of funded research projects of the Laboratory for Maritime Transport of NTUA. The author was continuously involved as research engineer in funded and non-funded research projects of this Laboratory for ten years (2005 – 2015). During this period the author has worked in research projects in various thematic areas such as maritime safety, maritime risk, oil pollution response and others. The list of projects that are relevant to the work included in this thesis are listed below:

1. “Assessment of Environmental Impact in Marine Transportation and Related Activities,” project funded by the American Bureau of Shipping (June 2008 – May 2011).
2. “Supporting EU’s Freight Transport Logistics Action Plan on Green Corridors Issues – project SuperGreen” - 7th Framework Programme, DG---MOVE (Coordinated Action, Consortium Leader: NTUA, H.N. Psaraftis Consortium Manager) (January 2010 – January 2013).
3. “Centre of Excellence in Ship Total Energy – Emissions – Economy”, project funded by The Lloyds Register Educational Trust (Feb. 2010 - Feb. 2015)
4. “EnviShipping: Environmental Footprint of Ships from a Life Cycle Perspective”, multi – partner project funded by the General Secretariat of Research and Technology, Consortium Leader: NTUA, N.P. Ventikos. (May 2011 – Oct 2014).

An indicative description of the research work conducted in the above projects and included in this thesis follows:

- In the research collaboration with the American Bureau of Shipping (ABS) the work focus was to develop models for the Life Cycle Assessment of air emissions for tankers. Moreover, the project studied the implications to various ship types of the introduction of the Energy Efficiency Design Index (EEDI). The impact of speed in the EEDI has been examined and alternative indices were proposed to minimise the dominant influence of speed in the EEDI.
- In the Centre of Excellence for Ship Emissions, a five years research Synergy established between NTUA and Lloyd's Register Foundation, the author studied ship emissions and their impacts in a life cycle perspective. He developed models for assessing ship air emissions and carried out life cycle assessment studies with the purpose to examine alternative solutions for reducing the environmental impact of shipping (i.e. LNG vs. HFO as marine fuels, different ship speed etc.) Finally, in the context of this project the author examined and presented results of case studies of ship air emissions and their impacts using the external cost approach.

- In the "ENVISHIPPING" research project, the author adjusted the methodology of Life Cycle Assessment (LCA) to the ship environment with the purpose to perform a holistic assessment of environmental drivers (emissions, wastes, ballast water) from merchant ships. Moreover, the author identified and listed mature solutions for the improvement of the environmental footprint of ships. Part of the work in this project concerned the assessment of impacts of ship emissions in relation to port activities.

2.5 Publications

The publications in the context of this thesis are listed below:

2.5.1 Chapter in Book

1. **Chatzinikolaou, S. and Ventikos, N.P., (2015) "**Critical Analysis of Air Emissions from Ships: Lifecycle Thinking and Results", in Book Green transport logistics: the quest for win-win solutions, *Springer Series: International Series in Operations Research & Management Science,* Ed.: H. Psaraftis. ISBN 978-3-319-17175-3

2. **Chatzinikolaou, S., Ventikos, N., Bilgili, L., and Celebi, U. B. (2016) "**Ship Life Cycle Greenhouse Gas Emissions" In Book Energy, Transportation and Global Warming, Green Energy and Technology, Springer International Publishing Switzerland 2016 P. Grammelis (ed.), DOI 10.1007/978-3-319-30127-3_65

2.5.2 Peer-Reviewed Journals

1. **Chatzinikolaou, S. and Ventikos, N.P., (2015) "**Holistic Framework for Studying Ship Air Emissions in a Life Cycle Perspective", *Ocean Engineering Journal* Elsevier Series Ed.: Osman Touran
2. **Chatzinikolaou, S., Oikonomou, S., and Ventikos, N.P. (2015)** "Health Externalities of Ship Air Pollution at Port-Piraeus Port Case Study" in *Transportation Research Part D: Transport and Environment*, 40 (2015) 155–165.

2.5.3 Scientific Conferences

1. **Chatzinikolaou, S., Ventikos, N., Bilgili, L., and Celebi, U. B. (2015) "**SHIP LIFE CYCLE GREEN HOUSE GAS EMISSIONS", in proceedings of the Global Conference on Global Warming, 24-27 May, Athens, Greece.

2. **Daskalakis I, Chatzinikolaou S., Ventikos N.P. (2015),** "Platform for assessing ship emissions from a life cycle perspective", Technologies, Operations, Logistics and Policies towards meeting 2050 emission targets (SCC 2015), Glasgow, UK, Osman et al. (eds), Vol. 1, pp. 113-122.

3. **Bilgili L., Celebi U. B., Chatzinikolaou S., and Ventikos N. (2015), "**An investigation on impact of painting and operation emissions in a ship's life cycle to the environment" 18th International Symposium on Environmental Pollution and its

Impact on Life in the Mediterranean Region, MESAEP 2015, September 26-30, 2015, Crete – Greece.

4. **Chatzinikolaou, S. and Ventikos, N.P., (2014) "** Assessing Environmental Impacts of Ships from a Life Cycle Perspective", In Proceedings of the 2nd International Conference on Maritime Technology and Engineering , MARTECH 2014, 15-17 Oct 2014, Lisbon Portugal.
5. **Chatzinikolaou, S. and Ventikos, N.P., (2014)** "Applications of Life Cycle Assessment in Shipping" in Proceedings of the 2nd Int. Symposium of Naval Architecture and Maritime, YTU GIDF, Istanbul, 23-24 October 2014
6. **Chatzinikolaou S.D., Ventikos N.P. (2013),** "Assessment of Ship Emissions in a Life Cycle Perspective", Proceedings of the 3rd International Energy, Life Cycle Assessment and Sustainability Workshop & Symposium (ELCAS3), Eds: Koroneos C., Rovas D. and Dompros A., ISBN: 978-960-243-691-2, Nisyros, Greece, pp. 1225-1234
7. **Chatzinikolaou S.D., Ventikos N.P. (2013), "**Lifecycle Impact Analysis for Ships", Proceedings of the 2013 Annual Meeting of the Hellenic Institute of Marine Technology: The Book of Marine Technology, Piraeus, Greece, pp. 71-82
8. **Χατζηνικολάου Σ., Βεντίκος Ν. (2012)** «Συνολικό Περιβαλλοντικό Αποτύπωμα Πλοίων: Το Πλαίσιο Αναγνώρισης», ΕΛΙΝΤ 2012, Αθήνα, 2012 (με κρίση στο κείμενο)
9. **Chatzinikolaou S.D., Ventikos N.P. (2011),** "Sustainable maritime transport: an operational definition", Sustainable Maritime Transportation and Exploitation of Sea Resources, (IMAM 2011), CRC Press, vol. 2, pp. 931-939
10. **Ventikos N.P., Chatzinikolaou S.D., Zagoraios G. (2009),** "The Cost of Oil Spill Response in Greece: Analysis & Results", Proceedings of the 13th Congress of Intl. Maritime Assoc. of Mediterranean (IMAM 2009), vol. II, ISBN: 978-975-561-357-4, Istanbul, Turkey, pp. 771-778, 2009.
11. **Ventikos N.P., Chatzinikolaou S.D., (2008)** "Hazardous Waste Management and Ship Recycling: Friends or FOEs?" Proceedings of the 1st International Conference on Hazardous Wastes Management, Chania, Greece, CD-ROM, 2008.
12. **Chatzinikolaou S.D., Nitsopoulos S.C., Ventikos N.P. (2007)** "Shipboard Wastes: Elements & Critical Review", Proceedings of the Int. Conference of Environmental Management, Engineering, Planning and Economics, Skiathos, Greece, vol. III, pp. 1597-1602, 2007

2.5.4 Non Reviewed journals

1. **Chatzinkolaou, S. and Ventikos, N.,** (2014) "Holistic Impact Assessment of Ship Emissions", Logistics and Management Magazine (in Greek)

2. **Chatzinikoloau, S., and Ventikos, N.**, (2013) "Sustainability in Maritime Transport" article published in Nautika Xronika journal (in Greek)

2.5.5 Selected invited speeches in relation to the thesis topics

1. **Ventikos, N., and Chatzinikolaou, S**. **"**Shipping and Sea Pollution" (2009) In Proceedings of the MESOGEIOS SOS public workshop, Eleusina, Greece.
2. **Chatzinikolaou, S. and Ventikos, N.**, (2014) "Ship Life Cycle Assessment – Case Studies" (2014), In Proceedings of the 2nd International MARINELIVE Conference on "All Electric Ship" February 12-13, 2014, Athens, Greece
3. **Chatzinikolaou, S.** (2015). "Energy Governance onboard and ashore" Representing RINA in Proceedings of the Greener Shipping Summit, Athens, 10.11.2015
4. **Chatzinikolaou S.** (2015)."Energy Governance Software", Representing RINA in proceedings of the Annual Meeting of the Hellenic Institute of Marine Technology. Athens, 15.11.2015
5. **Chatzinikolaou S.** (2016)."Solutions to Ship Energy Efficiency" Representing RINA in the proceedings of the 3rd Mare Forum, Maritime Energy Transportation 2016, 2.03.2016, Athens Hilton, GR.
6. **Chatzinkolaou S**. (2018). "Ship Air Emissions – Main Chalenges, Policies and Industry Developments" invited speech, representing RINA in the technical seminar of IMAREST, Branch UAE, Dubai, 10 May 2018.

3. SUSTAINABILITY IN MARITIME TRANSPORT

Summary

This Chapter discusses the theoretical concept of Sustainability and introduces a definition for “Maritime Transport Sustainability”.

The sustainability concept is suffering from low credibility because of the plethora of definitions and uses that have been launched from a variety of agencies around the globe. The maritime sector is not an exception to this, since there are numerous initiatives within this sector claiming to have a sustainability orientation; however, many of them are often diverse in terms of interpretation and implementation of the sustainability principles. The aim of this work has been to contribute in the discussion for redefining in an operational manner the sustainability concept of the maritime transport sector by following the initial notion of this concept.

In 2013, two years after the conclusion of the work within this chapter and the submission/presentation of the paper to IMAM 2011 Conference, an IMO symposium that was held during the World Maritime Day (26 September 2013) introduced on a global agenda a formal definition of the sustainable maritime transportation system.

Structure of the Chapter

First, a review of selected sustainability issues and challenges within shipping is presented. Then, sustainability and transportation sustainability literature is explored in order to select information on the interpretation of sustainability in the broader transport sector. The operational definition for maritime transport sustainability is then presented and described. Finally, after the definition is introduced some indicative techniques from the broader transport area are reviewed and methodological concepts for assessing sustainability in shipping are presented.

Publications from this Chapter

Chatzinikolaou S.D., Ventikos N.P. (2011), “Sustainable maritime transport: an operational definition”, Sustainable Maritime Transportation and Exploitation of Sea Resources, (IMAM 2011), CRC Press, vol. 2, pp. 931-939

3.1 Introduction

The concept of sustainability is adopted either as international or national policy principle but also as a key notion for business, industrial, scientific and many other initiatives around the globe. With regard to the maritime transport sector, the EU's central policy for the future of this sector is based on values of sustainable development, such as economic progress and open markets in fair competition as well as high environmental and social standards (EC, 2009).

Many people consider maritime transport an environmentally sound practice, mainly because ships in broad terms use lower energy and produce less air emissions per amount of transport work compared to other transport modes. It is evident that within the maritime sector there are several efforts made in policy, technology and research level to reduce the environmental impacts of shipping and to achieve certain sustainability goals. Yet, in absolute terms, air emissions from shipping are significant and keep rising, while the emissions from land-based sources are gradually decreasing (European T&E Federation, 2010). This is somewhat explained by the massive growth that the maritime transport sector has experienced the previous years, supporting the demand for the international movement of goods and the globalisation of commercial activities. Only during the last two decades, the international seaborne trade has over-doubled (from 2.253 to 4.742 billion tons) and currently (in 2010) accounts for nearly 90 percent of world trade (UNCTAD, 2010).

Despite its international nature and enormous growth, the maritime transport sector has been extremely slow in achieving global agreements for the reduction of ship emissions and has, so far, "managed" to be left out of the Kyoto Protocol. Hence, a great amount of criticism towards this industry targets its social agenda (i.e. working conditions, safety, ship dismantling practices, etc.) as well as certain mechanisms established within the industry that artificially keep the international costs of maritime shipping low at the expense of environmental and labour concerns (McGuire and Perivier, 2011).

As has been assured for other transportation modes, for sustainability to be successfully implemented it is essential that its concept is adequately understood, quantified and applied (Zietsman, 2000). Thus, the aim of this chapter is to contribute to the discussion for defining and assessing the sustainability concept within the maritime sector by following its initial concept.

3.2 Sustainability Challenges in Maritime Transport

In the effort to define the maritime transport sustainability, it would be helpful first to identify some of the most significant environmental challenges this sector faces and some illustrative unsustainable shipping practises as well.

The main environmental issues of the maritime transport sector are currently the reduction of air emissions from international shipping and energy efficiency solutions form technical and operational perspective. The contribution of the shipping sector to gases and particles that impact the Earth‘s climate has only recently begun to be fully understood. In 2007, shipping was responsible for approximately 3.3 percent (over 1 billion tonnes) of global CO2 emissions (Buhaug et al, 2009). Recent official calculations made in the third Greenhouse gas study of IMO, reduce this figure to less than 3 percent (IMO, 2014). In the absence of emission reduction policies, and the continuance of business as usual practises in international shipping, emission scenarios predict a doubling to tripling of 2007 emission levels by 2050 (IMO, 2010).

Emissions from commercial shipping vessels contribute significantly to perturbations in air quality, visibility and climate. The link between Particulate Matter, (PM) emissions and health effects was recently assessed for global shipping emissions when it was estimated that up to 60,000 premature deaths result annually (Corbett et al., 2007), (Eyring et al., 2007). The primary reason for the negative effect of shipping emissions to health is that 70 percent of shipping activity occurs within 400 km of land (Corbett et al., 2007), (Wang et al., 2008) and major shipping ports are located in areas surrounded by large populations.

Considering that the introduction of new fuels in shipping is emerging slowly, the energy efficiency concepts are getting considerable acceptance. From operational point of view, energy efficiency often involves speed reduction (slow steaming), an option which also reduces air emissions at least at the ship level; nevertheless, other issues may arise from speed reduction (i.e. ship out of optimal condition), (Faber et al., 2010). The main drivers for slow steaming remain the market mechanisms especially when the global shipping industry faces an oversupply of ships (Platou, 2010) and the considerable savings in bunker fuels money offered by reduced speeds.

Ocean-going vessels are mainly following the regulatory framework enforced by the International Maritime Organization (IMO). IMO efforts to mitigate environmental impacts of emissions and wastes from global shipping try to keep pace with the growth of the industry and the evolution of emission and waste control technologies. It is evident that the shipping industry is taking quick steps for introducing technologies for the control of emissions (e.g. scrubbers, catalysts technologies, quality fuels), for energy efficiency, and for ballast water treatment and waste handling.

Enforcing new international agreements is however complicated by the complex relationships that exist between those nations to which most ships are registered and the large shipping interests (typically headquartered in other nations) that own most of the ships. The system of ships registration has been criticised for being fundamentally unsustainable since it allows the international shipping sector to avoid internalising its true environmental and social costs in market transactions (McGuire et al, 2011). An illustrative example of the above inefficiency is the current ship dismantling industry in S. Asian countries, which was settled due to the need of steel and recycled materials and the existence of poverty and availability of cheap (and childhood) labour. Methods applied in many ship-dismantling sites of countries such as Bangladesh, Pakistan, and India measured against general norms expected within the industrialised countries generally fail to comply with any environmental, safety or health standards in almost all respects. However, nearly 80 percent of the global volume of end of life ships is still heading to these countries for “recycling” providing this way an extra profit making opportunity to ship-owners (Ventikos and Chatzinikolaou, 2008).

Sustainability challenges refer also to Ports that tend to increase in size following the expansion of world trade and the trend to build larger ships. From economic perspective, this makes many ports attractive as economic growth poles and may also provide some social opportunities (e.g. job availability, accessibility). At the same time, port expansion poses environmental and social challenges since it becomes more difficult for port activities to integrate into urban environments. This is particularly due to the increased air, noise and optical pollution and annoying security standards of modern ports.

Other environmental issues within shipping are, oil pollution and handling of garbage, wastes and antifouling paints. The maritime industry has in general succeeded in reducing oil pollution over the last years (ITOPF, 2011), especially with respect to the accidental pollution. Still, evidence shows that there is an increasing tendency in operational (illicit) discharges in regional areas such the East Mediterranean (Topouzelis et al. 2007). Garbage and solid and nonoil liquid wastes from the daily operations of ships (some of them are not yet regulated) may be a negligible environmental issue in a global level but there are specific regional sea areas (e.g. Caribbean Sea, Alaska) facing major problems due to the large quantities of wastes produced by certain ship types (Chatzinikolaou et al, 2007).

The above represent only a short indication of sustainability challenges within shipping. More environmental, social and economic challenges of shipping are discussed and analysed in the following chapters.

3.3 Sustainability Definitions

3.3.1 Sustainability and sustainable development

Dealing with sustainability has become a fashion in recent years. It would be very difficult for one to find a research project, conference, policy action or other initiative within the broader transport sector that, in one way or another, did not include the term sustainability or sustainable development (Zegras, 2006). While the general idea of this concept is sound, since it emphasizes the integrated nature of the impact of human activities (Litman, 2007), it also establishes links with many issues of concern (i.e. poverty, environmental quality, safety and security, social equity, economic development and so on) and therefore has attracted the interest of many people with diverse backgrounds and objectives.

At the time that this study was contacted (2010 -2011), there was no globally accepted definition for sustainability or sustainable development in maritime transport or even in transport (Beatley, 1995), (Jeon, 2005). The most well-known definition for sustainable development is the one introduced by the World Commission on Environment and Development, (WCED, 1987), in the so called "Brundtland Report" which has set the original notion for this concept: *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*".

In a rough interpretation, sustainability or sustainable development can be seen as strictly scientific construct related to, for example, carrying capacities, ecosystem functioning and biological processes (Zegras, 2005). However, the initial “Brundtland” definition has offered plenty of room for various interpretations of the concept in the years followed. Many of these interpretations have extended the concept to include mainly institutional and political dimensions or various aspects of life and life systems. Inevitably, the concept of sustainability has become to mean different things to different people. These have made the terms of sustainability and sustainable development, subjective and user defined (Keiner et al., 2004).

As a result, presently there are numerous human activities, which perceive the term “sustainable development” as a vehicle to continue many and varied corporate and institutional interests whilst giving the impression of devotion in environmentally sound principles (Johnston et al., 2007).

Although the establishment of a standard framework in which sustainable development is considered is still missing, there seems to be a consensus that sustainable development should be made uniformly on at least three fronts or pillars: economy, society, and environment. A fashionable way of expressing these three pillars is known as People, Planet, Prosperity (or PPP or P3), where People represent the social pillar, Planet the environmental pillar, and Prosperity the economic pillar. Prosperity has replaced the term Profit (decision made at the World Summit on Sustainable Development in Johannesburg in 2002), to reflect that the economic dimension covers more than the company profit. Other well-known terms are the Triple Bottom Line (TBL) and the UN‘s Global Compact.

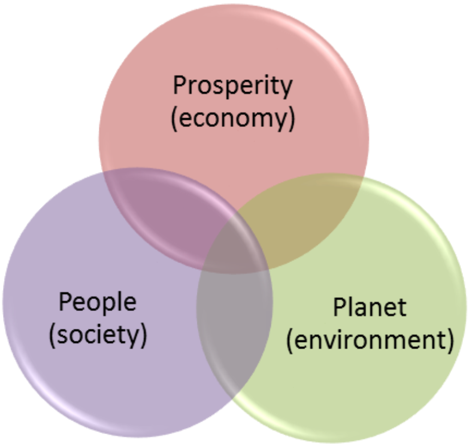


Figure 1: The three pillars of Sustainability

However, there are different opinions on the relation between the three pillars of sustainability. According to the Oregon Sustainability Act, there is an implicit hierarchy since the natural systems (the environment) are critical for the well-functioning of social systems (for example safe transport systems) which themselves are crucial for the economic systems productivity. Therefore this initiative argues that the sustainability hierarchy has to start from the environmental pillar.

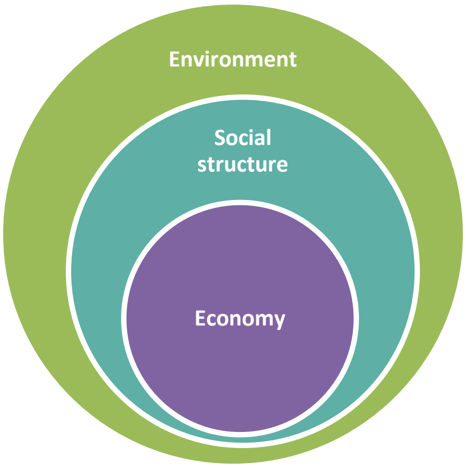


Figure 2: Proposed hierarchy for the sustainability pillars (adapted from Oregon Sustainability Act, 2009)

Many people accept that sustainability and sustainable development have the same meaning. However, a rational distinction between the two definitions states that sustainability is a condition in which economic, social and environmental factors are already optimized, taking into account indirect and long-term impacts, whereas sustainable development is a progress toward this condition of sustainability (Litman, 2010).

A well-established approach to define the concept of sustainability is the economists approach which distinguishes the concept into Weak Sustainability, (WS) and Strong Sustainability (SS), subject to the way that humans chose to utilise the natural capital (i.e. the range of functions the natural environment provides for humans and for itself), (Ekins et al., 2003).

Definitions of these two terms are provided below.

- Strong Sustainability (SS): This approach considers that the natural capital provides some functions that are not substitutable by manmade (produced) capital and therefore they should be maintained.
- Weak Sustainability, (WS): This approach considers that manmade (produced) capital of equal value can take the place of natural capital.

A general delineation between these two approaches of sustainability is presented in Table 1.

Table 1: Strong Sustainability vs. Weak Sustainability

Strong Sustainability	Weak Sustainability
Natural and manmade capital are complements	Natural capital and manmade capital are substitutes
All forms of capital should be kept intact	Only total capital stock should be kept intact
Not only an economic problem, but also a problem of maintaining non-replaceable recourses	Environment problems may always be treated as economic problems
Accepts precautionary principals & safe minimum standards	Accepts monetary valuation & cost-benefit approach

3.3.2 Transportation Sustainability

There is an extended scientific literature available on sustainable transportation the majority of which refers to the urban and road transportation and many definitions of this concept may be explored. Most of these definitions answer to the question what essentially is a sustainable transport system and therefore may be categorised as policy oriented definitions; however they do not answer to the question of how to make the system sustainable. To answer the later question for the sustainable transport systems an operational definition is required. Defining a concept in an operational manner is an important prerequisite before trying to measure this concept (Meier, 2002). Therefore, the focus here is to explore the existing operational definitions of sustainability or transportation sustainability in order to come up with an operational definition for “maritime transport sustainability”.

The literature review illustrates that many of the available definitions of transportation systems sustainability capture attributes of system effectiveness, and system impacts on the economy, environment, and social quality of life (Jeon, 2005). However, there seems to be a higher focus in addressing the effectiveness of the system as well as some of the resulting environmental impacts (mainly air quality impacts), and less of a focus on economic and social impacts.

The principle of “eliminating our contribution” has been proposed in the effort to avoid the above weakness and deliver an adequate operational definition for the concept of sustainability (Johnston et al. 2007). According to this approach, *operational sustainability principles should be developed with the aim to eliminate the human contribution to*:

1. …systematic increases in concentrations of substances from the Earth's crust.
2. …systematic increases in concentrations of substances produced by society.
3. …systematic physical degradation of nature.
4. …conditions that systematically undermine people's capacity to meet their needs.

This operational approach to sustainability has become known as “The Natural Step Framework” after the organization promoting it (TNS), (Robèrt et al., 2002). From the international organisations perspective, for example the World Bank has taken an economic oriented focus by emphasizing the efficient use of resources in the following three dimensions:

a. Economic & financial;
b. Environmental & ecological; and
c. Social.

In contrast, an operational definition of sustainable transport which focuses more on the environmental dimension of sustainable transportation has been proposed by the Organization for Economic Cooperation and Development, (OECD, 1996). This definition states that: “*An environmentally sustainable transport system is one that does not endanger public health or ecosystems and meets needs for access consistent with”:*

a. Use of renewable resources at below their rates of regeneration, and
b. Use of non-renewable resources at below the rates of development of renewable substitutes.

The OECD sustainable transport system approach is based on the World Health Organisation, (WHO) guidelines for air pollution, noise levels acidification and eutrophication as well as climate change and ozone depletion.

A well-known organisational perspective comes from the Centre for Sustainable Transportation of Canada, (CST), which has introduced the so-called comprehensive sustainable transportation definition. The CST definition has been given official status since the official EU description for sustainable transportation was taken almost word to word from it. These two similar statements constitute by far the most widely accepted definitions of sustainable transportation (Hall, 2002).

In the EU definition a sustainable transport system is defined as one that:

a. Allows the basic access and development needs of individuals, companies and societies to be met safely and in a manner consistent with human and ecosystem health, and promotes equity within and between successive generations;
b. Is affordable, operates fairly and efficiently, offers choice of transport mode, and supports a competitive economy, as well as balanced regional development; and
c. Limits emissions and waste within the planet's ability to absorb them, uses renewable resources at or below their rates of generation, and, uses non-renewable resources at or below the rates of development of renewable substitutes while minimising the impact on the use of land and the generation of noise.

This interpretation as other interpretations in the international literature generally observe the three basic principles (Figure 3) that a transport system should follow in order to be considered sustainable. Hence, these three principles are in harmony with the original definition of sustainable development given by the Brundtland Commission in 1987.

The first principle that a sustainable transport system should observe is the accessibility which corresponds to the ability (of humans in general) to obtain or have access to desired goods, services, activities and destinations.

The second principle that a transport system should accept and observe is the existence of resource constrains. These constrains reflect the natural limits of the environment. Accepting the existence of resource constraints by the transport system, (e.g. the shipping company) essentially means that measures should be in place for the sound use of non-renewable energy sources, for energy efficiency, and pollution reduction. The existence of constraints of social nature may be added in this second principle. An illustrative example of social constraints for a transport system are safety and security measures, which are both very important especially for the case of maritime transport.

The third principle of equity (or justice) requires the equal distribution of profits and impacts between the various population groups of the same generation but also future generations. For the case of transport, this reflects the need to understand that the development due to transportation should not pose negative impacts to the society in the long term. The process of transferring impacts of (the transportation) activity to other people not getting any benefit from this activity is called external cost and will be thoroughly examined in this thesis in the impact assessment of maritime transport.

Figure 3: Principles that a Sustainable Maritime Transport System need to observe

Accessibility is essentially the ability to obtain desired goods, services and activities and it will be further discussed in the following sections. The principal of equity essentially reflects the interaction between the other two principals particularly in the sense of intergenerational equity. In addition, equity also refers to a balanced distribution of transport benefits (reflected by access) and costs (reflected by various resources constrains) within the current generation (Zegras, 2005).

Cabezas-Basurko et al. (2008) are the first attempted to provide a definition for sustainable shipping or a sustainable waterborne transport. According to their approach a sustainable transport system could be better defined as “a cost-effective commercial activity, in which the environmental load is not bigger than that which the environment can currently and in the future bear, and that the social community (directly and indirectly) in contact with it is not being negatively affected”. They have also developed a conceptual method that enables studying and evaluating the performance in the three pillars of sustainability.

In closing this review of sustainable transport definitions and theoretical concepts, it is stated that none of the above definitions corresponds to a comprehensive operational definition of sustainable transport since their focus is more on the description of a sustainable transport condition rather than the course to get to this condition.

There are many definitions of sustainability and sustainable transport which however more or less agree that the goals of sustainability should spread in three areas of interest (i.e. economy, society, and environment). No standardised sets of indicators for the case of transport systems have been found in the literature review.

A comprehensive set of indicators for transport system planning is given by the Victoria Transport Policy Institute (Littman, 2018) together with the specific goals and objectives that these indictors serve.

Table 2: Indicators for a sustainable transport system (Adapted from Littman, 2016)

Sustainability target	Objective	Performance Indicator
I. Economic		
Economic productivity	Transport Systems efficiency. Transport system integration. Maximize accessibility. Efficient pricing and incentives.	1. Per capita GDP and income. 2. Portion of budgets devoted to transport. 3. Per capita congestion delay. 4. Efficient pricing (road, parking, insurance, fuel, etc.). 5. Efficient prioritization of facilities
Economic development	Economic and business development	6. Access to education and employment opportunities. 7. Support for local industries.
Energy efficiency	Minimize energy costs, particularly Petroleum imports.	8. Per capita transport energy consumption 9. Per capita use of imported fuels.
Affordability	All residents and potential users can afford access to basic (essential) services and activities..	10. Availability and quality of affordable modes 11. Portion of low-income households that spend more than 20% of budgets on transport.
Efficient transport operations	Efficient operations and asset management maximizes cost Efficiency.	12. Performance audit results. 13. Service delivery unit costs compared with peers. 14. Service quality.
II. Social		
Equity / fairness	Transport system accommodates all users, including those with disabilities, low incomes, and other constraints.	15. Transport system diversity. 16. Portion of destinations accessible by people with disabilities and low incomes.
Safety, security and Health	Minimise safety risk security risk, protect health and support physical fitness.	17. Per capita traffic casualty (injury and death) rates. 18. Traveller crime and assault rates. 19. Human exposure to harmful pollutants. 20. Portion of travel by walking and cycling.
Community development	Help create inclusive and attractive communities. Support community cohesion	21. Land use mix. 22. Walkability 23. Quality of transport infrastructure and surrounding environments.
Cultural heritage preservation	Respect and protect cultural heritage. Support cultural activities.	24. Respect and protect cultural heritage. 25. Support cultural activities.
III. Environment		
Climate change	Reduce global warming emissions Mitigate climate change impacts	26. Per capita emissions of global air pollutants (CO2, CFCs, CH4, etc.).

Prevent air pollution	Reduce air pollution emissions Reduce exposure to harmful pollutants	27. Per capita emissions of local air pollutants (PM, VOCs, NOx, CO, etc.). 28. Air quality standards and management plans.
Prevent noise pollution	Minimize traffic noise exposure	29. Transport noise levels
Protect water quality and minimize hydrological damages	Minimize water pollution. Minimize impervious surface area	30. Per capita fuel consumption. 31. Management of used oil, leaks and storm water. 32. Per capita impervious surface area.
Open space and biodiversity protection	Minimize transport facility land use. Encourage compact development. Preserve high quality habitat.	33. Per capita land devoted to transport facilities. 34. Support for smart growth development. 35. Policies to protect high value farmlands and habitat
IV. Planning		
Integrated, comprehensive and inclusive planning	Planning process efficiency. Integrated and comprehensive analysis Strong citizen engagement. Lease-cost planning (the most overall Beneficial policies and projects are implemented).	36. Clearly defined goals, objectives and indicators. 37. Availability of planning information and documents. 38. Portion of population engaged in planning decisions. 39. Range of objectives, impacts and options considered. 40. Transport funds can be spent on alternative modes and demand management if most beneficial overall.

3.4 Proposed Definition for Sustainable Maritime Transport System

Entering into the maritime sector some reasonable questions when trying to define sustainability may emerge. The first of these is whether there is any real value in trying to define and subsequently measuring the maritime transport sustainability. Other questions may refer to the scale of the experiment or time and geographical constraints. For example, whose sustainability do we wish to measure, the whole sector, a country sector, specific ship type, or of just a ship?

The answer to the first question derives from the fact that sustainability initiatives are already a reality in central policy, industry, research and other areas of the broader maritime transport sector and contributing to the process is at least useful. Hence, the necessity also derives from the fact that the environmental and social standards as well as the economic/financial practices within the shipping industry leave much to be desired even though some positive examples are already in place. These questions actually call for a robust operational definition of maritime transport sustainability, which will then be useful to establish a well-functioning framework for studying this concept.

As has been depicted in the previous paragraphs of this Chapter, when trying to get closer to an operational definition, one must discriminate between some different approaches.

With respect to the economic approach to the problem of transport sustainability, the key choice is whether the society believes that natural capital should be attributed with special protection, or whether other forms of capital, especially manmade (produced) capital, can substitute it or in other words whether people are willing to trade natural goods for money.

This is the choice between weak sustainability and strong sustainability, (Dietz et al., 2007), (Kosz, 1998). The operational definition presented here, is similar to the definition for urban transport that first drafted by Zegras (2005) and accepts the strong sustainability approach.

A central word included in the proposed definition is the word accessibility. Accessibility (or just access) refers to the ease of reaching goods, services, activities and destinations, which are named opportunities (Litman, 2011b). Accessibility is seen also in terms of potentials (opportunities that may be reached) or in terms of activity (opportunities that are reached).

Maintaining non-declining accessibility, increases the human capital because more opportunities are provided. The definition therefore, appreciates this way the fundamental role of (maritime) transport in the global economy and in human development in general.

Simultaneously, while increasing accessibility and human capital other capital stocks such as the natural capital (e.g. fuel consumption) and manmade capital decrease (e.g. land use). In addition, the initial notion of sustainable development requires that the welfare provided to the current generation by accessibility should not compromise the welfare of future generations. To address the aforementioned requirement, the concept of the strong sustainability is used. Dally (2006) introduced the concept of throughput as more useful and measurable compared to utility when we are talking about sustainability. He defined throughput as: *the entropic physical flow from nature‘s sources through the economy and back to nature‘s sinks. In his opinion, the throughput has to be sustained*. This equals to strong sustainability (intact natural capital).

Adopting the definition of Dally (2006) that sustainable development "*might be more fruitfully defined as more utility per unit of throughput*", Zegras (2005), has defined the sustainable transportation as "*more utility, as measured by accessibility, per unit of throughput, as measured by mobility*".

Taking into account the above meanings of accessibility and by observing the strong sustainability approach this dissertation introduces an operational definition of a sustainable maritime transport system, which is as follows (Chatzinikolaou and Ventikos, 2011):

Proposed Definition on a Sustainable Maritime Transport System
A Maritime Transport System is sustainable when it has the capability to offer and maintain non-declining and efficient accessibility by observing equity and resource constrains

An example of what is proposed by this definition is that a target of a sustainable maritime system should be less fuel consumption per movement and service provided or per accessibility derived. Therefore, the target is not the increased accessibility but the efficient accessibility.

The basic features of the definition for sustainable maritime transport that is proposed here, are the following:

- It integrates the basic principles of sustainable development (intergenerational equity, continuance of development)
- It is simple
- It is operational (can be measured)
- It may be applied in different scales within the maritime transport system (i.e. product scale/ship, fleet, sector, etc.).

3.5 Goals & Objectives of a Sustainable Maritime Transport System

The literature reveals that the transport sustainability is largely being measured by the system effectiveness and efficiency as well as by the environmental impacts of the system. The variances observed in the mission and policy priorities of several initiatives are accordingly reflected in the selection of indicators (JRC, 2007).

A general observation is that the indicators used for measuring the transportation sustainability are typically classified into the following four major categories (Jeon, 2007): transportation system effectiveness-related, economic, environmental, and socio-cultural/equity-related indicators.

Assessors sometimes focus on easy-to-measure impacts and objectives, while overlooking more-difficult-to-measure impacts and goals (Litman, 2006). For example, accessibility, one of the main goals of transport activities is difficult to measure; hence transport indicators systems tend to include traffic (vessels movement) and mobility indicators (the ability to move people and goods). This may reduce the range of impacts and solutions considered in transport planning (VTPI, 2002).

Another illustrative example is the use of Gross Domestic Product (GDP) as an indicator for measuring welfare. Welfare (as used by economists) refers to total human wellbeing and happiness. Economic policies are generally intended to maximize welfare, although this is difficult to measure directly. Instead, monetary income, wealth and productivity such as GDP, are used as economic indicators. These indicators can be criticized on several grounds (Dixon, 2004), (Carvalho, 2011), because they measure only market goods and therefore may overlook other factors that contribute to wellbeing such as health, friendship, community, pride, environmental quality, etc.

3.5.1 Sustainability goals

When trying to assess the performance of any system it is important to avoid confusing goals and objectives. Goals are what society ultimately wants. Objectives are things that help achieve goals, but are not ends in themselves and indicators are variables selected and defined to measure progress toward an objective (Litman, 2011a). A sound description of sustainability goals is given by Litman (2010) as shown in Table 3.

Table 3: Sustainability Goals (Adapted from Litman, 2010)

Economic	Social	Environmental
Productivity	Equity/fairness	Climate change prevention
Growth	Human safety & security	Pollution prevention
Resource efficiency	Community development	Conservation of non-renewables
Affordability	Cultural heritage preservation	Open space preservation
Operational efficiency	Labour rights protection	Biodiversity protection

An interpretation of goals and objectives for a sustainable transport system is provided by Jeon (2007). In this, there are three dimensions (economy, society, and environment) commonly considered as the essential dimensions of a sustainable transportation system. In each one of these dimensions' specific main goals to achieve sustainability are described (see Figure 4).

Zegras (2006) presented the Sustainability Indicator Prism that includes the hierarchy of goals, indexes, indicators, and raw data as well as the structure of multidimensional performance measures. In the four-layered pyramid, the top of the pyramid represents the community goals and vision, the second layer represents a number of composite indexes around the selected themes, and the third layer represents indicators or performance measures building from raw data at the bottom of the pyramid.

Figure 4: Comprehensive Sustainability – Goals in the three dimensions

Zietsman et al. (2003), introduce a corridor-level index that incorporates travel rates, fuel consumption, local pollutant emissions, travel cost, and safety using multi-attribute utility theory. An international comparative index (Rassafi, 2004) has been developed by using the concordance analysis technique to evaluate transportation system sustainability of selected countries.

The literature on sustainability measurements shows that there is a variety of approaches subject to the targets of work. The challenge in the creation of indicators is not only to take into account environ-mental, economic and social aspects. Although, it could be argued that indicators could serve supplementary to each other, sustainability is more than an aggregation of the important issues, it is also about their inter-linkages and the dynamics developed in a system (Singh et al. 2009).

On September 2015, the UN adopted a set of 17 sustainable development goals with 169 associated targets that came into effect from January 2016. The UN proposed this agenda to mobilise the global actions from all for the next 15 years.

The 17 goals for sustainable development are listed below.

1. Goal 1. End poverty in all its forms everywhere
2. Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3. Goal 3. Ensure healthy lives and promote well-being for all at all ages
4. Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5. Goal 5. Achieve gender equality and empower all women and girls
6. Goal 6. Ensure availability and sustainable management of water and sanitation for all
7. Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all
8. Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9. Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
10. Goal 10. Reduce inequality within and among countries
11. Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable
12. Goal 12. Ensure sustainable consumption and production patterns
13. Goal 13. Take urgent action to combat climate change and its impacts
14. Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15. Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16. Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17. Goal 17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

Figure 5: The United Nations Sustainable Development Goals (UN, 2018)

In 2017, the DNV.GL classification society published a report to address the relevance of the UN SDGs for the shipping industry. The report explored the potential contributions of international shipping to the SDGs and proposed five main opportunity areas where the shipping industry can effectively contribute. Overall, the view of DNV.GL is that shipping has a critical role to play in the effort to meet the SDGs, due to its international nature and the vital role that this sector has established in the global economy (DNV.GL, 2017).

There is evidence that shipping companies are introducing practices towards SDGs as a response to the launching of the UN initiative. Pakbeen (2018), reviewed the sustainability and responsibility reports of selected cruise lines and concluded that shipping companies in this sector show significant similarities in their sustainability approach. In his paper, Pakbeen identified companies (i.e. Costa Cruise Line) that have a direct reference to SDGs in their recent sustainability reports.

3.5.2 IMO perspective

Following an announcement from its secretary general in the proceedings of the Conference on Sustainable Development (UNCSD, or Rio+20) in 2012, IMO launched in 2013 its official view for the "sustainable maritime transport system". This view is included in the document entitled "A Concept of a Sustainable Maritime Transport System" which reflects the first reaction of IMO to the criticism from the international community against the international shipping industry for not seriously contributing to the global efforts as regards sustainability. The document includes a definition for the concept of a sustainable maritime transport system which is as follows: "*the Maritime Transportation System must deliver safe, secure, efficient and reliable transport of goods across the world, while minimizing pollution, maximizing energy efficiency and ensuring resource conservation*".

In the above document, IMO generally accepts the definition given for sustainability by the Brundtland Report, entitled "Our Common Future", in 1987. IMO also accepts the three pillars of sustainability, namely the economic, environmental and social dimensions, as equally important also in the context of maritime transport.

The main outcome of the Rio+20 conference was the text called 'The Future We Want' which covers the themes of energy, transport, green economy and looks to future implementation by way of sustainable development goals (SDGs). To create these SDGs, the UN hopes to establish a "transparent intergovernmental process", a process which will involve input from all stakeholders the shipping industry included. IMO's vision for these goals corresponds to a concept with the following seven main areas of future actions towards a sustainable maritime transport system:

1. Energy efficiency, including technical and operational measures to reduce emissions from ships;
2. new technology and innovation and the promotion of green technology;
3. maritime education and training,
4. maritime security, including anti-piracy initiatives;
5. maritime traffic management and the promotion of marine electric highways;
6. the improvement of maritime infrastructure and lastly; and
7. the promotion of global standards.

3.5.3 Industry perspective

Some initiatives have been launched for addressing specific sustainability goals.

The Sustainable Shipping Initiative (SSI) is a consortium of high-profile industry stakeholders who have agreed to define tangible milestones across selected areas of sustainability in order to meet the so called by them 2040 Vision. Members include shipping companies (MAERSK), Classification Societies, shipbuilders and NGOs.

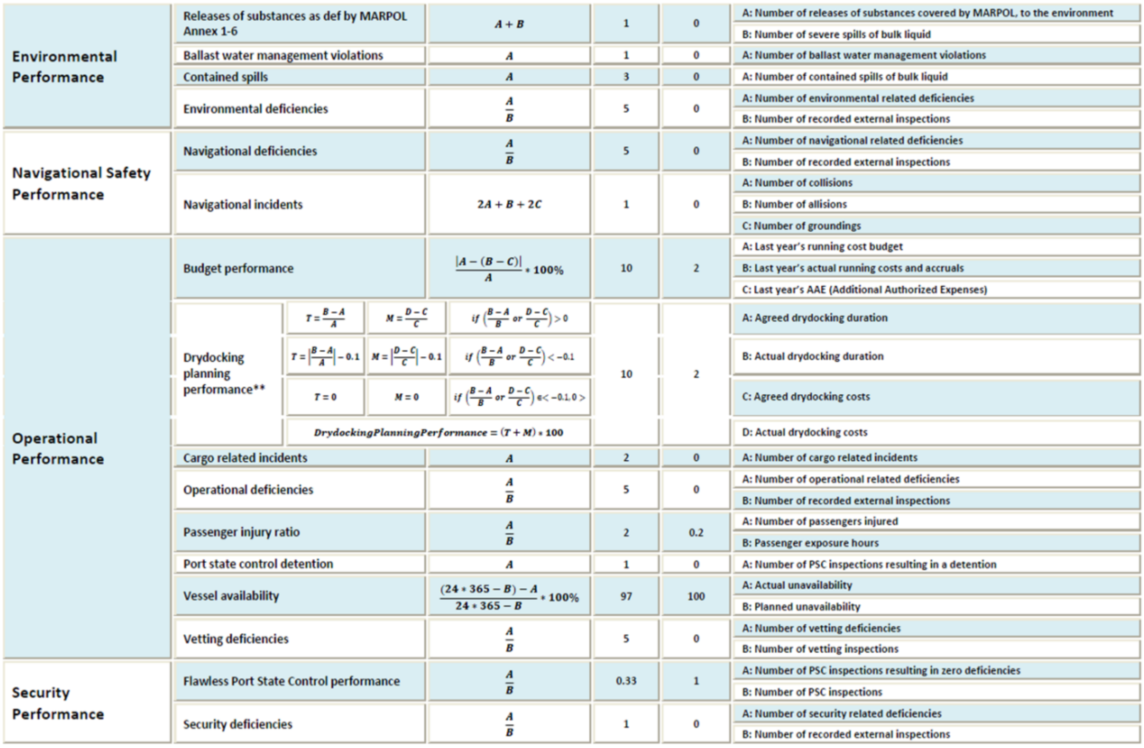
The vision of the SSI identifies the following areas of actions which illustrate how this initiative understands sustainable shipping (SSI, 2018):

1. *Changing to a diverse mix of energy sources, using resources more efficiently and responsibly, and dramatically reducing greenhouse gas intensity;*
2. *Providing safe, healthy and secure work environments so that people want to work in shipping, where they can enjoy rewarding careers and achieve their full potential;*
3. *Earning the reputation of being a trusted and responsible partner in the communities where we live, work and operate;*
4. *Developing financial solutions that reward sustainable performance and enable large-scale uptake of innovation, technology, design and operational efficiencies;*
5. *Transparency and accountability drive performance improvements and enable better, sustainable business decision-making;*
6. *Proactively contributing to the responsible governance of the oceans.*

In May 2011 SSI launched a Case for Action which explored the social, environmental and economic challenges the industry faces and how best to react to them. They have also established a roadmap for what the sustainable shipping industry will require by 2040. (http://www.ssi2040.org/).

Another illustrative example from the industry is the indicator system developed by InterManager (InterManager, 2018) which is focused on the performance assessment of the ship during her operational life against a number of identified Key Performance Indicators, KPIs, which are quantifiable using ship data. This system represents an illustrative example of subjective take-up of the notion of sustainability, narrowly defined with relatively easy to measure parameters and limited only to internal issues that concern a ship management company.

Figure 6: The InterManager indicator system (InterManager, 2011)



Environmental Performance	Releases of substances as def by MARPOL Annex 1-6	$A+B$	1	0	A: Number of releases of substances covered by MARPOL, to the environment B: Number of severe spills of bulk liquid
	Ballast water management violations	A	1	0	A: Number of ballast water management violations
	Contained spills	A	3	0	A: Number of contained spills of bulk liquid
	Environmental deficiencies	$\frac{A}{B}$	5	0	A: Number of environmental related deficiencies B: Number of recorded external inspections
Navigational Safety Performance	Navigational deficiencies	$\frac{A}{B}$	5	0	A: Number of navigational related deficiencies B: Number of recorded external inspections
	Navigational incidents	$2A+B+2C$	1	0	A: Number of collisions B: Number of allisions C: Number of groundings
Operational Performance	Budget performance	$\frac{\|A-(B-C)\|}{A} * 100\%$	10	2	A: Last year's running cost budget B: Last year's actual running costs and accruals C: Last year's AAE (Additional Authorized Expenses)
	Drydocking planning performance**	$T=\frac{B-A}{A}$ $M=\frac{D-C}{C}$ $if\left(\frac{B-A}{B}\ or\ \frac{D-C}{C}\right)>0$ $T=\left\|\frac{B-A}{A}\right\|-0.1$ $M=\left\|\frac{D-C}{C}\right\|-0.1$ $if\left(\frac{B-A}{B}\ or\ \frac{D-C}{C}\right)<-0.1$ $T=0$ $M=0$ $if\left(\frac{B-A}{B}\ or\ \frac{D-C}{C}\right)\in<-0.1,0>$ $DrydockingPlanningPerformance=(T+M)*100$	10	2	A: Agreed drydocking duration B: Actual drydocking duration C: Agreed drydocking costs D: Actual drydocking costs
	Cargo related incidents	A	2	0	A: Number of cargo related incidents
	Operational deficiencies	$\frac{A}{B}$	5	0	A: Number of operational related deficiencies B: Number of recorded external inspections
	Passenger injury ratio	$\frac{A}{B}$	2	0.2	A: Number of passengers injured B: Passenger exposure hours
	Port state control detention	A	1	0	A: Number of PSC inspections resulting in a detention
	Vessel availability	$\frac{(24*365-B)-A}{24*365-B} * 100\%$	97	100	A: Actual unavailability B: Planned unavailability
	Vetting deficiencies	$\frac{A}{B}$	5	0	A: Number of vetting deficiencies B: Number of vetting inspections
Security Performance	Flawless Port State Control performance	$\frac{A}{B}$	0.33	1	A: Number of PSC inspections resulting in zero deficiencies B: Number of PSC inspections
	Security deficiencies	$\frac{A}{B}$	1	0	A: Number of security related deficiencies B: Number of recorded external inspections

The system is not mandatory, however due to the support it enjoys from leading representatives in international ship management it aspires to become an international standard for the measurement of the operational vessel's performance. Specifically, the system contains definitions and mathematical expressions as indicators and uses minimum and maximum limits of measuring these indicators with the aim of:

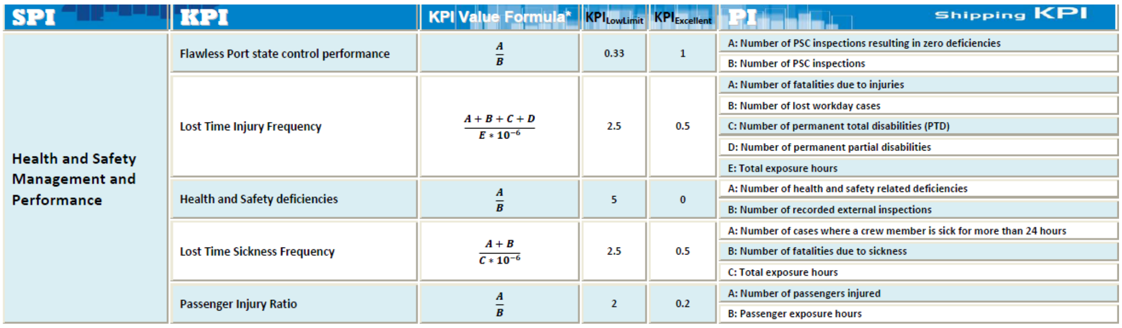
- Performance improvement of ship (or fleet of ships) managed, through the monitoring and continuous gathering of information relevant to the examined indicators, and
- Provision of a trusted information platform for the activity of ships and communication of the results to various internal and external bodies (at company level, partners, customers and society).

The framework consists of categories of indicators, ranked and grouped into Shipping Performance Indexes (SPI), Key Performance Indicators (KPI), and Performance Indicators (PI). A Shipping index Performance Index (SPI) is formed by connecting a group of KPIs, representing the ability of the company to the individual category of indicators. The thematic SPI indicators identified by this framework is as follows:

1. Environmental Performance
2. Health & Safety Performance
3. Security Performance
4. Technical Performance
5. Human Resources Management Performance
6. Navigational Safety Performance
7. Operational Performance
8. Other

The last category includes indicators that cannot be grouped in any of the previous (e.g. Port state control deficiency ratio). Key indicators Performance Indicators (KPIs), are expressions of the performance in a specific subject area. The combined values of indicators of one area form the value of the overall SPI index (e.g. Health and Safety Management and Performance). Each KPI index is a mathematical expression of values returned to Performance Indicators (PI). Examples of indicators system KPIs: Budget performance, performance planning and Dry-docking Vessel availability.

Table 4: Example of SPI, KPI and PI indexes (InterManager, 2011)



SPI	KPI	KPI Value Formula*	$KPI_{LowLimit}$	$KPI_{Excellent}$	PI
Health and Safety Management and Performance	Flawless Port state control performance	$\frac{A}{B}$	0.33	1	A: Number of PSC inspections resulting in zero deficiencies
					B: Number of PSC inspections
	Lost Time Injury Frequency	$\frac{A+B+C+D}{E*10^{-6}}$	2.5	0.5	A: Number of fatalities due to injuries
					B: Number of lost workday cases
					C: Number of permanent total disabilities (PTD)
					D: Number of permanent partial disabilities
					E: Total exposure hours
	Health and Safety deficiencies	$\frac{A}{B}$	5	0	A: Number of health and safety related deficiencies
					B: Number of recorded external inspections
	Lost Time Sickness Frequency	$\frac{A+B}{C*10^{-6}}$	2.5	0.5	A: Number of cases where a crew member is sick for more than 24 hours
					B: Number of fatalities due to sickness
					C: Total exposure hours
	Passenger Injury Ratio	$\frac{A}{B}$	2	0.2	A: Number of passengers injured
					B: Passenger exposure hours

Even if there have been identified many indicators suitable for use in the maritime transport there are no available indicator frameworks explicitly for this sector. Thus, since indicators should be constructed within a coherent framework (i.e. the scale in which the problem should be studied) and this network has not been formulated yet it is decided not to propose any framework of indicators at this paper.

The development of the framework for assessing sustainability in accordance to the principals under which the definition of sustainable maritime transport has been formulated is being elaborated in more detail in the following chapters of this dissertation.

4. LIFE CYCLE THINKING – LIFE CYCLE ASSESSMENT

Summary

This Chapter discusses the Life Cycle Thinking concept. Life Cycle Thinking is the conceptual basis on the road to sustainability assessments. It considers the full life cycle of the product/process and it aims at a holistic evaluation of environmental aspects included in life cycle stages

There is a growing interest in analysing systems from a life cycle perspective which is demonstrated by the fact that in recent years, there are major official initiatives launched for this concept at European and global level.

The link between sustainability and life cycle thinking is first presented. Then the methodology of Life Cycle Assessment is described. A literature review with applications of the LCA method in ships follows and finally, the most important results from this review are drafted.

Acknowledgments

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2. Part of the work included in this chapter was conducted in the context of the research project “EnviShipping: Environmental Footprint of Ships from a Life Cycle Perspective”, a multi – partner project funded by the General Secretariat of Research and Technology.

Publications from this Chapter

1. **Chatzinikolaou, S. and Ventikos, N.P., (2014)** “Applications of Life Cycle Assessment in Shipping” in Proceedings of the 2nd Int. Symposium of Naval Architecture and Maritime, YTU GIDF, Istanbul, 23-24 October 2014

4.1 Introduction

As already highlighted in the previous Chapter, preservation is a central idea in the notion of sustainability. Therefore, the sustainable system and its consequent goals and objectives should have the ability to be maintained. As a result, the time perspective should be carefully considered when the sustainability assessment of systems is to be addressed.

The Life Cycle Thinking approach represents a transition from traditional environmental protection strategies towards the new concept of sustainability. This theoretical concept also reflects the growing awareness of modern societies about the real life cycle impacts of products and services. The full life cycle of the system, (i.e. the ship) is being considered in such an analysis: from the extraction of resources and raw material production, through transportation, assembly, operational life, up to the recycling and final disposal of wastes.

Significant benefits evolve when studying industrial systems in a life cycle perspective; for instance unwanted shifts of environmental impacts from one stage of the life cycle to another are prevented or weak environmental processes within the life cycle chain can be identified. Most importantly, the life cycle approach is particularly relevant when the environmental effects of the system are to be addressed.

The growing interest in analysing systems from a life cycle perspective is demonstrated by the fact that in recent years, there are major official initiatives launched for this concept at European and global level. The European Platform of Life Cycle Assessment (EPLCA, 2018) run by the Joint Research Centre (JRC), is the official EU initiative created to facilitate communication on life-cycle data and commence a co-ordination scheme involving both ongoing data collection efforts in the EU and existing harmonisation projects.

The United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC), launched another major initiative cooperatively namely the UNEP/SETAC Life Cycle Initiative (UN, 2018). The mission of this initiative is to bring together different science-based Life Cycle approaches worldwide and explore the possibilities to achieve a global consensus on how to use these methods.

The Life Cycle Thinking approach is one of the most important amendments in the revised ISO 14001:2015, launched in September 2015. In particular, the revised version of this standard introduces the Life Cycle Perspective, an approach that calls for attention to be paid to safeguarding the environment in all phases of production:

- Design and development
- Identifying raw materials
- Packaging and distribution
- Reuse and recycling
- Final disposal.

According to the new ISO 14001:2015, the Life Cycle Perspective places greater emphasis on the environmental requirements involved when procuring goods and services, and when controlling processes that are outsourced.

This perspective translates into an explicit normative requirement for:

- Controlling processes outsourced
- Determining environmental requirements for procurement
- Considering the environmental requirements for development, delivery and end-of-life treatment of the products / services
- Given the need to provide information on the potential environmental impacts during delivery and end-of-life treatment of products and services.

4.2 Assessment Concepts for Sustainability

The real and substantial implementation of the sustainability concept remains a challenge. One core question of this challenge is how sustainability performance can be measured, especially for products and processes.

Life Cycle Thinking is the conceptual basis on the road to sustainability assessments. It considers the full life cycle of the product/process and it aims at a holistic evaluation of environmental aspects included in life cycle stages. Finkbeiner (2010) uses the Maslow pyramid concept for physiological needs and adapts it to sustainability goals and assessments. While Maslow uses needs such as food, breathing at the bottom of his physiological pyramid the Sustainability Assessment pyramid according to the authors approach starts at the bottom with the life cycle thinking approach. On the way to the top, one can see single-issue methods like Carbon Footprint, Life Cycle Assessment, and Eco-Resource Efficiency and finally Life Cycle Sustainability Assessment, which is placed at the top of the pyramid, makes the holistic assessment.

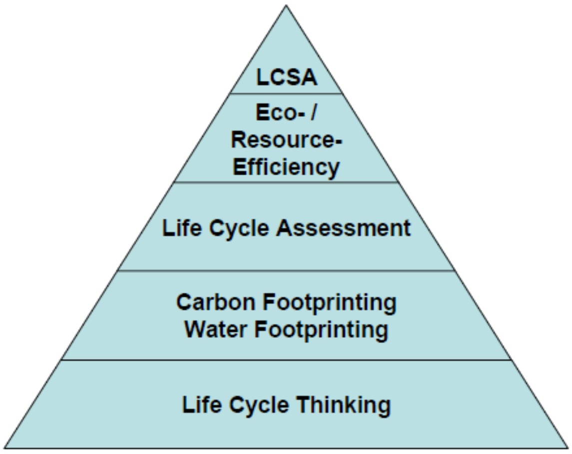

Figure 7: Adaptation of Maslow's pyramid for life cycle sustainability assessment approaches (Finkbeiner et al, 2011)

Environmental System Analysis (ESA) is the broader area of science that deals with the assessment of the interaction between human-made systems and the environment. A large number of ESA tools are available which may be divided into procedural and analytical tools. Procedural tools focus on improving the procedures leading to decision-making, while analytical tools provide information that may be utilized as means of communication, optimisation of the studied system, comparisons of different alternatives for the system, etc. (Finnveden et al, 2005).

There are available techniques that address the different dimensions of sustainability that take into account the time parameter. A method used for environmental reporting is the Corporate Social Responsibility (CSR). Although there are many available definitions (Dahlsrud, 2008), CSR in general is a non-standardised reporting procedure for companies containing some social, environmental or social information of business operations on a voluntary basis.

4.3 Life Cycle Assessment

The Life Cycle Assessment (LCA) method is an analytic ESA technique that is widely used for assessing the environmental impacts of technologies and products. An often-quoted definition of LCA is the one provided by the ISO standard: LCA is the “*compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 14040, 2006)”.*

Recently, the LCA method has gained wide acceptance as a suitable tool for analysing the impact that different solutions have on their external environment throughout the duration of their lifetime (Ellingsen H. et al, 2012). LCA is a structured method for calculating a product’s environmental load throughout all its phases; i.e. from the extraction of raw material through production, distribution, use and to recycling and the treatment of waste. One of the most important benefits of an LCA is that it allows studying an entire product system hence avoiding potential sub-optimization that could result if only a single process were the focus of the study. An effective LCA allows analysts to (EPA, 2006):

- Calculate a product’s environmental impact
- Identify the positive or negative environmental impact of a process or product
- Find opportunities for process and product improvement
- Compare and analyse several processes based on their environmental impacts
- Quantitatively justify a change in a process or product

The LCA method initially developed for the environmental assessment of industrial products in the 1960’s. The term ‘product’ can include not only product systems but also service systems, or processes. Since its beginning, the method has been improved considerably and numerous LCA studies have been conducted in different industries and explicitly in transportation.

An ISO standard (ISO 14040 – 14044) is available for LCA that consists of a theoretical framework, terminology and some methodological choices. However, this does not necessarily mean that LCA methods are standardised in detail. Within the document of the ISO 14040, it is clearly stated that ‘there is no single method for conducting an LCA (ISO, 2006).

4.3.1 Structure of the Life Cycle Assessment (LCA) Methodology

The LCA process usually consists of four main components: goal definition and scoping, inventory analysis, impact assessment, and interpretation as illustrated in Figure 8:

1. Goal Definition and Scoping: Definitions of the product, process or activity. Establishment of the context in which the assessment is to be made and identification of the boundaries and environmental effects to be reviewed for the assessment.
2. Life Cycle Inventory (LCI): Identification and quantification of energy and materials use and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).
3. Life Cycle Impact Assessment (LCIA): Assessments of the potential human and ecological effects of energy and material usage from environmental releases identified in the inventory analysis.
4. Interpretation: Evaluation of the results of the inventory analysis and impact assessment in order to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate these results. Communication of the results to the interested parties.

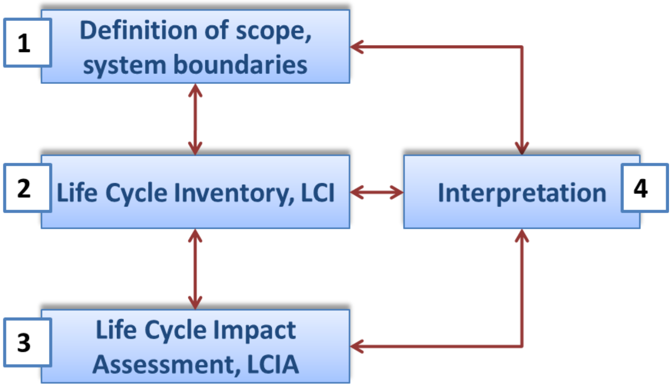

Figure 8: Phases of Life Cycle Assessment (adapted from: Hou, 2011)

The Life Cycle Inventory (LCI) of the LCA involves the process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity. Without a valid LCI, no basis exists to evaluate comparative environmental impacts or potential improvements. The level of accuracy and detail of the data collected is reflected throughout the remainder of the LCA process. As a basis for the formulation of the Inventory flow diagrams should be developed which map the inputs and outputs to a process or system. The “system” or “system boundary” varies for every LCA project. The goal definition and scoping phase establishes initial boundaries that define the processes to be included in a particular LCA; these are used as the system boundary for the flow diagram.

To obtain the data needed, several extensive databases and software applications are available and may be used. These include data based on observations, quantitative research, and manufacturer information to calculate national averages. However, the limitations of the method are mainly subject to the data availability. Other regular limitations of the method are the recourse and time constrains. LCA may be complicated and time consuming especially when the system examined consists of many separate sub-systems.

4.3.2 Life Cycle Impact Assessment in LCA

The Life Cycle Impact Assessment (LCIA) phase of an LCA is the evaluation of potential human health and environmental impacts of the resources and releases identified during the LCI. Impact assessment should address ecological and human health effects; it should also address resource depletion.

The Life Cycle Impact Assessment may be conducted in the following steps:

a. Identification of Impact Categories - identifying relevant environmental impact categories (e.g., global warming, acidification, toxicity, eutrophication etc.).
b. Classification - assigning LCI results to the impact categories (e.g., classifying carbon dioxide emissions to global warming).
c. Characterization - modelling LCI impacts within impact categories using science-based conversion factors (e.g., modelling the potential impact of carbon dioxide and methane on global warming).
d. Normalization - expressing potential impacts in ways that can be compared (e.g. comparing the global warming impact of carbon dioxide and methane for the two options).

Impact assessment is the subject of Chapter 9 and Chapter 10; therefore, the different approaches and tools available for assessing the impact of maritime transport systems will be covered in detail in this chapter.

4.4 Sustainability and Life Cycle Assessment

The LCA is not capable of determining which product or process is the most cost effective or works in a more efficient way. Therefore, the information developed in an LCA study should be used as one component of a more comprehensive decision process assessing the trade-offs with cost, performance and social aspects.

The analysis following the principles of sustainability requires that the product or system (e.g. ship system, or maritime transport system) which is under the spotlight to be examined in the three pillars of economy, society and the environment. Overriding principle for the prosperity and progress of the society is the preservation of the natural environment and equality. The traditional concept of environmental protection accepts measures to reduce the environmental impact of human activities (Finkbeiner et al, 2010). The contemporary methodological approach consists in the overall analysis and improvement of the three dimensions of sustainability in the life cycle of the system (construction – operation – recycling). This approach allows to include additional cost/benefit parameters that are usually omitted in traditional studies. Figure 9, describes the differences between the traditional perception (blue line) where only private costs are counted, and more recent concepts (red line) where cost and benefits are expanded to include the so called external costs or externalities created during the life cycle of the product or system. These external costs will be further examined in following chapters of this thesis.

Similar to LCA which deals with the environmental notion of sustainability, other life cycle methods are focusing on the two remaining notions of this concept i.e. the economy and the society.

Figure 9: Externalities in connection with the sustainability pillars (UNEP/SETAC, 2011)

The latest developments in life cycle analysis refer to the preparation of a framework for a simultaneous analysis of the dimensions of sustainability (Heijungs et al, 2009) namely:

1. Life Cycle Assessment, LCA (environmental dimension)
2. Life Cycle Costing, LCC (economic dimension)
3. Social Life Cycle Assessment, SLCA (social dimension)

The Social Life Cycle Assessment (SLCA) is a recently introduced methodology to assess the social impacts throughout a product’s life cycle. SLCA is presently at an early stage of development and several matters have still to be tackled. The most difficult of these matters is the quantification of social performance. Since social aspects are often of qualitative nature and could be highly subjective, their assessment is not a straightforward process. Issues faced within an SLCA often require a consensus on the impact categories to be included in the assessment and how to measure these. In the effort to employ a more analytical approach and quantify the social impacts the challenge is to avoid making assumptions which could result in a simplified social life cycle model (Heijungs et al, 2009).

The Life Cycle Costing (LCC) is the method used for assessing the total costs of a product, process or activity discounted over its entire life span (Ness et al., 2007). As a tradition, LCC has been used for investment purposes to rank different investment alternatives, supporting this way decisions on the best alternative. However, recently it has also emerged as a potential tool for the evaluation of the second dimension of sustainability, i.e. economic aspects associated with a product’s life cycle (Rebitzer and Seuring, 2003).

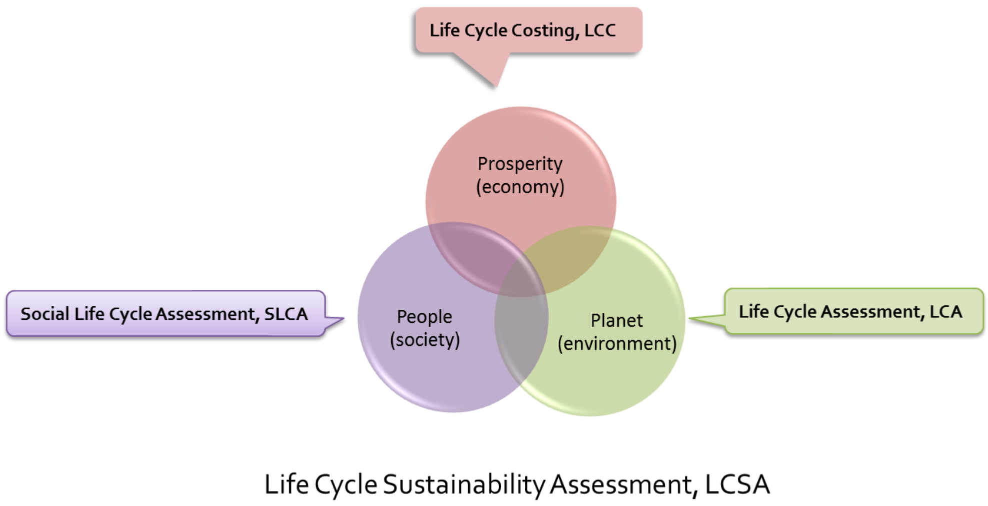

Figure 10: Sustainability Assessment Concept (Adapted from Zamagni et al., 2009)

A first attempt for developing an integrated framework for the analysis of sustainability has been recently proposed, namely the Life Cycle Sustainability Analysis (LCSA). The LCSA framework broadens the scope of current LCA from mainly environmental impacts only, to covering all three dimensions of sustainability (environmental, social, and economic). It also broadens the scope from predominantly product-related questions (product level) to questions related to sector (sector level) or even economy-wide levels (economy level). In addition, it deepens current LCA to include other than just technological relations, e.g. physical relations (including limitations in available resources and land), economic and behavioural relations, etc. (Zamagni et al, 2009).

The international initiative that deals with the incorporation of the concept of sustainability in life cycle assessment methodology is the UNEP/SETAC Life Cycle Initiative created with the collaboration of UNEP (United Nations Environmental Programme) and SETAC (Society for Environmental Toxicology and Chemistry).

SETAC has published a code of practice for environmental life-cycle costing (LCC), which provides a framework for evaluating decisions with consistent, but flexible systems boundaries as a component of product sustainability assessments (Swarr et al, 2011). The main objective of the code is to provide readers with a solid understanding of how to apply LCC in parallel with LCA to stimulate additional case studies and peer-reviewed research to further refine the methodology. The code of practice is based on a conceptual framework for life-cycle sustainability assessment (LCSA) that allows for a separate analysis in each one of the three pillars of sustainability, environment, economy, and society. The integration is left to the analyst who has to decide on the weighting of the three dimensions to arrive in a final overall figure for sustainability assessment.

The establishment of a conceptual framework that would broaden and deepen the LCA method was the main goal of the Coordination Action for innovation in Life Cycle Analysis for Sustainability, (CALCAS). CALCAS was a pan-European project, financed by the Sixth Framework Programme of the European Commission. Results of the project included strategies for new LCA and definition of medium-and long-term research lines in terms of research road maps for realising priorities in specific FP7 research programmes (Heijungs et al, 2009). In the CALCAS project the researchers stress that LCA, LCC and SLCA can be seen as three ways of looking at the same system and that allocation, treatment of time and other boundary selection issues should also be treated in distinct manner (Zamagni et al, 2009).

It is acknowledged, that the conceptual framework for life cycle sustainability needs further scientific elaboration to rise to consistency. A reasonable justification for this is that sustainability is more than just the summation of environmental, economic and social impacts. Interconnections between the three dimensions that exist within the examined system should be carefully observed. Some theoretical frameworks for assessing sustainability are available for other modes of transport (Zegras, 2006).

There are identified efforts to formulate the framework for sustainability for the maritime transport sector however, these are currently in conceptual stage. Cabezas-Basurko et al (2008), proposed a combination of available techniques for the development of a framework for analysis of the ship (as a product) in a life cycle perspective taking into account the three dimensions of sustainability. Their model also treats separately the three pillars (Cabezas-Basurko et al, 2008).

A generic conclusion from this review is that the maturity of methods and tools is different for the three sustainability dimensions (Finkbeiner et al, 2010). The environmental dimension can be covered quite well today with existing frameworks and available evaluation methods. The economic perspective is quite well covered in the case of internal costs (in a similar approach to a cost benefit analysis). However, if broader costs are to be considered (the so called external costs) the maturity of LCC is not that obvious. For the social perspective of life cycle analysis indicators and social data inventories and evaluation methods still require major scientific progress.

4.5 LCA Studies in Maritime Transport

Within the maritime transport sector, initial LCA studies have been conducted in the 1990’s. These studies have demonstrated and confirmed that the LCA method may well be employed for environmental life cycle evaluation of a ship. The most illustrative of these studies concern a Screening LCA method (which is a simplification of the LCA method) applied on a RO-RO passenger vessel (Johnsen and Fet, 1998). Authors of the aforementioned study commented that the LCA method is very time consuming and methodological simplification is needed. However, by following the break – down approach which essentially means breaking the ship – system into sub – systems (i.e. hull, machinery, equipment for cargo etc.) the assessment may become straightforward and effective. It is highlighted that this break down might not always be helpful since other problems such as bad data quality and inconsistency in the system boundaries might lead to uncertain results. The unavailability or bad data is especially the case in the construction and dismantling – recycling stages of ship’s life. Finally, the authors stated that evaluation techniques within LCA should be used very critically. This study is considered as the basis for later LCA studies which have utilised the same methodological framework in order to evaluate the ship’s environmental performance in a life cycle perspective.

Another LCA application within the maritime sector made comparisons between intermodal and traditional transportation, and examined the environmental load of different ship types (Holmegaard-Kristensen, 2002).

Several dedicated LCA software have been developed to assess the environmental impact of a ship. The Norwegian University of Science and Technology developed a dedicated tool for fishing vessels (Ellingsen et al, 2002). The National Maritime Research Institute of Japan has investigated the environmental impact of different cargo vessels (Kameyama, 2004). A consortium of Swedish maritime organisations has launched the so called LCA-Ship, a life cycle design tool for evaluating the energy efficiency of ships (Jiven et al, 2004). The above LCA tools are based on the SimaPro® software platform that is the most widely used commercial tool for life cycle analysis applications.

The software SSD after "Sustainable Ship Design" which is also based on the SimaPro® software platform has been developed by environmental consultants (EVEA), and is commercially available today as design tool for designers, shipyards, suppliers and researchers. The goal of this product was not to perform a full ship LCA, but to evaluate different "green" technologies in terms of environmental impacts in a life cycle perspective. Therefore, the SSD tool assesses the environmental benefits of a technical solution for one sub system on a specific ship design without going through the detailed LCA of the whole ship. The software was built in association with shipbuilders and subcontractors who supplied data on their technologies. Developers claim that the software offers a simple – but decisive design criterion for the selection of environmental alternatives depending on a unique ship energy efficiency index (Tincelin et al, 2010).

In another LCA study it was analysed the superstructure of a cruise ship (Hou, 2011). This study assessed in a comparative manner the environmental impact of different superstructure materials (traditional steel and aluminium vs new-type composite sandwich material).

Recent life cycle studies have focused on the area of marine fuels. Ryste, (2012), has used the LCA framework to conduct a life cycle analysis of the bunkering process of LNG as marine fuel looking, in particular, to the climate change impacts of this type of fuel. The International Council on Clean Transportation, ICCT (2013) has recently published an analysis of the life cycle greenhouse gasses and the possible benefits of using LNG as an alternative marine fuel. A comparative LCA study has examined, in a life cycle perspective, the impact of LNG and HFO used as marine fuels (Laugen, 2013). Comparisons of different options of marine fuels (HFO, MGO, gas-to-liquid fuel, and LNG, combined with two exhaust abatement techniques) has been performed in another study, by using the life cycle approach with the necessary steps from extraction of raw material to transportation of one tonne cargo in one km on a Ro-RO vessel (Bengtsson et al., 2011).

There are several studies in the literature dealing with environmental loads of maritime transport in a life cycle perspective without making use of the standardised LCA method or dedicated software. One of these studies investigated how the average annual cost of ship transport varies with the corrosion additions elected at the design stage. The results clearly indicated that ships built with sufficient corrosion allowances, truly adequate for the ship's design life, have a lower life cycle cost per annum despite the fact that such ships would carry a slightly smaller quantity of cargo. Furthermore, the safety and environmental benefits due to the reduced repairs and extended lifetime of such ships were briefly discussed. The debate of how "robust" a ship needs to be, has been also transferred to IMO in the context of the Goal Based Standards, following a submission by Japan which stated that the increased steel weight of a more robust ship will result in increased CO2 emissions due to a reduced cargo carrying capacity. Greece replied by submitting a summary of the aforementioned paper and preliminary estimations on life cycle CO2 emissions disputing the Japanese contentions. However, taking on-board the challenge, an update is now provided, using the final Common Structural Rules (CSR) of the International Association of Classification Societies (IACS) bulk carrier corrosion margins and taking into account the major environmental implications of the heavier ship scantlings for two bulk carrier size brackets, Panamax and Handymax. The results show that the more robust ships would produce less CO2 emissions over their lifetime (Gratsos et al, 2010).

4.6 Conclusions

There is an extended literature on LCA in many different fields of science. New emerged interest for the method is recorded in recent years following the growing interest of society in environmental issues.

Within the maritime transport sector pioneer studies conducted in the 1990s have shown that the method is applicable for assessing the environmental impacts of ships.

Following the introduction of the life cycle thinking approach in management systems (such as ISO 14001:2015) with wide use in the industry, the maritime transport included, there is a re-growing interest in life cycle studies. The literature review conducted for the purposes of this thesis ended in 2014 and therefore the conclusions shown below concern that period.

The following the main conclusions derived from the LCA review are presented in brief.

- The LCA method is applicable for assessing the environmental impact of ships however it is time consuming due to the large amount of data needed and the complexity of the system.
- For the benefit of the analysis it is recommended to analyse the system (ship) into sub-systems and if possible further more to system elements.
- The boundaries of the study are of great importance and reflect the validity of the study.
- The access in reliable data is not always possible. Data collection stage should target site specific information from manufactures, shipbuilders etc.
- The most challenging task is to access reliable data for the shipbuilding and ship recycling stages.
- The impact assessment processes within the LCA has not been formulated for the specific needs of maritime transport and therefore should be carefully used.

5. SHIP LIFE CYCLE ASSESSMENT FRAMEWORK

Summary

The Chapter presents a novel framework suitable for conducting environmental assessments of ship air emissions from a life cycle perspective.

The life cycle ship framework within which the life cycle examination of ship emissions will take place is presented. The overall system (ship) is viewed as a series of subsystems. Subsystems themselves are detailed in system-elements. Important processes in terms of emissions within the subsystems and system elements are identified and the related algorithms are presented.

Acknowledgments

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2. Part of the work included in this chapter was conducted in the context of the research project “EnviShipping: Environmental Footprint of Ships from a Life Cycle Perspective”, a multi – partner project funded by the General Secretariat of Research and Technology.
3. Part of the work included in the chapter has been carried out in the context of the research project ‘Assessment of Environmental Impact in Marine Transportation and Related Activities’ which was funded by the American Bureau of Shipping.

Publications related to this Chapter

1. Chatzinikolaou, S.D., Ventikos, N.P., (2015) Holistic framework for studying ship air emissions in a life cycle perspective. Ocean Engineering Journal. (2015), http://dx.doi.org/10.1016/j.oceaneng.2015.05.042i

2. Χατζηνικολάου Σ., Βεντίκος Ν. (2012) «Συνολικό Περιβαλλοντικό Αποτύπωμα Πλοίων: Το Πλαίσιο Αναγνώρισης», ΕΛΙΝΤ 2012, Αθήνα, 2012 (με κρίση στο κείμενο)

3. Chatzinikolaou S.D., Ventikos N.P. (2013), “Assessment of Ship Emissions in a Life Cycle Perspective”, Proceedings of the 3rd International Energy, Life Cycle Assessment and Sustainability Workshop & Symposium (ELCAS3), Eds: Koroneos C., Rovas D. and Dompros A., ISBN: 978-960-243-691-2, Nisyros, Greece, pp. 1225-1234

5.1 Introduction

Despite its international nature and enormous growth, the maritime transport sector, receives criticism for being rather slow in achieving global agreements for the reduction of its air emissions footprint. Recently (from 1.1.2013) regulations for greenhouse gases of shipping have entered into force through MARPOL. Recent figures from the third IMO Greenhouse gas study show that the international shipping sector while carrying over 90 percent of the world's trade contributes not more than 2.8 percent to the global anthropogenic CO2 emissions (International Maritime Organization, 2014). Yet, in absolute terms, emissions from international shipping are significant and keep rising; moreover, there is evidence that the impact of these emissions in certain areas is not negligible (Corbett et al., 2007) and calls for further actions. It has been estimated that in the absence of emission reduction policies, a doubling to tripling of 2007 emission levels is expected by 2050 (International Maritime Organization, 2014).

Life cycle thinking is continuously earning acceptance in environmental assessments of industrial products and services as a response to the growing awareness of society about the long term impacts of human activities.

5.2 Description of the Framework

The methodology behind the framework makes use of basic knowledge from Systems Theory and the LCA method. It is acknowledged here that there is an obvious difference between the real system (ship) and the system framework. The latter which will be presented in this chapter has been developed explicitly for the purposes of the study in this thesis and inevitably is only a theoretical simplification of the ‘real’ system.

Simplification is also essential for data collection purposes. The main goal which was the description of the final system has been successfully met. This description includes the equations for calculation of air emissions in all identified processes; the background data used (along with explicit information of sources) and the routine for incorporating the calculations in order to arrive at the final life cycle air emission results.

5.2.1 Subsystems - system elements – processes

The overall system (ship) is viewed as a series of subsystems. A subsystem is defined as an individual step that is part of the defined total system. Some steps in the system may need to be grouped into a subsystem due to lack of specific data for the individual steps. Subsystems themselves are detailed in system-elements. Important processes in terms of emissions within the subsystems and system elements are identified. A commonly used break down concept which is very often used as reference in the shipbuilding industry divides the ship in eight subsystems.

The eight ship sub-systems with possible environmental implications and their consequent system elements are given in Figure 11. This break down of ship systems has been developed in the EnviShipping project (Chatzinikolaou et al., 2013).

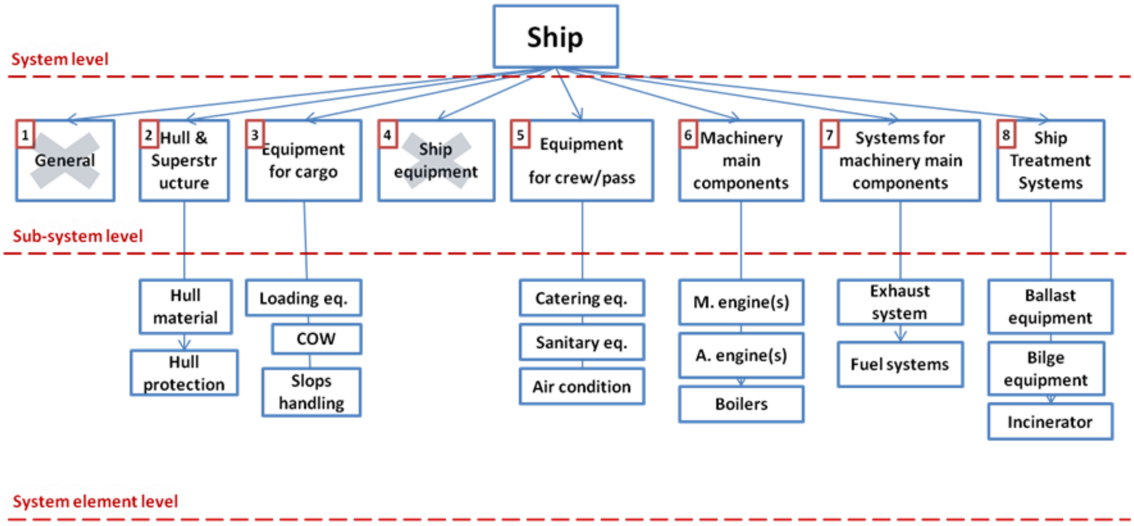


Figure 11: Ship sub-systems and system elements (Chatzinikolaou and Ventikos, 2013)

It is noted that the categorisation made in Figure 11 covers all possible environmental drivers of ships (liquid, solid, air). The framework shown in Figure 11, has been utilised within the EnviShipping project to conduct a full LCA. Results of this work are presented later on in this thesis (in Chapter 6 and Chapter 10).

With respect to air emissions in particular, only two subsystems (out of eight) may be qualified as important sources of air emissions throughout the life of cargo ships. These are the hull subsystem, and the machinery subsystem (machinery main components and systems for machinery main components).

The machinery main components subsystem includes the primary components of the engine room of a cargo ship: main and auxiliary engines, boilers, and generators. This selection of important subsystems is consistent with the examined scientific literature on LCA. Finally, for the study of air emissions the methodology breaks down the overall ship-system into two major subsystems as follows (see also Figure 12):

a. Hull subsystem
b. Machinery subsystem

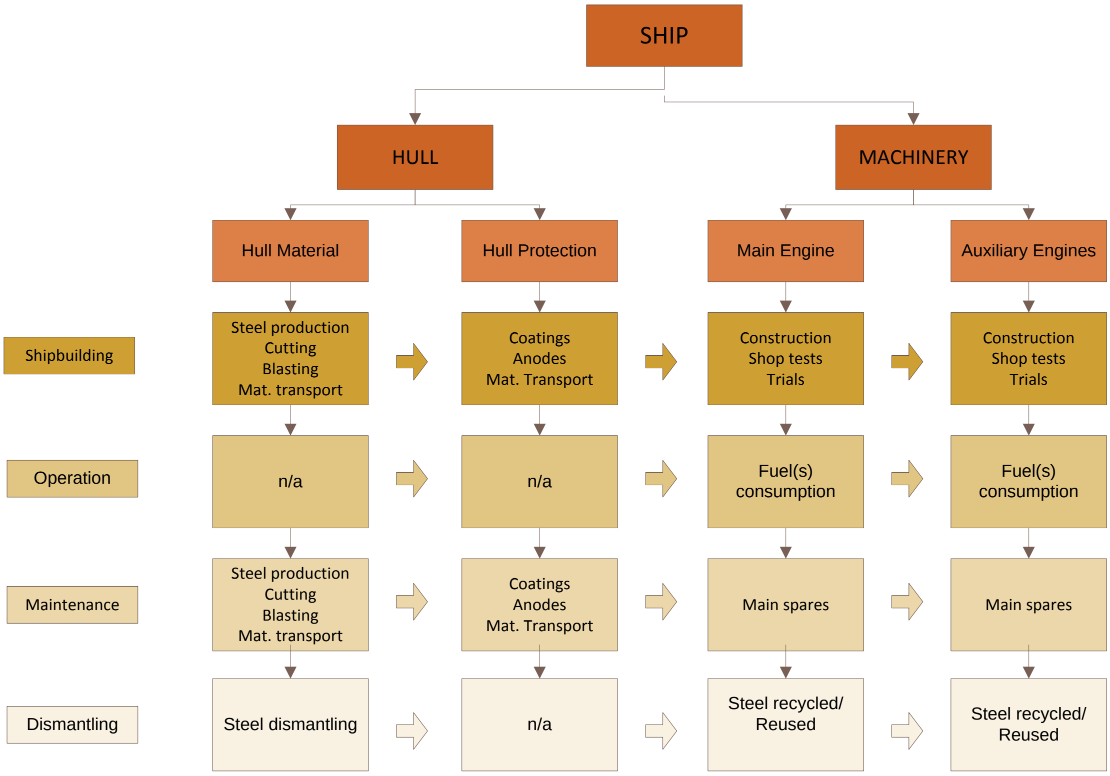


Figure 12: Ship – LCA framework for the assessment of air emissions in a life cycle perspective (Chatzinikolaou and Ventikos, 2015)

At the system element level, a distinction is made between the different components of the subsystem that may be individually elaborated. In the process level all the important processes are identified per system element in the context of inputs (energy and raw materials) and outputs (air emissions). This identification is performed per life cycle stage since one system element may not have the same processes in different life cycle stages.

The hull subsystem is divided in the hull material and hull protection system elements. This partition has been used in previous LCA studies (Johnsen and Fet, 1998). For the hull subsystem no important processes (with respect to air emissions) are considered during the life stage of operation.

For a cargo ship, steel is the main hull material with respect to air emissions production. In the shipbuilding life cycle stage important processes of the hull material system element are steel welding, cutting, and abrasive blasting. The boundaries of the shipbuilding include the production of steel and a transportation scenario of the steel material from the production site to the shipyard. In the life cycle stage of operation, no important processes in terms of emissions production are considered for the hull material system element. The processes included in the maintenance life cycle stage are identical to the shipbuilding stage although quantities of materials and resulting emissions are considerably less. The processes included in the recycling stage is steel recovery which takes into consideration the specific way that the steel is being recovered (re-rolling of steel) in the selected site (Alang, India) for which data was available.

Coating is a major process in the hull protection system element. This concerns mainly the life cycle stages of shipbuilding and ship maintenance. Some painting activities are performed also during the operational life of the ship (usually by the on-board personnel) but they are not considered important air emission contributors.

The process of anodes installation (on the hull, rudder and water ballast tanks) is also included in the hull protection system element in the stages of shipbuilding and ship maintenance. A specific scenario is also considered for transporting the relevant materials to the shipyard. For the ship recycling stage, the fate of materials used for hull protection is not known. Therefore, for this life cycle stage no process has been incorporated in the hull protection system element.

The machinery subsystem is divided in two system elements: the main engine(s) which provide the propulsion power to the ship, and the auxiliary engines which offer electrical power for accommodation, cargo and other ship needs. These two system elements have identical processes in the framework.

The great portion of ship environmental impact derives from the operational life when the consumption of fuels takes place. Detailed information on the initial stages of the life cycle of diesel engines before they are installed into the ship is not widely available. However, the study has collected data for the construction and testing processes of engines before they are transported to the shipyard for on-board installation. Therefore, the processes of engine construction and testing are included in the analysis. The operational phase includes the consumption process and the maintenance phase considers some major replacement of main engines parts for which data were available. The dismantling phase considers the specific practice adopted in the selected recycling site (Alang, India). The production of fuels to be used in ship engines is a matter of boundaries selection. The fuel production process is not included in the life cycle boundaries of this framework. In the discussion paragraph of this chapter the issue of boundaries selection in LCA is discussed in detail. A dedicated study on the life cycle of different fuels is presented in Chapter 7 of this thesis.

5.2.2 Framework capabilities

The framework comprises a series of algorithms which calculate the air emissions during the life cycle of the ship. These calculations lead to the development of the Life Cycle Inventory (LCI) of ship air emissions. The LCI may be then utilized with the adaptation of an Impact Assessment technique to calculate the environmental impact of air emissions.

The Framework’s output main capabilities are the following:

- Inventory of air emissions from any identified process
- Emissions covered: CO_2, CO, SO_2, NOx, PM (all), CH_4, VOCs
- Air emissions per life cycle stage
- Air emissions per process, system element, subsystem, and total
- Annual air emissions analysis
- Emission comparisons between different operational ship profiles
- Examination of different operational scenarios (initial scenario, slow steaming, speed limit, fleet distribution, etc.)

Some basic naval architecture calculations are initially performed for determining important ship details which are going to be useful for the air emissions calculations. These refer to the calculations of wetted surface, hull, deck and superstructure surfaces, cargo holds surfaces, water ballast tanks surfaces and steel weight. The study has made effort to avoid using generic or databases data and developed algorithms that model important processes in the ship life cycle.

Unique features from this effort are the algorithms developed explicitly for the calculation of emissions during welding and coating operations in shipyards, the algorithms for assessing the added resistance effect due to marine growth on the ship's hull, and the algorithms for assessing air emissions in different scenarios of the operational life (Chatzinikolaou and Ventikos, 2013).

The framework also includes an algorithm for calculating the various time periods of ship operation and the trips accomplished per year of the life cycle. These calculations lead to the estimation of the transport work accomplished (throughput) in trip and year basis. The user should determine some basic variables such as the distance covered per trip, the relevant speeds (ballast, laden leg), the waiting times (outside port, manoeuvring) the number of ships used for the required transport work and the life cycle years. The round trips per year are calculated using formulas for the unavailability of tankers which as function of the age of the ship (Turan et al., 2009).

5.3 Mathematical modelling

The mathematical modelling of the Framework includes algorithms which calculate emissions per identified process. The following paragraphs will present these algorithms.

5.3.1 Ship details

Some basic naval architecture calculations are initially performed for determining the following ship details which are going to be useful for the Life Cycle Tool calculations. Important ship details that are commonly available such as the main particulars of the ship are used for these generic calculations which will provide information on the following items:

1. Wetted surface
2. Hull, deck and superstructure surfaces
3. Cargo holds surfaces
4. Water ballast tanks surfaces (from the General Arrangement plan)
5. Steel weight (using the Shneekluth method)

The total welding length is calculated from a unique algorithm developed in NTUA which essentially makes use of the main particulars of the ship and common shipbuilding structure concepts (i.e. longitudinal system, double hull structure). The equation for wetted surface is also provided in this Table. Steel weight is calculated using the well-known Shneecluth method provided by Papanikolaou (2009).

5.3.2 Operation – Activity

For the activity of the ship various scenarios may be used. The goal set was for the Tool to have flexibility in order to cover various scenarios of operation. The Tool includes a routine for calculating the various time periods of ship operation and the trips accomplished per year of the life cycle. These calculations lead to the estimation of the transport work accomplished (throughput) in trip and year basis. The user should determine some basic variables such as the distance covered per trip, the relevant speeds (ballast, laden leg), the waiting times (outside port, manoeuvring) the number of ships used for the required transport work and the life cycle years. The routine of basic calculations is shown below.

Table 5: Ship activity algorithm

Ship Activity		
Ship Name	xxx	
Type	Cargo xxx ship	
Port of Departure	Port A	
Port of Arrival	Port B	
Distance (A-B)	D_{AB} :	n.m
Speed laden (A-B)	$V_{A\to B}$:	knots
Speed ballast (B-A)	$V_{B\to A}$:	knots
Time (A-B)	$t_A = \dfrac{D_{AB}}{V_{A\to B}} \times \dfrac{1}{24}$	days
Time (B-A)	$t_B = \dfrac{D_{AB}}{V_{B\to A}} \times \dfrac{1}{24}$	days
Time at sea (cruise)	$t_A + t_B$	days
Total time at port	$t_{port} = t_{loading} + t_{unloading}$	days
Time at anchorage	t_{wait} :	Days
Manoeuvring time	t_{manouv} :	days
Duration of 1 trip	$t_{trip} = t_A + t_B + t_{port} + t_{manouv} + t_{wait}$	days
Time off-duty	$t_{off} = 1.499 \times Age + 14.382$	Days/year
Number of trips	$N_{trips(year)} = \dfrac{(365 - t_{off})}{t_{trip}}$	trips/year
Ship life cycle	$T_{LifeCycle}$:	years
Total trips in life cycle	$N_{trips(LifeCycle)} = N_{trips(year)} \times T_{LifeCycle}$	trips
Cargo Throughput		
PAYLOAD	$Payload$:	tonnes
Throughput/year (1 ship)	$Capacity_{ship(year)} = N_{trips(year)} \times Payload$	tonnes/yea
Throughput in life cycle (1 ship)	$Capacity_{ship(LifeCycle)} = N_{trips(LifeCycle)} \times Payload$	tonnes

Fleet	N_{ships} :	
Total fleet Throughput	$Capacity_{fleet(LifeCycle)} = Capacity_{ship(LifeCycle)} \times N_{ships}$	tonnes

5.3.3 Hull Subsystem

The Hull sub-system has two main system elements i.e. the hull material and hull protection. Algorithms have been developed for the most important processes of these two elements. For the hull sub-system, the life cycle stages of shipbuilding and maintenance are assumed to have the same processes. Therefore, it is considered that the algorithm of maintenance is identical to the algorithm of shipbuilding; however, it is reasonable that different amount of materials is used.

Hull material

5.3.3.1.1 Shipbuilding

5.3.3.1.2 Process: steel production

Literature data have been used for the calculation of air emissions during the industrial process of steel production (Eco Indicator 99 method). The equation for the calculation of mass of emissions from this process is as follows:

$$m_i^{steel} = EF_i \cdot W_{steel}, \tag{4.1}$$

Where:

- EF$_i$, is the emission factor of emission i for the steel production process and
- W$_{steel}$ is steel weight of the ship.

5.3.3.1.3 Process: steel welding

Steel welding is an important shipbuilding process. The mass of emissions from this process (m_i^{weld}) is subject to the welding length of the ship and the energy demand for accomplishing the welding work for that length.

$$m_i^{weld} = \sum_{k=1}^{v} EF_{i,k} \cdot E_k^{weld} \cdot L_k \tag{4.2}$$

Where:

- $EF_{i,k}$ is the emission factor of substance i for the steel welding type k;
- E_k^{weld} is the Energy for welding one meter in welding type k
- L_k is the length welded by using welding type k.

The obtained Length of welding is then used for assessing the energy used for this process and resulting emissions.

5.3.3.1.4 Process: steel cutting

Cutting process calculations are based on knowledge from previous LCA studies (Kameyama et al, 2004). The algorithm uses as input the ship's dwt and the information on the required energy to cut the ship's steel. The equation is as follows:

$$m_i^{cut} = EF_i \cdot E_{1ton}^{cut} \cdot dwt \tag{4.3}$$

Where,

- E_{1ton}^{cut} , is the energy used for cutting onr ton pf ship's steel
- dwt, is the ship's dead weight

5.3.3.1.5 Process: abrasive blasting

Abrasive blasting is the most common method for paint removal and surface preparation. Copper slag, coal slag, steel grit, steel shot, glass and garnet are common blasting abrasives that provide a range of particle size and hardness. The algorithm for the calculation of abrasive blasting emissions impact is provided below. Major areas of the ship require the application of abrasive blasting before they are coated. The nature of the abrasive grain (i.e. size, shape, and most important mass) determines how efficiently the abrasive will work on the steel. In addition, the type of steel surface, its allocation, and the complexity of its configuration should be also considered. Information on diesel oil consumption is based on the work of Fet (2002). The amount of the blasting material used is estimated using information from the same source.

$$m_i^{blst} = EF_i \cdot E_{m^2}^{blst} \cdot A^{blst} \tag{4.4}$$

where,

- m_i^{blst}, is the emission of substance i (CO_2, NO_X, SO_X, CO, VOC),
- EF_i, is the emission factor for substance i (PM not included),
- $E_{m^2}^{blst}$, is the energy used for the blasting of 1m^2,
- A^{blst}, is the total blasting surface of the ship.

All air emissions are calculated from the above routine except for PM for which the information derives from the Emission Estimation Technique Manual for Shipbuilding Repair and Maintenance, (National Pollutant Inventory, 2014). For the calculation of PM emissions (in kg) of the process the following equation is used:

$$m_{PM}^{blst} = EF_{PM} \cdot C_{m^2}^{blst} \cdot A^{blst} \tag{4.5}$$

where:

- $C_{m^2}^{blst}$, is the blasting material used for the blasting of 1m^2.

Hull protection

5.3.3.1.6 Process: coatings

The algorithm for the calculation of emissions in coating/painting operations uses information from paint manufacturers and emissions factors for energy consumption from LCA databases. The selection of coatings for application onto a ship is a difficult task which is affected by numerous factors, the cost being the most dominant one. Other important factors are the operating profile of the ship and the location of the surface. The selection of coatings drastically affects the emissions (most importantly VOC) to the environment. Manufacturers provide datasheets with detailed information for assisting this selection.

$$m_i^{paint} = \sum_{j=1}^{v} EF_{i,j} \cdot n_j \cdot E_{j(m^2)}^{paint} \cdot A_j^{paint} \tag{4.6}$$

where:

- m_i^{paint}, is the emission of substance i (except for VOC)
- $EF_{i,j}$, is the emission factor of substance i for paint type j,
- n, is the number of layers of paint type j,
- $E_{j(m^2)}^{paint}$, energy used to paint 1 m^2, and
- A_j^{paint}, is the surface painted with paint type j.

VOC emissions are estimated by taking into account the theoretical coverage which is an essential characteristic of the paint (usually provided by the paint manufacturer).

$$m_{VOC}^{paint} = \sum_{j=1}^{v} EF_{VOC,j} \cdot n_j \cdot TC_J \cdot A_j^{paint} \tag{4.7}$$

where:

- TC_J is the theoretical coverage of paint type j (in m^2/lt)

5.3.3.1.7 Process: sacrificial anodes

The hull protection system element includes the process of sacrificial anodes which models the emissions deriving from the cathodic protection of seagoing vessels. Zinc is the widely used material for this process. Sacrificial anodes applications concern the ship hull as well as the water ballast tanks of the ship. The model estimates the emissions from the production of the required quantities of zinc anodes. Common practice of shipyards has been used for the placement of the anodes onto the hull and ballast tanks. The model used here has been developed by the Netherlands National Water Board – Water Unit in collaboration with DELTARES and TNO (2008).

$$m_i^{and} = \sum_{j=1}^{2} EF_i \cdot \frac{A_J \cdot I_j \cdot t_j}{1000 \cdot e} \tag{4.8}$$

where:

- A_J, is the surface where the anode is placed (1: wetted surface and 2: ballast tanks)
- I_j , is the electrical current density (for the wetted surface is equal to 15 mA/m^2 and for the ballast tanks is equal to 5 mA/m^2)
- t_j, is the time that the anode is spending in the seawater (in hours)
- e , is the electrical capacity of anode in seawater (780×1000 Ah/kg)

5.3.4 Machinery Subsystem

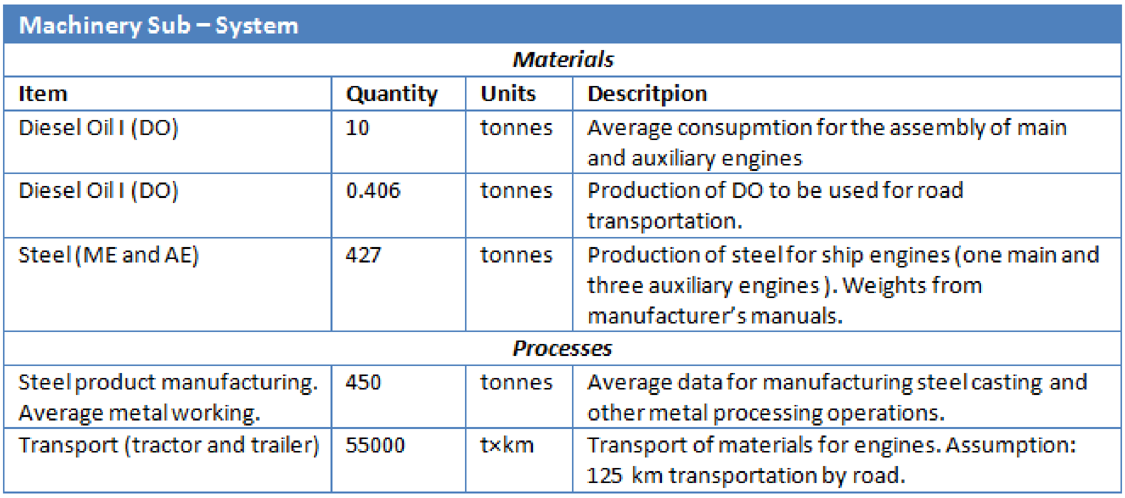
In the machinery subsystem two life cycle stages have been modelled: the construction stage and the operational stage. The final stage of recycling was not modelled due to the absence of reliable data.

Machinery in shipbuilding

5.3.4.1.1 Engine construction

Generally, the life cycle of engines before they are installed onto the ship is not known. A simplified scenario has been used for modelling the construction process of marine engines. This scenario includes materials (i.e. steel, fuels), and processes (i.e. assembly, welding, transport). Table 6, encloses the quantities of materials and processes for the construction and installation of one main engine (2 stroke, 12240 kW) and three auxiliary engines (4 stroke, 740 kW each) on board the Panamax oil tanker case study which will be used later on in the LCA case studies.

Table 6: Shipbuilding Inventory – Machinery Main Components subsystem



Machinery Sub – System			
		Materials	
Item	**Quantity**	**Units**	**Descritpion**
Diesel Oil I (DO)	10	tonnes	Average consupmtion for the assembly of main and auxiliary engines
Diesel Oil I (DO)	0.406	tonnes	Production of DO to be used for road transportation.
Steel (ME and AE)	427	tonnes	Production of steel for ship engines (one main and three auxiliary engines). Weights from manufacturer's manuals.
		Processes	
Steel product manufacturing. Average metal working.	450	tonnes	Average data for manufacturing steel casting and other metal processing operations.
Transport (tractor and trailer)	55000	t×km	Transport of materials for engines. Assumption: 125 km transportation by road.

Representative air emissions from this particular scenario of engines construction are presented in the following Table. These results derive from the use of specialized LCA databases (Eco-Indicator 99).

Table 7: Representative emissions from the shipbuilding Inventory – Main Machinery subsystem

	Substance	*Unit*	*Quantity*	*Per kW installed*
1	CO2	kg	1.23E+06	84.827
2	CO	kg	2.64E+03	0.183
3	CH4	kg	1.51E+03	0.104
4	NO2	kg	4.94E+02	0.034
5	NOx	kg	3.41E+03	0.236
6	PM (all)	kg	8.06E+03	0.557
7	SO2	kg	4.03E+03	0.279
8	SOx	kg	1.53E+02	0.011
9	VOC	kg	5.37E+00	0.000
10	NMVOC	kg	2.66E+02	0.018

5.3.4.1.2 Process: engine shop tests

The process of shop tests of the engines before they are installed onboard produces air emissions due to the consumption of fuels in the tested engines. Information for fuel consumption during this process comes from previous work found in the literature (Alkaner and Zhou, 2006). According to this study during the testing stage of engine manufacturing (specific diesel oil engine manufacturer), 0.350 kg/kW of marine diesel oil (MDO) and 1.886 kg/kW of heavy fuel oil (HFO) is consumed. Therefore, the quantities of fuels used in the shop tests are made available (in kg) from the following equation:

$$m_{FC}^{shop\ tests} = \sum_{i}^{n} a_i \cdot n_i \cdot MCR_i, \tag{4.9}$$

where:

- a_i, is the average specific fuel consumption of engines (0.350 kg/kW for auxiliary engines and 1.886 kg/kW for main engines).
- n_i, the number of engines i

5.3.4.1.3 Process: <u>Sea trials</u>

The process of sea trials before the delivery of the ship is included in the shipbuilding stage in the machinery subsystem. Since no specific information is available on how the sea trials of cargo ships are conducted, a generic scenario may be applied for the approximation of fuels consumption and corresponded emissions. This scenario considers the duration of sea trials in order to have an estimation of the working hours of engines and the corresponding average loading of engines (as a fraction of MCR). The equation for the estimation of fuels used during the sea trials process is as follows:

$$m_{FC}^{trials} = \sum_{i=1}^{m} [LF_i \cdot MCR_i \cdot SFC_i \cdot T] \tag{4.10}$$

where:

- LF_i, the loafing factor of engine i during the trials period

- MCR_i, the maximum continuous rating of engine i
- SFC_i the specific fuel consumption of engine i, during the trials period
- T, The duration of trials (in hours)

Machinery in operation

The operation of main and auxiliary engines operation produces the vast amount of emissions in the life cycle of the ship. There are three different approaches to estimate emissions of engines operation: Fuel Consumption, Engine Power and Energy. All three methods are applied in the literature and their accuracy depends largely on the data availability.

The fuel consumption data method is highly dependent on the availability of fuel consumption data, which is reported in the daily noon reports of the ship or included in information deriving from direct measurements using a set of sensors and flow meters. A simple formula to calculate emissions using fuel consumption information is as follows:

$$E_{Trip,i,j,m} = \sum_1^p FC_{j,m,p} \times EF_{i,j,m,p} \tag{4.11}$$

Where:

- E_{Trip}: emission over a complete trip
- FC: fuel consumption
- EF: emission factor
- i: pollutant
- j: engine type
- m: fuel type
- p: the different phases of trip

The engine power (or engine loading) method is based on activity information of the ship and information on the loading of the engine during the trip phases. A typical formula for calculating the fuel consumption in this context is provided below:

$$FC_{TOTAL} = \sum_{j=1}^{v} FC\,(t_j\,) = 24 \cdot 10^{-6} \cdot \sum_{i=1}^{m} \sum_{j=1}^{v} \left[LF_{i,j} \cdot MCR_i \cdot SFC_{i,j} \cdot t_j \,\right] \tag{4.12}$$

Where:

- FC_{TOTAL}: is the total fuel consumption per round trip
- i: is the engine i of the ship
- m: the number of engines installed onboard
- j: the ship mode j
- v: the number of different modes of a round trip
- $LF_{i,j}$: the loading factor of engine i in mode j (given as percentage of MCR)
- MCR_i: the maximum continuous rating of engine i
- $SFC_{i,j}$: the specific fuel oil consumption of engine i in mode j

Detailed information per trip which is demanded in this method is not always available. The first case study that has been conducted using the life cycle framework has employed this method.

The third method is not actually an independent method since it calculates the energy production of the engine using the fuel consumption data (deriving for one of the two previous methods) and the calorific values of fuels burnt. In the case study of alternative fuels this method is employed for the calculation of fuel life cycle emissions (see also Chapter 8).

6. SHIP LCA SOFTWARE

Summary

This chapter presents a software application (developed in the Matlab environment), which can be used to assess ship air emissions for cargo ships in a life cycle perspective. 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 modelled with algorithms, empirical equations, and input data. Algorithms and empirical equations are provided from the theoretical ship-LCA framework of the previous Chapter.

For demonstration purposes the results of a case study (Capesize bulk carrier; 200,000 tonnes dwt) in which the software has been tested are presented.

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1. Part of the work included in this chapter has been carried out in the context of the diploma thesis of Mr Giannis Daskalakis and submitted to the School of Naval Architecture and Marine Engineering. The title of the thesis in Greek is, *'Λειτουργικός υπολογισμός αέριων εκπομπών στον κύκλο ζωής πλοίων: Ανάπτυξη υπολογιστικού προγράμματος'*. The supervisor was Ass. Prof Ventikos. The author provided also assistance to Mr. Daskalakis and would like to acknowledge his motivation and excellent cooperation.

Publications related to this Chapter

1. Daskalakis I, Chatzinikolaou S., Ventikos N.P. (2015), “Platform for assessing ship emissions from a life cycle perspective”, Technologies, Operations, Logistics and Policies towards meeting 2050 emission targets (SCC 2015), Glasgow, UK, Osman et al. (eds), Vol. 1, pp. 113-122.

6.1 Introduction

The accurate calculation of air emissions remains a challenge for the case of ships. 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 CO2 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 this thesis to comment on the accuracy of the two aforementioned approaches. The main goal of the work reported in this chapter is to develop a systematic and easy to use software 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.

6.2 Literature Review

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 which was presented previously in this thesis and has been published in scientific literature, Chatzinikolaou and Ventikos (2014a, 2014b, 2015a, 2015b).

6.3 Description of the LCA application

The main goal set was to develop an 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 presented in the previous chapter, 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 steel structure of the ship and includes all fixed metal parts of the ship’s hull and superstructure. Processes related to the aforementioned parts 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 (not covered) from the software application.

The machinery subsystem includes processes such as the construction of engines, shop tests, engines installation onboard, sea trials, maintenance of main components and fuel consumption. The latter is the dominant process in terms of emissions. Three fuels can be handled by the software; namely, 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 of the fuels examined, have been those included in official IMO documents (IMO, 2014).

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 which call the user to insert the required input. Dialog boxes are also used to record the 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.

The software consists of 11 m-files (1 file for the main program and 10 files of functions) and it spreads in approximately 1,800 lines of code.

The software character is interactive since in order to perform specific calculations it requests and accepts various inputs from the user. All dialog boxes and other text are written in English. The software specifies also the units in which the various data must be imported.

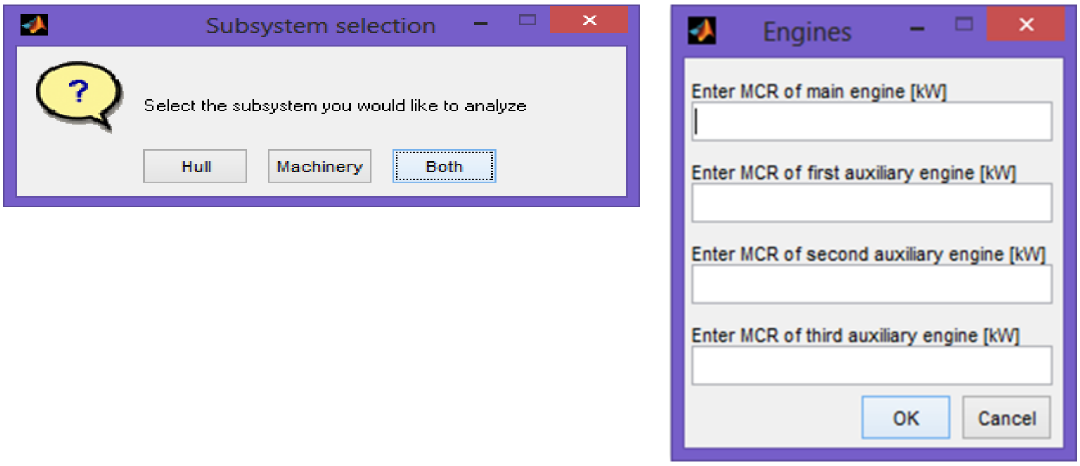
The main program file is the backbone of the software tool through which, depending on the user's inputs, the files of functions are called in order to execute certain commands. These commands relate either to the calculation and application of mathematical equations or to the drafting of charts, tables and graphs based on the computed results.

In the Table below the names and functions of the eleven files of the software are shown.

Table 8: Files of the software application

File name	*File type*	*Function*
main_program.m	Script file	Input – Output
engines.m	Function file	Data entry
dimensions.m	Function file	Entry - Calculations
engines_construction.m	Function file	Entry data - Calculations
sea_trials_shop_tests.m	Function file	Entry data - Calculations
operation_single_trip.m	Function file	Entry data - Calculations
operation_many_trips.m	Function file	Entry data - Calculations
machinery_total.m	Function file	Machinery – Calculations
hull_stages.m	Function file	Hull - Calculations
graphs_engines	Function file	Results in graphs
graphs_hull	Function file	Results in graphs

The software has a user-friendly interface in the sense that is does not demand from the user to have advanced knowledge in software programming. This is feasible through simple dialog boxes that guide the user in the process of data entry, asking simple questions to understand the specific analysis he/she tries to carry out. The following figures show screen shots from the software's dialog boxes.



Select the subsystem you would like to analyze

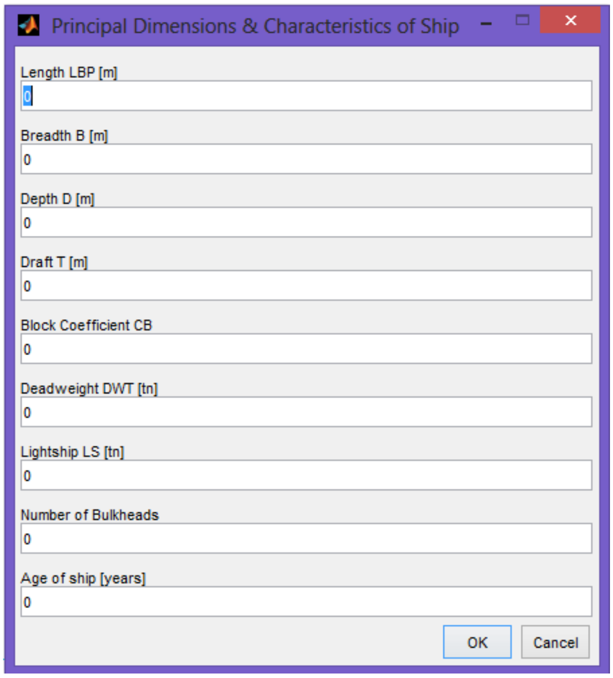
Enter MCR of main engine [kW]

Enter MCR of first auxiliary engine [kW]

Enter MCR of second auxiliary engine [kW]

Enter MCR of third auxiliary engine [kW]

Figure 13: Screen shots from dialog boxes of the software – Selection of subsystem and Entry of engines data



Principal Dimensions & Characteristics of Ship

Length LBP [m]
0

Breadth B [m]
0

Depth D [m]
0

Draft T [m]
0

Block Coefficient CB
0

Deadweight DWT [tn]
0

Lightship LS [tn]
0

Number of Bulkheads
0

Age of ship [years]
0

Figure 14: Screen shot from dialog box of the software – Data entry of ship main details

6.4 Demonstration 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 9.

Table 9: 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

6.4.1 Ship Operational Data

Information for the operational profile 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 full load leg and the ballast leg. Overall, data for twenty-one single trips (in ballast and laden legs) have been available. An example of the information used as inputs in the case study that is presented in this paper, is given in the following Table 10, (it concerns the first three trips of the case study ship).

Table 10: 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.

6.4.2 Fuel consumption data

Fuel consumption data per trip were also provided by the shipping company. In Figure 15, a comparison is displayed between the reported data and the data calculated by the software. The comparison reveals some reasonable differences which are attributed to the fact that the software calculations do not consider the parameters that can affect fuel consumption (such as weather conditions, sea state, sea currents etc.).

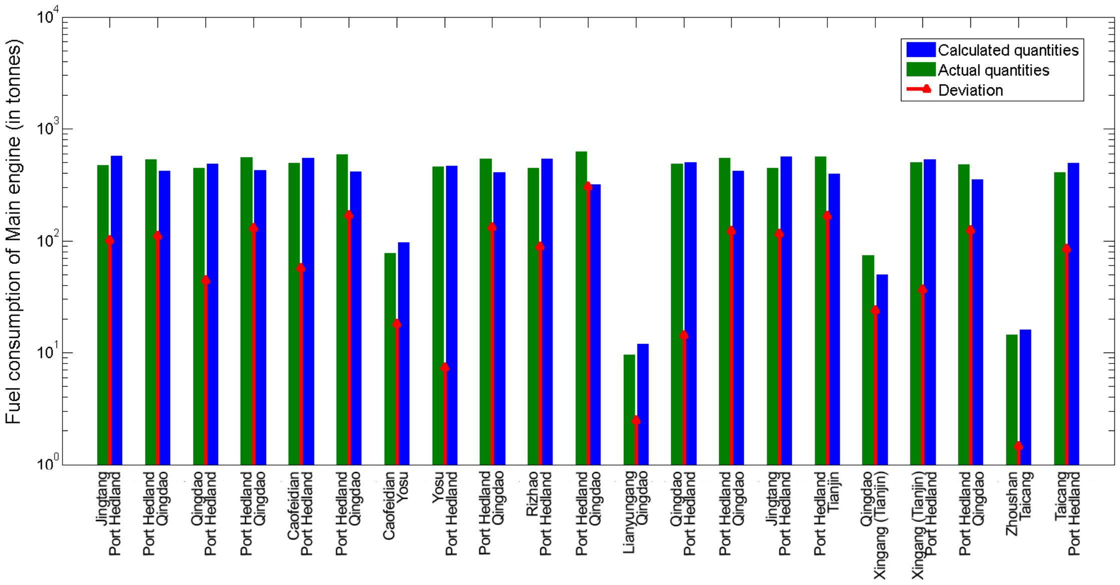


Figure 15: Calculated vs. reported fuel consumption data

6.4.3 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 in twenty one trips). The ship spent 230 days sailing at sea and 116 days at port (exact hours per port call were available). According to information provided by the ship operator the total fuel consumption was 8,033 tonnes in the main engine, and 1,199 tonnes in the auxiliary engines.

The operation of main and auxiliary engines is the most important process in this subsystem, being responsible for the larger portion of GHG and air pollutants emitted over the life cycle.

The operation of a ship may include a number of different functions such as normal operation, manoeuvring movements, port time, loading and unloading, and towing. In this sense, the total time, in days, of a round trip is obtainable, as the sum of the time of individual functions occurring during ship 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. Off-hire days were also reported by the company.

The resulted CO_2 emissions of the machinery subsystem in one year reveal the dominance of emissions from engines operation. 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 faith of the engines at the final ship dismantling/recycling phase is not known.

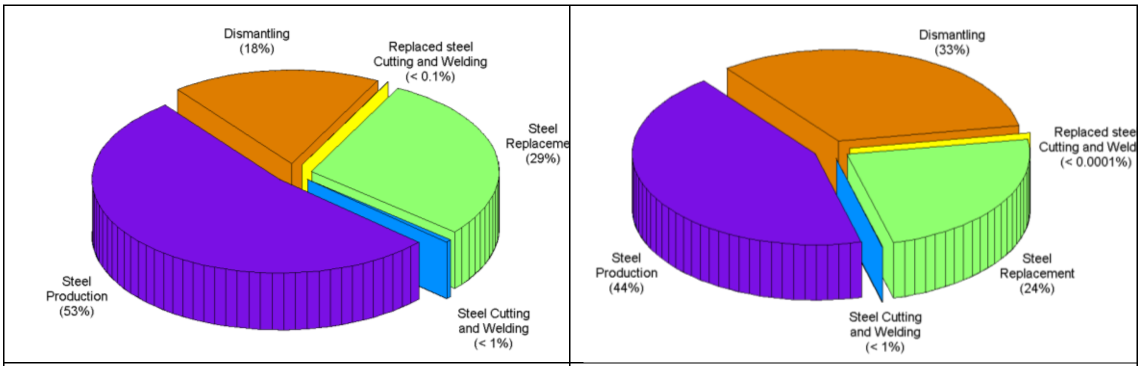
The overall emission results for the period with the aforementioned characteristics are given in Table 11. The software provides emissions results for different fuels. In Table 11, HFO (with 2.5% sulphur content) is the actual fuel used by the ship. Results of two alternative fuels are also available. The emissions results can be drafted also on annual basis. The usual life cycle of this ship type is twenty years or more. The software has the capability to project the life cycle emissions of the machinery subsystem; however since the available data illustrate that the ship was largely practicing slow steaming, the author decide not to make life cycle emissions projections for this case study, based only on this information.

Table 11: 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

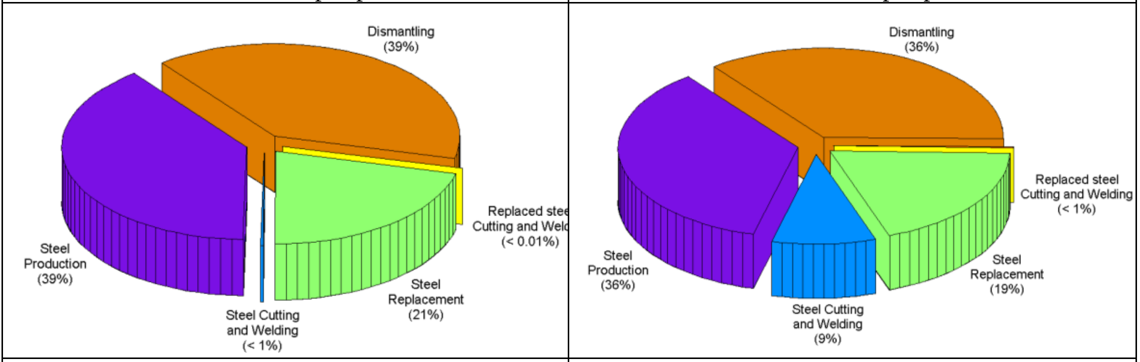
6.4.4 Hull Subsystem Results

In the hull sub-system and for demonstration purposes a different set of results is presented which is also interesting since it reveals the processes that have a large environmental impact (at least in terms of quantity).



CO2 emissions distribution per process

NOx emissions distribution per process



PM emissions distribution per process

NMVOC emissions

Figure 16: Hull sub system life cycle – Emissions distribution per process

The distribution of emissions per process reveals the processes which have increased contribution in certain environmental loads. In this respect in the hull subsystem and as regards the CO2 emissions the main process is steel production. Dismantling has also increased contribution with regard to NOx emissions (33 percent of life cycle emissions), as well as to PM emissions (39 percent of the total emitted in the life cycle).

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 16, emissions from all steel related processes of the hull subsystem are projected for a period of twenty years.

Overall the emissions Inventory of the hull subsystem for this ship is provided in Figure 17. 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 tit 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).

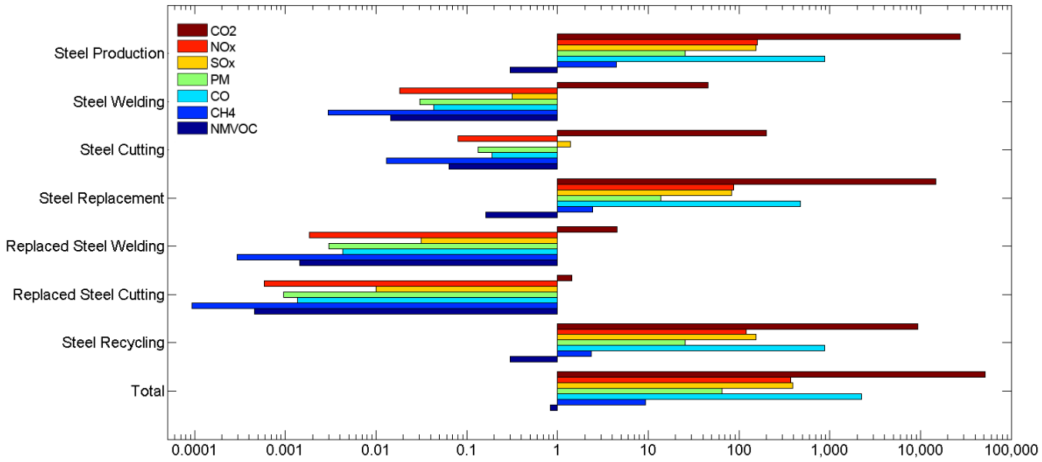


Figure 17: Hull subsystem. Life cycle emissions per process (in tonnes)

6.5 Emissions per trip

Monitoring emissions per trip is important for ship energy management as foreseen also in new regulations (e.g. the EU MRV regulation). In this paragraph, emissions are provided per trip and comparisons with some existing regulations are made.

The following two graphs show GHG (CO_2 emissions and CH_4 emissions) per trip for three different fuels which the software is capable of calculating.

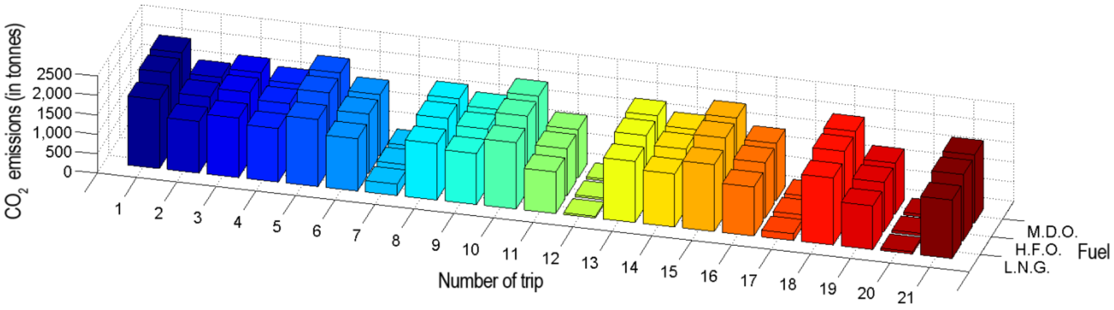


Figure 18: CO2 emissions per trip for three different fuels (MDO, HFO, and LNG)

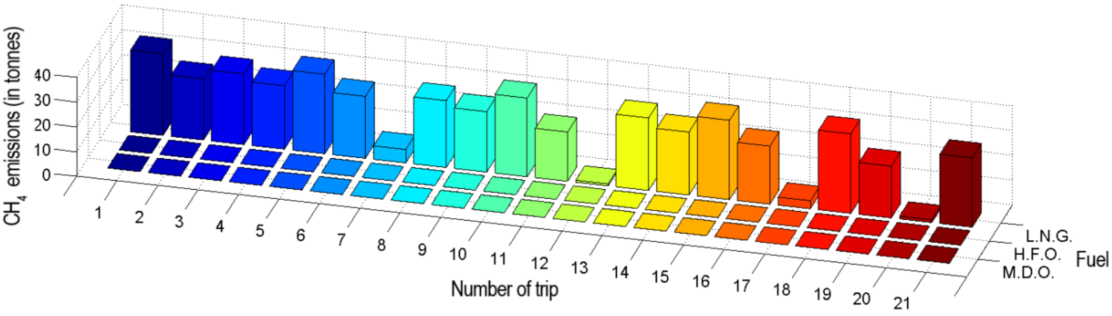


Figure 19: Methane emissions per trip for three different fuels (MDO, HFO, and LNG)

6.6 Emissions per cargo carried and distance travelled

In Figure 20, the 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.

The green line in Figure 20 depicts the average CO2 per tonne-mile for Capesize bulk carriers for the period 2010 -2014 (IMO, 2015). The red line is the EEDI threshold for 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 below the service speed which depicts a slow steaming practice.

In Figure 21, the NOx emissions per ton-mile are shown. NOx emissions limits are regulated by IMO in Tiers that are gradually getting stricter (IMO, 2014). The three tiers are shown in Figure 21: Tier I (red line), Tier II (blue line), and Tier III (green line). The results of 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.

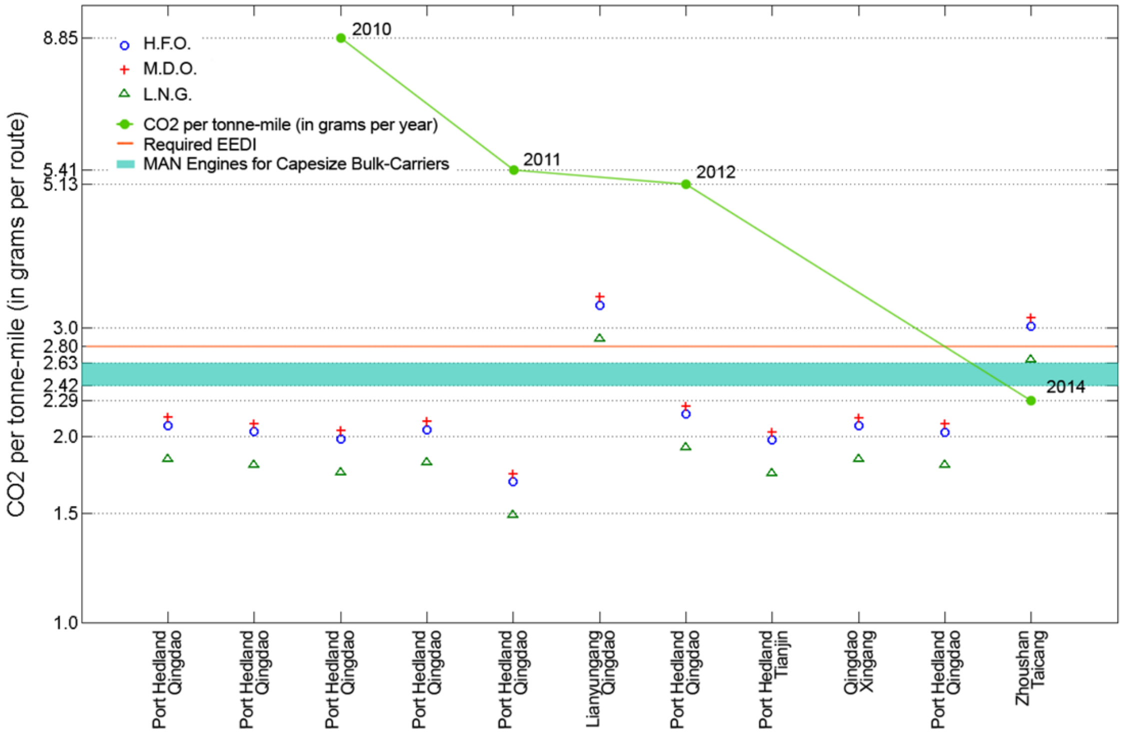


Figure 20: CO2 emissions per tonne-mile for laden trips

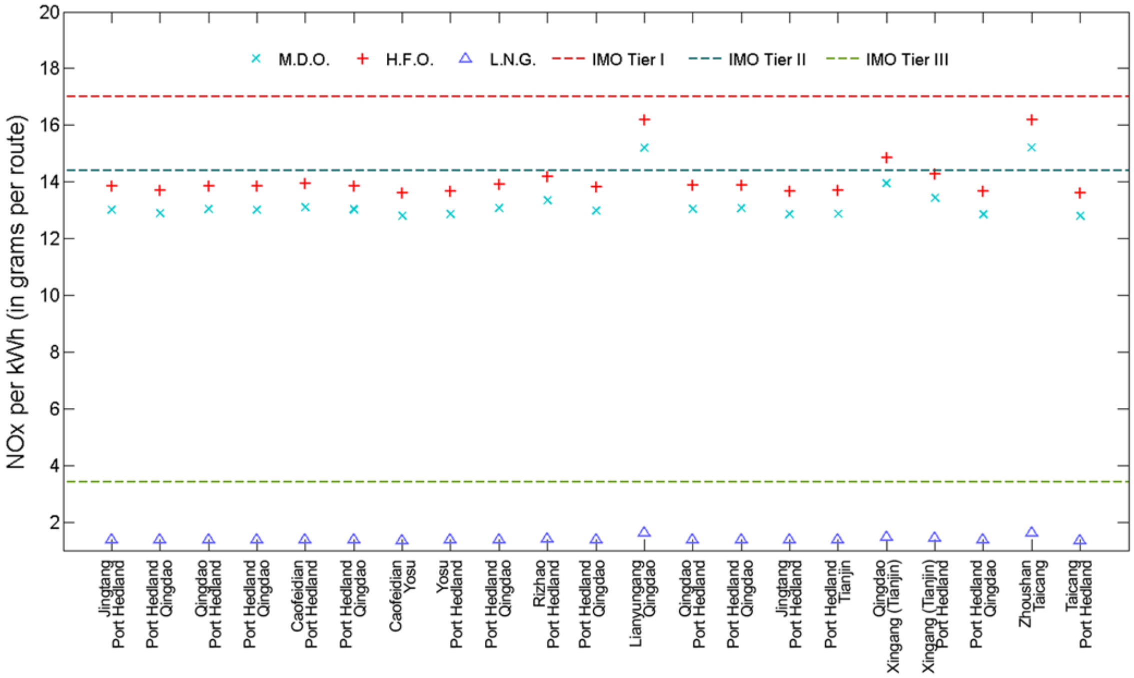


Figure 21: NOx emissions per tonne-mile for laden trips

6.7 Conclusions

This chapter presents a software application which can be used to assess ship air emissions for cargo ships in a life cycle perspective. 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 modelled 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).

For demonstration purposes the results of a case study (Capesize bulk carrier; 200,000 tonnes dwt) in which the software has been tested are presented. 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 illustrate that the dominant stage of the ship's 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 variances.

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 (Daskalakis et al, 2016).

7. SHIP LCI STUDIES

Summary

This chapter presents four case studies conducted with the purpose to test the Life Cycle Framework. The scope and specific features of these case studies are given below:

Case Study	Scope	Sample ship	Specific features
No1	Emissions Life Cycle Inventory	Panamax Oil Tanker	Modelling shipbuilding emissions Fixed ship operation scenario
No2	Annual Emissions Inventory	Panamax Oil Tanker	Activity data for fuel consumption of main engines Added resistance due to marine growth Fuel consumption and emissions from boilers
No3	Alternative operational scenarios' to accomplish the same transport work	Panamax Oil Tanker, Suezmax Oil Tanker	Effect of slow steaming Effect of speed limit Effect of fleet distribution
No4	Emissions from coating operations	General cargo 30,000 dwt	VOC emissions in shipbuilding, ship repair

Acknowledgments

1. Part of the work included in this chapter has been carried out in the context of the research activities of the Centre of Excellence in Ship Total Energy-Emissions-Economy of the National Technical University of Athens, School of Naval Architecture and Marine Engineering. The Centre has received financial support by the Lloyds Register Foundation (LRF) which is gratefully acknowledged. LRF helps to protect life and property by supporting engineering.
2. Part of the work included in this chapter was conducted in the context of the research project “EnviShipping: Environmental Footprint of Ships from a Life Cycle Perspective”, a multi – partner project funded by the General Secretariat of Research and Technology.
3. Part of the work included in the chapter has been carried out in the context of the research project ‘Assessment of Environmental Impact in Marine Transportation and Related Activities’ which was funded by the American Bureau of Shipping.

Publications related to this Chapter

1. **Chatzinikolaou, S.D., Ventikos, N.P., (2015)** Holistic framework for studying ship air emissions in a life cycle perspective. Ocean Engineering Journal. (2015), http://dx.doi.org/10.1016/j.oceaneng.2015.05.042i

2. **Chatzinikolaou, S. and Ventikos, N.P., (2015)** “Critical Analysis of Air Emissions from Ships: Lifecycle Thinking and Results”, in Book Green transport logistics: the

quest for win-win solutions, *Springer Series: International Series in Operations Research & Management Science,* Ed.: H. Psaraftis. ISBN 978-3-319-17175-3

3. **Bilgili L., Celebi U. B., Chatzinikolaou S., and Ventikos N. (2015), “**An investigation on impact of painting and operation emissions in a ship’s life cycle to the environment” 18th International Symposium on Environmental Pollution and its Impact on Life in the Mediterranean Region, MESAEP 2015, September 26-30, 2015, Crete – Greece

7.1 Introduction

This chapter presents the case studies conducted with the application of the framework for ship LCA that has already presented previously in this thesis. The case studies were conducted in the context of funded research projects and therefore had specific aims which follow within the scope of work of these projects. Therefore, the LCA boundaries and the scenarios examined are specifically reflecting the scope of work of the project. Hence, there are other case studies conducted in the context of non-funded research which use boundaries conditions and scenarios that depict specific objectives set in cooperation between the undersigned and his supervisors. All case studies conducted in the period between 2012 and 2015.

The LCA framework serves as the basis in all case studies; however, in cases where additional information has been available the results are modified and improved using this information. For example in Case Study 2, the loading diagram of the main engine has been made available. In addition, further information for the added hull resistance due to marine growth has been used. This new information was taken into account in the calculations for the formulation of the Inventory of ship emission in the operational life of the ship.

In case study 3, specific speed limits were set for a fraction of the ship’s life cycle as a request from the research programme.

Finally, the case studies shown in this chapter include only ship emissions Inventories results and not impact assessment results. The final step of LCA, which is the impact assessment, is studied separately in chapter 9 (theoretical concept) and chapter 10 (case studies).

7.2 Case Study 1 – Emissions LCI of Panamax Oil Tanker

The first case study with application of the LCA framework is a screening life cycle exercise. The Screening Life Cycle example refers to a Panamax oil tanker (built in 2009 at S. Korea). The details of the ship are shown in Table 12. The ship is equipped with a 2-stroke main engine and three auxiliary engines. The ship’s steel weight has been calculated using suitable Naval Architecture methods (namely the Schneecluth method).

The weights of main and auxiliary engines are those provided in the engine manuals. For the calculation of the wetted surface area, the formula used was the one suggested by A. Denny as result of investigations made by E.R. Mumford. It is noted that for cargo vessels of moderate speed (about 14-15 knots) and fairly full hull form which is the case here, the wetted surface may be obtained from this formula with accuracy often well within 1% (Lewis, 1989).

Table 12: Case Study 1 - Details of the examined ship

Panamax Oil Tanker	
Year of built	2009
Country	S. Korea
General data	
Displacement (tonnes)	88221

DWT (tonnes)	74296
Lightship (tonnes)	13925
Steel weight (tonnes)	12022
Design Speed (knots)	15.30
Main Particulars	
L_{BP} (m)	219.00
Breadth (m)	32.24
Depth(m)	20.60
Draught (m)	14.17
Block Coefficient C_B	0.85
Main Engine	
STX-MAN B&W 6S60MC	2 stroke
Country	S. Korea
Power of ME (kw)	12240
RPM	105
Weight of ME (tonnes)	368
Auxiliary Engines (3)	
MAN B&W	4 stroke
Country	S. Korea
Power of ME (kw)	740
RPM	720
Weight of ME (tonnes)	19.7

7.2.1 Ship system description – Boundaries

Steel is the main hull material with respect to air emissions as already stated in the previous paragraphs. The boundary conditions for the system element of hull material in this particular case study is shown in the following Figure 22. The processes included are transport of steel to yard, cutting of steel, sandblasting and welding. Apart from the processes shown in Figure 22, the production of materials is also included in this system element.

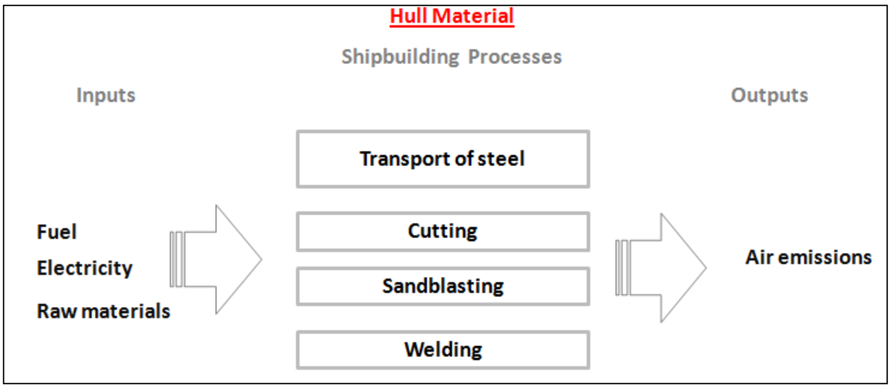


Figure 22: Shipbuilding processes included in the Hull Material system element

Painting and coating operations are the main processes in the hull protection system element. Painting is performed at many stages from the initial priming of the steel, to the final paint application. Outdoor painting (layers of paint applied to the outer skin of a ship hull), is in general higher than indoor painting (layers applied to the inner parts of the ship). Foreground data were used for the calculation of VOC emissions during the shipbuilding operations. Calculations are based on the study of Celebi (Celebi et al, 2008) who reported that the painting process during shipbuilding operations of a 3,500 DWT tanker vessel caused around 5.5 tonnes of VOC emissions (0.00157 tonnes/dwt). Inventory data from the EcoIndicator 99 database were used for the transport of paints, primers and antifouling to the shipyard. The transportation scenario for transporting materials to the shipyard is using a containership in a trip distance of 200 km. The hull protection system element with its boundaries is shown in Figure 23.

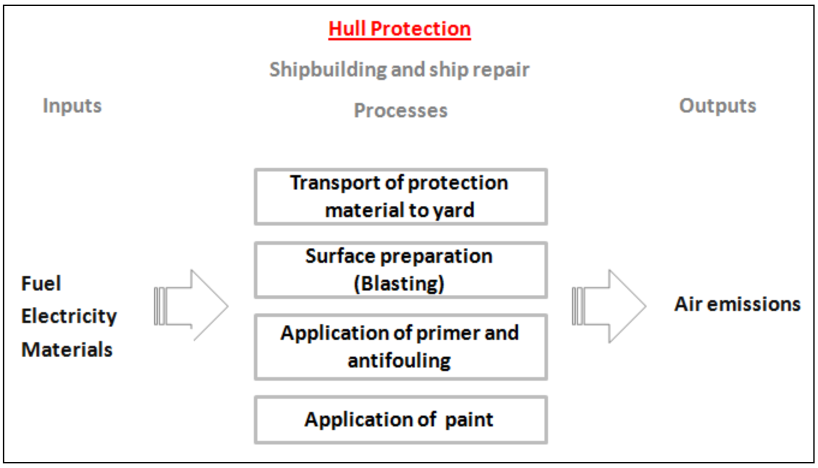


Figure 23: Processes included in the material protection system element (shipbuilding and ship repair)

Table 13 summarises the shipbuilding Inventory of materials and processes included in the Hull Sub System. The work collected information from generic (from life cycle database) but also ship specific data, for the important, with respect to air emissions, shipbuilding processes and materials. Efficient use of materials is a common goal for shipyards and ship-owners. However, the boundaries of the shipbuilding phase may be placed at the point where the materials are ready to be shipped to the yard therefore some (or all) of the items under materials in the following Table could be left out of the hull sub system. This is a matter of boundaries selection and scope of the study.

Table 13: Shipbuilding materials and processes – Hull Sub System

Hull Sub System			
Materials			
	Quantity	**Unit**	**Comments**
Heavy Fuel Oil, (HFO)	1409	tonnes	Production of HFO for materials transportation. Assumption: 500 km transportation by sea.
Diesel Oil (DO)	600	tonnes	Production of DO for materials transportation. Assumption: 500 km transportation by sea.
Ship's Steel (type St 13l)	13225	tonnes	Production of steel plates for ship structure. Calculations based on Sneekluth method.

Paper packaging	3.23	tonnes	Packaging material for shipbuilding. Calculation based on previous LCA studies.
Processes			
Energy from Electricity	3050000	MJ	Electricity for welding process. Calculation based on total welding length and average energy for welding process from previous studies.
Bulk carrier	13225×500	t×km	Transport of steel to the shipyard. Assumption: 500 km transportation by sea.
Containership A	113×200	t×km	Transport of sandblasting materials. Assumption: 200 km transportation by sea.
Containership B	6630×200	t×km	Transport of paints primer, antifouling Assumption: 200 km transportation by sea.
Energy from Electricity	828000	MJ	Energy for steel cutting process. Calculation based on previous LCA studies.
Energy from Electricity	490000	MJ	Energy for paint application. Calculations based on average data for painting process by previous studies.

There is an extensive Inventory of air substances emitted during the shipbuilding process of the hull sub system. Representative air emissions extracted from this inventory are provided in the following Table 14. The estimated total CO_2 emissions for the specific ship are 188.946 kg per tonne of dwt built.

Table 14: Representative emissions from the shipbuilding Inventory – Hull Sub System

	Substance	Unit	Quantity	Per tonne dwt
1	Carbon dioxide total	kg	1.40E+07	188.946
2	Carbon monoxide total	kg	4.22E+05	5.686
3	Methane total	kg	3.83E+03	0.052
4	Nitrogen dioxide	kg	1.53E+04	0.206
5	Nitrogen oxides	kg	6.92E+04	0.932
6	NMVOC	kg	9.74E+02	0.013
7	PM total	kg	1.27E+04	0.171
8	Sulphur dioxide	kg	7.77E+04	1.046
9	Sulphur oxides	kg	4.18E+03	0.056
10	VOC	kg	1.17E+05	1.571

Generally, the life cycle of engines before they are installed onto the ship is not known. A simplified scenario has been used for modelling the building process of a marine engine. This scenario includes specific materials (i.e. steel, fuels), and processes (i.e. assembly, welding, transport). The literature confirms that nearly all the environmental impact of engines derives from the operational phase of the engines when the consumption of fuels takes place. Table 15 contains the quantities of materials and processes for the construction and installation of one main engine and two auxiliary engines for the specific ship under examination.

Table 15: Shipbuilding Inventory – Machinery Main Components sub system

Machinery Main Components Sub – System			
Materials			
	Quantity	**Units**	**Comments**
Diesel Oil I (DO)	10	tonnes	Average consumption for the assembly of main and auxiliary engines
Diesel Oil I (DO)	0.406	tonnes	Production of DO for road transportation.
ME and AE Steel (type St 13I)	427	tonnes	Production of steel for ship engines (one main and three auxiliary engines). Weights from manufacturer's manuals.
Processes			
Steel product manufacturing. Average metalworking.	427	tonnes	Average data for manufacturing steel casting and other metal processing operations.
Transport (tractor and trailer)	55000	t×km	Transport of materials for engines. Assumption: 125 km transportation by road.

Representative air emissions from the Inventory of Main Machinery sub system are presented in the following Table 16. The column on the right provides the emission per total kW (one main and three auxiliary engines).

Table 16: Representative emissions from the shipbuilding Inventory – Main Machinery subsystem

	Substance	Unit	Quantity	Per kw installed
1	CO2	kg	1.23E+06	84.827
2	CO	kg	2.64E+03	0.183
3	CH4	kg	1.51E+03	0.104
4	NO2	kg	4.94E+02	0.034
5	NOx	kg	3.41E+03	0.236
6	PM (all)	kg	8.06E+03	0.557
7	SO2	kg	4.03E+03	0.279
8	SOx	kg	1.53E+02	0.011
9	VOC	kg	5.37E+00	0.000
10	NMVOC	kg	2.66E+02	0.018

7.2.2 Ship operation

For the operational phase, a specific scenario of ship operation was formulated. This scenario essentially considers that the ship is carrying oil from Novorossiysk (Russia) to Augusta (Italy). The one way distance of this trip is 2,464 nmiles which is covered in approximately eight days in the laden leg (assuming an average speed of 14 knots) and in nine days in the ballast leg (assuming an average speed of 11 knots). Details of the scenario are shown in the following Table 17.

Table 17: Scenario for the operation of the ship

Scenario of operation	
Loading Port	Novorossiysk
Unloading Port	Augusta
Distance (one way)	2464 nm
Days at Port	3
Trips per year	Years 1-13: 17 Years 13-25: 16
Trips in life cycle (25 years)	414
Speeds	Laden leg: 14knots Ballast leg: 11 knots

The round trips per year have been calculated using the formulas for unavailability of tankers which are shown in the following figure (Figure 24). These formulas derived from the work of Touran et al. (2009), and calculate the unavailability of oil tanker ships (days off-duty) due to repairs as subject to the age of the ship.

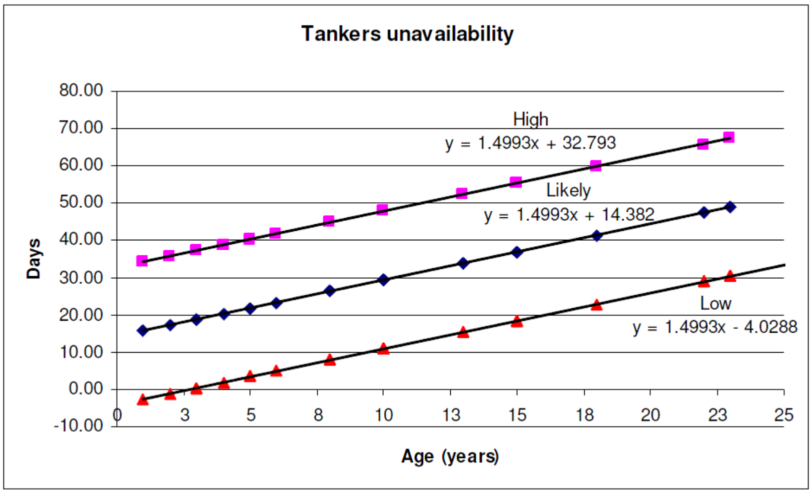


Figure 24: Unavailability vs. age for tankers (Touran et al., 2006)

The elements taken into consideration in the machinery subsystem are the main engine and auxiliary engines. The calculations were carried out using real engine's loading data provided by the ship owner. According to common practice, the examined ship uses one generator when on voyage and three generators at port. The speed vs fuel consumption curve of the examined ship is provided in Table 18 below.

Table 18: Main and auxiliary engines loading and consumption data

Speed (knots)	RPM	ME Power (kw)	SFC ME (gr/kWh)	ME FC (t/day)	AE FC (t/day)	Total FC (t/day)
11	66.1	3060	186.67	13.71	5	18.71
12.6	83.3	6120	178.73	26.25	5	31.25
13.1	95.4	9180.0	174.0	38.33	5	43.33
13.6	101.4	11016.,0	172.7	45.65	5	50.65
14	105	12240.0	177.1	52.03	5	57.03

The emission factors for nitrogen emissions have been also provided by the ship-owner and refer to the particular fuels used by the ship in various engine loads. These coefficients are given in the following Table 19.

Table 19: Fuel and emission factors data

	Main Engine	Auxiliary engines
Fuel type	RMG 380	RMG 380, (or MDO)
S content	4.5 % max	4.5% (or 0.1% for MDO)
CO2 coef.	3114400 g/tonne fuel	3206000 g/tonne fuel
NOx coef.	15.05 g/kwh at 100% rpm	11.25 g/kwh at 100% rpm
	15.88 g/kwh at 75% rpm	12.11g/kwh at 75% rpm
	16.16 g/kwh at 50% rpm	8.37g/kwh at 50% rpm
	16.12 g/kwh at 25% rpm	7.85g/kwh at 25% rpm

For the machinery subsystem only the combustion of fuels has been considered in the operational phase since there are no activities identified during engine maintenance that may have a considerable impact to the environment.

Using the data above, the total NO_x and SO_x emissions from the operational life of the specific ship have been calculated and results are provided in Table 20. For all other pollutants included in the following Table the corresponded data from the Extremis database have been used (i.e. ME and AE datasheets for oil tanker with length between 150 – 250 m in Greece).

Table 20: Emissions from ME and AE operation – Main Machinery subsystem

	Substance	Unit	Quantity	Per ship year (this study)	Per ship year (Fet)
1	CO2	kg	1.54E+09	6.18E+07	0.73E+08
2	NOx	kg	3.97E+07	1.59E+06	1.73E+06
3	SOx	kg	2.64E+07	1.06E+06	4.20E+05
4	CH4	kg	3.80E+04	1.52E+03	-
5	CO	kg	4.75E+06	1.90E+05	0.40E+04
6	HC	kg	9.51E+05	3.80E+04	0.80E+04
7	PM	kg	3.99E+06	1.59E+05	-

Including the production stage of fuels in the environmental life cycle of the ship is a matter under debate. Some previous LCA studies have included the production of fuels in the ship's operational phase (Kameyama et al., 2004).

Our study has calculated separately the production of fuels used during the whole life cycle (using fuel production data from Eco Indicator 99 database) in order to have a reference of the magnitude of this process. The fuel consumption during one round trip of the specific ship is 1027.45 tonnes of HFO (ME and AEs). For simplicity reasons it is assumed that AEs burn HFO (AEs of the specific ship have this capability). The total consumption in 25 years (i.e. 414 round trips) is 42,5364 tonnes HFO. Air emission breakdown for producing this quantity of HFO with current practice, (which is a crude assumption) is given in the following Table 21.

Table 21: Emissions from HFO production

	Substance	Unit	Quantity	Per ship year
1	Carbon dioxide total	kg	1,82E+08	0.73E+07
2	Carbon monoxide total	kg	2.13E+05	0.08E+05
3	Methane total	kg	2.73E+06	109E+03
4	Nitrogen oxides	kg	8.20E+05	0.03E+05
5	NMVOC	kg	1.28E+06	5.12E+04
6	PM total	kg	9.21E+04	0.03E+05
7	Sulphur dioxide	kg	3.39E+05	0.14E+05

Comparing the emissions of the two cases (production of fuels included and production of fuels excluded) it can be noted that excluding the production of fuel from the ship life cycle assessment may not affect some of the pollutants (such as CO_2) but may greatly affect other pollutants (such as Methane).

7.2.3 Maintenance

During the operational life of the ship's steel replacement takes place. Steel replacement may be required from the first year of operational life but in regular practice, this is rare before 10 years of age. Steel replacement usually takes place every 2.5 years following either the intermediate or the special surveys of the vessel.

Previous LCA studies have used some simplified assumptions for the amount of replaced steel during the ship's life cycle (i.e. 10% of the ship's steel is assumed replaced in 20 years according to Jiven et al. (2004).

An index representing the amount of replaced steel has been developed in the project IMPROVE (EC funded FP6 project). This index is represented as the amount of replaced steel divided by lightweight for a particular year. It is noted that this index derived by regression analysis of selected tankers data sample. The equation describing this index is as follows:

$$ARS = Lightweight \times 0.0306 \times (e^{0.2772 \times (age)} \tag{4.13}$$

where:

- ARS is the amount of replaced steel (in tonnes)
- Lightweight is the ship's lightweight (in tonnes)
- Age, is the age of the ship at the time of calculation (in years)

Similar results derive for the amount of steel replaced by utilizing the formula above and the 10% replacement rule. The first option results in a total amount of steel replacement during the life cycle of the ship (25 years) of 115.24 tonnes whereas the second one results in 132.25 tonnes of steel replacement over the life cycle.

With respect to the system element of hull protection it is not straightforward to estimate the amount of hull protection work carried out during the ship's life cycle. The nature of shipbuilding and repair requires several types of paints to be used for a variety of applications. It has been impossible to collect real data for application of paint primer and antifouling during maintenance operations. It is however reasonable to assume that the largest portion of hull protection maintenance works takes place every 5 years during the dry-docking of the vessel.

Previous studies (Jivén et al, 2004) have accepted that 50% of the area below the water line can be assumed painted with primer and antifouling during the dry-docking period. The assumption considered here is that primer and antifouling that will be applied in four dry-dockings over the life cycle will be twice as much as the quantity used in the shipbuilding phase. Moreover, as a conservative assumption it is considered that the paint application over the 25 years of ship's life will be at least twice the paint applied during shipbuilding. In the following Table 22, the quantities of materials and processes of the hull sub system during the maintenance phase are being presented.

Table 22: Maintenance materials and processes – Hull Subsystem

Hull Sub System – Maintenance			
Materials			
	Quantity	**Unit**	**Comments**
Heavy Fuel Oil, (HFO)	1409	tonnes	Production of HFO for materials transportation. Assumption: 500 km transportation by sea.
Diesel Oil (DO)	600	tonnes	Production of DO for materials transportation. Assumption: 500 km transportation by sea.
Ship's Steel (type St 13I)	132.25	tonnes	Production of steel plates for ship repair (10% of ship's steel).
Paper packaging	3.23×2	tonnes	Packaging material for shipbuilding materials. Calculation based on previous LCA studies.
Processes			
Energy from Electricity	305000	MJ	Electricity for welding process. Calculation based on total welding length and average energy for welding process from previous studies.
Bulk carrier	132.25×500	t×km	Transport of steel to the shipyard. Assumption: 500 km transportation by sea.
Containership A	2×113×200	t×km	Transport of sandblasting materials. Assumption: 200 km transportation by sea.
Containership B	2×6630×200	t×km	Transport of paints primer, antifouling Assumption: 200 km transportation by sea.
Energy from Electricity	82800	MJ	Energy for steel cutting process. Calculation based on previous LCA studies.
Energy from Electricity	2×490000	MJ	Energy for paint application. Calculations based on average data for painting process by previous studies.

The Inventory of emissions during the repair operations of the ship hull is shown in Table 23.

Table 23: Emissions from hull repair

	Substance	Unit	Quantity	Per ship year	Per ship dwt
1	Carbon dioxide total	kg	9.99E+05	4.00E+04	13.45
2	Carbon monoxide total	kg	3.40E+01	1.36E+00	0.00
3	Methane total	kg	1.95E+01	7.78E-01	0.00
4	Nitrogen oxides	kg	8.12E+04	4.49E+02	0.15
5	Nitrogen dioxide	kg	1.53E+02	6.13E+00	0.00
6	VOC	kg	2.34E+05	9.36E+03	1.57
7	PM total	kg	7.99E+02	3.20E+02	0.01
8	Sulphur dioxide	kg	5.82E+03	5.82E+02	0.08

7.2.4 Ship dismantling/recycling

The recycling stage is the most difficult stage of the ship's life with respect to the availability of environmental information. This was the outcome also from the literature review for ship recycling stage conducted in the context of this thesis.

Some information on recyclables from merchant ships originates from recycling yards in India. Table 24 displays data from Indian ship recycling yards. Steel in India is mostly recovered as reroll plate: steel plates that are rerolled into new sheet metal products without first being re-melted. This is a common practice in Asia but nearly unknown in developed countries. Incidentally, everywhere else in the world, the scrap from the demolished ships are usually sent into melting furnaces. South Asian countries utilise this technique of re-rolling scrap into producing construction steel without having to first cast scrap as billets and ingots. Information on emissions from the above process is unknown. The data in the following Table 24, represent average recovery results from the recycling of approximately 1700 ships of all kinds at Alang, India over more than 10 years (during the 1990's).

Table 24: Recovery materials weight data (Hess et al, 2001)

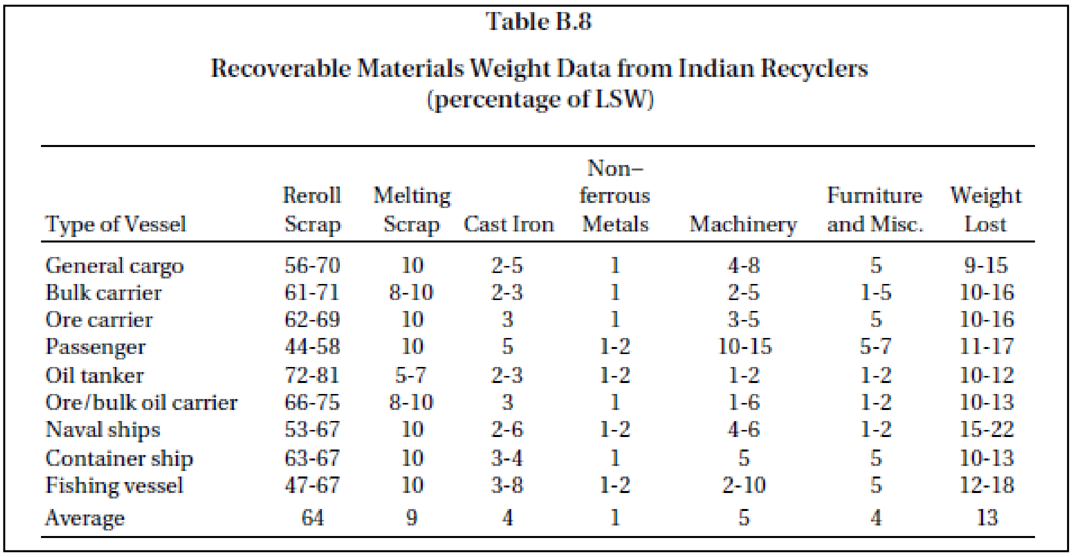


Table B.8

Recoverable Materials Weight Data from Indian Recyclers
(percentage of LSW)

Type of Vessel	Reroll Scrap	Melting Scrap	Cast Iron	Non–ferrous Metals	Machinery	Furniture and Misc.	Weight Lost
General cargo	56-70	10	2-5	1	4-8	5	9-15
Bulk carrier	61-71	8-10	2-3	1	2-5	1-5	10-16
Ore carrier	62-69	10	3	1	3-5	5	10-16
Passenger	44-58	10	5	1-2	10-15	5-7	11-17
Oil tanker	72-81	5-7	2-3	1-2	1-2	1-2	10-12
Ore/bulk oil carrier	66-75	8-10	3	1	1-6	1-2	10-13
Naval ships	53-67	10	2-6	1-2	4-6	1-2	15-22
Container ship	63-67	10	3-4	1	5	5	10-13
Fishing vessel	47-67	10	3-8	1-2	2-10	5	12-18
Average	64	9	4	1	5	4	13

Ship recyclers at the aforementioned sites report that they recycle all but about 3 percent of the as-received ship. The difference between this figure and those in Table 24 represents the amount of a ship's original as-built Lightship weight that is lost due to corrosion during its service life. These figures appear in Table 25 in the Weight Lost column.

The calculation of recoverable weights for the oil tanker under examination is provided in the Table 25 below. Emissions production during the processes scrap rerolling, melting and casting in Indian recycling sites is not known.

Table 25: Recovered materials from the examined ship

PANAMAX tanker LSW: 13925 tonnes	Reroll scrap	Melting scrap	Cast iron	Machinery	Weight Lost
(tonnes)	10583	835.5	348.125	417.75	1531.75

7.2.5 Case Study 1: Results – Discussion

The results of the case study 1, concern the development of emissions inventory for shipbuilding and operation of a PANAMAX oil tanker. Unfortunately, it was impossible to make calculations for the emissions production during the last stage of the ship life (ship recycling). Therefore, Figure 25 below, presents the calculated air emissions from shipbuilding and ship operation. The Y-axis of this figure is in logarithmic scale.

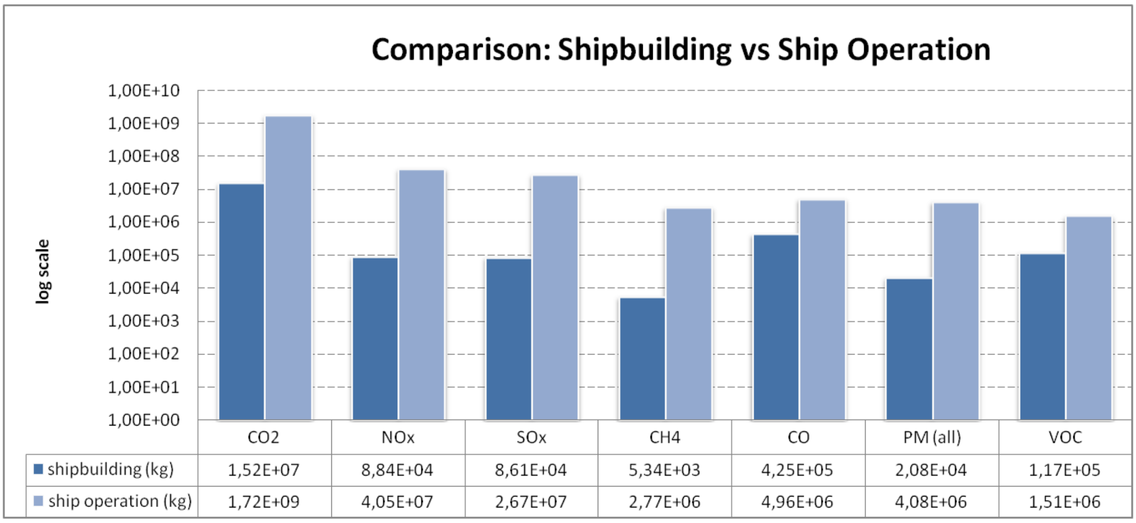


Figure 25: Comparison of emissions from shipbuilding and ship operation.

For a complicated system the inventory results can be quite excessive, both with respect to the number of parameters identified and with respect to how the results can be broken down into sub-systems and system elements. Here only the most important emissions (in terms of quantities) are presented.

As it has been demonstrated in previous studies the operational phase is the dominant in terms of emissions production which is attributed to the combustion of fuels in ME and AE engines. According to our calculations the CO2 which is produced over the operational life of the ship accounts for the 99% of the total CO2 emissions of the ship over its life span. The same stands for the other major air pollutants with exception of

VOC emissions which have a non-negligible amount produced during the hull protection activities.

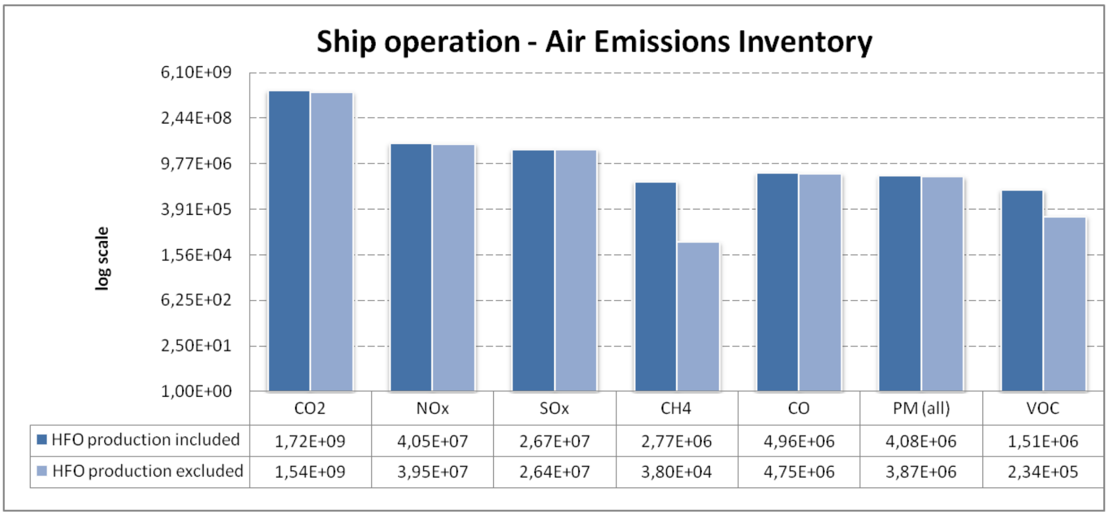
Table 26: Emissions share - Shipbuilding vs ship operation

	OPERATION	SHIPBUILDING
CO2	99.12%	0.88%
NOX	99.78%	0.22%
SOX	99.68%	0.32%
CH4	99.81%	0.19%
CO	92.12%	7.88%
PM (ALL)	99.49%	0.51%
VOC	92.83%	7.17%

Kameyama et al (Kameyama et al., 2004) reported that the contribution of ship operation over a period of 25 years accounts for about 98% of the total impact. In the same study the contribution of the shipbuilding stage has been measured to account for about 1.6%.

One crucial step in LCA is the selection of boundaries of the study. This selection may sometimes drastically affect the results. In the Figure 26, a comparison is being made between two different options of boundaries selection. The first option includes the production stage of fuels used in ME and AE engines (blue columns in Figure 26), in the operational stage of the ship life while the other option excludes it. As it can be seen the overall results of the operational inventory may be drastically affected by this selection. For example, the inventory of methane (which has severe environmental impact) is drastically reduced if the production of fuels is excluded from calculations.

As has been demonstrated in previous LCA studies, the overall environmental impact could be reduced by about 60% if the recycling of materials could be taken into consideration. However, in all previous ship LCA studies examined, the estimations of impact of the recycling stage were based on crude assumptions about the type and amount of materials recycled. Since the majority of ship scrapping activities currently takes place in the S. Asian sites (nearly 80% of the world’s scrapping capacity) with procedures which are based around the principle of maximum separation of the steel structure but do not make use of any technology similar to shipbuilding, estimates of environmental impacts are very difficult if not impossible. Only recycling processes accommodated in a shipyard could be candidates for making such estimations (i.e. perhaps if it is assumed that they are based on reverse shipbuilding operations). Due to the unavailability of adequate data in the literature this study has not attempted to make any emissions estimations during ship recycling.



	CO2	NOx	SOx	CH4	CO	PM (all)	VOC
■ HFO production included	1,72E+09	4,05E+07	2,67E+07	2,77E+06	4,96E+06	4,08E+06	1,51E+06
■ HFO production excluded	1,54E+09	3,95E+07	2,64E+07	3,80E+04	4,75E+06	3,87E+06	2,34E+05

Figure 26: Emission Inventories: HFO production included vs. HFO production excluded

7.2.6 Conclusion

The final step of any LCA study should be to try to interpret its results. More specifically the issues that should be addressed after the completion of the study should be:

- To combine if possible the conclusions with the results.
- To check the effect of assumptions taken and uncertainties of the elaborated data.
- To check whether the purpose of the study has been met.

Starting from the purpose of the study, the results indicate that the screening LCA study presented in this case study has met its overall goal which was to analyse air emissions of ships from a life cycle perspective. The results have been cross checked with results from previous studies and were found comparable in most cases.

One of the main goals of this study was to use as less as possible background data (i.e. average or generic data from databases) and to increase the utilization of foreground data (i.e. data explicitly referring to the specific system examined). Although background data have been used for certain processes and materials in all stages of the ship life cycle, this study has gone further than previous in the sense that it managed to increase the use of specific ship data within the ship LCA (for example the calculations of welding length, the details of the operational profile of the ship, etc.).

It can be concluded that the results of any ship-LCA study greatly depend on the system boundaries. One illustrated dilemma, which was exclusively examined previously, is whether to include the production stage of materials (i.e. bunkers fuels) in the operational phase of the ship. As demonstrated, the production of materials has a significant effect in the inventory results (especially for specific air pollutants). One option is to exclude bunkers production from the calculation since the shipyards (or the ship-owners) are more concerned about the consumption than the production of those materials. Moreover, it might be that the producer of the raw material has already submitted his contribution for the environmental impact of related activities. In practice, since there is no agreed reference system for the selection of boundaries in an LCA the choice is on the analyst in accordance with the goals and needs of the specific study.

There have been identified some serious uncertainties in the elaborated data. Illustrated example of these concerns the hull protection system element and more specifically the amount of materials used for primer, antifouling, and paint operations. Reliable information for these major shipyard activities was not available. Nearly all the studies examined have used crude assumptions for the amount of materials and energy used for the protection of the hull throughout the life cycle. Assumptions taken for hull protection (in shipbuilding and ship repair phases) are acknowledged as the greatest uncertainties of this present study.

7.3 Case Study 2 – LCI using activity data

The second case study's objective is the development of an emissions life cycle inventory using the algorithms of the framework. The studied ship is the same as in case study 1.

The main difference of this case study is the estimation of emission from machinery, which is based in the activity method but also takes into account the loading diagram of the main engine and the added hull resistance effect due to marine growth. The results also are available per life cycle year in this case study. Moreover, in this case study the emissions from the fuel consumption of boilers are added.

7.3.1 Main Engine Power and resulting emissions

The basic assumptions for the propulsion and auxiliary power requirements are given below. The model takes into account the loading diagram of the main engine (provided by the ship operator). In cases when the loading diagram does not include the scenario examined, the power is derived by using the Admiral coefficient.

For the main engine 75% of MCR is the required propulsion power in order to achieve the ship's service speed in the laden leg. The 25% of MCR power availability is justified by considering a power reserve of 15% of MCR due to rough weather conditions and another 10% of MCR power increase due to transmission system power losses.

In real conditions, the propulsion power needs are even higher due to the added resistance effect, which is subject to the hull condition. To introduce the impact of this effect into the calculations the diagram shown below is used. The diagram estimates the power needs which are increasing continuously (reflecting the periods between major dry dockings). For reasons of simplicity, the curves between the five-year periods are approximated as 1st degree curves. The numerical value of the slope of these lines (five lines in a 25 years life cycle) enters into the calculation. The real propulsion power is subject to the year examined.

$$P_{MEji} = \left(1 + i \times a_j\right) \times P_{MEj}, i = 1,2 \ldots,5 \; and \; j = 1,2, \ldots 5$$

Where:

- P_{MEji} *is* the real propulsion power after the introduction of the added resistance effect for the year i of the five –year period j,
- P_{MEj}, is the propulsion power at the beginning of the five year period j (for j=1, PME1 = PME),
- $a_j$is the slope of the line in Figure 25, for the five year period j divided by P_{MEj}:

$$\frac{\Delta P_{MEj}}{5\,P_{MEj}} = a_j$$

- ΔP_{MEj} is the increase in power from the beginning to the end of the five year period j.

Figure 27 is a schematic representation of the sequence of calculations for the estimation of emissions production deriving from the machinery operation. The emissions outcome is given per trip and year basis. P_{MEj} is assumed increasing linearly with time and therefore it can be written:

$$P_{MEj} = [1 + (j-1) \times \beta] \times P_{ME} \qquad j = 1, 2, \ldots, 5$$

$$\frac{P_{ME5} - P_{ME}}{4P_{ME}} = \beta$$

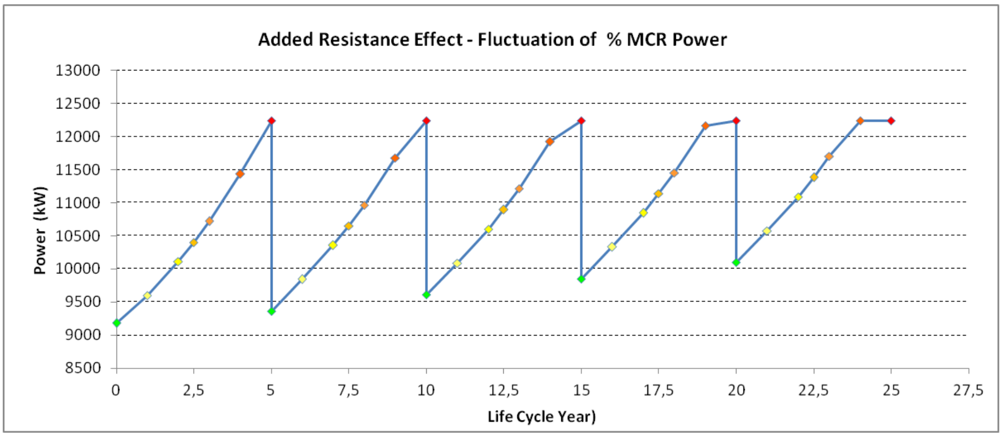


Figure 27: Fluctuation of power due to the added resistance

Considering the above, the final algorithm for the calculation of main engine emissions derives in Table 27.

Table 27: Algorithm for the calculation of emissions from main engine operation

Fuel Consumption	Main Engine
Ship Name	Xxx
Fuel Type	HFO
Engine type	Xxx
Installed Power (kW)	MCR
Specific Fuel Consumption (gr/kWh)	SFC
Speed laden (A-B) (knots)	$V_{A\to B} = V_{SERV}$
Propulsion Power – Laden (kW)	$P_{ME} = 0.75 \times MCR$
Real Propulsion Power – Laden (kW)	$P_{MEji/laden}$
Daily consumption - Laden (tons)	$FC_{A\to B(day)} = 24 \times P_{MEji/laden} \times SFC_{ME/laden} \times 10^{-6}$

Total Consumption - Laden (tons)	$FC_{A\to B} = t_A \times FC_{A\to B}$
Speed ballast (B-A) (knots)	$V_{B\to A}$
Propulsion Power - Ballast (kW)	$P_{ME(ballast)} = \dfrac{\Delta^{2/3} \times V_{B\to A}^3}{C_N}$
Real Propulsion Power – Ballast (kW)	$P_{MEji/ballast}$
Daily consumption – Ballast (tons)	$FC_{B\to A(day)} = 24 \times P_{MEji/ballast} \times SFC_{ME/ballast} \times 10^{-6}$
Total Consumption – Ballast (tons)	$FC_{B\to A} = t_B \times FC_{B\to A}$
Consumption outside port (tons)	FC_{wait}
Consumption in port	-
Consumption in manoeuvring (tons)	$FC_{manouv} = 0.25 \times MCR \times SFC_{0.25mcr} \times (24 \times t_{manouv}) \times 10^{-6}$
Consumption per trip (tons/trip)	$FC_{ME(trip)} = FC_{A\to B} + FC_{B\to A} + FC_{wait} + FC_{manouv}$
Total consumption per year (tons/year)	$FC_{ME(year)} = N_{trips(year)} \times FC_{ME(trip)}$
Emissions	Main Engine
Emissions per trip (tons/trip)	$m_{i/MEoperation(trip)} = EF_i \times FC_{ME(trip)} \; (i = CO2, ...etc)$
Total emissions per year (tons/year)	$m_{i/MEoperation(year)} = EF_i \times FC_{ME(year)} \; (i = CO2, ...etc)$

Assumptions considered in the algorithm for the calculation of auxiliary power:

- The auxiliary power at voyage is the power specified by the EEDI formula of IMO, for ships with installed main engine of over 10,000 kW. Therefore, the auxiliary power requirements are the same for the laden and ballast leg (although consumption is different).
- The ship makes use of the 75% of available auxiliary power when at port (for loading and unloading).
- Emission factors are those provided by the ship operator for CO_2, NOx, and SO_2 and from Extremis database for other emissions.

Table 28: Algorithm for the calculation of emissions from auxiliary engines operation

Fuel Consumption	Auxiliary Engines
Ship Name	xxx
Fuel Type	MDO
Engine type	xxx
Number of auxiliary engines	n_{AE}
Installed Auxiliary Power (kW)	$n_{AE} \times KW_{AE}$
Specific Fuel Consumption (gr/kWh)	SFC_{AE}
Used Power – Laden (kW)	$P_{AE(laden)} = 0.025 \times MCR_{ME} + 250$

Daily consumption - Laden (tons)	$FC_{A\rightarrow B(day)} = 24\times P_{AE(laden)} \times SFC_{AE} \times 10^{-6}$
Consumption per trip - Laden (tons)	$FC_{A\rightarrow B(trip)} = t_A \times FC_{A\rightarrow B(day)}$
Used Power - Ballast (kW)	$P_{AE(ballast)} = P_{AE(laden)}$
Daily consumption – Ballast (tons)	$FC_{B\rightarrow A(day)} = FC_{A\rightarrow B(day)}$
Consumption per trip– Ballast (tons)	$FC_{B\rightarrow A(trip)} = t_B \times FC_{B\rightarrow A(day)}$
Consumption outside port (tons)	$FC_{wait(trip)} = t_{wait} \times FC_{A\rightarrow B(day)}$
Used power in Port (kW)	$P_{AE(port)} = 0.75\times n_{AE} \times KW_{AE}$
Daily consumption in port (kW)	$FC_{Port(day)} = 24\times P_{AE(port)} \times SFC_{AE} \times 10^{-6}$
Consumption in port per trip (kW)	$FC_{Port} = t_{Port} \times FC_{Port(day)}$
Consumption in manoeuvring (tons)	$FC_{manouv(trip)} = t_{manouv} \times FC_{A\rightarrow B(day)}$
Consumption per trip (tons/trip)	$FC_{AE(trip)} = \sum_i FC_{i(trip)}$
Total consumption per year (tons/year)	$FC_{AE(year)} = N_{trips(year)} \times FC_{AE(trip)}$
Emissions	Auxiliary Engines
Emissions per trip (tons/trip)	$m_{i(AEoperation)(trip)} = \sum_i (EF_i \times FC_{AE(trip)}) \quad ,(i = CO2,...etc)$
Total emissions per year (tons/year)	$m_{i(AEoperation)(year)} = \sum_i (EF_i \times FC_{AE(year)}) \quad ,(i = CO2,.etc)$

The algorithm for the calculation of boilers emissions is shown below.

Table 29: Algorithm for the estimation of emissions in boilers

Fuel Consumption	Boilers
Ship Name	xxx
Fuel Type	MDO
Boiler type	xxx
Number of boilers used in voyage segment	$n_{boil(i)}$
Consumption per boiler (tons/day)	$FC_{Boiler(day)}$
Consumption – Laden (tons)	$FC_{Boiler(A\rightarrow B)} = n_{boil(A\rightarrow B)} \times FC_{Boiler(day)} \times t_A$
Consumption – Ballast (tons)	$FC_{Boiler(B\rightarrow A)} = n_{boil(B\rightarrow A)} \times FC_{Boiler(day)} \times t_B$
Consumption – port (tons)	$FC_{Boiler(port)} = n_{boil(port)} \times FC_{Boiler(day)} \times t_{port}$
Consumption per trip (tons/trip)	$FC_{Boiler(trip)} = \sum_i (n_{boil(i)} \times FC_{Boiler(day)} \times t_i)$

Consumption per year (tons/year)	$FC_{Boiler(year)} = N_{trips(year)} \times FC_{Boiler(trip)}$
Emissions	Boilers
Emissions per trip (tons/trip)	$m_{i(Boiler)(trip)} = \sum_i (EF_i \times FC_{Boiler(trip)}) ,(i = CO2,.etc)$
Emissions per year (tons/year)	$m_{i(Boiler)(year)} = \sum_i (EF_i \times FC_{Boiler(year)}) ,(i = CO2,.etc)$

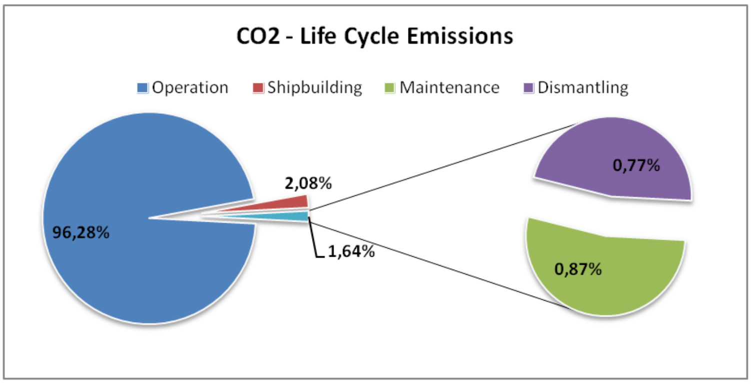
7.3.2 Case Study 2: Results – Discussion

Emissions of CO_2 are by far the largest emissions produced during the ship's life cycle. For the Panamax tanker examined and for a life cycle of 25 years the overall CO_2 emissions are over 1 million tons.

Table 30: Case Study 2: Ship total Life Cycle Emissions

Emissions	Unit	Operation	Shipbuilding	Maintenance	Dismantling	Life Cycle
CO2	tons	1,06E+06	2,29E+04	9,62E+03	8,51E+03	1,10E+06
CO	tons	3,17E+03	4,53E+02	8,16E+01	7,72E+02	4,48E+03
CH4	tons	2,81E+01	4,06E+00	1,48E+00	2,13E+00	3,58E+01
NOx	tons	3,04E+04	1,28E+02	9,20E+01	1,07E+02	3,07E+04
PM (all)	tons	2,45E+03	2,29E+01	8,69E+00	2,25E+01	2,51E+03
SO2	tons	1,57E+04	1,02E+02	7,39E+01	1,28E+02	1,60E+04
VOC	tons		2,00E+01	5,78E+01	2,99E-01	7,81E+01

The results justify the dominance of the operational life of the ship in the emissions production. However, the importance of the life cycle stage is subject to the emission type examined. For the types of emissions which are directly connected with the combustion of fuels in engines (i.e. CO_2, SO_2, NOx, PM) the share of operational emissions is well over the 90%. Emissions of CO however, are not negligible in other life cycle stages. Higher concentrations of CO emissions in shipbuilding and dismantling are attributed to the steel handling processes (welding, cutting etc.).



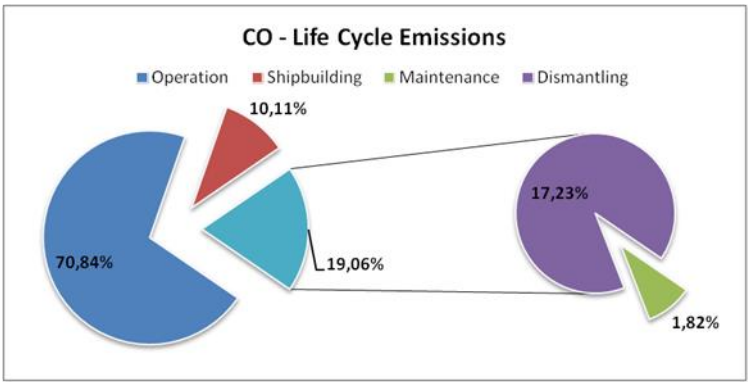


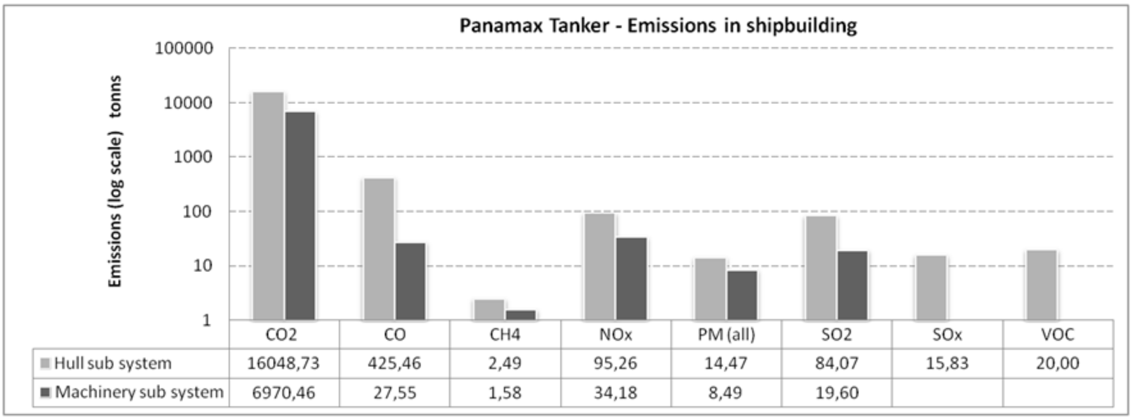
Figure 28: CO2 and CO emissions per life cycle stage

Table 31: Share of emissions in life cycle stages

	Shipbuilding	*Operation*	*Maintenance*	*Dismantling*
NOx	0.42%	98.94%	0.30%	0.35%
PM (all)	0.92%	97.84%	0.35%	0.90%
SO2	0.64%	98.10%	0.46%	0.80%
CH4	78.58%	11.34%	4.13%	5.95%

Emissions in shipbuilding

The shipbuilding stage results show that the hull sub system produces larger amount of emissions compared to the construction of the machinery sub system.



	CO2	CO	CH4	NOx	PM (all)	SO2	SOx	VOC
Hull sub system	16048,73	425,46	2,49	95,26	14,47	84,07	15,83	20,00
Machinery sub system	6970,46	27,55	1,58	34,18	8,49	19,60		

Figure 29: Case study 2 - Emissions in shipbuilding

Looking deeper into the hull sub system the emissions results of the two system elements of this sub system (i.e. the hull material and hull protection system elements) are presented below. Hull material system element produces the larger amount of emissions in the hull sub system. However the VOC emissions are almost totally attributed to the hull protection system element and more explicitly to the paint application processes. These processes are being modelled in detail in the Life Cycle Tool using foreground emissions data from major paints manufacturers.

Table 32: Hull subsystem emissions results

Emissions	units	Hull material	Hull protection	Total
CO2	tons	13710.58	2338.14	16048.73
CO	tons	421.74	4.27	426.02
CH4	tons	2.20	0.31	2.51
NOx	tons	80.44	17.90	98.34
PM (all)	tons	13.50	1.05	14.55
SO2	tons	72.15	14.37	86.52
SOx	tons	6.75	9.78	16.53
VOC	tons	0.17	21.38	21.56
NMVOC	tons	0.28	0.46	0.74

In the hull material system element, the dominant process is the steel production process. Information for the emissions in this process derives from SimaPro software and Eco Indicator databases.

Table 33: Hull material system element emissions results

		Shipbuilding - Hull material system element processes					
Emissions	**units**	**steel production**	**steel welding**	**steel cutting**	**steel blasting**	**raw materials transport**	**Total**
CO2	tons	13172.06	298.63	71.75	0.94	167.20	13710.58
CO	tons	420.92	0.28	0.07	0.00	0.47	421.74
CH4	tons	2.16	0.02	0.00	0.01	0.01	2.20
NOx	tons	77.25	0.12	0.03	0.00	3.04	80.44
PM (all)	tons	12.29	0.20	0.05	0.95	0.01	13.50
SO2	tons	69.70				2.46	72.15
SOx	tons	4.15	2.09	0.50	0.01	0.01	6.75
VOC	tons	0.17				0.01	0.17
NMVOC	tons	0.14	0.10	0.02	0.02	0.00	0.28

Emissions in operation

Considerable emissions in the phase of operation are produced only from the machinery subsystem. The framework has the capability to provide results per year of operation. The initial scenario examined assumes that the ship operates for 25 years.

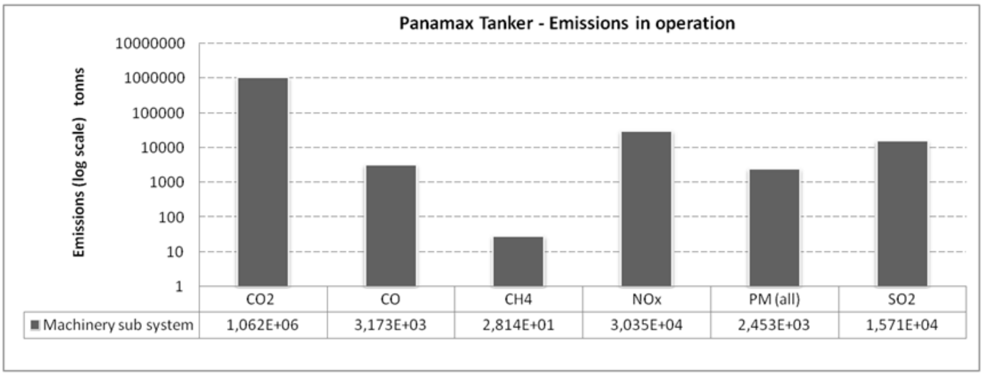


Figure 30: Case Study 2 - Emissions in operational life of the ship

Emissions results in the operational ship life cycle stage are shown below. In this initial scenario the ballast and laden speeds remain constant (at 14 knots) for simplicity reasons. It is however noted that speed inputs may be added in the framework by the user.

The analysis per year of operation reveals that emissions are continuously increasing in every five years which corresponds to the period between major maintenance works (dry-docking periods). Every five years an emission peak occurs, which reflects the impact of the added resistance effect. Another unique feature in this case study, is the estimation of the trips per year, using scientific information for the unavailability of tankers (Touran et al., 2009). This is illustrated in the following diagrams by the fact that the 5 year emission peak is decreased from year 5 to year 10 and so on, reflecting the lower number of trips accomplished as the ship life cycle grows.

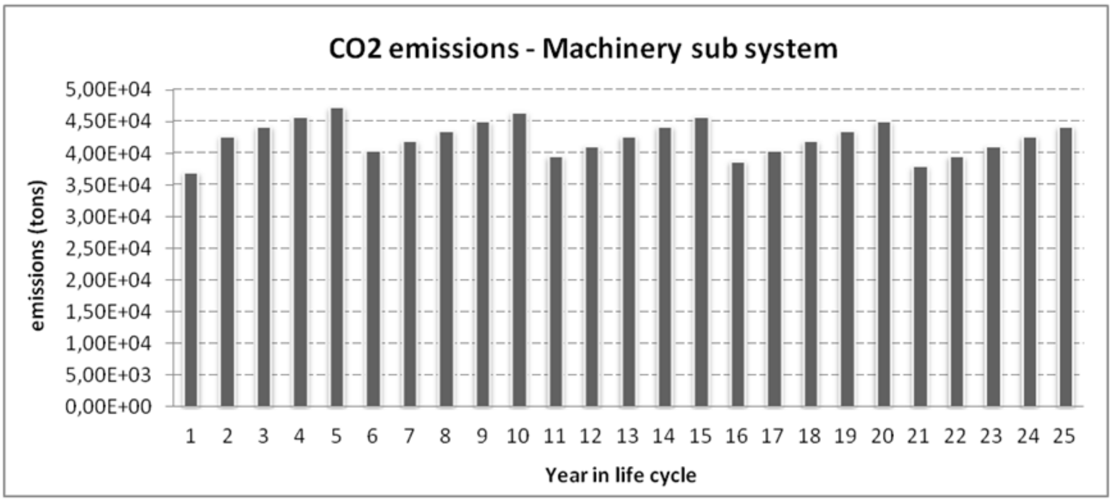


Figure 31: Case Study 2 - CO2 emissions of machinery (per year)

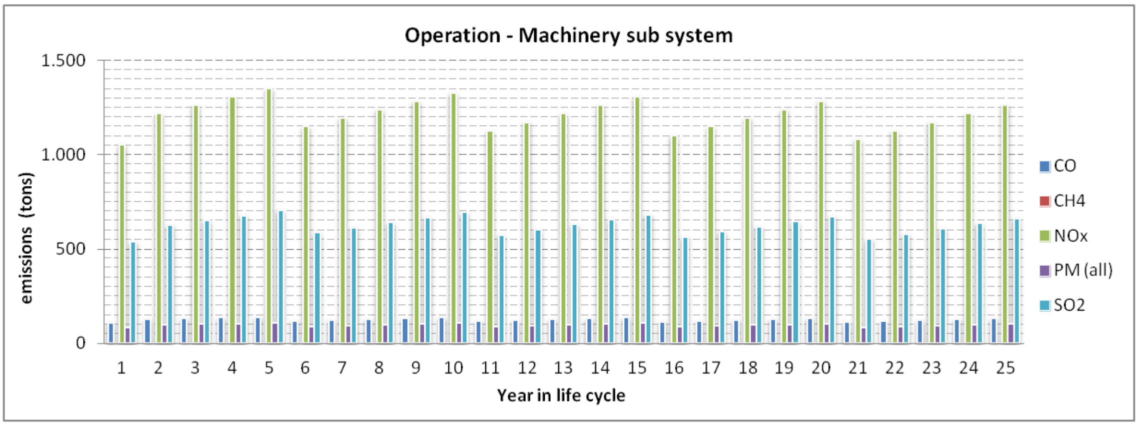


Figure 32: Case Study 2 – Non CO2 emissions of machinery (per year)

Emissions in maintenance

Emissions in maintenance are mainly produced from the hull sub system. No important maintenance processes have been identified for the machinery subsystem. The processes are considered identical to the shipbuilding processes but with different use of energy and materials. The main assumptions made are for the paints application that is carried out during the major dry docking periods.

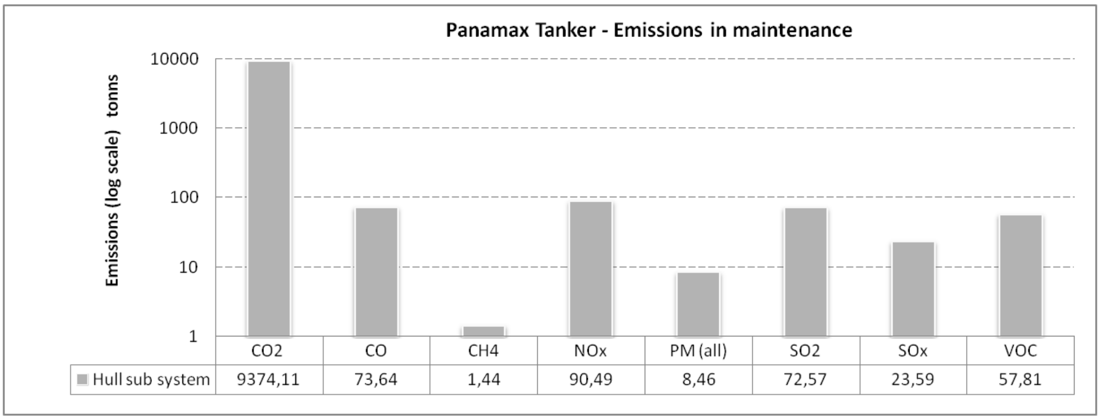


Figure 33: Case Study 2 – Emissions in maintenance

The framework makes emission estimations of primer, antifouling and paints for different areas of the ship (i.e. wetted surface, deck, cargo holds, and ballast tanks). With respect to the application of primers, antifouling and paints application the main uncertainty is the number of layers applied. The calculations may be greatly affected by the choice of layers. The layer parameter which is subject to the specific type of coating, the operational profile of the ship and other factors is included in the framework.

Emissions in recycling

This case study assumes that the ship is to be recycled in S. Asia and the main recyclable material which is steel is to be recovered as reroll plate: steel plates that are rerolled into new sheet metal products without first being re-melted. Information on emissions from the above process is generally not available. One source (Tilwankar et al., 2006) has indicated that the contribution to global warming of the virgin sheet metal steel obtained from iron ore mining is near about 2.7 times more than second process i.e. manufacturing of sheet metal steel obtained from dismantled ships. The amount of steel of the ship treated and recovered with this specific method of re-rerolling varies subject to the type of ship. According to Mahindrakar (Mahindrakar et al, 2008) for a tanker it ranges from 72 to 81% of the recycled steel. Hence, according to the same study the steel weight losses for tankers range from 8-10% of the lightship weight, which is attributed to the corrosion effect.

The scenario which has been examined in this case study uses the above information. It is acknowledged though, that using only this information, the obtained results by no means manage to cover the true environmental impacts of the ship recycling process.

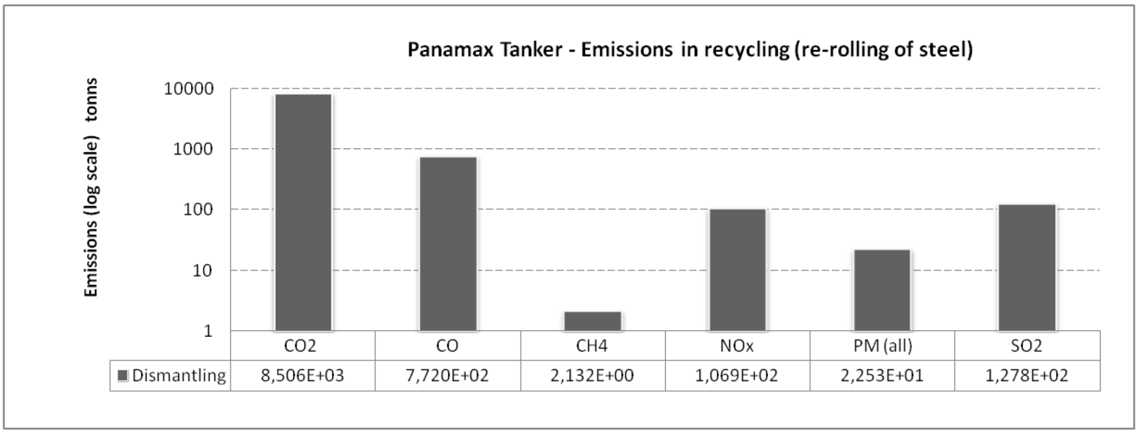


Figure 34: Case study 2 - Emissions in recycling (re-rolling process of steel)

These results provide only an indication of the emissions related to the re-rolling process which is largely applied in S. Asian dismantling sites. It is also acknowledged that the current mechanisms established in the majority of these ship recycling sites form severe threats to the environment and human health at the local level. In fact, the example of these practices could be used in the future to promote the clear benefits from studying the ship system with the life cycle thinking approach.

7.4 Case Study 3 – Alternative operational scenarios

The LCA Framework has the flexibility to cover various scenarios of operation. It includes a routine for calculating various periods of ship operation and ship trips accomplished per year. These calculations lead to the estimation of the transport work accomplished (throughput) in trip and year basis. The user enters the values for some basic variables such as the distance covered per trip, the relevant ship speeds (in ballast and laden leg), the waiting times (i.e. outside port, manoeuvring) the number of ships used for the required transport work and the life cycle years. The examined ship is the same as in Case Study 2; therefore, all comparisons made here use as basis the results of this case study.

7.4.1 Alternative scenarios of operation

Table 34, includes three scenarios with different operating characteristics (i.e. a slow steaming scenario, a cold ironing scenario and a speed limit scenario), which are compared to the initial one. Results show that there is a clear positive effect in emissions for the two scenarios with lower speeds (speed limit and slow steaming) compared to the initial scenario. The cold ironing scenario however, has resulted in minor benefits, which supports the rational that this solution is not very attractive for the particular case of tanker ships.

As already stated the characteristics and main assumptions of the alternative scenarios are selected in accordance to the scope of work of the research project within which this study was conducted.

Table 34: LCI emissions comparison of three alterative operational scenarios with the initial scenario

	Slow steaming	Cold Ironing	Speed limit
	Initial Mode: years 1 – 15 Slow steaming: years 16 – 25 Speed (Laden): 11.5 knots Speed (Ballast): 13 knots	Availability of short side electricity in all port calls	Initial Mode: years 1 – 5 Speed Limit: years 6 – 25 Speed (Laden): 12 knots Speed (Ballast): 12 knots
CO2	-7.65%	-0.96%	-10.57%
CO	-5.40%	-0.88%	-10.23%
CH4	+0.68%	-0.72%	-1.80%
NOX	-8.95%	-0.58%	-12.65%
PM(all)	-11.67%	-0.01%	-20.12%
SO2	-15.09%	-1.24%	-15.55%

7.4.2 Fleet Distribution

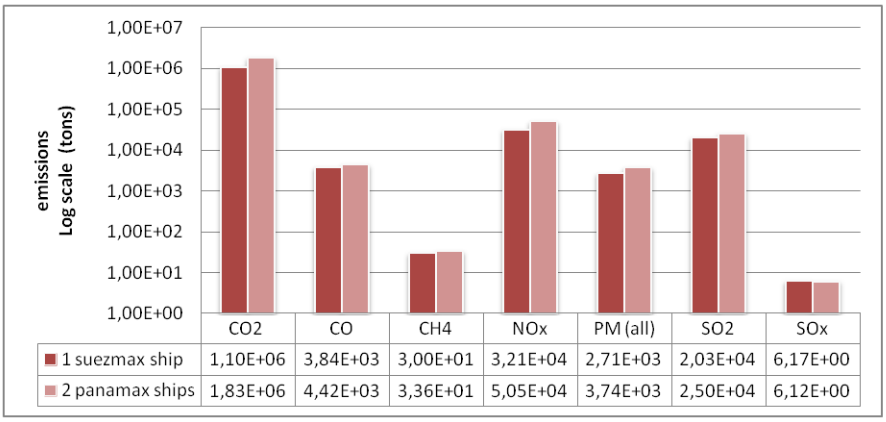
The developed framework has been used to examine the influence of fleet distribution in life cycle emissions. For demonstration purposes a simplified scenario has been formulated and comparisons have been made between two different fleet compositions. The first option is to employ two Panamax ships which are considered sister ships to the ship of the initial scenario shown previously (Panamax tanker of 75,000 tonnes dwt). The second option is to employ one Suezmax ship to carry the same throughput in a life cycle scenario of 25 years. Details of the trip, speeds and throughput are provided in Table 35.

Table 35: LCI emissions comparison of three alterative operational scenarios with the initial scenario

Scenario Details	units	Option1	Option 2
Ship type		**2 Panamax ships**	**1 Suezmax ship**
Port of Departure (A)		A	A
Port of Arrival (B)		B	B
Distance covered (A-B)	n.m.	2464.00	2464.00
Speed laden (A-B)	knots	14.00	15.00
Speed at ballast (B-A)	knots	11.00	11.00
Days (A-B) Laden	days	7.33	6.84
Days (B-A) Ballast	days	9.33	9.33
Days at see	days	16.67	16.18
Days at port (loading)	days	1.50	2.50
Days at port (unloading)	days	1.50	2.50
Total days at port	days	3.00	5.00
Duration of 1 trip	days	20.67	22.18
Days off /year	days	15.00	15.00
Days outside port per trip	days	1.00	1.00
Number of trips / year	trips	16.89	15.84
Ship life cycle	years	25.00	25.00
Total trips in life cycle	trips	422.18	396.11

DWT	tonnes	74296.00	158370.00
Throughput/year (1 ship)	tonnes	1254643.74	2509287.48
Throughput in life cycle (1 ship)	tonnes	31366093.55	62732187.10
Fleet (number of ships)		2.00	1.00
Total Throughput (fleet)	tonnes	62732187.10	62732187.10

The results obtained from this comparison reveal that employing one Suezmax ship (option 2) will produce less overall emissions in the life cycle of twenty-five years. Looking at the overall CO_2 emissions of the two options it is obvious that the Suezmax ship produces 73,2850 tons less CO_2 in 25 years of life than the two Panamax ships together. This can be also rephrased as follows: the Suezmax has an average rate of 6.94 tons CO_2 per tonne of dwt while the two Panamax ships have an average of 12.33 tons CO_2 per tonne of dwt. Hence, the Suezmax has lower emissions results for all for all emissions categories.



	CO2	CO	CH4	NOx	PM (all)	SO2	SOx
■ 1 suezmax ship	1,10E+06	3,84E+03	3,00E+01	3,21E+04	2,71E+03	2,03E+04	6,17E+00
■ 2 panamax ships	1,83E+06	4,42E+03	3,36E+01	5,05E+04	3,74E+03	2,50E+04	6,12E+00

Figure 35: One Suezmax vs. two Panamax tankers. Comparisons of total life cycle emissions

7.5 Case Study 4 – LCI in coating operations

The focus of this study is the estimation of Volatile Organic Compounds (VOC) emissions during painting operations. Kura (1998), has estimated VOC emissions as well as hazardous air pollutants (HAPs) formed as a result of painting processes in shipyards and boatyards. Lin and Kenny (1996) have studied the control and effect of VOC in generic industrial operations, and Malhebre and Mandin (2005) presented a risk assessment for VOC emissions during outdoor painting operations and concluded that health risks exist for people living in the site surroundings.

7.5.1 Materials and methods

The VOC emissions related to the painting process are calculated on the basis of the equations developed for the holistic framework for studying ship emissions on a life cycle perspective as presented in Chapter 4. For the calculations of VOC emissions, specific formulas developed in the work of Celebi and Bilgili (2015) have been used.

Total VOC emissions formed during three life cycle stages (new building, repair and operation) of a cargo ship are calculated. Greenhouse gas (GHG's) and heavy metal emissions, which are formed during the operational stage, are also calculated. For the purposes of this study and during the shipyard activities, only the painting process which is responsible for most of the VOC emissions in shipbuilding and ship repair is considered. The ship of the case study is a bulk carrier with the characteristics shown below.

Table 36: Main Characteristics of the case study ship

Main Characteristics	
DWT (tonnes)	30000
Design Speed (knots)	14.5
LBP (m)	180
Breadth (m)	25
Depth(m)	20.60
Draught (m)	10
Main Engine	
	2 stroke
Power (kw)	7860
Auxiliary Engines (3)	
	4 stroke
Power (kw)	600

The main processes of the shipbuilding are welding, blasting and painting. Amongst all, the most of the VOC emissions are formed during painting process. All ships must be put under maintenance in a dry dock and, and if necessary, repaired once every five years. During this process, the hull surface of the ship should be maintained. The VOC calculations are mainly based on the formulas of Celebi and Bilgili, which are presented and explained as follows

$$[EVOC_i^k]_j^x = [Q_{\rho_{VOC_i}} \left(\frac{VOC_i}{100}\right)\left(1 - \frac{CE_i}{100}\right)] \quad (1)$$

$$[ETVOC^k]_j^x = \sum[Q_{\rho_{VOC_i}} (\frac{VOC_i}{100})\,(1 - \frac{CE_i}{100})] \quad (2)$$

where;

i: pollutant type

j: surface type

k: paint type

x: ship type

$[EVOC_i^k]_j^x$: i emission from paint k applied to the hull surface j of ship x (g/m^2)

$[ETVOC^k]_j^x$: total EVOCs from paint k applied to the hull surface j of ship x (g/m2)

Q: total quantity of coating used per m2 (l/m2)

ρ_{VOCi}: density of VOC type I (g/l)

VOCi: proportion of VOC type i in total VOC

CEi: control efficiency for pollutant i

7.5.2 Case Study 4: Results – Discussion

Emissions in painting (shipbuilding and ship repair)

First, the total VOC emissions are calculated for the shipbuilding life cycle stage. The total amount of paints used is obtained from the shipyard and the painting contractor. To simplify the very complex shipbuilding process, which is mainly carried out by building and subsequently merging many different parts, the study considers that the painting activity is implemented in six sub-units (bottom & side, topside, cargo, deck, machinery and tanks). The contents of VOC's are different for each type of paint. While the main content of solvent based paints are toluene (37.87%), isomers of xylene (8.17%), ethyl acetate (2.04%) and acetone (1.27%), the main content of primer paints are toluene (44.31%) and isomers of xylene (2.68%). 50.65% and 52.01% of solvent based paints and primer paints are other VOC's, respectively.

The total VOC emissions are calculated by multiplying the total paint consumption and VOC contents of the paint type and the results are provided per sub-unit.

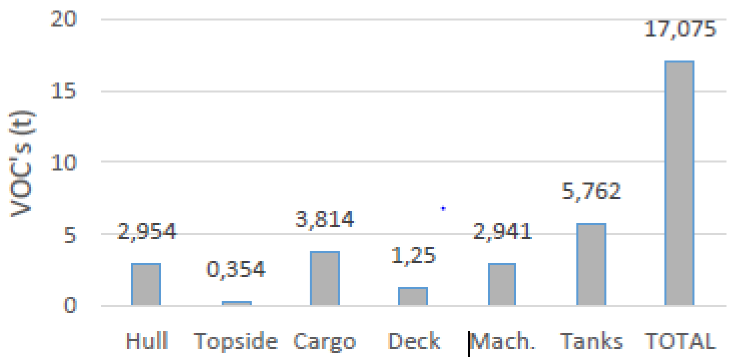


Figure 36: Case study 4 – VOC Emissions in shipbuilding

The study assumes that paint in repair applies only in four sub units (topside, bottom, vertical sides and flat bottom) of the ship. VOC emissions in ship repair are shown below.

This case study included in the work of Bilgili et al. (2015) in which the undersigned conducted assistant research work.

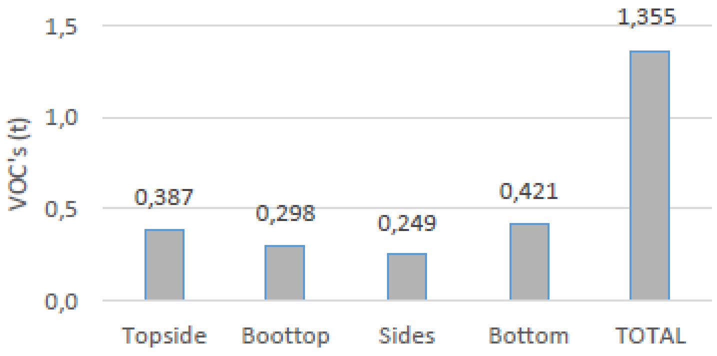


Figure 37: Case study 4 – VOC Emissions in ship repair

8. COMPARATIVE LCA: LNG VS. HFO

Summary

The study included in this Chapter employs the life cycle assessment method with the aim to comparatively evaluate the environmental impacts of two marine fuel alternatives. The life cycle of two different marine fuels are examined; the liquefied natural gas (LNG) and the low sulphur heavy fuel oil (1% sulphur content HFO). Specific geographical boundaries and scenarios as regards the supply chain of the examined fuels are used. The fuel supply chain includes extraction, sea transportation, and storage in oil and gas terminals and final bunkering and combustion on-board a car/passenger ferry. The purpose is to identify the overall environmental impact of main air emissions produced during the entire life cycle of the two alternatives.

The Chapter starts with a short introduction encompassing the motivation and literature review on fuels with focus on the LNG. The scope of the comparative LCA methodology is then presented and boundary conditions and functional units are described. LNG and HFO Life Cycle Inventory results are formulated and comparisons in quantities and impact perspective are finally carried out and commented.

Acknowledgments

1. Elements work included in this chapter has been carried out in the context of the diploma thesis of Mr Dimitrios Diamantakis and submitted to the School of Naval Architecture and Marine Engineering. The title of the thesis in Greek. The supervisor was Ass. Prof Ventikos. The author provided also assistance to Mr Diamantakis and would like to acknowledge his motivation and excellent cooperation.

2. Part of the work included in this chapter has been carried out in the context of the research activities of the Centre of Excellence in Ship Total Energy-Emissions-Economy of the National Technical University of Athens, School of Naval Architecture and Marine Engineering. The Centre and consequently this study have received financial support by the Lloyds Register Foundation (LRF), which is gratefully acknowledged. LRF helps to protect life and property by supporting engineering-related education, public engagement and the application of research.

8.1 Introduction

International shipping is widely accepted as an environmental friendly mode of transport due to its energy efficiency advantage over competitive transport modes. Cargo ships carry the vast majority of global transport demands (nearly 90% of global trade) and at the same time are responsible for less than 3% of the anthropogenic carbon dioxide emissions. However, emissions of shipping are expected to double or even triple until 2050 if no actions are taken by the industry (IMO, 2014). Hence, there is now sufficient evidence that ship emissions effects can harm the environment and human health especially in the proximity of populated areas (Endresen et. al, 2003), (Corbett et. al, 2007), (EEA, 2013). Through International Maritime Organisation (IMO), regulations are in place for dominant air emissions of shipping. These regulations are gradually imposing stricter limits regarding the quality of marine fuels and resulting emissions. The European Union has also put in place regulations beyond MARPOL Annex VI with Directive 2005/33/EC calling for more strict limits on the sulphur content of marine fuels in European sea-port areas.

The global merchant fleet currently consumes approximately 330 million tonnes of fuel annually, 80-85% of which is residual fuel with high sulphur content (Chryssakis et al., 2014). Increased environmental awareness, stricter emission regulations, economic incentives as well as developments in the fuel products industry have triggered discussions on fuel alternatives within the shipping sector.

8.1.1 Liquefied Natural Gas as Marine Fuel

Natural gas is continuously receiving attention as a promising alternative to conventional transport fuels. Natural gas offers some inherent advantages such as reduced emissions that have environmental and health impacts or emitting less carbon per unit of energy than petroleum-based fuels (ICCT, 2013). Liquefied Natural Gas, (LNG) is considered as an alternative for marine applications. Environmental benefits of LNG are known however in order to understand the overall environmental impact of fuel alternatives, the entire fuel supply chain of fuels should be considered. This involves the life cycle of fuel from extraction to processing transport and storage until the final stage of combustion. Liquefied natural gas (LNG) is natural gas, the main content of which is methane (typically between 70-90%). Other contents include ethane (5-15%) and small portions of propane and butane of not more than 5%, (Verbeek et al., 2011). LNG is the elaborated product of natural gas in liquid condition, which derives when natural gas is cooled down to -163 ^{o}C at atmospheric pressure. The LNG volume in liquid condition is approximately 600 times less compared to natural gas.

Natural gas contains far less carbon per content of energy which makes it one of the cleanest burning fossil fuels, emitting much lower air emissions than other fossil fuels such as oil or coal (Ryste 2011). Therefore, LNG is seen as an attractive option to meet current air emission requirements of shipping and as a promising alternative fuel for the shipping industry in the short term perspective (Chryssakis et al., 2013).

LNG uptake is expected to grow in the next 5 to 10 years, especially on relatively small ships operating in areas with developed gas bunkering infrastructure, where LNG prices are competitive to HFO prices (Chrysakis et al., 2014). Especially for passengers ships in Europe which are facing stricter environmental regulations the LNG is considered a promising fuel. This is depicted in the order book of LNG fuelled fleet of passenger vessels, which is growing faster than other segments (Chrysakis et al., 2014).

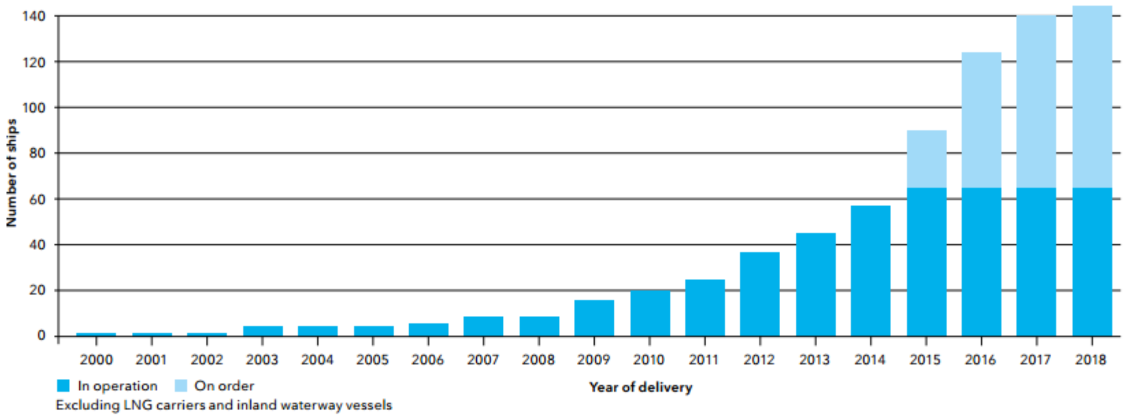
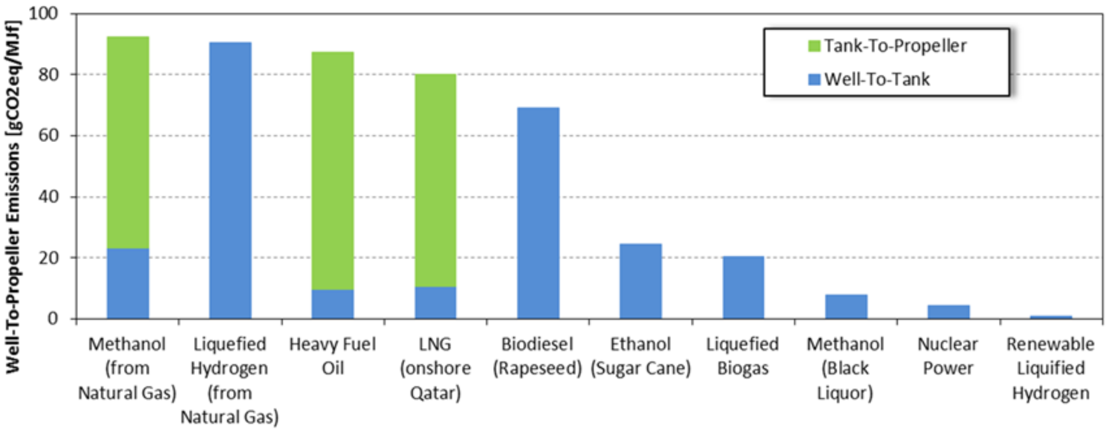


Figure 38: Development of LNG fuelled fleet (DNV.GL, 2015)

Alternative fuels are continuously addressed recently as possible solutions for enhancing the environmental footprint of ships. The life cycle thinking is the best approach to systematically examine the environmental impact of fuels. This approach has been extensively used in other modes of transport for analysing different fuels. For example, the automotive sector has long time experience in the so-called Well-To-Wheel studies; however, Well-To-Propeller studies are relatively new (Bengtsson et al., 2011). An example of the important information that the life cycle thinking approach could provide is given below. The assessment includes the production and transportation phases for each fuel, as well as the use on board a ship.

Figure 39: Alternative fuels - Green House Gas assessment form a life cycle perspective (Longva, 2014)



The blue shaded bars represent GHG emissions during production and transportation of the fuel (Well-To-Tank), whereas the green shaded bars represent emissions from combustion on board the ship (Tank-To-Propeller). For most fossil-based fuels, roughly 10-20% of their total emissions come from production and transportation, and the rest from combustion. However, for biofuels the GHG footprint is quite different. This is mainly due to the process used for producing the fuel (how energy intensive it is). Another illustrative example is the liquefied H_2. This is produced from natural gas and seems a weak option from an environmental point of view even if the combustion of this fuel does not produce any negative environmental effect.

8.1.2 LNG in maritime transport –studies

A number of studies have examined in a comparative manner alternative fuels for marine applications. Most recent studies have utilised the concept of life cycle thinking in making such comparisons. Many of the studies reviewed come from N. Europe (i.e. Norway) and area with mature infrastructure in marine LNG.

Laugen (2013), studied the environmental impact of heavy fuel oil and liquefied natural gas as marine fuels in a life cycle perspective. This is a very relevant study to the present due to the similar structure of boundaries and identical functional unit and will be used for evaluation purposes. Bengtsson (2011) have studied four options of marine fuels. Ryste (2012) conducted a screening life cycle assessment of greenhouse gas emissions related to LNG as ship fuel.

Oberg (2013), performed life cycle assessment in order to evaluate six fuel choices for ship propulsion including bio fuels. Corbett and Winebrake (2008), have studied the air emissions trade-offs among alternative marine fuels from a life cycle perspective.

Alkaner and Zhou (2006) assessed the life cycle environmental performance of molten carbonate fuel cell as an on-board auxiliary power system in comparison with a conventional diesel engine. Their analysis included manufacturing of the main components of the two alternatives, production of fuels, on-board operation and decommissioning aspects at end-of-life of the systems.

In the Third IMO GHG Study (2014) on greenhouse gas emissions from shipping, a remarkable increase of estimated methane emissions from ships is noted. In this study, reference is made to the International Gas Union (IGU), which considers methane as a critical GHG that needs to be reduced throughout its chain including the unburned methane on production, in transportation, in provision and elsewhere. Emissions of methane to the atmosphere are mainly associated with vessels carrying and/or using LNG as fuel and include three main mechanisms namely venting, leakage and methane slip.

The Third IMO GHG Study 2014 found that the emissions of methane to the atmosphere are associated with LNG powered vessels and include venting, leakage and methane slip.

In the third IMO GHG Study, venting and leakage related to maritime LNG operations are not included. The Republic of Korea has carried out supplementary research on methane venting which is to be submitted for consideration in the MEPC 71 on July 2017 (MEPC 71 INF.23). This study, which is based on operational data of three LNG carriers (138,000 cbm) over a period of 15 years, describes three cases of methane venting and estimates methane venting quantities. Specific methane venting cases are identified as follows:

a. Gas free and warm up operation;

b. Purge for fuel gas pipe; and

c. Safety valve releasing (including cargo venting valve)

Among these three cases, gas free operation and fuel gas pipe purge have been studied but safety valve releasing has been excluded due to ship safety reasons.

In cases of cargo tank repairs or dry dock operation, the remaining gas (LNG or NG) in the LNG carrier's cargo tank has to be vented. Before the gas free operation, the LNG carrier entirely discharges its LNG cargo at the LNG terminal, however, still some residual LNG or NG remains in the cargo tank.

Using operational data, it was identified that both LNG (55.428 m^3 to 169.835 m^3) and NG (237.74 to 278.21 tonnes) remained in the cargo tanks.

A certain amount of the residual natural gas is used for vessel's fuel or incinerator but unused NG is finally released into the atmosphere. The estimated amount of methane emission at a certain warming up and gas free operation is seen at the table.

Gas free and warm up operation normally occurs every 5 years and so, when annualized, it stands for a methane emission of 15.11 tonnes on average to the atmosphere.

Table 37: Amount of methane emission at warming up and gas free operation (MEPC 71, INF23)

	Warming up and Gas free (Methane)	**Warming up and Gas free (CO2 equivalent)**
Average	75.59 tonnes	2,116.52 tonnes
Min	25.12 tonnes	703.36 tonnes
Max	121.69 tonnes	3,407.32 tonnes

The calculation to transform the methane to CO_2 equivalent is based on the Climate Change Report of IPPC (IPPC, 2014) which considers that the methane is 28 times stronger than carbon dioxide.

LNG carriers use the Boil off Gas (BOG) from the cargo as fuel. As soon as the BOG burning for fuel stops, the NG in fuel gas pipes is replaced by nitrogen and the remaining NG is released to the atmosphere.

According to the same study, which was submitted to MEPC 71, it is approximately, 30 times per month that fuel gas pipe is purged, with 10.55 tonnes of methane per month released into the atmosphere. Annually, this amounts to methane emissions of 126.27 tonnes.

Altogether, having studied the release of methane from gas free operation and fuel gas pipe purge, LNG carrier's methane venting is found to be approximately 141.38 tonnes per year or around 3,958.64 equivalent CO_2 tonnes. In the Third IMO GHG study, the estimated annual CO_2 emissions of an average LNG Carrier (DWT 68.500 tonnes approximately) equal to 63,246.2 tonnes of CO_2. According to the above results, these emissions are by almost 6% higher due to methane venting.

8.2 Methodology and Tools

8.2.1 Fuel(s) supply chain scenario

The study included in this Chapter implements the life cycle approach to comparatively assess the environmental impact of different marine fuels. Life Cycle Assessment, (LCA) is the ISO standardised methodology applied for this purpose. Two different marine fuels are examined; namely, the liquefied natural gas (LNG) and the low sulphur heavy fuel oil (HFO). For the purpose of comparisons, specific life cycle scenarios (in terms of boundary conditions) of the two different fuels been have been formulated which take into account recent developments in the exploitation of energy reserves emerging in the East Mediterranean. In particular, the natural gas field off the southern coast of Cyprus Island located at the exploratory drilling block 12 in the country's maritime Exclusive Economic Zone has been recently declared mature for exploitation. Therefore, it is most probable this particular field will support the Greek natural gas supplies in the future considering also the traditional close relations between the two countries.

The total life cycle of the two marine fuel alternatives (LNG and 1% sulphur HFO) is included in the analysis; namely, production, transportation, storage, and combustion on-board ships. For the stage of on-board combustion the case of a passenger vessel operating in a fixed round schedule between the port of Piraeus and an island port in the Aegean Sea is considered. The purpose is to identify the overall environmental impact of main air emissions produced during the entire life cycle of the two alternatives.

8.2.2 Impact categories compared

The focus of the study is on the environmental aspect of air emissions. Important ship air emissions are covered such as: Carbon dioxide (CO_2), Methane (CH_4), Sulphur oxides (SO_x), Nitrogen oxides (NO_x) and Particulate Matter (PM).

The environmental impact is divided into two major categories: the climate change impact and the air pollution impact. Climate change is attributed to the greenhouse gases which for the case of marine fuels are mainly carbon dioxide and methane, whereas air pollution impact are caused mainly by particulate matter, sulphur and nitrogen oxides and volatile organic compounds. In this sense, the study aims at providing a holistic view of the environmental aspects connected with the use the two alternatives as future marine fuels in short sea shipping activities (and in particular in the coastal passenger market).

The basic steps of LCA are followed for this assessment from scope and goal to selection of boundaries and functional unit to the collection of data and formulation of the life cycle inventory and impact assessment. The results are compared at an inventory level (quantities of emissions) as well as at the impact level (using characterisation factors for the emissions).

8.2.3 LCA System definition

The life cycle of the two alternative fuels is divided in four main phases as follows:

a. The extraction of raw material (crude oil and natural gas) and their transfer to the processing plant.

b. The production stage at the plant from raw material to the end product (low sulphur HFO, LNG)
c. The transport by sea of the HFO and LNG and the storage to oil and LNG import facilities.
d. The bunkering and consumption of the two alternative fuels on-board a typical Car/passenger ferry vessel.

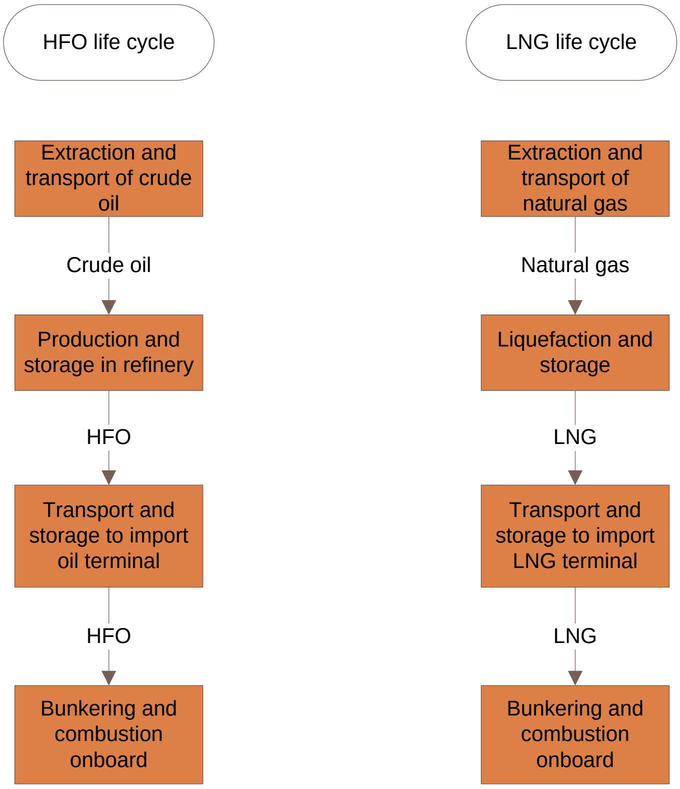


Figure 40: The LCA system for the two alternative fuels

8.2.4 Geographical boundaries

According to the United States Geological Survey (2010), the Levant Basin in the Eastern Mediterranean holds around 122 trillion cubic feet (or 3.45 trillion m3) of undiscovered, technically recoverable natural gas, along with 1.7 billion barrels of crude oil. Despite the geopolitical uncertainty in the region, some of the recently discovered gas fields in the Eastern Mediterranean are now considered mature to move from exploration to exploitation. Recently, it has been announced that the natural gas reserves at block 12, south of Cyprus (the so-called Aphrodite field), is commercially viable. The reserve in this field is estimated to hold about 140 to 225 billion m3 of gas (Watkins, 2012). Hence, there are pre-agreements between the Cypriot government and the companies in charge of the exploration to build a liquefied natural gas (LNG) plant, though there are remaining questions about financing.

The boundaries selection has been formulated according to the aforementioned scenario which has many possibilities for realisation in the near future. This scenario (shown in Figure 41), as described earlier, accepts that Cyprus will be an important fuel supplier in the near future for Greece due to the mature conditions of exploitation of the field 12 at the EOZ south of the Island.

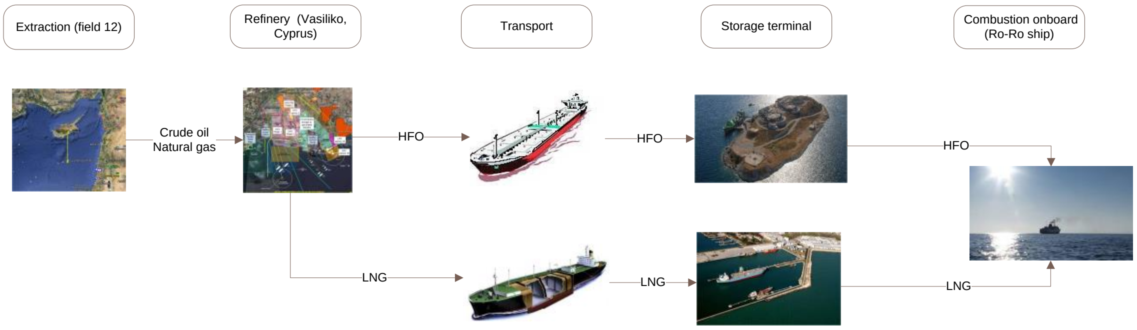


Figure 41: The geographical boundaries of LNG and 1%S HFO

The supply chains of the two marine fuels are assumed identical. The extraction location is the same (field 12) as well as the transfer to the processing plant, which is at Vasiliko area in Cyprus Island. Sea transportation from Cyprus to Greece foreseen and the storage of fuels will be made in the Saronikos Bay in the already existing oil and LNG terminal facilities.

The final stage, which is the use of the two alternatives as fuels on-board a car/passenger ferry vessel in the Aegean Sea. As mentioned previously, the passenger ferries segment shows more interest than other segments in using LNG as fuel. The scenario accepts that the examined fuel is going to be used as the main fuel for the propulsion needs on-board the vessel. Auxiliary propulsion needs are not taken into account in the emissions inventory development. The car/passenger ferry vessel is assumed to have the same time schedule and operating profile (speeds, loading conditions) in both occasions (fuelled with LNG, fuelled with HFO).

8.2.5 Functional unit

Functional unit selection is of paramount importance in an LCA study. According to ISO 14040 standard: the functional unit "is a measure of the performance of the functional outputs of the product system. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA result".

The functional unit of this study is the emissions produced from the transport of one tonne of cargo in one km with the typical (for the Aegean Sea) sailing conditions on the same Car/passenger ferry vessel. The emissions produced at all life cycle stages are normalised according to the functional unit.

The purpose of the functional unit is to properly describe the outcome of emissions because of the final utilisation of the fuels on-board a vessel. Emissions produced during the fuel supply chain (or the life cycle of the fuel) are converted in the functional unit enabling this study to assess to holistic impact of the examined fuel.

8.3 Life Cycle Inventories

Values used in this study for the emissions from natural gas extraction, processing, pipeline transport, liquefaction, and imported LNG transport are taken from a 2012 analysis by the National Energy Technology Laboratory (NETL), (Skone 2012). This data source has been selected because the supply chain included in it, is similar to the present study. The NETL analysis has modelled the emissions produced along the LNG supply chain from offshore wells in Trinidad and Tobago transported by underwater pipelines to liquefaction facilities and finally transported to the United States in large LNG carrier ships, (ICCT, 2013).

8.3.1 LNG Inventory

The assumptions that formulate the geographical boundaries of the LNG life cycle are the following:

1. Off shore natural gas recovery at the so-called field 12 which is located south of Cyprus Island. The natural gas is then forwarded through an underwater pipeline system to Vasiliko area in Cyprus Island, at a liquefaction plant. This is the most probable scenario since the Cypriot government has plans for retrofitting the existing oil refinery plant at Vasiliko with natural gas liquefaction capabilities.
2. Transport of LNG to Greece (530 nautical miles distance) with LNG carriers. The transportation scenario assumes the use of an LNG carrier powered by a steam turbine (28,000 kW) with a service speed of 19.5 knots. This ship uses boil-of-gas for fuel.
3. Storage of LNG in the existing terminal at Revithousa Island, located at Saronikos Bay very close to Piraeus port, which is the central hub of the Greek coastal shipping system.
4. Use of LNG as fuel on a conventional car/passenger ship that serves on a coastal ferry line in the Aegean Sea. The ship has a fixed round trip schedule between Piraeus port and port of Island X.

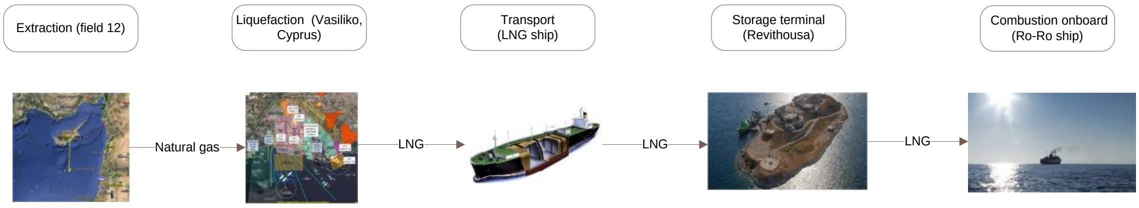


Figure 42: LNG life cycle scenario

Extraction and transport of natural gas

The data source (Skone, 2012) considers the following processes for the inventory of offshore extraction and underwater transport of natural gas.

a. Compression of natural gas and forwarding to distribution pipelines,

b. Dehydration which removes water content,

c. Removal of toxic gases,

d. Burning of natural gas in cases when it is not possible to distribute the complete, production quantities. Data sources accept that 0.35% of the recovered natural gas is burned and;

e. Separation of natural gas from crude oil.

The inventory for the aforementioned processes of the first stage is shown in Table 38. The results are converted in the functional unit (gr/ton×km) with an LNG conversion factor that represents the sea transportation activities along the supply chain.

Table 38: LNG Emission Inventory – Extraction and underwater transport of natural gas

Emissions	Inventory value (g/kg natural gas)	LNG conversion factor (g LNG/ton km)	Functional unit value (g/ ton km)
Greenhouse gases			
CO2	107.4229	39.46	4.2389
CH4	1.1421	39.46	0.0451
Air pollutants			
NOx	0.4173	39.46	0.0165
SOx	0.0116	39.46	0.0005
PM	0.0078	39.46	0.0003

Liquefaction and storage of LNG

There are two main processes in a liquefaction plant: pre-treatment and liquefaction. Pre-treatment removes acid gases and reduces CO_2 levels to prevent freezing in the main cryogenic exchanger. Then, traces of mercury are removed to prevent corrosion in the heat exchanger equipment. The liquefaction cools natural gas down progressively from a temperature around -30°C to the final liquefaction temperature of -163°C (Laugen, 2013).

LNG is a cryogenic gas and its storage in tanks cannot be totally insulated due to the large temperature differences. Therefore, there are losses of gas during the supply chain of LNG the so called boil-off gas (BOG). BOG losses are inevitable in any stage of the supply chain. The processing plant in the scenario of this study assumes that the energy demands are entirely covered by BOG which is compressed and feeds back the fuel system. JRC (2008), reports illustrative production and liquefaction processes in European plants.

Table 39: LNG Emission Inventory – Liquefaction and storage of natural gas

Emissions	Literature value (g/kg natural gas)	LNG factor (g LNG/ton km)	Functional unit value (g/ ton km)
Greenhouse gases			
CO2	227.900	36.37	8.289
CH4	1.940	36.37	0.071
Air pollutants			
NOx	0.187	36.37	0.007
SOx	0.00127	36.37	0.000046

PM	0.00124	36.37	0.000045

Transport and storage to LNG import terminal

The transportation stage of LNG considers the use of an LNG ship, which carries the LNG form Cyprus to Greece and delivers it in the existing LNG terminal of Revithousa Island. The scenario takes the following assumptions:

- The ship has a steam turbine plant used for main propulsion, which utilises the BOG of cargo and has an average performance of 30%.
- The density of LNG is 440kg/m3
- The LNG is free of sulphur, thereby no SOx emissions are observed in the exhaust gases

Table 40: LNG Emission Inventory – Transport and Storage

LNG sea transportation scenario		
Ship type	LNG Carrier	
Fuel	LNG	
Cargo tanks capacity	m3	138000
Density LNG	kg/m3	440
Load Factor		0.55
LNG cargo	tonnes	33396
Distance covered	nm	530
Service speed	knots	19.5
Trip duration	hours	27
BOG produced	% per hour	0.625
Total BOG	tonnes	56.35575
Heating value of LNG	MJ/kg	48
Steam turbine performance	%	30
Specific Fuel Consumption	kg LNG/kWh	0.25
transported LNG (net)	tonnes	33005.68
Main Engine Power	kW	28000
Main Engine load factor	%	85
Energy use (normalized)	KWh/km	659.02
LNG consumption	kg/ tonne LNG	4.90
g LNG / tonne km (Car/passenger ferry)		36.196
g LNG / tonne km (LNG carrier)		0.177
g LNG / tonne km (Car/passenger ferry + LNG carrier)		36.373
Emissions Inventory		
Emission factor CO2	gr / gr LNG	2.74
CO2 in functional unit	gr CO2/ tonne km	0.48527
Emission factor CH4	gr / kg LNG	0.05
CH4 in functional unit	gr CH4/ tonne km	0.00001

Emission factor NOx	gr / kg LNG	1.8
NOx in functional unit	gr NOx / tonne km	0.00032
Emission factor PM	gr / kg LNG	0.17
PM in functional unit	gr PM/ tonne km	0.00003

Bunkering and consumption on-board a Car/passenger ferry vessel

The last stage is the Tank-to-Propeller stage where the combustion of the fuel takes place. The vessel is a typical car/passenger ferry operating in the Aegean Sea. The propulsion unit is a spark-ignited (SG) gas only engine (or lean burn gas engine) with a shaft efficiency range 41– 48 percent. The operating profile of the ship was provided by the shipping company and it is described in Table 41. The gas engines emission factors in the literature vary, subject to the engine manufacturer, ship type and operating profile. In this study, emission factors are according to Bengtsson (2011), because this source reports emissions for the manufacturer of the specific engine installed on-board the car/passenger ferry.

Table 41: LNG, Tank to Propeller - Bunkering and Consumption on-board

Car/passenger ferry		
Fuel		LNG
DWT	tonnes	6174
Load Factor		0.9
Cargo Loaded	tonnes	3889.62
Service speed	knots	20.5
Main Engine Power	kW	34377
ME Utilisation factor	%	85
Energy Consumption	KWh/km	769.6478428
Energy Consumption normalised	g KWH / tonne km	0.197872245
Low calorific value LNG	MJ/kg	48
Performance	%	41
Specific consumption	kg LNG/KWh	0.182926829
LNG consumption (normalised)	g LNG/tonne km	36.19614243
Emissions Inventory		
Emission factor CO2	gr / gr LNG	2.736
CO2 in functional units	gr CO2/ ton km	99.032
Emission factor CH4	gr/gr LNG	0.014
CH4 in functional units	gr CH4/ ton km	0.489
Emission factor NOx	gr / gr LNG	0.008
NOx in functional units	gr NOx / ton km	0.303
Emission factor PM	gr / gr LNG	0.0005
PM in functional units	gr PM / ton km	0.016

LNG Life Cycle Inventory Results

The results of the life cycle inventory of the LNG case show the obvious dominance of the final stage which corresponds to the combustion of LNG as main fuel in the engine of the car/passenger ferry vessel. 88% of the life cycle CO_2 emissions are produced during this final stage. Extraction of LNG contributes with a 4% and liquefaction adds 7% to the total CO_2 emissions. The transport stage has minor contribution in CO_2 (approximately 1%). The life cycle of LNG is nearly free of SOx emissions except for the extraction phase; however, even in this stage sulphur oxides are emitted in very small quantities.

Table 42: Life Cycle of LNG

(gr/ton km)	LNG Life Cycle Stages			
	Extraction	**Liquefaction**	**Transport**	**RO-PAX Engine**
CO_2	4.2385	8.2894	0.4853	99.0417
CH_4	0.0451	0.0705	0.000009	0.4894
NOx	0.0165	0.0068	0.0003	0.3030
SOx	0.0005	0.0000	0.0000	0.0000
PM	0.00031	0.00005	0.00003	0.01631

Only 0.5 grams of CH_4 emitted per ton×km, during the burning of LNG as fuel in the car/passenger ferry vessel (the corresponded CO_2 value is 99 grams per ton×km). Extraction stage contributes by 7% and liquefaction stage by 12% to the total CH_4 releases. These results are consistent with the National Energy Technology Laboratory (2014) study results which stated that the majority of methane coming from the LNG supply chain is emitted during natural gas recovery and processing whereas lesser amounts are emitted during pipeline transport of natural gas and from storage, transport, and bunkering activities of LNG.

The life cycle scenario resulted that air pollutants releases are negligible for the case of LNG, illustrating the clear benefits of this fuel with respect to the protection of the local environment and human health.

8.3.2 HFO Inventory

In order to avoid inequalities in the comparison of the two fuel alternatives the boundaries of the HFO life cycle are assumed identical to those of the LNG. Therefore, the extraction location remains field 12 and the refinery location is at Vasiliko, which has already in place oil refinery facilities. The transport scenario of HFO from Cyprus to Greece assumes transportation by sea using oil tankers. The arrival location is at oil storage facilities of Aspropyrgos, which is not far from Piraeus port. Identical to the LNG case is the final stage of the HFO life cycle. Therefore, the same Car/passenger ferry ship is used on the same round trip form Piraeus central hub port to an Aegean Sea Island.

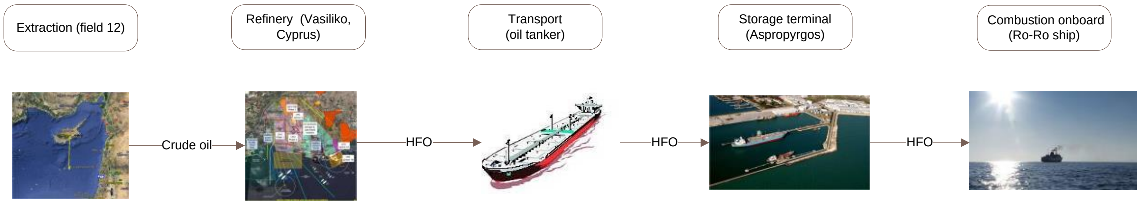


Figure 43: HFO life cycle scenario

Extraction – Refinery

The data used for the extraction and refinery stage of HFO are collected from the European Commission Joint Research Centre from dedicated database on life cycle assessment, called the European reference Life Cycle Database 3.0 (ELCD). The data set covers all relevant process steps over the supply chain of the heavy fuel oil with a good overall data quality.

Table 43: HFO, Inventory for extraction and refinery stage

Emissions	Inventory value (g/kg HFO)	HFO conv. factor (g HFO/ton km)	Functional unit value (g/ ton km)
Greenhouse Gases			
CO2	2.69E-01	39.46	10.6265
CH4	2.99E-03	39.46	0.1181
Air pollutants			
NOx	6.22E-06	39.46	0.00025
SOx	1.56E-03	39.46	0.06155
PM	1.80E-05	39.46	0.00070

Transport to oil terminal

The sea transportation scenario is identical to the LNG case, but with the use of an oil tanker. The characteristics of the ship and operation assumptions made for the development of the inventory are provided in Table 44. The oil terminal in Greece is Aspropyrgos, which is also in the Saronikos Bay area.

Table 44: HFO sea transportation scenario

HFO sea transportation scenario		
Ship type	Tanker	
Fuel	HFO	
Speed	14.45	knots
Speed	26.76	km/hr
Main Engine (2-x)	9466	KW
Engine Load	85%	% MCR
DWT	37384	tonnnes
Distance covered	530	nm
Duration	36.68	hr
Pay Load	0.95	
Energy – Consumption		
Energy consumption	300.68	kWH/km
Cargo Loaded	19533.14	ton
SFOC	0.213	kg HFO/KWh
HFO per ton HFO	3218.279	g HFO/ ton HFO

HFO per ton cargo km (ro - ro)	39.333	g HFO/ cargo ton km
HFO per ton cargo km (tanker)	0.127	g HFO/ cargo ton km
HFO per ton cargo km (ro - ro + tanker)	39.460	g HFO/ cargo ton km
Emissions Inventory		
Emission factor CO2	677	g CO2/KWh
CO2 per ton HFO	10228.99	g CO2/tonne HFO
CO2	0.402337	g CO2/ cargo ton km
Emission factor NOx	14	g NOx/KWh
NOx per ton HFO	211.5301	g NOx/tonne HFO
NOx	0,008320	g NOx/ cargo ton km
Emission factor CH4	0.004000	g CH4/KWh
CH4 / ton HFO	0.060437	g CH4/ton HFO
CH4	2.38E-06	g CH4/cargo ton km
Emission factor SOx	4.5	g SOx/KWh
SOx per ton HFO	67.99181	g SOx/ton HFO
SOx	0.002674	g SOx/ cargo ton km
Emission factor PM	0.8	g PM/KWh
PM per ton HFO	12.08743	g PM/ton HFO
PM	0.000475	g PM/ cargo ton km

Consumption on-board a Car/passenger ferry

The final stage of the HFO scenario involves the consumption as fuel on-board the same car/passenger ship as in the LNG case. The scenario considers the real engine of the ship, a N.K.K-Pielstick 14PC4-2V with a total installed power of 34377 kW. Information regarding the ship and its operating parameters comes from the shipping company and shown in Table 46.

Table 45: Tank-to-Propeller HFO – Consumption on-board a RO-PAX ship

Car/passenger ferry vessel		
Ship type	RO-PAX ferry	
Fuel	Low sulphur (1%) HFO	
Speed	20.5	knots
Engine	34377	kW
Engine Loading	85%	% MCR
DWT	6174	tonnes
Distance covered	206	nm
Duration	10.05	hr
Pay Load factor	0.75	
Energy Use – Consumption		
Energy consumption	769.57	kWh/km
Cargo Loaded	4167.45	tonnes
SFOC	0.213	kg HFO/KWh
Energy consumption	0.185	KWh/ ton km
HFO per ton km	39.333	g HFO/ ton km

Emissions Inventory		
Emission factor CO2	677	g CO2/KWh
CO2	125.02	g CO2/ ton km
Emission factor Nox	12	g NOx/KWh
NOx	2.216	g NOx/ ton km
Emission factor SOx	4.5	g SOx/KWh
SOx	0.831	g SOx/ ton km
Emission factor CH4	0.004	g CH4/KWh
CH4	0.00074	g CH4/ ton km
Emission factor PM	0.8	g PM/KWh
PM	0.14773	g PM/ton km

The HFO life cycle results

Table 46 shows the inventory results of the HFO life cycle chain. The dominant emission is CO_2 which derives during the final stage of the life cycle as the outcome of the combustion process in the marine engines of the Car/passenger ferry vessel (92% of the total CO_2 emissions). A non-negligible amount of CO_2 though is produced during the extraction and processing activities of crude oil (8% of the total). Overall, methane is produced in minor amounts compared to CO_2. The majority of CH_4 (99% of the total) is produced in the production and processing stages (0.11 gr per ton×km).

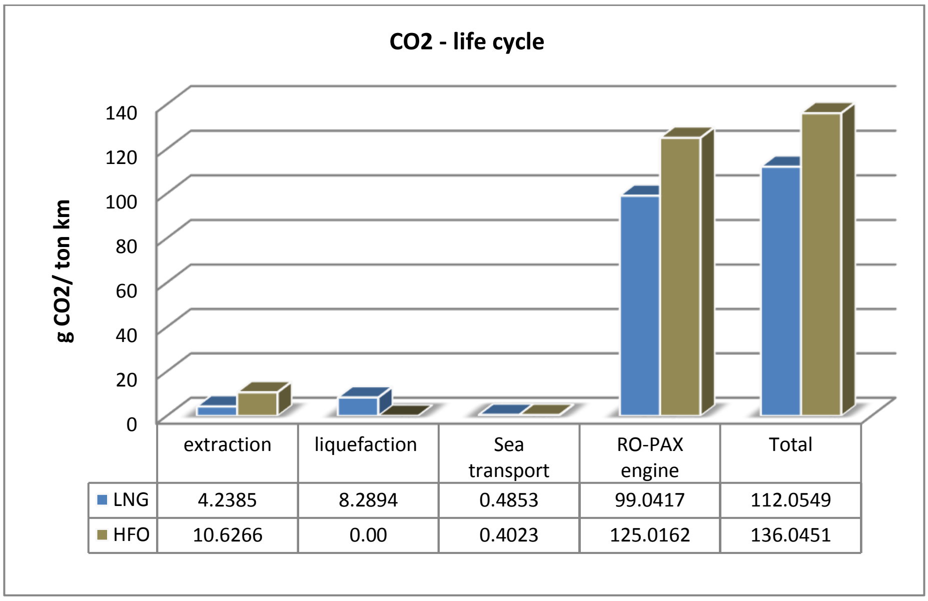
Table 46: HFO life cycle results

units: gr/ton×km	**Life cycle stages of HFO**		
	Extraction and refinery	Sea transport	Use as fuel in Ro- Ro
CO2	10.6266	0.4023	125.0162
CH4	0.1181	0.000002	0.0007
NOx	0.0002	0.0083	2.2159
SOx	0.0007	0.0027	0.8310
PM	0.0007	0.0005	0.1477

Air pollutants are produced during the combustion of HFO in marine engines of the Car/passenger ferry vessel (last stage of the life cycle). It is reminded that the fuel has low sulphur content 1%); the SOx emissions of 2.2 grams per ton×km.

8.4 Comparative Assessment

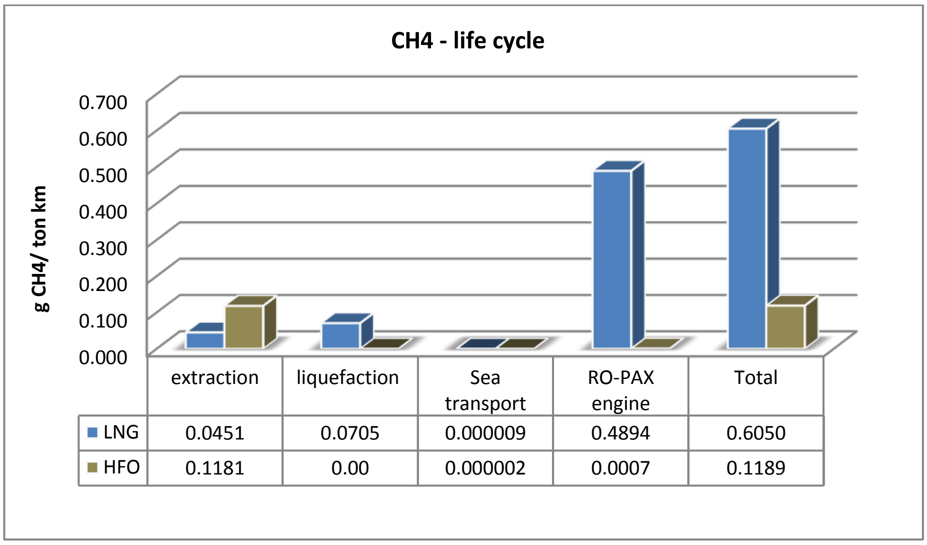
First, a comparative assessment of the inventory results is presented. With respect to the total quantities during the entire life cycle the CO2 emissions of LNG are 82.4% of those emitted during the HFO life cycle (112 gr/ton×km and 136 gr/ton×km respectively). Laugen (2013) study which have made the same comparisons (same fuels, life cycle stages and functional units) concluded to similar CO_2 figures. Both fuels emit their vast amount of CO_2 during the final life cycle stage (combustion in the car/passenger ferry engine).



	extraction	liquefaction	Sea transport	RO-PAX engine	Total
■ LNG	4.2385	8.2894	0.4853	99.0417	112.0549
■ HFO	10.6266	0.00	0.4023	125.0162	136.0451

Figure 44: LNG vs. HFO - Comparison of CO2 emissions

LNG emits five times more CH_4 life cycle emissions than the HFO. In LNG, most of the methane (nearly 81% of the total) is emitted during the final life cycle stage while for the HFO, only the extraction and refinery (1st life cycle stage) produces considerable amounts of methane. Methane, which is a strong greenhouse gas, is released in all stages of the LNG life cycle but in considerably lesser amounts compared to CO_2.



	extraction	liquefaction	Sea transport	RO-PAX engine	Total
■ LNG	0.0451	0.0705	0.000009	0.4894	0.6050
■ HFO	0.1181	0.00	0.000002	0.0007	0.1189

Figure 45: LNG vs. HFO – Comparison of CH_4 emissions

The clear benefits of LNG appear when the comparison of air pollutants (NOx, SOx and PM) takes place. The LNG life cycle overall produces the 14.2% of nitrogen oxides compared to the HFO life cycle. For both fuels the combustion stage is obviously the main contributor to the overall NOx emission results. LNG as fuel actually eliminates SOx emissions from the life cycle. Finally, PM emissions during the LNG supply chain are also considerable less (nearly 9% of those emitted during the HFO life cycle).

The final comparison between the two alternatives is according to the environmental impact over the life cycle. Three impact categories are selected namely: climate change, acidification and human health. The emissions inventory is converted to impact using typical characterisation factors from the literature (IPCC, 2014). The conversion is provided in the following table. As stated previously, impact assessment involves other steps apart from characterisation; however this task is out of the scope of this study

Figure 46: Conversion factors used for impact assessment

Conversion for impact assessment	
Emissions	Characterisation factor
Climate Change ($CO2$ – eq.)	
CO2	1
CH4	25
Acidification (SOx – eq.)	
NOx	0.7
SOx	1
Human health (PM – eq.)	
PM	1

The life cycle impact assessment justifies that LNG is marginally better compared to HFO when it comes to the climate change. The comparison is shown in Figure 47. The comparison here is given in a slightly different way than previous results in this study. Two major stages in the supply chain of fuels are considered namely the well-to-tank (WTT), which includes all stages form extraction to final supply on-board the vessel and the tank-to-propeller (TTP) which includes only the combustion of the fuel at the final stage (in the marine engine of the ferry in this study). When the WTT impact is considered the option of LNG has fewer benefits, since the climate change impact of extraction, processing and storage of LNG is higher than HFO. This result is consistent with results from the study of Laugen (2013) which had similar scope to the present one (same fuels examined, life cycle stages, functional unit). Total emissions in the aforementioned study were calculated to be 127 g CO_2-eq/ton km and 137 g CO_2/ton km for LNG and low sulphur HFO respectively (the LNG cycle produces 9% less CO_2).

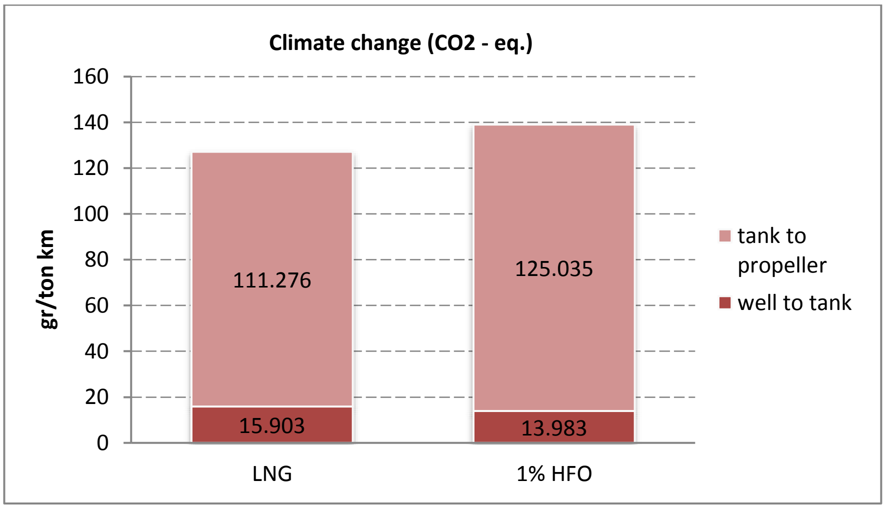


Figure 47: LNG vs. HFO –Climate change impact potential

More obvious are the benefits of the LNG when it comes to the next two categories of impact as shown in Figure 48, and Figure 49 (note that results are presented in log scale in these two figures). The acidification impact is 91% less for the life cycle of LNG. Large is the difference in the human health impact also (LNG impact is 89% less than HFO).

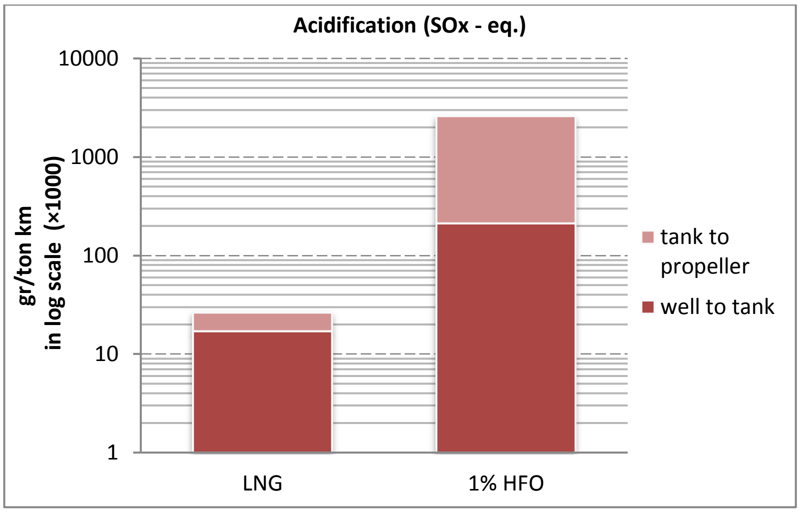


Figure 48: LNG vs. HFO – Acidification impact potential

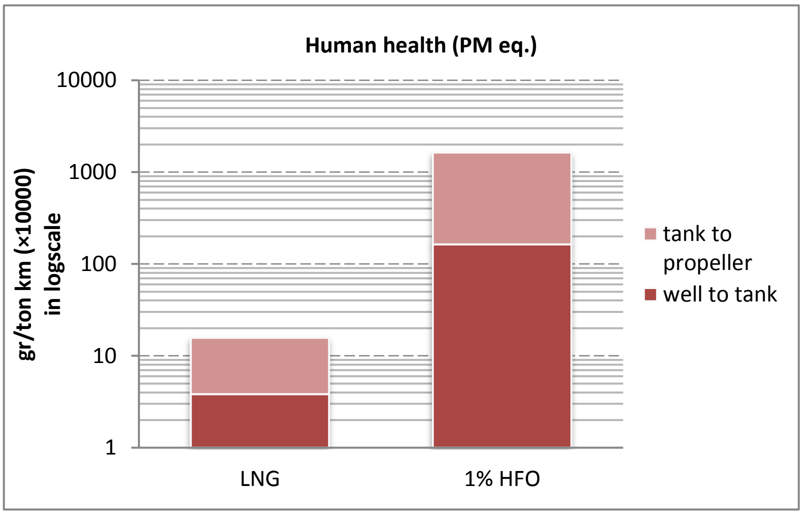


Figure 49: LNG vs. HFO – Human health impact potential

8.5 Conclusions

The study in this Chapter has made a comparative assessment of LNG and low sulphur HFO as marine fuel alternatives. Basic principles of the Life Cycle Assessment methodology have been observed. The fuel supply chain which formulates the life cycle includes extraction and crude product processing, sea transportation of fuels, storage in import terminals and final bunkering and use on-board a car/passenger ferry.

The comparison of LNG and low sulphur HFO has been made in the same boundary conditions by using a hypothetical (but possible to be realised in the future) scenario of a supply chain of LNG (and HFO) from Cyprus to Greece. The final stage of the life cycle is the combustion of fuels on-board a typical medium speed car/passenger ferry operating in the Aegean Sea.

It is justified that LNG as fuel offers benefits due to the elimination of SOx emissions which is an important air pollutant and the reduction of NOx which has negative effects in the environment (and human health). Reduction of PM emissions (the main driver of human health impacts) is also achieved with LNG. Overall, the results show that the benefits of LNG are clear only for the case of ship air pollutants (SOx, NOx, and PM) and marginal for the case of greenhouse gas emissions (CO_2 and CH_4).

The production and processing of fuels inventories have been developed by using literature information that matches to the specific boundary conditions. Inventories of transportation and combustion of fuels have been calculated in detail according to the specific boundary conditions. It is acknowledged that there is an amount of uncertainty in the inventories developed in this study (as in any study) which are related to various parameters such as emission factors, BOG estimations, energy use in refinery and liquefaction plants to name a few. Comparisons with other similar studies have been made for evaluation purposes and results are found consistent.

In concluding, the study reveals that the option of LNG as future marine fuel in the specific scenario examined is a promising solution with respect to the reduction of air pollution which might be more favourable if the Mediterranean Sea falls in the ECA regime in the future. From a strict environmental point of view, LNG will be more attractive as marine fuel in the future, if climate change impacts are reduced along the supply chain. In this respect, life cycle analysis will have to be applied in order to justify and evaluate the possible environmental benefits of such selections.

9. UNCERTAINTY ANALYSIS

Summary

This chapter discusses the main parameters of uncertainty in the estimation/calculation of ship air emissions.

First the impact of the speed parameter in the Energy Efficiency Design Index is investigated. Calculations were conducted for containerships, bulk carriers and tankers.

Then the probabilistic study presented in this chapter has analysed fuel consumption and emissions of the main engine of a container ship taking into account real operating practices (i.e. Slow steaming). Fuel consumption has been detailed in random variables such as Loading Factor, Specific Fuel Oil Consumption and Time. Monte Carlo simulation, a well-known probabilistic methodology has been used to develop probabilistic distributions for fuel consumption from onboard reporting (i.e. noon report data), and a probabilistic model for fuel consumption and resulted emissions was constructed and tested. The study has also studied the impact of the three random input variables in the estimation of fuel consumption.

Acknowledgments

1. The part of the work devoted in the probabilistic analysis of fuel consumption has been carried out in the context of the diploma thesis of Mr Tasos Bourazanis and submitted to the School of Naval Architecture and Marine Engineering. The title of the thesis is Probabilistic Analysis/Estimation on Fuel Consumption and Ship Emissions. The supervisor was Ass. Prof Ventikos. The author provided also assistance to Mr Bourazanis and would like to acknowledge his motivation and excellent cooperation.

2. The part of the work devoted to the impact of speed in the EEDI has been carried out in the context of the research project ‘Assessment of Environmental Impact in Marine Transportation and Related Activities’ which was carried out by the Laboratory for Maritime Transport of NTUA and was funded by the American Bureau of Shipping.

9.1 Introduction

With the emerging global quest to reduce anthropogenic air emissions, the international shipping industry is under increased pressure to reduce its emissions and improve its energy efficiency. International shipping is relatively fuel-efficient in comparison to other modes of transport, but its volume and rapid growth make it an important consumer of energy and a rising source of emissions.

The shipping industry is largely reliant on fuel and in particular on heavy fuel oil (HFO) which accounts for approximately 77% of the fuel used by this industry; when it comes to ocean-going ships the HFO usage is well above the aforementioned figure. HFO is a viscous residual product remaining at the end of the crude oil refining chain and as such, is of low quality compared to other fuels containing an elevated share of impurities. To allow combustion in marine engines filtering and pre-heating of the HFO is needed. The combustion of fossil fuels in engines normally produces greenhouse gases (GHG) as well as non-GHG emissions (also called air pollutants). The low quality of HFO produces increased quantities in both aforementioned categories of air emissions; nonetheless, this type of fuel is widely available in low-cost, which have made it more compatible for use in current large marine engines.

As already presented in this thesis, emissions from international shipping represent less than 2.6 percent of the anthropogenic greenhouse gas (GHG) emissions (IMO, 2014) and about 11% of all transport sectors. Yet, in case that the anticipated growth of international marine transport comes without any significant environmental gains, it may result in higher shipping emissions in the future.

In reaction to social pressure, international marine regulations came into force from 2013 from the International Maritime Organisation (IMO) which ask for the implementation of design measures (through the Energy Efficiency Design Index, EEDI) as well as operational/technical measures (through the Ship Energy Efficiency Management Plan, SEEMP) to effectively reduce GHG. Moreover, the EU, through the MRV Regulation demands that fuel consumption and resulting GHG emissions data have to be reported to EMSA on a voyage basis for all ships of 5,000 gt or more, which arrive or depart from EU ports.

The cost of fuel is the dominant cost parameter in ship operation and the shipping industry is continuously seeking technical and operational solutions to reduce the energy demands onboard ships. Despite progress in understanding the state of ship efficiency, the available data remains relatively sparse compared with that of other industrial sectors and modes. Moreover, it is apparent that different energy efficiency measures are applied which are subject to the specific characteristics of the heterogeneous shipping segments.

However, a widely applied measure, which results also in energy efficiency, is slow steaming; namely the reduction of the operational speed of the ship. The use of slow steaming also addresses the overcapacity of ships and the fuel costs, and it is seen as the industry’s reaction to the global economic crisis. Different slow steaming practices apply for various size segment of containerships. According to Psaraftis and Kontovas

(2013), the trend for containerships is to reduce the 24–26 knots maximum speed to 21–22 knots, and in some trades to may even go as low as 15–18 knots.

In this context, this chapter discusses two important parameters that affect the energy efficiency of shipping; the speed parameter, which is used as a design as well as an operational measure for energy efficiency, and the parameter of fuel consumption and the uncertainty in relation to its monitoring and reporting.

9.2 Speed as an energy efficiency measure

The reduction of operating speed usually referred to as slow steaming is not a new concept for shipping. It is based on the fact that the relation between speed and fuel consumption is exponential which means that a small reduction in speed can result in a larger decrease in fuel demand. The method is widely applicable when the demand is low and capacity is high. What makes slow steaming more attractive as a solution for energy efficiency is that especially for new (electronic) engines it comes without investment costs and is easy to implement from an operational point of view. Moreover, the operator may easily estimate the overall efficiency (economic and environmental) of the solution. Praraftis and Kontovas (2013) made a through servey for speed as an energy efficiency measure. Acknowledging that emissions estimations often assume fixed ship's speed which for the case of ships may lead to fluctuating results Gkonis and Psaraftis (2012), developed a model to optimise the speed and air emissions of oil tankers.

Two important issues should be considered in connection with a lower operating speed of the ship:

1) Main engines' ability to operate at low loads for long periods of time;
2) Fuel oil consumption at such low load.

The relation between power and speed for a typical modern large Post Panamax container vessel with a new MAN power plant capable of operating at low loads for long periods of time is shown in the following figure.

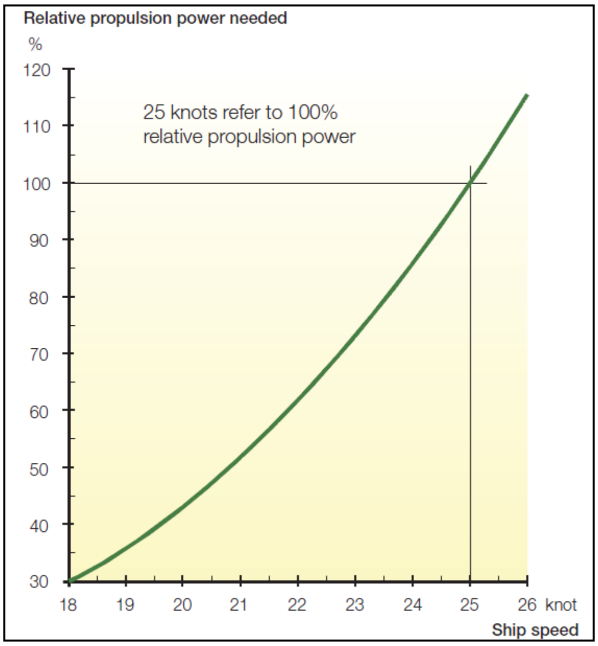


Figure 50: Relative propulsion power needed for a Post Panamax container vessel shown as a function of ship speed (source: MAN, 2010)

The power and ship speed curve shown in Figure 50, is very steep in the upper speed range. It is therefore obvious that with reducing the ship speed, the power requirement reduces substantially. As a reaction to the increasing fuel prices, some ship-owners/operators are reducing the service ship speed of both new and existing container vessels. For the particular engine shown in the example of Figure 50, reducing the ship speed by e.g. 4 knots reduces the power requirement up to 50% (MAN, 2014).

SFOC change of these engines at low loads is not straightforward. For this particular engine, when operating with part load optimisation the SFOC reduction may be up to 4 g/kWh when compared to the obtainable reference full load economy mode SFOC. The SFOC increases in the high and full load area up to 4 g/kWh, compared to the obtainable reference full load economy mode SFOC. Part load optimisation of this engine offers significant SFOC reductions at 70% MCR or lower loads.

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

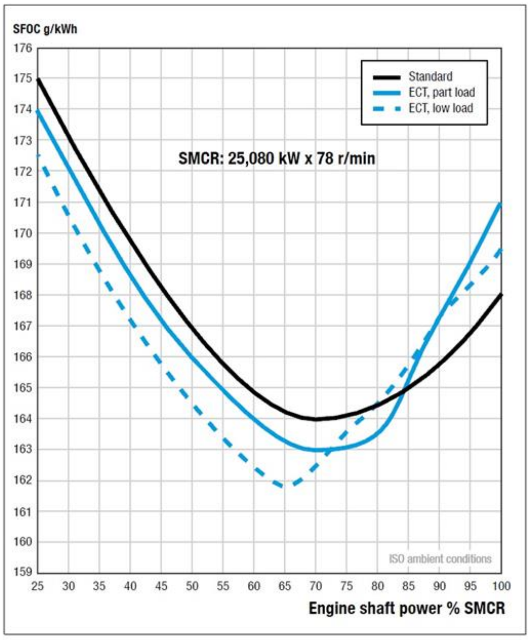


Figure 51: Example of SFOC diagram for a two-stroke engine 6S80ME-C8.2 with ECT (MAN, 2013)

Due to the unavailability of more detail data, the above important issues (engine's ability of low loads, and SFOC change at these loads) have not been taken into consideration in the study shown in this chapter. It is therefore assumed that the engines are capable of operating at low loads and the SFOC changes at these loads are not substantial.

9.2.1 Containerships

In the following figure, the results of the investigation of the speed impact on the EEDI are shown for the case of containerships. The blue curve corresponds to the containerships EEDI baseline. The baseline derived from own calculations following the requirements of IMO (the details of the baseline calculation are given in Appendix 1).

Kontovas and Psaraftis (2011) performed regression analysis of about 4000 container vessels built from 1999 on, using data from the online Sea-Web database. They concluded that the relation of the installed power and the design speed is higher than cubic. However their calculation did not take into account the extra power needed as sea margin, which is in the order of 15%. The authors provided evidence in the same paper that are other literature sources that claim the same for ships having a design speed of more than 20 knots.

The attained EEDI for four representative containerships sizes (i.e. feeder ship, panamax, post panamax, Ultra Large) and four different speeds is demonstrated in this figure. For example, for the feeders size bracket the EEDI value ranges from 19.84 to 31.73 g CO_2/ tonne × nm (baseline value: 29.0 g CO_2/ tonne × nm). According to our calculations a 20%, speed reduction (3.8 knots) in a feeder ship may reduce the EEDI value by 31.72% (almost 10 units).

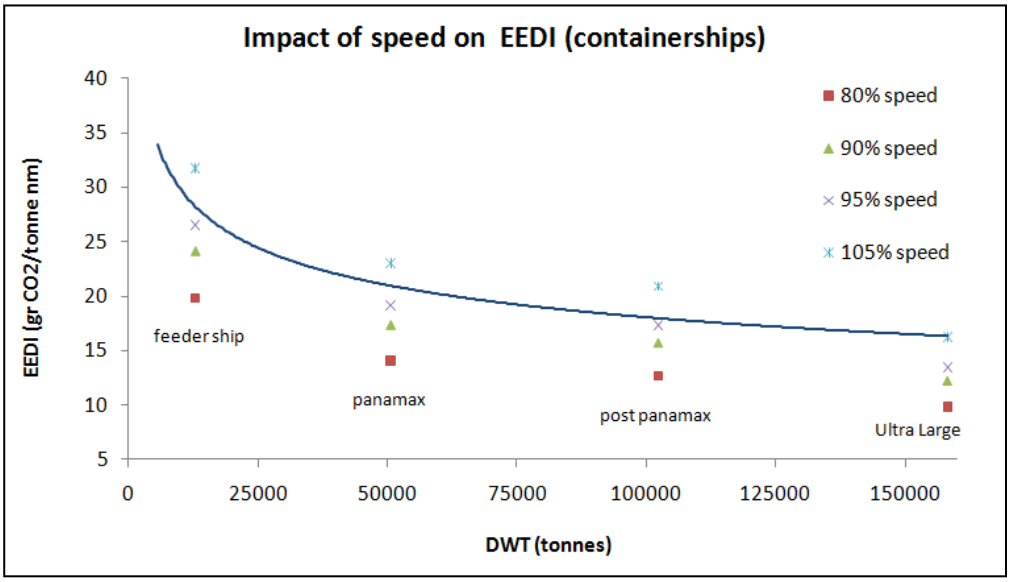


Figure 52: Speed impact on the EEDI (containerships)

Illustrative details of this analysis for four representative size brackets of containerships are shown in the following table. The "Baseline" column refers to the 100% service speed from which the EEDI baseline has derived.

Table 47: Containerships. Speed impact on the EEDI

		80%V_{serv}	**90%V_{serv}**	**95%V_{serv}**	**105%V_{serv}**	**Baseline**
1,000 TEU (Feeder)	**V_{SERV} (knots)**	15.20	17.10	18.05	19.95	19.00
	P_{ME} (kw)	3736	5319	6257	8448	7297
	EEDI	19.84	24.16	26.54	31.73	29.06
	EEDI delta (%)	-31.72%	-16.88%	-8.70%	+9.19%	-
4,500 TEU (Panamax)	**V_{SERV} (knots)**	19.60	22.05	23.27	25.73	24.50
	P_{ME} (kw)	14039	19989	23509	31742	27420
	EEDI	14.07	17.35	19.15	23.07	21.06
	EEDI delta (%)	-33.20%	-17.62%	-9.06%	+9.56%	-
8,000 TEU (Post Panamax)	**V_{SERV} (knots)**	20.00	22.50	23.75	26.25	25.00
	P_{ME} (kw)	26358	37529	44138	59594	51480
	EEDI	12.69	15.70	17.35	20.93	19.09
	EEDI delta (%)	-33.47%	-17.75%	-9.13%	+9.63%	-
12,500 TEU (Ultra Large)	**V_{SERV} (knots)**	19.60	22.05	23.27	25.73	24.50
	P_{ME} (kw)	31067	44235	5202	70243	60678
	EEDI	9.86	12.19	13.48	16.27	14.84
	EEDI delta (%)	-33.52%	-17.78%	-9.14%	+9.64%	-

Similar results obtained in other studies examining the speed influence on the EEDI. The results from ABS-HEC study[1] demonstrated that a speed reduction of 2 knots (from

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[1] John Larkin et al (2010), Influence of Design Parameters on the Energy Efficiency Design Index (EEDI), paper presented at SNAME & Marine Board Symposium, 16-17 Feb 2010.

18.50 to 16.50) on a feeder containership reduces the EEDI by 27%. For the Panamax size bracket the same study concluded that a 4 knots speed reduction might reduce the EEDI by 37%. Note that the aforementioned study has utilised different data sample and made extra assumptions for fuel consumption estimations.

Practically the above results indicate that a ship could easily reach the desirable index value by simply slowing down the service speed instead of implementing other measures for reducing CO_2 emissions. Lower speeds have already been widely applied by containerships operators due to high fuel costs and the overcapacity of ships. However, lower service speeds and consequently lower installed power onboard ships may pose serious safety problems and increase in CO_2 production under certain conditions (i.e. rough seas).

9.2.2 Tankers

Calculations have been carried out with the assumption that the required power increases by roughly the cube of the variation in service speed. Similar with above are the results for the tankers fleet. The aforementioned assumption is reasonable for tankers, bulk carriers, or ships of small size, but may not be realistic at slow or near-zero speeds and also for some other ship types such as high-speed large container vessels (Psaraftis and Contovas, 2014).

The results show that the EEDI for tankers is very sensitive to speed. Slowing down the service speed by less than 1 knot reduces the EEDI by almost 9%. Moreover, for the three major size brackets of tankers (i.e. Panamax, Aframax, and Suezmax) the difference in EEDI values for speeds between 12 and 15 knots is over 30%.

Figure 53: Impact of speed on the EEDI (tankers)

Looking at the P_{ME} rows at Table 48, one can see the enormous decrease of power requirements when the service speed slows down. For example, for a typical Panamax of 70,000 dwt, slowing down the service speed by 20% (3 knots) reduces the power requirements of the vessel to more than 50%.

Table 48: Tankers. Speed impact on the EEDI

		80%V_{serv}	90%V_{serv}	95%V_{serv}	105%V_{serv}	Baseline
Chemical tanker (13,000 dwt)	**V_{SERV} (knots)**	10.72	12.06	12.73	14.07	13.40
	P_{ME} (kw)	1705	2427	2855	3855	3330
	EEDI	8.22	10.01	10.99	13.15	12.04
	EEDI delta (%)	-31.72%	-16.89%	-8.70%	+9.20%	-
Panamax (70,000 dwt)	**V_{SERV} (knots)**	12.00	13.50	14.25	15.75	15.00
	P_{ME} (kw)	4339	6178	7266	9811	8475
	EEDI	3.37	4.11	4.52	5.41	4.95
	EEDI delta (%)	-31.95%	-17.00%	-8.75%	+9.25%	-
Aframax	**V_{SERV} (knots)**	12.00	13.50	14.25	15.75	15.00

(120,000 dwt)	**P_{ME} (kw)**	5207	7414	8719	11773	10170
	EEDI	2.51	3.07	3.37	4.05	3.70
	EEDI delta (%)	-32.25%	-17.15%	-8.83%	+9.33%	-
Suezmax (160,000 dwt)	**V_{SERV} (knots)**	12.00	13.50	14.25	15.75	15.00
	P_{ME} (kw)	6473	9217	10840	14636	12643
	EEDI	2.23	2.74	3.02	3.62	3.31
	EEDI delta (%)	-32.54%	-17.29%	-8.90%	+9.40%	-
VLCC	**V_{SERV} (knots)**	12.40	13.95	14.73	16.28	15.50
	P_{ME} (kw)	9786	13934	16388	22127	19114
	EEDI	1.68	2.07	2.29	2.75	2.51
	EEDI delta (%)	-32.96%	-17.50%	-9.00%	+9.50%	-

9.2.3 Bulk carriers

The influence of speed on the EEDI of four representative bulk carriers size categories are shown in Figure 54 and Table 49. The calculations used the same assumptions as previously (cubic relation between power and speed).

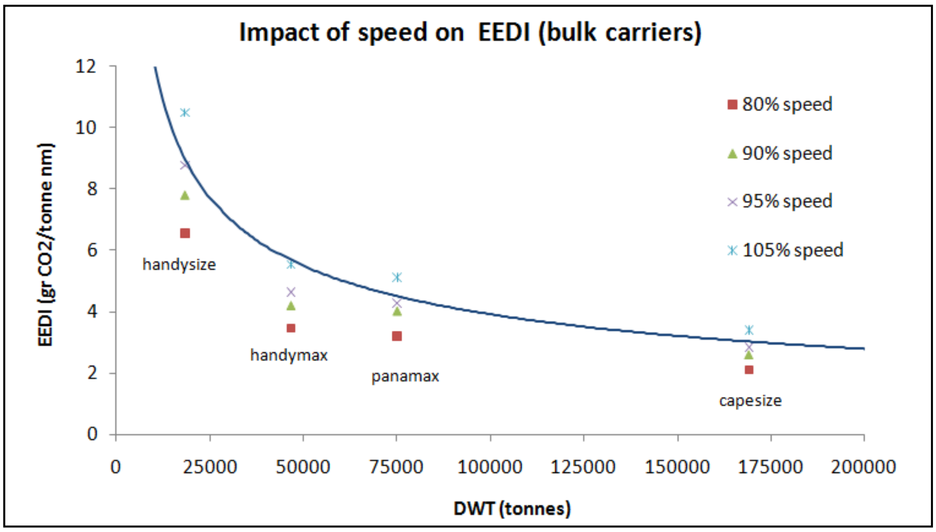

Figure 54: Impact of speed on the EEDI (bulk carriers)

Table 49: Bulk carriers. Speed impact on the EEDI

		80%V_{serv}	**90%V_{serv}**	**95%V_{serv}**	**105%V_{serv}**	**Baseline**
Handysize (18,000 dwt)	**V_{SERV} (knots)**	10.80	12.15	12.83	15.44	13.50
	P_{ME} (kw)	1913	2724	3204	6130.49	3737
	EEDI	6.56	7.81	8.77	10.48	9.60
	EEDI delta (%)	-31.72%	-18.70%	-8.70%	+9.19%	-
Handymax (46,000 dwt)	**V_{SERV} (knots)**	11.60	13.05	13.78	15.23	14.50
	P_{ME} (kw)	2768	3941	4634	6258	5406
	EEDI	3.47	4.22	4.63	5.54	5.07
	EEDI delta (%)	-31.72%	-16.89%	-8.70%	+9.19%	-
Panamax (75,000 dwt)	**V_{SERV} (knots)**	11.60	13.05	13.78	15.23	14.50
	P_{ME} (kw)	4128	5877	6912	9333	8063
	EEDI	3.19	4.04	4.28	5.13	4.69

	EEDI delta (%)	-31.86%	-13.99%	-8.73%	+9.23%	-
Capesize (170,000 dwt)	**V_{SERV} (knots)**	12.00	13.50	14.25	15.75	15.00
	P_{ME} (kw)	6474	9218	10840	14637	12644
	EEDI	2.11	2.62	2.84	3.41	3.12
	EEDI delta (%)	-32.54%	-16.17%	-8.90%	+9.40%	-

9.3 Remarks

The sensitivity of the EEDI against the speed has been demonstrated in the previous paragraphs. For cargo ships of all capacity ranges, the most convenient way to reach the desired EEDI value is by simply reducing the service speed, in other words by moving vertically on the EEDI baseline diagram. Therefore, it can be concluded that even if the primary objective of the EEDI is to encourage design optimisations or introduction of new technology for the reduction of CO_2 emissions this is not effectively managed by the index in its current form. In contrast, what is evidently promoted is speed limits and consequently lower installed power onboard ships which could have multiple side effects.

The influence of speed parameter on the EEDI overwhelms the influence of any other parameter examined. Hull steel weight, hull shape changes, load line, main particulars, and other ship parameters were investigated in the literature, but none of them has more drastic effects than the speed has on the EEDI.

Concerns have been also raised for the capacity parameter in connection with the EEDI. According to a study carried out on behalf of EMSA[2] it could be easier for small size ships to reduce capacity in order to attain the desirable EEDI value. This is evident since the baseline curve is very steep in the small capacity area. A small ship which stands above the baseline could reduce (or count out) a small fraction of capacity in order to move left in the horizontal direction and pass below the baseline. This may also in some cases lead to artificial manipulation of ship’s capacity.

9.4 Fuel consumption estimation

Monitoring of fuel consumption and GHG emissions from international shipping is currently under the spotlight of the EU as well as of the IMO. The European Commission supports an internationally agreed global solution to decrease GHG emissions from ships. In October 2012, the European Commission announced 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 MEPC 63 of IMO agreed that the development of a globally accepted performance standard for fuel consumption measurement for ships could be a useful tool and that the standard should be considered at future sessions, and invited further submissions on specific aspects of such a standard.

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[2] Delta Marine Ltd. (2009). Report - EEDI Tests and Trials (2)

9.4.1 The EU MRV regulation

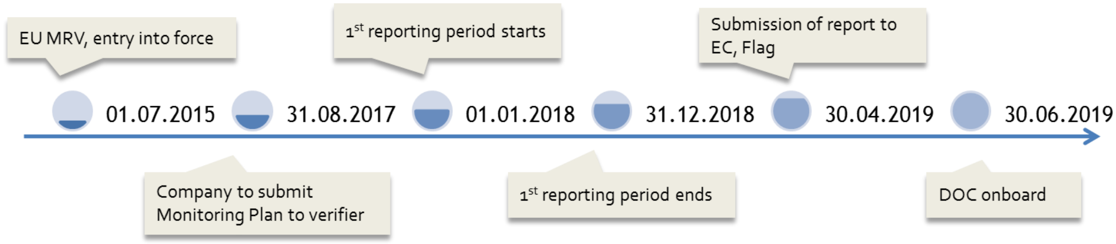


Figure 55: Timeline for the implementation of the EU MRV regulation.

The timeline for the implementation of the European regulation is shown in Figure 55. Apparently, the MRV regulation of EU is in force and the first reporting period starts at January 1st 2018. Ships will have to monitor and report fuel consumption data from all energy sources on-board (namely the main and auxiliary engines, boilers, gas turbines and inert gas generators).

The regulation will accept four possible options of retrieving the GHG emissions data. These are shown in Figure 56.

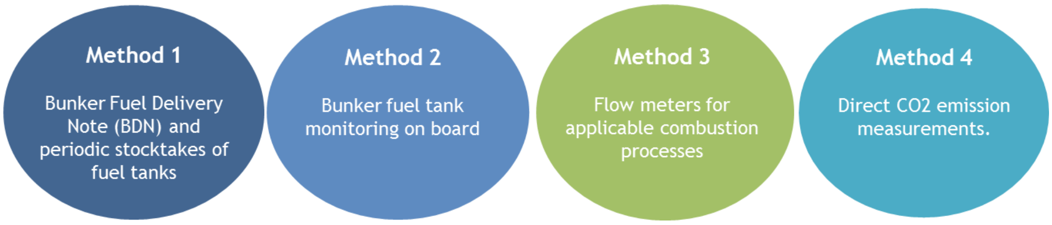


Figure 56: Four accepted methods of reporting GHG emissions for the purposes of EU MRV regulation

The calculation of ship emissions derives from fuel consumption from the simple formula shown below. The carbon factor is given for different fuels and derives from the IMO tables for EEDI calculations.

$$\text{Emissions CO}_2 = Fuel\ cons \times Cf\ \left[mass\ (CO2) \right]$$

The MRV regulation accepts that there is uncertainty in fuel consumption measurements on-board. The regulation comes with specific guidelines on how to handle the uncertainty in fuel consumption for the three first methods. For example, in the first method, the uncertainty associated with the BDN method shall be specified in the monitoring plan including the uncertainty in tank sounding and readings of dip tapes. Companies should also describe in the MRV monitoring plans the procedure to ensure that the total uncertainty of fuel measurements is consistent with the requirements of the MRV Regulation. The regulation also specifies that the uncertainty should be expressed as percentage and should describe a confidence interval around the mean value comprising 95 % of inferred values taking into account any asymmetry of the distribution of values.

9.5 Probabilistic model for fuel consumption and emissions estimation

Since the first reporting period of MRV regulation is currently running (June 2018), there is no evidence on how the shipping companies will handle the uncertainty in fuel consumption monitoring. In Appendix 2, are shown the guidelines for the estimation of uncertainty in method A (Bunker Delivery Notes and periodic stock takes) according to the EU MRV Regulation.

This chapter presents a methodology to estimate the uncertainty in a different context than the one provided by the regulators. The main objective was to develop a probabilistic model capable of estimating the daily fuel consumption and emissions of a vessel. The model estimates fuel consumption taking into consideration the specific operational profile of the ship. A container ship is used as the case study ship. Operational data from noon reports provided by the managing company of the ship reveal that slow steaming was largely being practiced in the examined period. Therefore, the model and overall the results presented herewith refer to low engine loads. The probabilistic modelling concerns the fuel consumption estimations and emissions of CO_2, NO_x, SO_x and PM.

9.5.1 Methodology

The most commonly method used to broadcast probability distributions is the Monte Carlo (MC) analysis. This method is implemented in many calculation tools and mainly consists of 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 or set of variables on the outcome of the model. For this particular study, applying Monte Carlo simulation to the model will generate a range of results based on different input values of the parameters, which will help to understand the impact from uncertainties in those key parameters.

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 modelling 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. far more flexible model; and
4. resulting charts and reports.

Without the aid of simulation, a spreadsheet model would only reveal a single outcome. Spreadsheet uncertainty analysis uses a spreadsheet model and simulation to analyse the effect of varying inputs or outputs of the modelled system automatically.

Simulation involves a large number of figures 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 derived. 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. Figure 57 is a graphical expression of this process. The process 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 may 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.

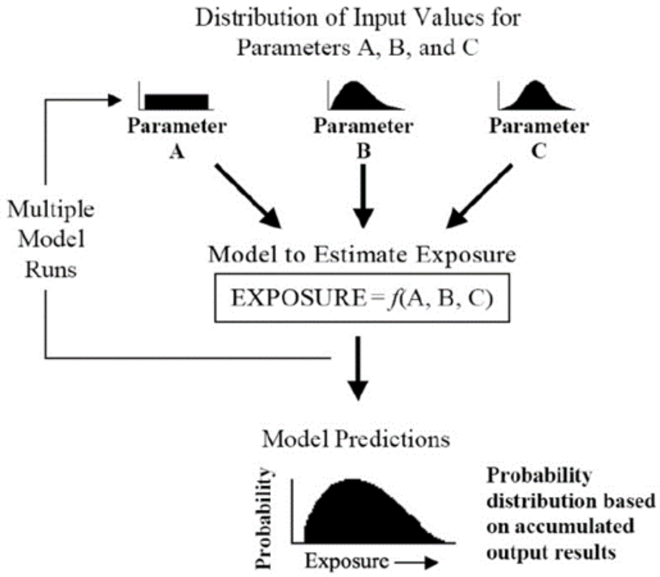


Figure 57: Diagrammatic representation of the application of Monte Carlo analysis to a model

Monte Carlo analysis does not require the probability distribution function to be defined for all input parameters. In case 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. The probabilistic model has the objective to:

1. Develop probabilistic distributions of fuel consumption coming from noon reports
2. Compare the fuel consumption estimates by the model with fuel consumption calculation from activity data.
3. Apply a robustness analysis to the model developed for fuel consumption
4. Calculate emissions of CO_2, NOx, SOx from the fuel consumption data

The calculations of fuel consumption and resulted emissions come from 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 the accumulated installed engine power for each subgroup

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

$\boldsymbol{t_{\frac{hrs}{day}}}$ is the 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 emissions calculation requires data for engine power and the loading factor, emissions or fuel rate, and time in service. Due to the incomplete set of data collected for the auxiliary engines' activity, the study finally focuses only in the modelling of the main engine consumption and resulting emissions.

9.5.2 Probabilistic distributions from input data

The model identifies for the random variables ($\boldsymbol{LF_{\%MCR}}$, $\boldsymbol{t_{\frac{hrs}{day}}}$ and $\boldsymbol{SFOC_{\frac{gr}{kWh}}}$) suitable distributions in order to estimate Fuel Consumption as a forecast.

Model assumptions

- From the average RPM in 24hrs (recorded in noon report), the average daily propulsion power is estimated via the propeller curve.
- Loading factor values derive from the formula: $\boldsymbol{LF_{\%MCR}} = \frac{P_{average}}{P_{MCR}}$
- Distribution for $\boldsymbol{t_{\frac{hrs}{day}}}$ is fitted in the data using inputs from the column "Steaming Time (24 hrs)" of the noon report.
- Distribution for $\boldsymbol{SFOC_{\frac{gr}{kWh}}}$ has to be provided by the user, due to lack of information (neither on noon report nor on the guide of the 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.
- From the data available, it is apparent that there is a correlation between SFOC-Loading Factor, which is shown in Figure 58.

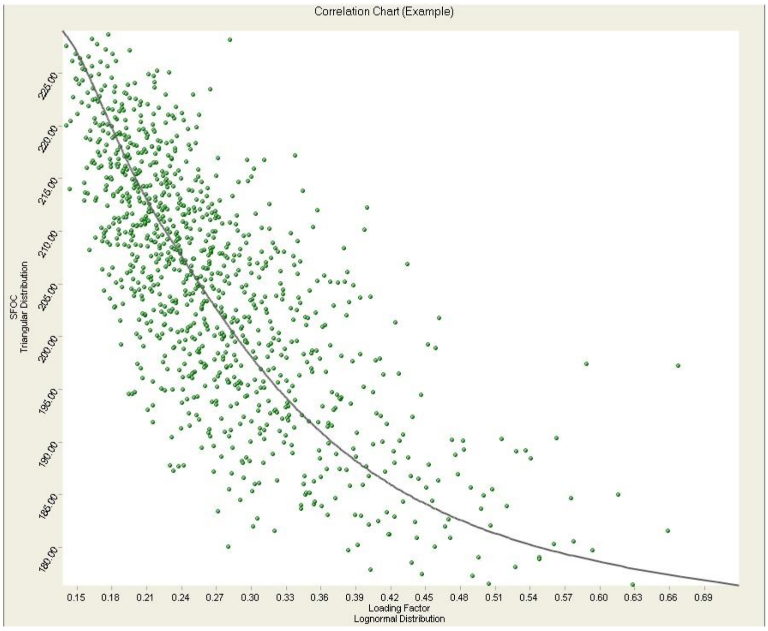


Figure 58: Correlation Chart of SFOC and LF in low load

- The P_{KW}-n_{rpm} diagram (propeller curve) is provided (in tables) by the operator. The power-rpm curve has been plotted in an Excel spreadsheet using the points available and extrapolation.

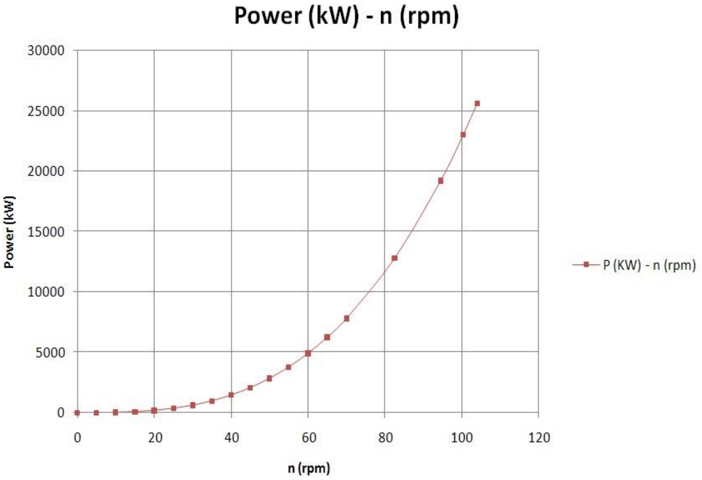


Figure 59: Propeller Curve of the 2,824 TEU Container ship

BestFit software is used for finding the distribution that best fits to the input data. For the uncertainty analysis, Crystal Ball software is used to develop scenarios for uncertainty inputs.

BestFit identifies a distribution that it is most likely to produce the given data. The software elaborates data through the following steps after the identification of the best fit for the 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 statistical tests, including Chi-square, Anderson-Darling, and Kolmogorov-Smirnov.

Model Input

Input data originate from the noon reports of a 2,824 TEU Container ship employed on the spot market. Data from noon reports cover a five years period. Ship particulars are given in the following table. Noon reports have a frequency of recording in once every 24h, and the fields reported generally include as a minimum the ship speed and position, fuel consumption, shaft rotational speed, wind speed and direction, current, date/time and draught.

Table 50: Ship particulars – Case study for the Monte Carlo Simulation

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)
Main Engine	1 MAN B&W 7K80MC-C

The available noon reports sample for this study contains 1,470 recordings with lots of data that are first filtered and reduced to a final sample data with 570 complete and usable recordings. The essential information to be used as input for the model includes the columns entitled:

1. “M/E Fuel Consumption (tonnes)”,
2. “Average Speed (24 hrs)”,
3. “Average RPM (24 hrs)” and
4. “Steaming Time (24 hrs)”.

The model creates (from the input data) three probabilistic distributions and a single value for P_{MCR}, multiplied together via Monte Carlo simulation. The resulting forecast is a new distribution (the distribution of the model) for fuel consumption (in tonnes per day).

Model Distribution for main engine loading factor

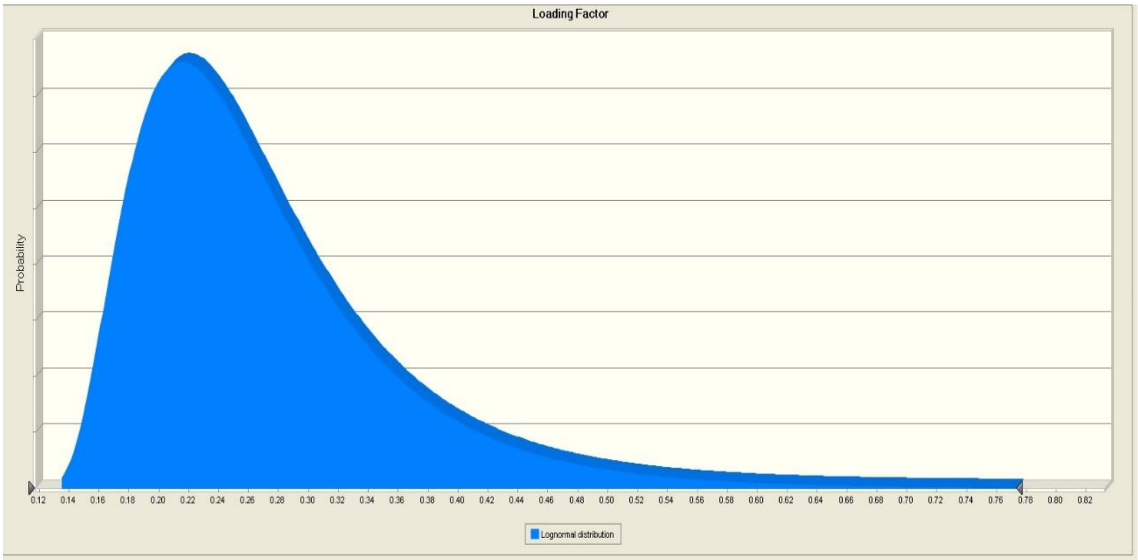


Figure 60: Distribution of the parameter "Loading Factor" of the model

Loading factor input data best fit corresponds to a lognormal distribution. The lognormal distribution is widely used when values are positively skewed (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 takes only positive real values.

Model distribution for Steaming Time

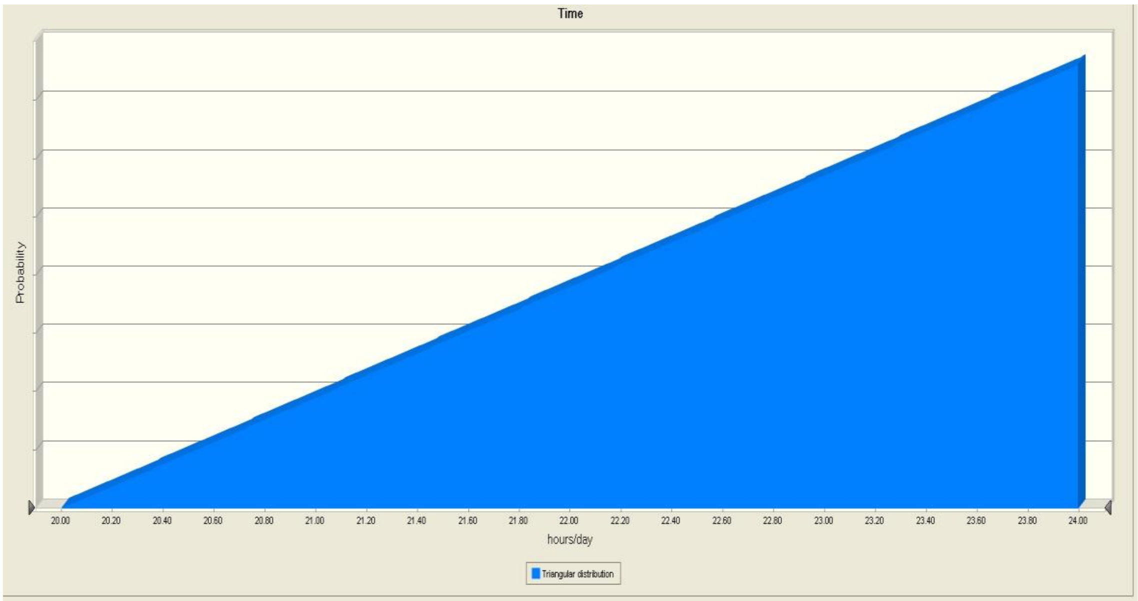


Figure 61: Distribution of the parameter "Steaming time per day"

The triangular distribution is commonly used when the minimum, maximum and most likely values of the distribution are known. It is a continuous probability distribution, in which the most likely value falls at a point between the minimum and maximum values, forming a triangular shaped distribution. The most likely value for the steaming time is 24 hours (most probable steaming time for a vessel engaged in international voyages).

Model distribution for SFOC

A triangular distribution is the best-fit distribution for the input data. The main engine is a ten years old engine with increased SFOC in lower loads.

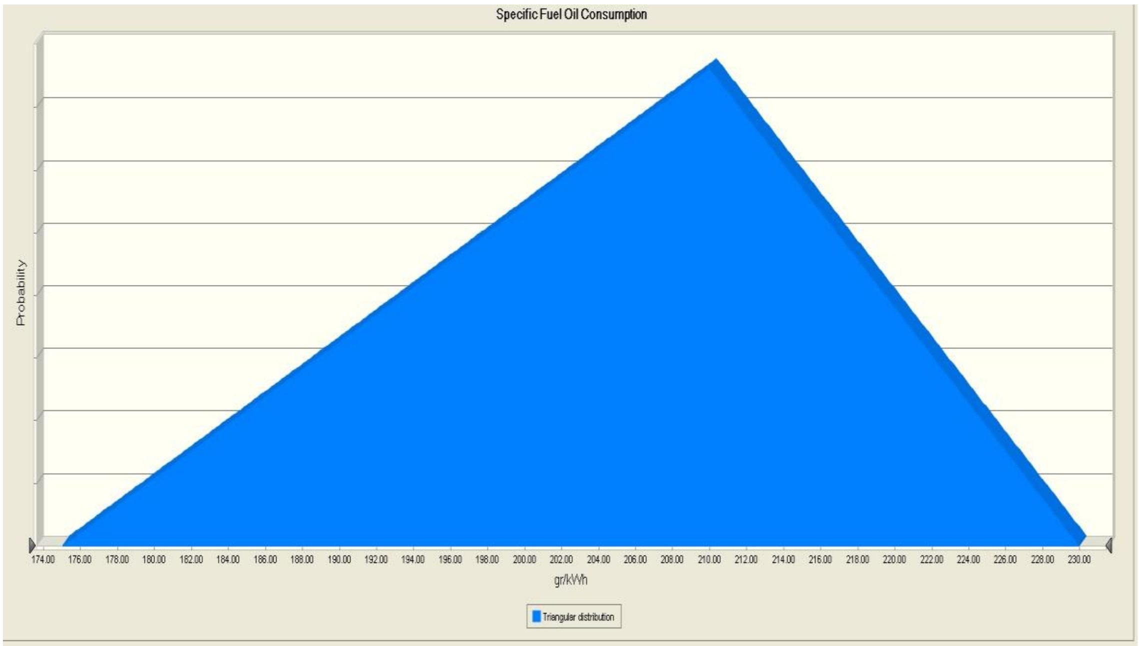


Figure 62: Distribution of the parameter "SFOC"

9.6 Results

The results of the probabilistic approach for the selected random variables are presented in this sub section. Comparisons are made using three statistics' measures: the mean, the median and the P80, which are explained here below:

- 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 are placed.

9.6.1 Comparison of fuel consumption from real data and simulation

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

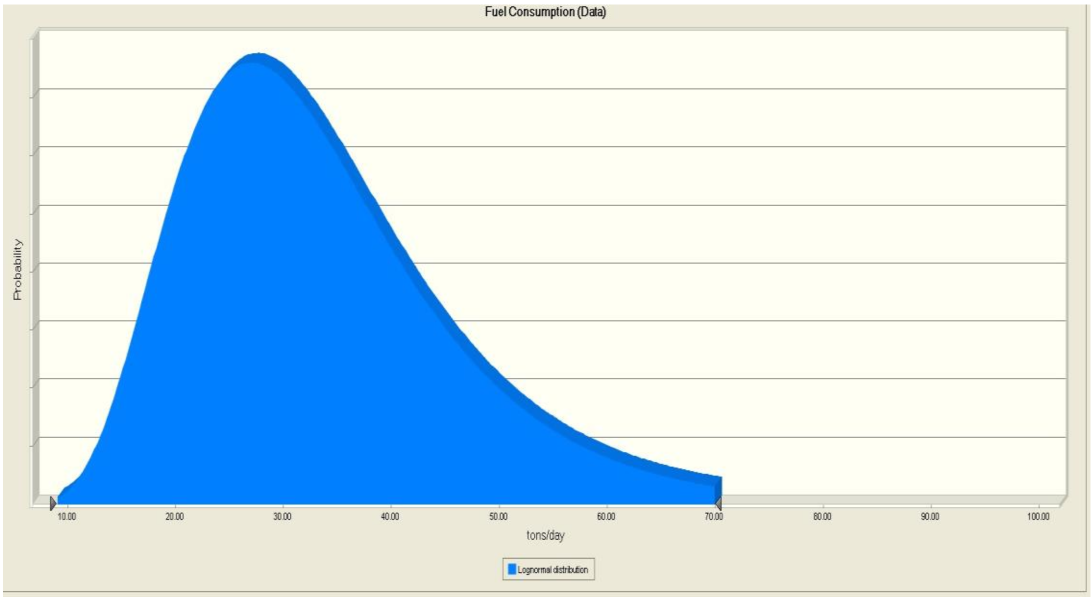


Figure 63: Lognormal distribution of Fuel Consumption from real data (noon reports)

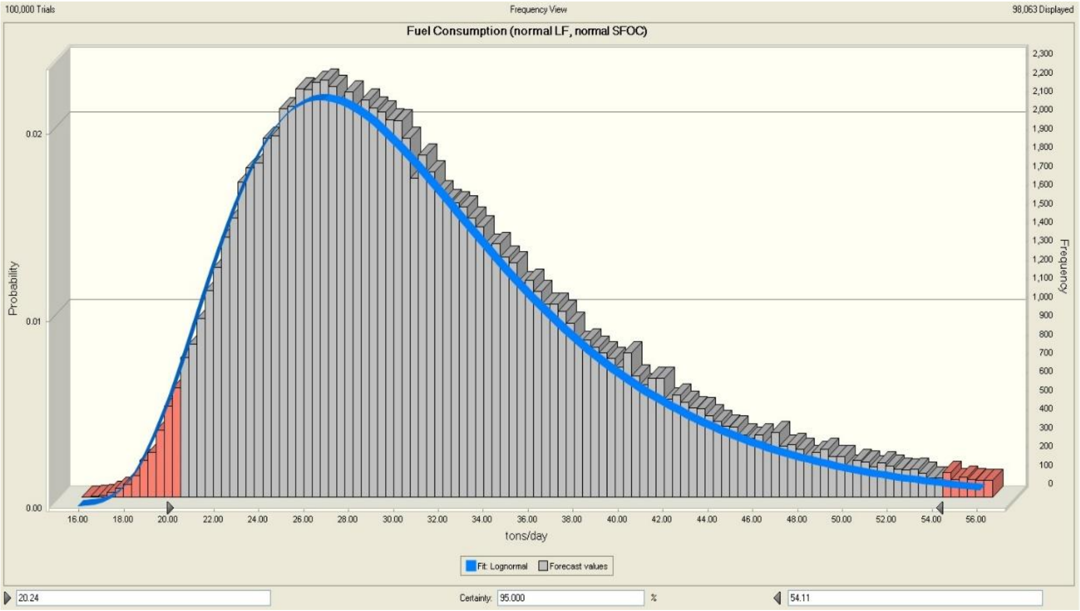


Figure 64: Lognormal distribution of Fuel Consumption from Monte Carlo simulation

Figure 63, shows the distribution that outlines the Fuel Consumption from real data taken from the noon reports of the case study ship. Figure 64, shows the distribution that outlines Fuel Consumption for the probabilistic model developed in this study. The total number of Monte Carlo trials was 100,000. Of the later, 98,063 trials used for the final distribution. The remaining trials were left out due to the fact that the results in the Monte Carlo simulation did not meet requirements and restrictions of the model.

Overall, the probabilistic model developed in this study approaches in a satisfactory way the real fuel consumption of the ship over the examined period for which noon report data have been available. As shown in Table 51, the difference in the estimation of fuel consumption by the model is one ton per day (mean and median values).

Table 51: Fuel consumption from real data vs. fuel consumption from probabilistic model

Fuel Consumption (tons/day)			
	Mean	**Median**	**P80**
Real data (Noon Reports)	32.65	30.89	42.02
Probabilistic Model	31.72	29.87	37.62

From the equation of random variables used in the model, sensitivity test carried out to identify which of the random variables plays an important role to the results. In this respect, the variable Loading Factor comes first with 66.9%, followed by Specific Fuel Oil Consumption 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.

According to the EU MRV Regulation, the highest acceptable range of uncertainty in the data reported is set at 10%. The Regulation requires ships to report the level of uncertainty in the data reported using accepted methods, as the one presented in Appendix 2. The operator is free however, to check the annual data referred to fuel consumption and report the uncertainty involved, by means of other methods if these are accepted. The model presented in this chapter is a suitable too to use for this purpose.

9.7 The use of big data

The LCA framework is based on theoretical modelling, which requires a certain amount of input by the user. This modelling employs either physical relations of ship parameters or some empirical equations for estimating the output of emissions.

The alternative approach to the above is the continuous monitoring of relevant ship parameters through automatic data acquisition (i.e. from torque meters, flow meters etc.) and the subsequent use of machine learning techniques which can provide reliable estimates (in a black box context) of the fuel consumption and other important energy and environmental parameters on-board.

The author did not have access to such systems or their data during his period of doctoral research. However, after the completion of the work in the context of this thesis, and in his professional position, he is involved in a project which utilises a continuous monitoring software, installed onboard ships to enhance energy performance. It is not in the scope of this thesis to elaborate more about the capabilities of continuous monitoring systems, still there are some clear advantages with the use of these systems which concern the proper exploitation of big data.

An example of this is demonstrated here which concerns the prediction of the propulsive power of the ship by using two different approaches namely the big data and the noon reports. Calculations were performed using real data onboard. The ship variables used were the speed through water, the environmental information for sea and wind state (all measured every 5 min), the ship's trim and displacement. It is obvious from Figure 65, and Figure 66, that the big data approach offers a more reliable prediction than the noon reports approach.

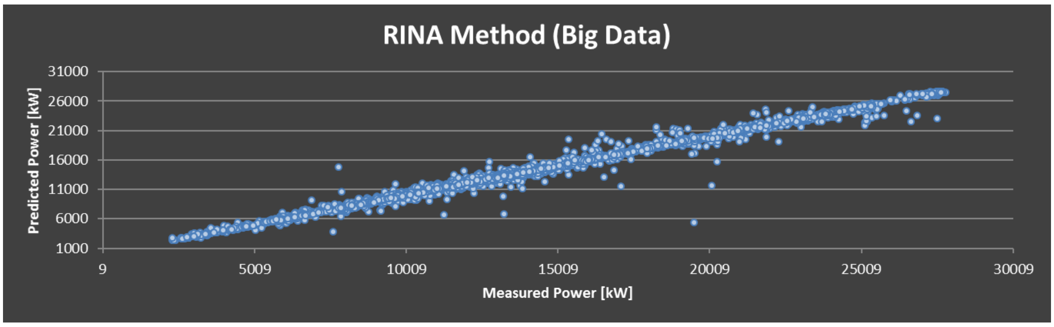


Figure 65: Power prediction using big data (source: RINA)

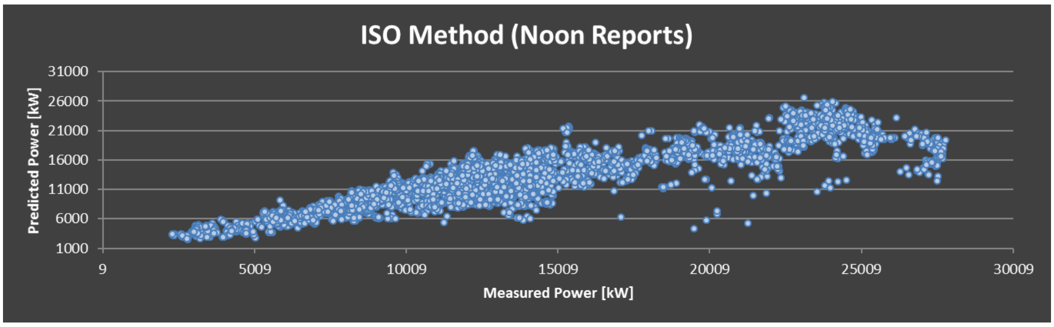


Figure 66: Power prediction using noon reports data (source: RINA)

The continuous monitoring system (RINA energy governance solution) from which data were retrieved in this example, enables the prediction of the relation of propulsive power and ship's speed with an average error of 1.8 percent. This is considerably lower than the 13 percent, which is the average prediction error from the ISO method which utilises the noon reports (see Figures 67, and 68).

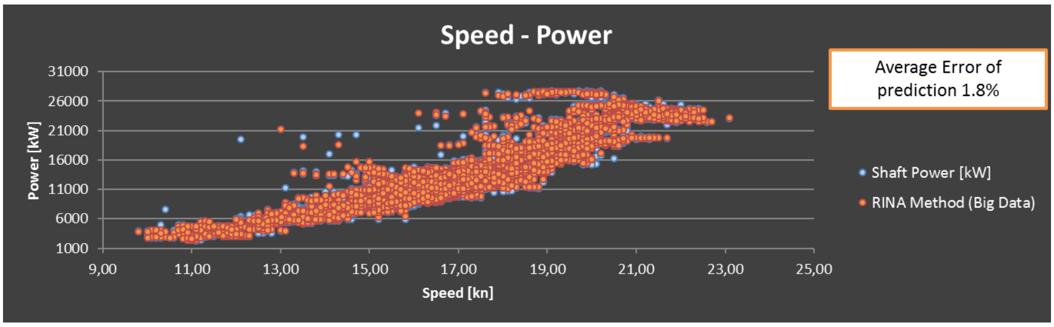


Figure 67: Speed – shaft power relation using big data (source: RINA)

Figure 68: Speed – shaft power relation using noon reports (source: RINA)

10. SHIP ENVIRONMENTAL IMPACT

Summary

This chapter discusses the environmental impact of shipping.

It starts with recognising the most important environmental and health impacts from shipping and continues with examining the available methods and tools for assessing these impacts.

Two different approaches have been selected as suitable for examining the impact of shipping, which however enclose certain limitations.

The first approach is the assessment in the context of the LCA methodology, the so called Life Cycle Impact Assessment step of LCA. A review of the available techniques in the context of the LCA is enclosed and a Life Cycle Impact Assessment Tool which observes one suitable LCIA technique is presented.

The second approach is the one using the external cost concept. The pros and cons of using the external cost approach are discussed, a review of available studies is presented and a suitable methodology (the impact pathway approach) is presented.

This chapter serves as the theoretical base for the conduction of the impact assessment case studies which follows in Chapter 10.

Acknowledgments

1. Part of the work included in this chapter has been carried out in the context of the research activities of the Centre of Excellence in Ship Total Energy-Emissions-Economy of the National Technical University of Athens, School of Naval Architecture and Marine Engineering. The Centre has received financial support by the Lloyds Register Foundation (LRF) which is gratefully acknowledged. LRF helps to protect life and property by supporting engineering.
2. Part of the work included in this chapter was conducted in the context of the research project “EnviShipping: Environmental Footprint of Ships from a Life Cycle Perspective”, a multi – partner project funded by the General Secretariat of Research and Technology.

Publications related to this Chapter

1. **Chatzinikolaou, S. and Ventikos, N.P., (2014) “** Assessing Environmental Impacts of Ships from a Life Cycle Perspective”, In Proceedings of the 2nd International Conference on Maritime Technology and Engineering , MARTECH 2014, 15-17 Oct 2014, Lisbon Portugal.

2. **Chatzinikolaou S.D., Ventikos N.P. (2013), “**Lifecycle Impact Analysis for Ships”, Proceedings of the 2013 Annual Meeting of the Hellenic Institute of Marine Technology: The Book of Marine Technology, Piraeus, Greece, pp. 71-82

10.1 Introduction

The process of calculating the impact in an LCA study is directly linked to the specific perceptions of environmental issues that are dependent on geographical, social, scientific and other features. Usually, the process of calculating the impact of the system under study, is performed with the help of an impact methodology or a damage model for the impacts which use databases combined with a conversion model of data (emissions, waste pollutants etc.) to impacts on the environment and/or on humans.

Studies covering the topic of impact assessment in shipping are scarce. Findings of the literature survey which has been conducted for the needs of this study are presented in this paragraph with the aim to develop a framework capable for conducting impact assessments of life cycle emissions. The majority of shipping impact studies is top-down studies. The present study follows the bottom up approach (estimation of emissions and impact at the ship level).

Therefore the specific goals set for the setting of the theoretical framework were:

- To collect information for the two selected generic approaches of impact assessment (LCIA approach, external costs approach).
- To identify the limitations of the available data methods sources for a bottom-up impact assessment exercise.
- The theoretical framework should be able to exploit the inventory of emissions that has been developed in previous work within the project.
- To adapt the available methods and tools in order to proceed to the calculation of ship emissions impacts.

10.2 Impact of Shipping

10.2.1 Human health impacts

Exposure to air pollution is now considered by the World Health Organisation (WHO) as *"the world's largest single environmental health risk*", causing 1 in 8 of total global deaths, or 7 million deaths in year 2012 (WHO, 2014). Explicitly for the case of shipping, there is evidence showing that PM emissions are responsible for approximately 60,000 premature deaths annually (Corbett et al., 2007), most of them occurring near populated coastlines in East Asia, Europe and South Asia.

There are available methods and tools to monetize the emissions impacts on human health which have been developed for land based sources of emissions but may be adapted for the case of shipping as well. One of these is the IPA, which was used as a basis for the methodology presented in this document.

10.2.2 Ecosystem impacts

Gases and particles emitted by ships may have considerable contributions on the acidification and eutrophication of water and soil in coastal regions due to deposition of sulphur and nitrogen compounds. Indicatively, it has been estimated (EMEP, 2012) that emissions from shipping in the Mediterranean Sea can contribute to more than 10 % of sulphur deposition in Cyprus (14 %), Italy (15 %) and Malta (56 %) and to more than 10 % of nitrogen deposition in Cyprus (30 %), Greece (21 %), Italy (15 %), and Malta (51 %).

However, model studies have shown that shipping can be responsible for up to 90 % of concentrations in pristine areas (e.g. NO_X). The relative contribution between shipping and other sources shows that there are several hotspot areas in Europe where the contribution of shipping can be up to 80 % for NO_X and SO_2 concentrations (EMEP, 2012).

10.2.3 Air quality impacts

Air quality problems of ship emissions arise through the formation of ground-level ozone, sulphur emissions and PM in coastal areas as well as port areas.

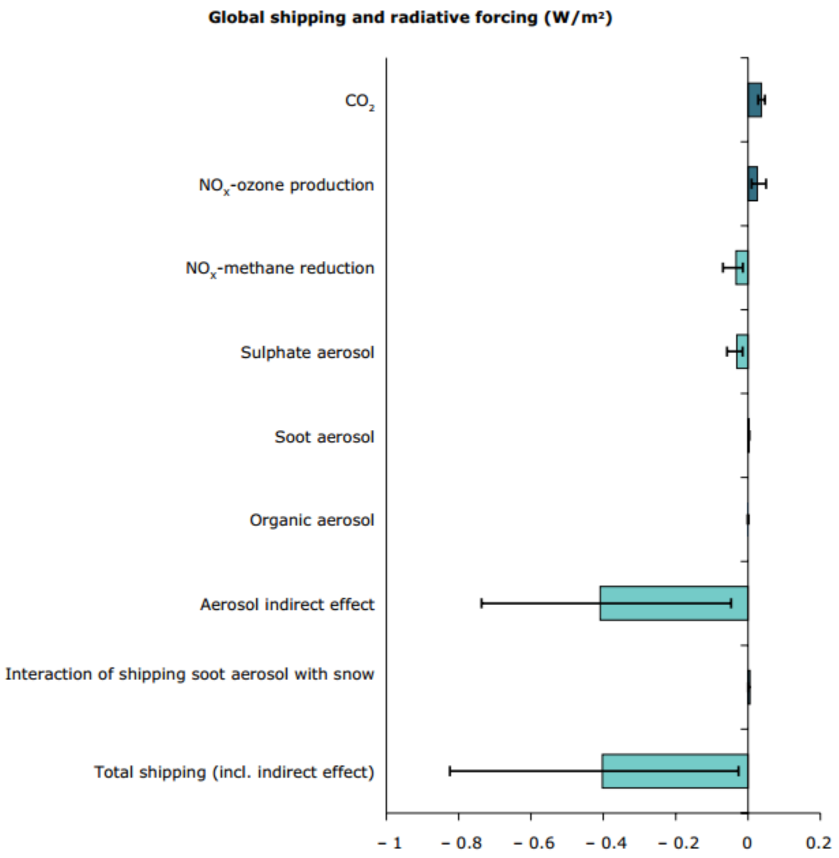
Moreover, ship emissions may be also transported and transformed in the atmosphere over several hundreds of kilometres, and thus contribute to air quality problems elsewhere, even though they are emitted at sea (Eyring et al., 2010). These emissions occur also by routine shipping operations in ports such as loading and unloading of goods and their transport by road.

The main effects of air quality degradation are on human health; other effects such as visibility or degradation of building materials may be also considered.

10.2.4 Climate change impacts

The climate change impact is measured in radiating forcing (RF) which expresses the imbalance between incoming radiation and outgoing radiation caused by a disruption of the atmosphere's composition (in watts per square meter, Wm-2). Positive values of RF mean a net warming, while negative values mean cooling. Emissions of GHGs and air pollutants from shipping contribute to RF in a rather complex way which results in cooling (SOx emissions) as well as warming (CO_2 emissions), the balance of which is very difficult to assess (EEA, 2013).

For the case of NO_x emissions, things become more complex since these emissions have an effect in both warming and cooling. NO_X emissions contributing to O_3 production result in positive RF but also reduce the lifetime of CH_4 (which is a very strong greenhouse gas) resulting in a negative RF. Estimates of the net effect of all RF show that in present-day ship emissions have a net negative RF but with a very large uncertainty range which may result in both a net negative RF and net positive RF according to Eyring et al. (2010).



Note: Dark blue bars represent a positive RF (warming), light blue bars represent a negative RF (cooling). Please note the relatively large uncertainty ranges. RF from shipping soot aerosol on Arctic snow does not have an uncertainty bar due to lack of data.

Figure 69: Global radiative forcing impact of global shipping emissions expressed in W/m2 (source: EEA, 2013 as adapted from Eyring 2010)

Since there is a strong connection between air pollution and impacts on human health and ecosystems, it is acknowledged that a trade-off game which would involve no future actions for air pollutant mitigation in the shipping sector to favour a (potential) net cooling effect of the shipping sector would be mistaken from a health and environmental perspective and risky due to the high ambiguity in the RF measurements (EEA, 2013).

10.3 Discharges into the sea (marine pollution)

Possible damage to the marine environment from shipping activities are caused by the following sources (JRC, 2009):

1. Port infrastructure development;
2. Contamination of the sea environment from oil and other toxic/hazardous substances from accidental and illicit discharges from ships;
3. Threats posed by the discharge of water ballast containing invasive species;
4. Discharges of non-oil liquid wastes and garbage; and
5. Release of toxic chemicals from ship coatings, heavy metals and zinc from hull anodes.

The pollution from ship accidents, although decreased in recent years (ITOPF, 2010), continues to cause sever environmental and economic consequences. The well-known Prestige accident off the coast of Galicia, which resulted in the release of 59,000 tonnes of heavy oil, has been studied in detail for the assessment of its economic impacts (Garza-Gil et al. 2006, Loureiro et al., 2006). For the estimation of the social costs of the accident, the annual economic losses in specific activities such as fisheries and fishing processing business have been taken into account, together with the economic impacts in the tourism industry and the loss of a specific number of birds and mammals due to the oil spill and the pollution of the coasts (Loureiro et al., 2006).

From the various forms of marine pollution cost deriving from oil spills, the most important one is the clean-up cost). This cost has been estimated for the case of the Aegean at 25,000 US $/ton (Ventikos et al., 2009).

In an NTUA study, ship accidents with oil spills included in the IOPC database have been analysed and a correlation between the clean-up-cost and the oil spill volume has been made available (Kontovas et al. 2010).

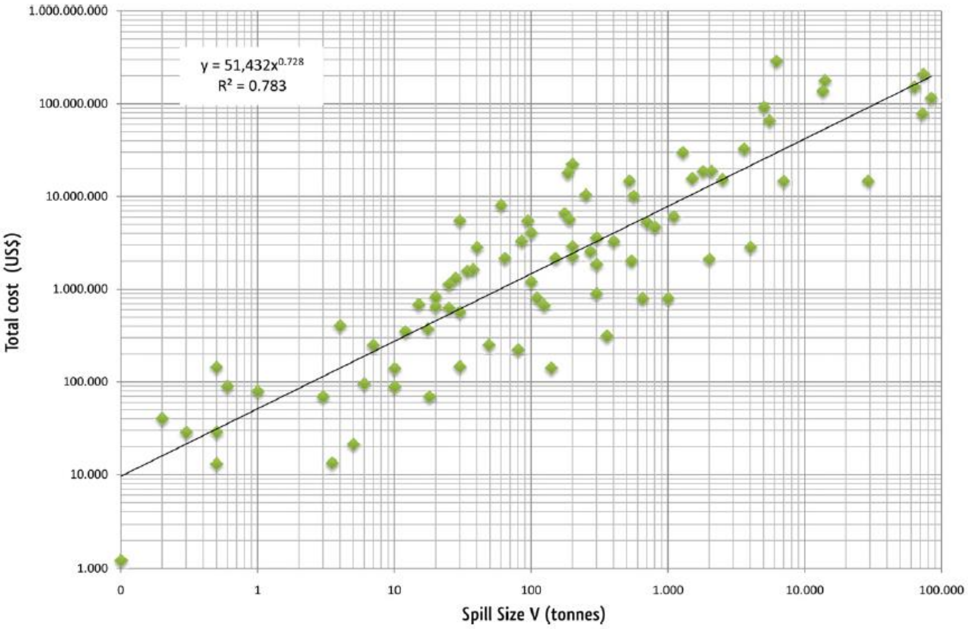


Figure 70: Regression analysis of the IOPC oil spill database. Spill size and total cost of oil spill (source: Kontovas et al. 2010)

Illegal operational ship discharges mainly refer to pollution from solid and liquid waste and oil residues that should be processed onboard and delivered to dedicated reception facilities in ports. It is very difficult to estimate the volume of waste discharges from ships and the consequential financial implications. An attempt was made through the exploitation of data from observations in marine areas of Europe, which are covered by satellite (North Sea, Mediterranean Sea, and Baltic Sea). The concentration of the recordings shows that for the period 1998 – 2004 the illegal discharges have an average of 23661 tons/year. According to the same study, the illegal discharges of the world fleet have a total external cost of 39 billion dollars (TRT, 2007).

Impacts due to maritime transport activities are evident to biodiversity. These are essentially estimated through the reduced number of endemic species and organisms and with the loss in fisheries (JRC, 2009). Damage to biodiversity occurs also through the transportation of alien species in the ship's ballast water over long distances. The estimation of external impacts from ballast water refers to economic losses in species that offer income to the local communities (e.g. fish). A typical example is the study of Ruiz et al., (2001), which estimated a $500/year, as the cost of reduced mussels due to the invasive species. Reasonably, these estimates are greatly dependant on geographical factors, since the effect of the ballast water in the marine biodiversity varies from one geographic region to another.

Grey and black water produced by ships cause minor effects to the marine environment. The quantities produced are subject to the people onboard (passengers and crew). Cruise ships are responsible for the 25 percent of the total grey & black water production (Butt, 2007). Grey and black water may contain organic matter, which has an eutrophication effect to the marine environment. There is no scientific evidence for the estimation of the external cost or environmental impact from the latter activity.

10.4 Origin and impact of ship air emissions

Air pollution has a significant impact on human health. The World Health Organization (WHO) recognizes that the exposure to air pollution is the greatest environmental hazard for human health. According to data of the WHO for the year 2012, one in eight deaths worldwide was due to exposure to air pollution (WHO, 2014).

Shipping activities may affect the human health due to the emission of gaseous pollutants from burning fossil fuels in internal combustion engines. Since the largest part of the maritime transport activity occurs in short distances from land (70% of transport activities in less than 400 km from the nearest coast) (Endresen et al., 2003), ship air pollutants contribute to air pollution near residential areas and may have impacts on human health. The main air pollutants of shipping that can affect the human health are sulphur and nitrogen oxides and Particulate Matter (PM).

In Europe, available data indicate that air pollution causes 100 million sick days per year and 350,000 premature deaths per year (European Environment Agency - EEA, 2013).

Other studies on ships air pollution have shown that PM emissions from maritime transport cause approximately 60,000 premature deaths per year worldwide, most of which occur in residential areas such as the Eastern coastline and South Asia, Europe and North America (Corbett et al., 2007).

The contribution of shipping in air pollution effects and especially human health effects is greater than its contribution to the global greenhouse gases. Recent studies suggest that the contribution of shipping greenhouse gas emissions does not exceed the 2.4% (IMO, 2014). However, for NOx, SOx, and particulate matter emissions, shipping contribution is much higher at 14%, 15% and 8% respectively, as reported in recent studies (EEA, 2011). The above are illustrated in the following figure.

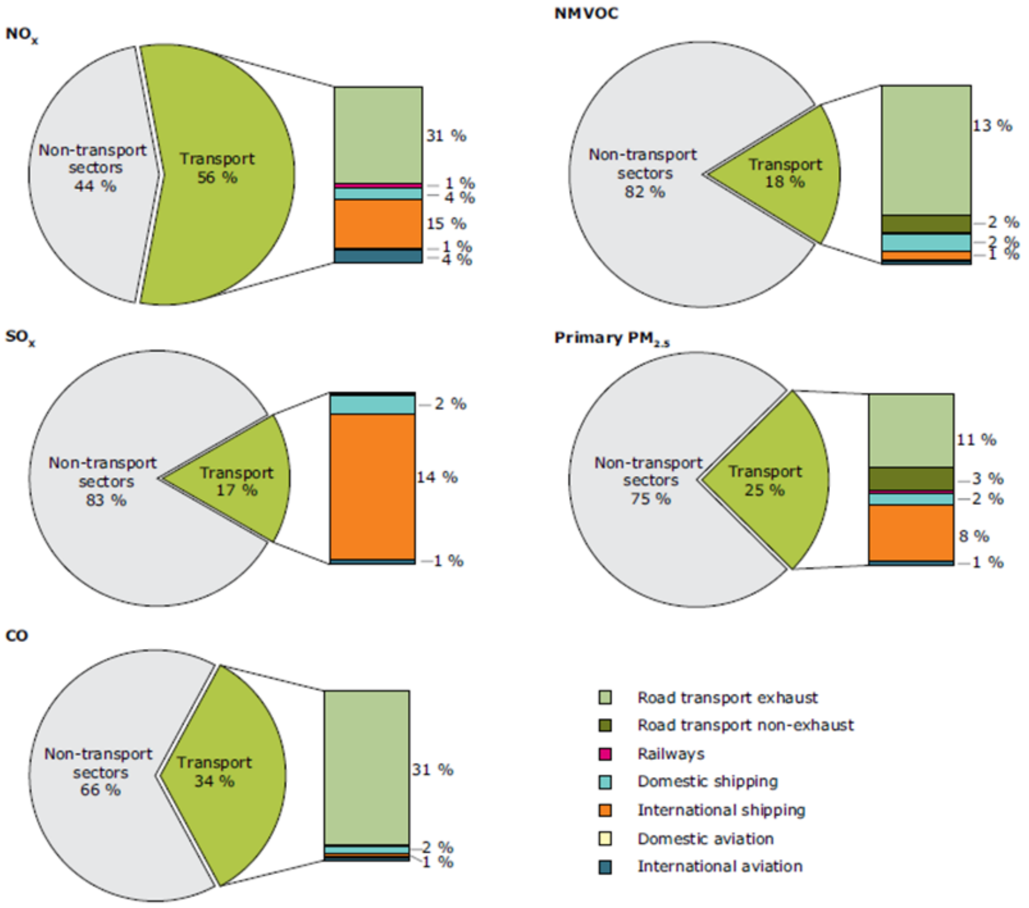


Figure 71: Contribution of transport in air pollution within EU (EEA, 2013)

Air emissions may be grouped subject to their general impact (to the environment and the human health) to emissions causing air pollution and emissions contributing to climate change. Emissions of the first category are: SOx, NOx, PM, CO, and VOC while in the second emissions are: CO_2, HCFC, and CH_4.

Another relevant distinction for emissions is in primary and secondary pollutants. Primary emission pollutants are those emitted directly by an emission source (e.g. all emissions resulting by the combustion process in marine engines). Secondary pollutants are not emitted directly by the emission source but they are formed later away from this source when chemical reactions take place between main air pollutants and the environment. The secondary pollutants caused by shipping activities are: ozone, sulphates and nitrates.

10.4.1 Particulate matter (PM)

PM is an ill-defined mixture of pollutants, from acids (such as nitrates and sulphates) to organic chemicals, metals, soil, dust particles or generally anything, solid or liquid that accumulates in a particle detector (Rabl A., 2001). It can be categorized in particles with less than 10 micrometres diameter (the "coarse" fraction) and particles with less than 2.5 micrometres diameter (the "fine" fraction) called PM10 and PM2.5 (Café, 2005). Fig. 72 shows an Illustration of PM size. In the atmosphere, PM can either originate from primary particles emitted directly or 'secondary' particles from chemical reactions between PM-forming (precursor) gases like SO2, NOx NH3, and non-methane volatile organic compounds (NMVOC) (EEA, 2013). Specifically for the 'secondary' particles, SO_2, NOx, and NH_3 form sulphate, nitrate and ammonium compounds which then condense into liquid form and produce new particles in the air, called secondary inorganic aerosols (SIA) (EEA, 2013). Secondary organic aerosols (SOA) are formed from the oxidation of VOC to less volatile compounds (EEA, 2013). The main chemical compounds of an aerosol (Black carbon (BC), nitrate ($NO3^-$), ammonium ($NH4^+$), organic matter concentrations (OM), non-sea-salt sulphate ($nssSO42^-$), sea salt and mineral dust), account for about 70% or more of the PM_{10} and $PM_{2.5}$ mass when the rest 30% is thought to be due to the presence of water or to the underestimation of the molecular mass to carbon mass ratio when calculating organic matter concentrations. In shipping, primary particles are emitted directly from the funnel due to incomplete combustion and secondary particles are formed from SO_2, NOx and VOC emissions (EEA, 2013).

The most consistent results, worldwide, have been found for PM and multipollutant analyses have usually concluded that they represent the most significant source of health damage costs (Rabl A., 2001). Numerous studies have found a link between particle levels and hospital admissions and emergency room visits, even death from heart or lung diseases (Denissis, 2009). WHO (2013) (World Health Organization) concluded that ''the evidence for a causal link between $PM_{2.5}$ and adverse health outcomes in humans have been confirmed and strengthened and, thus, clearly remain valid. As the evidence base for the association between PM and short-term, as well as long-term, health effects have become much larger and broader it is important to update the current WHO Guidelines for PM''. Also for black carbon and secondary inorganic aerosols (SOA) there is substantial exposure and health research finding associations and effects (WHO, 2013). New evidence links black carbon particles with cardiovascular health effects and premature mortality for both short-term (24 hours) and long-term (annual) exposures where epidemiological studies continue to report associations between sulphates or nitrates and human health (WHO, 2013). Long-term exposures of PM have been associated with reduced lung function, chronic bronchitis and premature death. Short-term exposures can aggravate lung disease, causing asthma attacks, acute bronchitis and increase susceptibility to respiratory infections (Denissis, 2009). The size of particles is crucial to their potential for causing health problems and thus the impact of shipping activity increases with decreasing particle size (EEA, 2013). In fact PM_{10} and $PM_{2.5}$ pose the greatest danger because they can penetrate the lungs and get into the bloodstream (Denissis, 2009). In Café (2005) it's been estimated that over 300,000 premature deaths equivalent a year in 2000 are the effects on life expectancy of exposure to particulates. Corbett et al. (2007) modelled ambient PM concentrations from oceangoing ships and found that PM emissions are responsible for approximately 60,000 cardiopulmonary and lung cancer deaths annually, with most deaths occurring near coastlines in East Asia, Europe and South Asia. Another analysis by WHO (2006b) indicate that PM (and especially $PM_{2.5}$), affects the most of Europe population leading to a wide range of acute and chronic health problems as well as to a reduction in life expectancy of 8.6 months on average in the 25 countries of the European Union (EU). Finally, PM_{10} emissions are closely associated with diesel engines which are 30 to 70 times higher than from gasoline engines (Denissis, 2009).

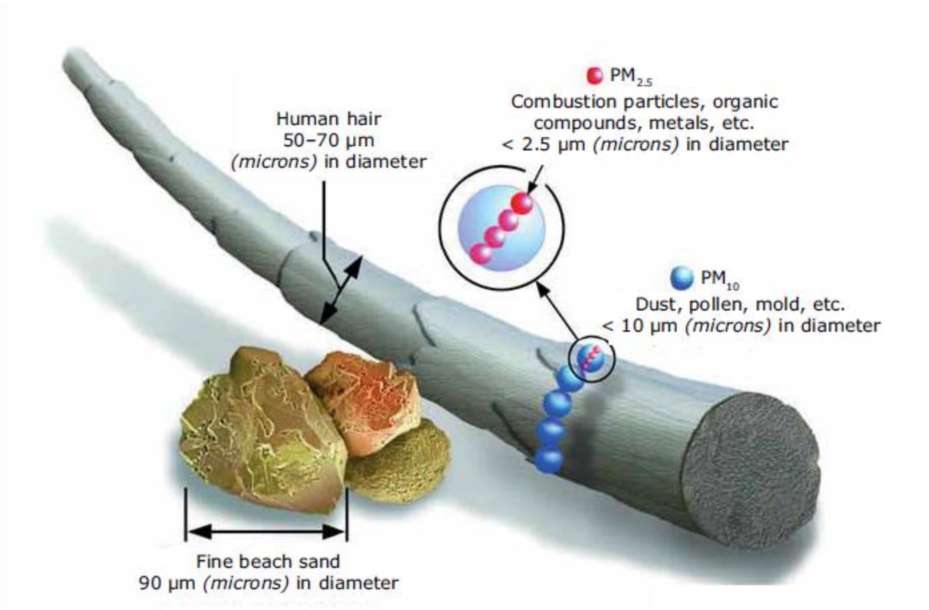


Figure 72: Illustration of PM10 and PM2.5 particle size (source: EPA, 2010)

10.4.2 Carbon monoxide (CO)

CO is a gas emitted from incomplete combustion of fossil fuels and biofuels (EEA, 2013) and therefore it is emitted directly from the funnel of the ship. In the atmosphere CO has a lifetime span of three months or so because it slowly oxidizes into CO_2 forming O_3 during the process (EEA, 2013).

CO is hazardous for humans and impossible to be detected from them as it is colourless and odourless. It affects not only the sensitive parts of a society like individuals with respiratory diseases, infants and elderly persons but also healthy individuals (Denissis, 2009). CO enters the body through the lungs and is strongly bound to haemoglobin and therefore reduces the amount of oxygen that can be transferred to the body (EEA, 2013). People that suffer from cardiovascular disease are the most sensitive because further reduction of oxygen to the heart can cause myocardial ischemia (EEA, 2013). High concentrations of CO can cause asphyxia and eventually death even to a healthy person. Some of the most common effects of a small increase in the level of carbon monoxide are impairing exercise capacity, learning functions, ability to perform complex tasks, affected coordination, difficult concentrating and damaged visual perception (Denissis, 2009). There is also epidemiological evidence which suggests that direct impacts of CO also appear to be statistically significant. However the resulting damage costs are low, even for the transport sector (Rabl A., 2001). In many studies CO is not examined as a possibly causative pollutant where in other studies it is considered but they fail to find a CO-related effect (Rainer Friedrich & Peter Bickel, 2001).

10.4.3 Carbon dioxide (CO_2)

CO_2 is naturally part of the atmosphere but it can also be produced from the combustion process of fossil fuels and like CO it is also emitted directly from the ship’s funnel.

CO_2 is a greenhouse gas which means that in large quantities can cause global warming. Global warming is the phenomenon where increasing concentrations of greenhouse gases cause a continuing rise in the average temperature of Earth's climate system (EEA, 2013).

10.4.4 Nitrogen oxides (NOx)

Emissions of NOx are produced from the combustion of fuels under high pressure and temperature (Denissis, 2009). More specifically, high air temperatures activate oxidation of nitrogen in the air passing through the engine as well as the potential formation of NOx from nitrogen in the fuel result in emissions of NOx (Concawe, 2007). Most NOx are emitted in the form of NO which is rapidly oxidized in the atmosphere to NO2 and then to nitric acid and other nitrates. A small part of NOx emissions is directly emitted as NO2, called NO2 fraction. This is less than 5% for petrol fuelled vehicles, whereas in diesel engines is higher at around 10–12% (Concawe, 2007).

As it was previously noted, most of the NOx emission come in the form of NO which is rapidly oxidized in the atmosphere to NO_2 and then to nitric acid and other nitrates. NO may be considered harmless as it is a reducing and not an oxidizing agent (Rabl A., 2001). The toxicity of NO2 is generally attributed to its oxidative capabilities although it is less reactive as an oxidant than O3 (Rabl A., 2001). NO_2 affects primary the respiratory system (EEA, 2013). Short-term exposure to NO_2 can change the lung function in sensitive population groups and long-term exposure can lead to more serious effects such as increased susceptibility to respiratory infection (EEA, 2013). Epidemiological studies have shown that long-term exposure to NO_2 is associated with an increase of symptoms of bronchitis in asthmatic children (EEA, 2013). NO_2 is highly correlated with other pollutants (especially PM), thereby it is difficult to distinguish the effects of NO_2 from those of other pollutants (EEA, 2013). There is no supportable evidence for direct health impacts of NO_2 except maybe for morbidity of children and therefore it seems that the main damage of NOx is the result of its second pollutants, O_3 and nitrates (Rabl A., 2001). In addition, NO_2 can also have adverse effects to ecosystems. Even though in normal concentration it is an important nutrient, excess deposition of reactive nitrogen can lead to a surplus of nitrogen in ecosystems, causing eutrophication (nutrient oversupply) in terrestrial and aquatic ecosystems (EEA, 2013).

10.4.5 Sulphur dioxide (SO_2)

The main fuel used in international shipping is HFO (Heavy Fuel Oil-used in 87 % of ships in 2010) which contains sulphur (EEA, 2013) and the combustion of sulphur-containing fuels leads to SO_2 emissions.

Further oxidation of SO_2 create acidic deposition which is called acid rain, which harms aquatic ecosystems in rivers and lakes, and cause damage to forests, and acidification of soils (EEA, 2013). However, SO_2 itself contributes to respiratory problems, in particular to children and the elderly, and aggravates existing heart and lung diseases (Denissis, 2009). According to epidemiological studies SO_2 can affect the respiratory system and lung functions, and causes irritation of the eyes (EEA, 2013).

10.4.6 Volatile organic compounds (VOC)

VOC (which include also HC) are produced from incomplete combustion and fuel evaporation and they play an important role in creating ground level-ozone when they chemically react with NOx (Denissis, 2009).VOC emissions are also attributed to the painting processes in shipyards.

VOC emissions contain Hydrocarbons (HC), some of which are carcinogenic. For example, prolong exposure to benzene (C_6H_6) can cause damage to genetic material of cells (EEA, 2013) which lead to cancer. In addition, chronic exposure to C_6H_6 can damage bone marrow and cause haematological effects such as decreased red and white blood cell counts (EEA, 2013).

10.4.7 Ozone (O_3)

Ground-level (tropospheric) O_3 is a secondary pollutant which unlike primary air pollutants is not directly emitted into the atmosphere; instead it is formed from complex chemical reactions following emissions of precursor gases such as NOx and non-methane VOCs (EEA, 2013). Also at continental scale methane (CH_4) and carbon monoxide (CO) play a role in O_3 formation (EEA, 2013).

Ozone is a highly oxidative compound and because of that is harmful to vegetation, materials and human health (WHO, 2008). Respiratory health problems, such as breathing problems, asthma, reduced lung function, and other lung diseases can be caused by high concentrations of O_3 (EEA, 2013). Recent epidemiological studies have strengthened the evidence that daily exposures to ozone increase mortality and respiratory morbidity rates and as for long-term exposures, new epidemiological evidence indicate inflammatory responses, lung damage and persistent structural airway and lung tissue changes early in life (however these results are not conclusive and future studies must confirm them) (WHO, 2008). Ozone can also damage buildings by increasing the rate of degradation and reduce agriculture crop yields by impairing reproduction and growth of plants (EEA, 2013). In addition, O_3 is a short lived (unlike CO_2) greenhouse gas, so its contribution to global warming is limited.

10.5 Impact Assessment in the context of LCA

10.5.1 Life Cycle Impact Assessment methods

Life cycle assessment (LCA) is the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (ISO, 2006a). Once all the required emission and resource data is collected in an inventory list, a life cycle impact assessment (LCIA) can be performed to calculate the potential environmental impact of the inventory data.

There are many methods available for analysing the impact of systems and products in a life cycle context. The choice of the appropriate method should be done based on the limits and purpose of LCA study. Representative LCIA methods for which data are available have been identified in a review study (Hischier et al, 2010) and listed below:

- CML 2002
- Cumulative energy demand
- Cumulative exergy demand
- Eco-indicator 99
- Ecological footprint
- Ecological scarcity 1997

- Ecosystem damage potential - EDP
- EDIP’97 and 2003 - Environmental Design of Industrial Products
- EPS 2000 - environmental priority strategies in product development
- IMPACT 2002+
- IPCC 2001 (climate change)
- TRACI
- Selected Life Cycle Inventory indicators

None of the above methods was developed exclusively for use in the life cycle analysis of ships and as such, these methods may only partially cover the needs of impact analysis of a maritime transport system.

Life cycle impact assessment (LCIA) is a field of active development. The last decade has seen numerous new impact assessment methods covering many different impact categories and providing characterization factors that often deviate from each other for the same substance and impact (Hauschild et al, 2012).

The outcomes of the assessment (the impact score) can be interpreted and further analysed to reduce uncertainties from imprecise inventory data, data gaps and important assumptions taken during the data collection and impact assessment (ISO, 2006b).

The LCIA consists of mandatory steps (1, 2, and 3) as well as optional steps (4 and 5), as shown in the following figure.

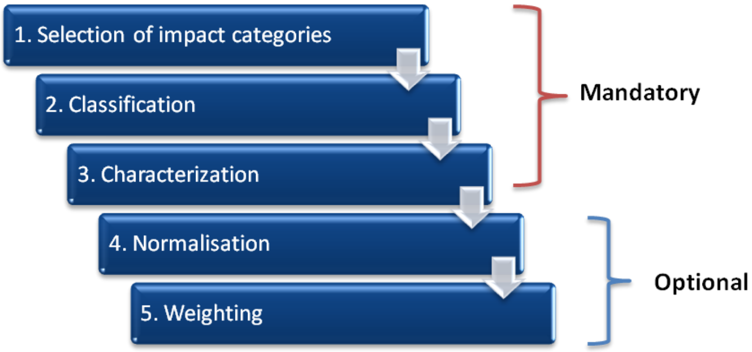


Figure 73: LCIA steps according to ISO standards

Selection of impact categories involves the identification of relevant categories of impact for the particular study’s needs (i.e. climate change, eutrophication acidification etc.) Classification is the assignment of inventory results to impact categories. This should be done by assigning the inventory results that are not only exclusive to one impact category but also relate to more than one impact category, including distinction between parallel mechanisms (e.g. SO2 is apportioned between the impact categories of human health and acidification), or relation to serial mechanisms (e.g. NOx can be classified to contribute to both ground-level ozone formation and acidification). Impact categories are supposed to reflect issues of direct environmental importance. As an example, waste should not considered as an impact category; it is the effects of waste processing that should be considered for its effects on climate change, toxicity, land-use, etc. (Goedkoop et al, 2013).

The focus of this thesis is the impact of ship air emissions. Emission impacts are of regional scale (air pollutants such as SOx, NOx, PM, VOCs) and global scale (greenhouse gases, such as CO2 and CH4). The effects are observed on both the environment and human health. The allocation of the emissions from the inventory list to categories of impact will help building the pathway from emissions to final impact. For this allocation, various approaches are available in the literature.

This study follows the principals of the approach suggested by the International Reference Life Cycle Data System (ILCD). The ILCD System has been launched by the Joint Research Centre (JRC) of the European Commission in order to develop technical guidance that complements the ISO Standards for LCA and provide the basis for greater consistency and quality of life cycle data, methods, and LCA studies.

The ILCD System recently has performed an evaluation of the existing LCIA concepts and offered a best practice framework for LCA research (EC-JRC, 2011). The connection of midpoint and endpoint impact categories of this system is preferred as the best option for the needs of this study.

Within LCA, a number of different characterization methods are formed together to address different environmental impacts (the impact categories) covered by the methodology. According to the ISO 14044 standard, the characterisation factors used in an LCA should be based on environmental mechanisms that link the man-made interventions to a set of areas of protection. The end of such mechanism is called the endpoint. A point positioned half way along the environmental mechanism can be also characterised (with an indicator); this point is often refer to as the midpoint.

Each one of the characterization methods uses a cause-effect pathway and impact indicator, to produce the so called characterization factors (CFs). Therefore, CFs are weighting factors that aggregate interventions (e.g. air emissions).

The impact score for impact category c (ISc), also defined as impact category indicator result, equals (De Schryver, 2010):

$$\mathrm{IS_c} = \sum_{i=1}^{x} \mathrm{CF_{x,c}} \times \mathrm{m_x} \qquad \text{where,}$$

- $CF_{x,c}$, is the characterization factor of emission substance x within impact category c (e.g. CO2 equivalents for climate change)
- m_x , is the mass of substance x emitted, which has been recorded in the emissions inventory.

In case the same units are applied, the impact scores over different impact categories can be added.

The type of impact indicator used in a characterization method to measure the effect will influence the indicator and thus also the impact score. Midpoint indicators are normally expressed as equivalent values. Examples are kg CO_2-equivalents for climate change, SO_2-equivalents for acidification and MJ-equivalents for resource use. An example of the pathway from emissions to final impact is provided below (De Schryver, 2010).

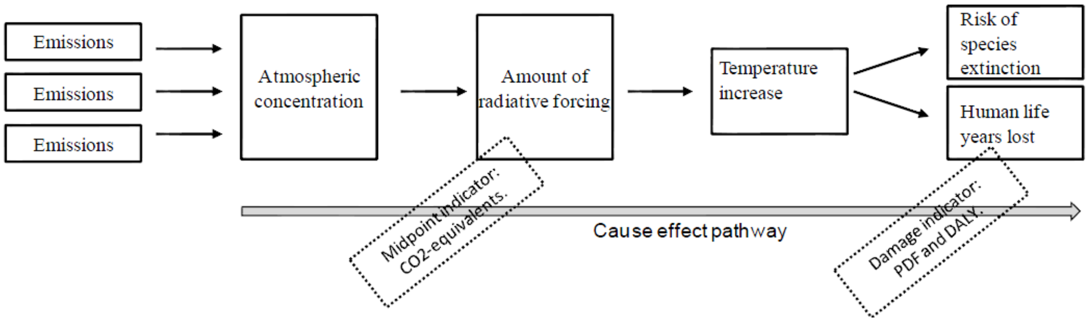


Figure 74: Example of a simplified cause-effect pathway for climate change. Different impact indicators are presented along the cause-effect pathway (De Schryver, 2010)

Normalization is an optional step in LCIA which involves the calculation of the magnitude of the category indicator results relative to some reference information. The aim is to understand the relative magnitude for each indicator result of the system under examination. Weighting is also an optional element with two possible procedures, either to convert the indicator results or normalized results with selected weighting factors, or to aggregate these converted indicator results or normalized results across impact categories.

The environmental mechanisms may have different validity for all regions or geographical areas. For example, acidification, eutrophication, photochemical ozone formation, toxicity, land-use and water-use, all depend on regional conditions and regionally different parameters. Therefore, the validity of characterisation factors should be taken into account on a case-by-case basis in LCA.

10.5.2 Impact assessment in LCA

A number of methods used for life cycle impact assessment (LCIA) translate the emissions of hazardous substances into impact category indicators. The categories of impact may reflect specific areas of damage to the environment such as acidification, climate change and ecotoxicity, while other impact categories may employ indicators of more generic nature such as damage to human health and damage to ecosystem quality.

The selection of the impact method should be made according to the needs of the study (i.e. boundaries, scope, and inventory). There are a number of available methods for use in the LCA framework that have been reported and analysed thoroughly in the literature (Hischier et al, 2010), (EC-JRC, 2011). The survey conducted for the needs of this study has concluded that Eco-indicator 99 method and the Recipe 2008 method are the most suitable in this respect. These two methods have a wide record of applications, they have open access of data and they both have impact categories that cover the case of a maritime transport study. The LIME method, which has also been used in previous maritime studies (Kameyama, 2004), is excluded because it addresses impacts only for the case of Japan.

Damage assessment is a relatively new step in impact assessment. The purpose of damage assessment is to combine a number of impact category indicators into a damage category (area of protection). In the damage assessment step, impact category indicators with a common unit can be added. For example, in the Eco-indicator 99 method, all impact categories that refer to Human health are expressed in DALY (disability adjusted life years). In this method it is allowed to add DALYs caused by carcinogenic substances to DALYs caused by climate change. It is noted that none of the above methods has been created to cover the specific case of shipping damages; however some ship LCA studies have applied damage assessment concepts (Kameyama, 2004), (Fet, 2002).

Eco-Indicator 99

Eco-Indicator 99 is the most widely used damage method in LCA. The method identifies eleven exposure and effect analysis categories at the midpoint level. These eleven midpoint effects are then allocated into three areas of protection or damage categories (i.e. human health, ecosystem health and resource availability). Databases are available for the midpoint and endpoint factors which are used in the method (http://www.ecoinvent.org).

The final three categories of damages are described below (Eco-Indicator Manual, 2013):

1. Damage to Human Health, expressed as the number of year life lost and the number of years lived disabled. These are combined as Disability Adjusted Life Years (DALYs), an index that is also used by the World Bank and the World Health Organisation;
2. Damage to Ecosystem Quality, expressed as the loss of species over a certain area, during a certain time; and
3. Damage to Resources, expressed as the surplus energy needed for future extractions of minerals and fossil fuels.

The Eco-Indicator 99 method produces one final indicator (the Eco-indicator) as a result of the weighting of impacts of the three types of damages that have been described previously. The unit of the final indicator is the Eco-indicator point (Pt) or milli-point (mPt). One point (1 Pt), corresponds to the 1/1000 of the yearly environmental load caused by the average European inhabitant (Eco-Indicator Manual, 2013).

The cause-effect pathway of the method, from the life cycle inventory (life cycle emissions for the case of this study) to midpoint and finally to endpoint impact categories is given in the following figure.

The allocation of emissions to midpoint impact follows exactly the pathway of the figure below. CH_4 is an important greenhouse gas; therefore its pathway matches with the pathway of CO_2. NMVOCs are non-methane volatile compounds which are treated in the same manner as the volatile organic compounds in the Eco-Indicator 99. CO falls in the category of air pollutants and has human health effects in the impact category of respiratory substances. The land use and land conservation has no relevant input. In the extraction of resources inventory only the iron needed for the ship's steel structure is considered. The input of fossil fuels is not relevant to the study's goals and therefore is omitted.

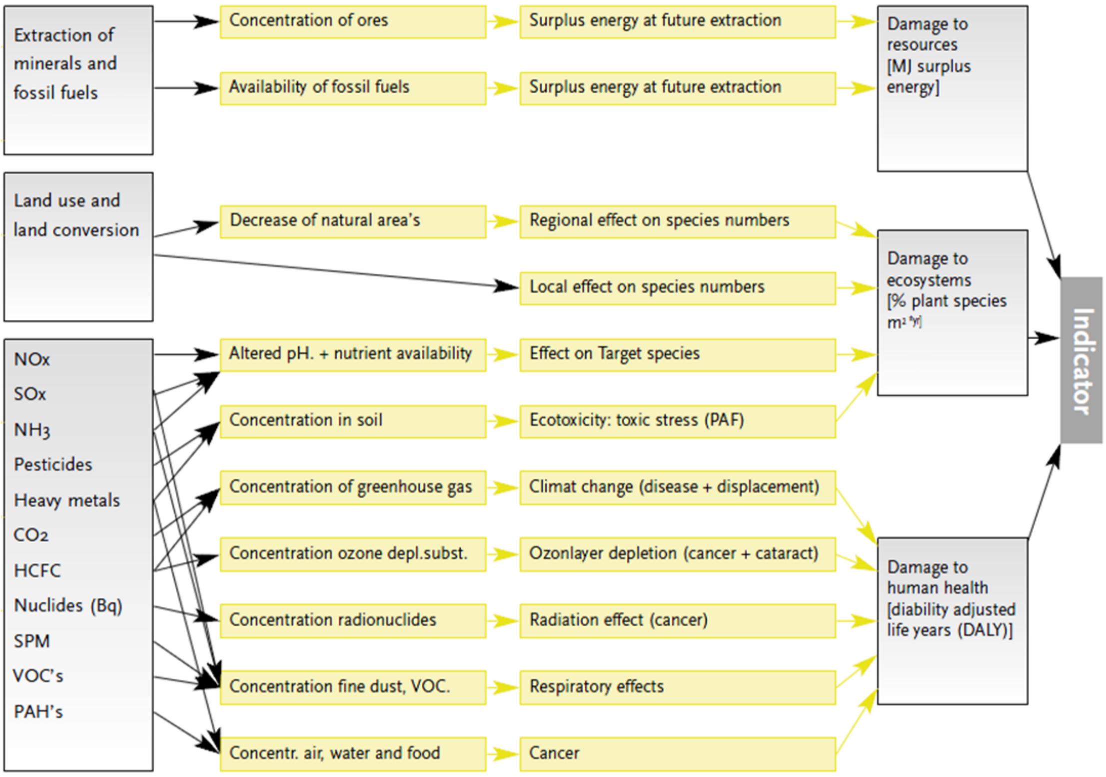


Figure 75: The Eco-Indicator 99 damage model (Eco – Indicator 99, manual for designers)

10.5.3 ReCiPe 2008

The objective of the ReCiPe 2008 method is the integration of two existing methods into one new integrated impact assessment method for the LCA. Essentially, the integrated methods are the CML method (midpoint-oriented method), which is used in the intermediate level of damage assessment and the Eco-indicator 99, (presented in the previous paragraph), which is used for endpoint effects.

ReCiPe, consists of two groups of effects associated with the respective characterization factors. The first objective is connecting the LCI list with the impact categories of the intermediate level (or midpoint level). The following eighteen impact categories have been identified for the intermediate level (Goedkoop et al., 2013)

1. Climate change, CC
2. Ozone depletion, OD
3. Terrestrial acidification, TA
4. Freshwater eutrophication, FE
5. Marine eutrophication, ME
6. Human toxicity, HT
7. Photochemical oxidant formation, POF
8. Particulate matter formation, PMF
9. Terrestrial ecotoxicity, TET
10. Freshwater ecotoxicity, FET
11. Marine ecotoxicity, MET
12. Ionizing radiation, IR
13. Agricultural land occupation, ALO

14. Urban land occupation, ULO
15. Natural land transformation NLT
16. Water depletion, WD
17. Mineral resource depletion, MRD)
18. Fossil fuel depletion, FD

In the second level (endpoint level), each one of the above intermediate category is connected with a final category of damage. For this, the final taxonomy damage of the Eco-indicator 99 method is used namely: damage to human health, (HH), damage to ecosystem diversity, (ED), and damage to resource availability, (RA).

Fig. 76 shows the links between the intermediate and the final categories of damage in ReCiPe 2008. A category from the intermediate level may be associated with more than one category of the final level.

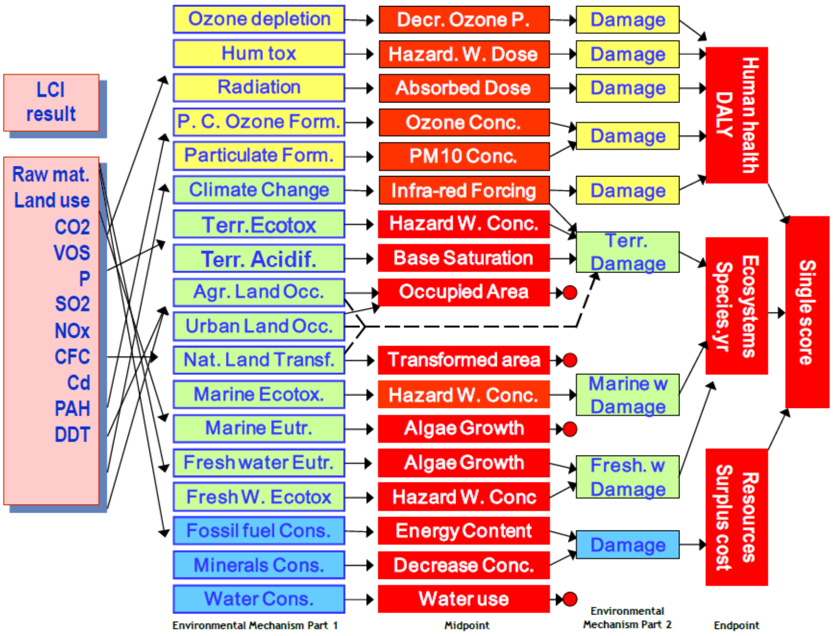
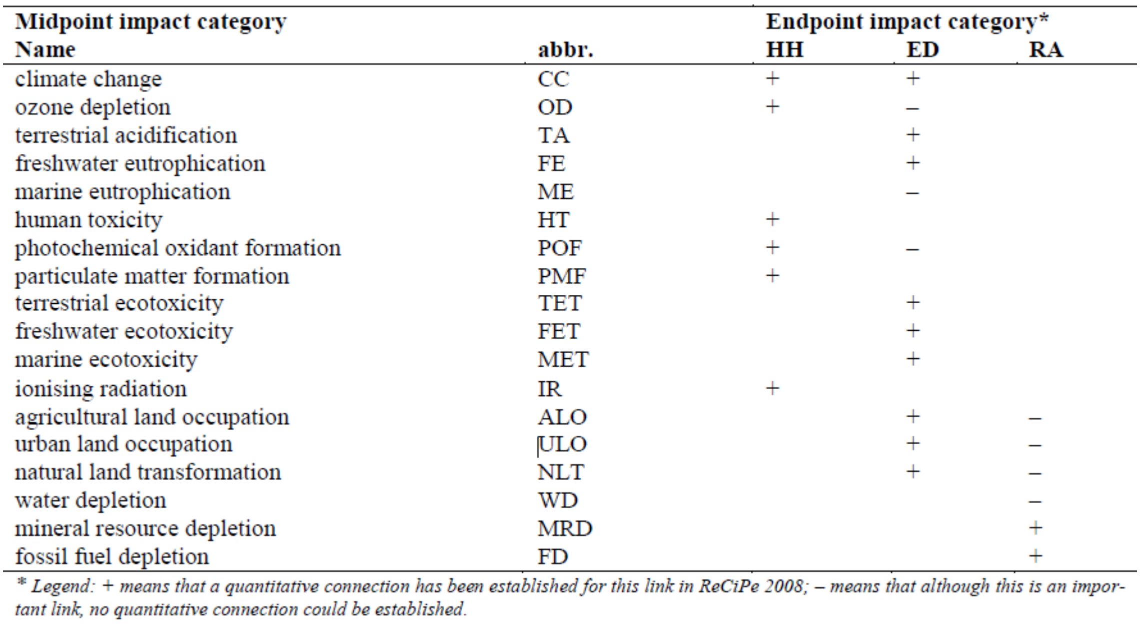


Figure 76: The ReCiPe 2008 damage model (source: Goedkoop et al, 2013)

There are cases where the link between the two levels is identified but there is no way that this link can be measured in a reliable manner. This case is marked with (-) in Table 56, and eventually is omitted from the final score of the impact assessment. A typical example of this weakness, which is also interesting for the objectives of the impact assessment of ship emissions, is the mid-term impact of eutrophication of marine environment (marine eutrophication, ME). In ReCiPe 2008, it was not possible to identify a reliable model for the conversion of this interim impact in some of the forms of the final stage (endpoint impact categories).

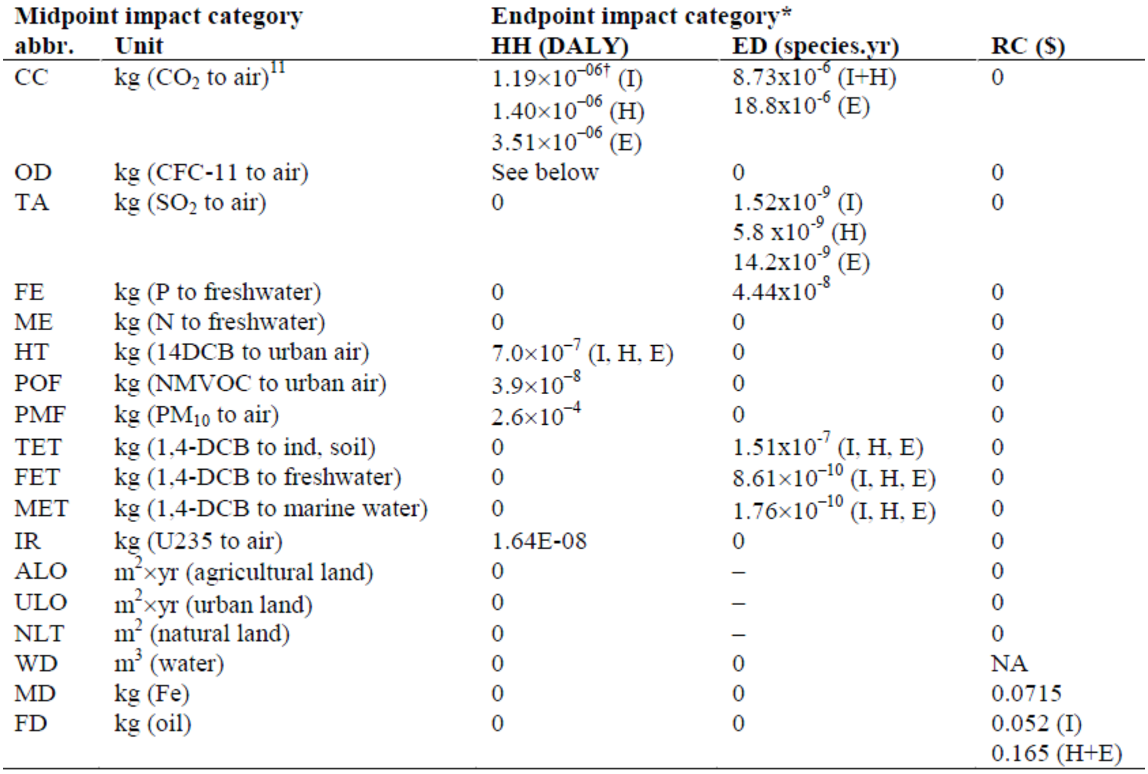


Midpoint impact category		**Endpoint impact category***		
Name	**abbr.**	**HH**	**ED**	**RA**
climate change	CC	+	+	
ozone depletion	OD	+	–	
terrestrial acidification	TA		+	
freshwater eutrophication	FE		+	
marine eutrophication	ME		–	
human toxicity	HT	+		
photochemical oxidant formation	POF	+	–	
particulate matter formation	PMF	+		
terrestrial ecotoxicity	TET		+	
freshwater ecotoxicity	FET		+	
marine ecotoxicity	MET		+	
ionising radiation	IR	+		
agricultural land occupation	ALO		+	–
urban land occupation	ULO		+	–
natural land transformation	NLT		+	–
water depletion	WD			–
mineral resource depletion	MRD			+
fossil fuel depletion	FD			+

* *Legend: + means that a quantitative connection has been established for this link in ReCiPe 2008; – means that although this is an important link, no quantitative connection could be established.*

Figure 77: Availability of quantitative connection between midpoint and endpoint impacts in ReCiPe 2008 (source: Goedkoop et al, 2013)

The method uses an open database for the characterization factors that is available in the site of ReCiPe 2008 (www.lcia-recipe.info). Figure 78, presents one of the most important features of the method, which is the quantitative links between the intermediate and final damage. In the left column of Figure 78, are listed in abbreviations the eighteen categories of the intermediate impacts. The second column lists the unit used to quantify the specific category (e.g. on climate change, [CC], kg CO2 to air). The next three columns contain the coefficients for conversion into the three respective final impact categories. Uncertainties are included with the instructions (I), (j), and (e), which corresponds to the archetypes of the individualist, the hierarchist) and egalitarian respectively.



Midpoint impact category		Endpoint impact category*		
abbr.	Unit	HH (DALY)	ED (species.yr)	RC ($)
CC	kg (CO_2 to air)^{11}	$1.19\times10^{-06\dagger}$ (I) 1.40×10^{-06} (H) 3.51×10^{-06} (E)	$8.73\text{x}10^{-6}$ (I+H) $18.8\text{x}10^{-6}$ (E)	0
OD	kg (CFC-11 to air)	See below	0	0
TA	kg (SO_2 to air)	0	$1.52\text{x}10^{-9}$ (I) $5.8\text{ x}10^{-9}$ (H) $14.2\text{x}10^{-9}$ (E)	0
FE	kg (P to freshwater)	0	$4.44\text{x}10^{-8}$	0
ME	kg (N to freshwater)	0	0	0
HT	kg (14DCB to urban air)	7.0×10^{-7} (I, H, E)	0	0
POF	kg (NMVOC to urban air)	3.9×10^{-8}	0	0
PMF	kg (PM_{10} to air)	2.6×10^{-4}	0	0
TET	kg (1,4-DCB to ind. soil)	0	$1.51\text{x}10^{-7}$ (I, H, E)	0
FET	kg (1,4-DCB to freshwater)	0	8.61×10^{-10} (I, H, E)	0
MET	kg (1,4-DCB to marine water)	0	1.76×10^{-10} (I, H, E)	0
IR	kg (U235 to air)	1.64E-08	0	0
ALO	$m^2\times yr$ (agricultural land)	0	–	0
ULO	$m^2\times yr$ (urban land)	0	–	0
NLT	m^2 (natural land)	0	–	0
WD	m^3 (water)	0	0	NA
MD	kg (Fe)	0	0	0.0715
FD	kg (oil)	0	0	0.052 (I) 0.165 (H+E)

Figure 78: Conversion factors in ReCiPe 2008 (source: Goedkoop et al, 2013)

10.5.4 LIME

The Life cycle Impact assessment Method based on Endpoints (LIME), developed in Japan and has applications only in this country. The method uses the same approach of assessment in two levels for the final impact assessment. Recordings of LCI directories are translated into impact indicators at the intermediate level and then to damage in the final level divided in four areas of protection. The relationship between intermediate and final impacts as illustrated in the following Table 52. Each intermediate impact category affects a single impact on the final level and then each endpoint impact corresponds to a single area of protection.

The allocation of weighting factors is based on willingness to pay (WTP). The cost assessment in LIME with methodologies that take into account the individual preferences of various groups of people in relation to the significance of the proposed protection areas (Itsubo et al., 2004). LIME, is evaluated as a well-established method (JRC, 2011b) that follows the specifications of the ISO 14040 standard, however it is referring exclusively to the case of Japan. The method has been used in a ship life cycle analysis and actually was included in the development of a software that investigates the basic phases of the life of a ship built, operated and scrapped in Japan (Kameyama et al, 2004).

Table 52: Connection between Intermediate and Endpoint impact categories in LIME (adapted from JRC, 2008)

Midpoint level	Endpoint level	Safeguards areas
Urban air pollution	Cancer	Human health
Indoor air pollution	Respiratory disease	
Human toxicity	Cataract	
Noise	Thermal stress	
Ozone layer depletion	Infectious disease	
Climate change	Starvation	
Photochemical oxidant formation	Disaster	
Ecotoxicity	Terrestrial species	Biodiversity
Eutrophication	Aquatic species	
Acidification	Crop	Primary production
Waste	Forestry	Social aspects
Land use	Fishery	
Mineral resources	Land loss	
Fossil fuels	Energy	
Biotic resource	Materials, resources	

10.6 LCIA Tool

This paragraph presents the Life Cycle Impact Assessment Tool (LCIA Tool) for ships, an excel application which has been developed in the context of the research project EnviShipping. The main objective of the tool is to record all pollutants (oil and non-oil liquid wastes, garbage, air emissions) generated by the various ship related processes and assess their environmental impact by analyzing the entire life cycle of the ship. The tool is based on the principles of the Life Cycle Assessment methodology (LCA) and the damage model of Recipe 2008 for the Life Cycle Impact Assessment (LCIA).

The LCIA Tool for ships could be used for monitoring the environmental impact of ships in local and regional level, and for estimating the outflow of pollutants. In addition, the tool could support decision making in environmental management processes, by identifying the most intense sources of pollution from ships.

This paragraph provides information on the structure, the graphical user interface and the capabilities of the tool. The main input data and user capabilities are described, and the methods to estimate the pollutants during shipbuilding, operation and scrapping are presented. The impact is assessed using the LCIA ReCiPe 2008 method, which is employed specifically for the case of ships.

10.6.1 Assumptions – System boundaries

In the LCIA Tool the life cycle of the ship is considered to start from placing the keel (keel laying) and to end with the total dissolution of the ship structure and her equipment. The system limits are placed on the boundaries of the yard. With regard to the operational phase of the ship, and especially in the ship-port interface the limits are placed, where the ship delivers to the port reception facilities the possible quantities of garbage and other wastes.

Therefore, the procedures that take place outside the yard are not covered, such as, for example, the export of raw materials, the production of fuel and consumables (such as chemicals, paints, etc.), the transportation of materials, waste treatment, etc.

These limits were chosen since they illustrate the specific ship profile, the modus operandi and the place and method used for the final ship recycling. These decisions are usually determined by economic and market conditions rather than environmental or social criteria.

Specific assumptions followed by the LCIA methodology employed here are as follows:

- The interaction of the ship with the port is taken into account in the valuation of waste streams (e.g. garbage, gray and black water, etc.) that are delivered by the ship in port, in accordance with MARPOL 73/78 in order to be processed before their final disposal.
- The local effects of air pollutants are not assessed (these are extensively covered in other case studies of this thesis).
- The performance of the energy system of the ship and the operation profile are considered stable during the ship's life.
- The maintenance takes place on shipyards (dry-dock) every 5 years and minor maintenance works outside the shipyard every 2.5 years.
- The final recycling or scrapping of the ship is modelled according to the current dismantling practices in countries like India, Pakistan and Bangladesh. These countries are leaders in ship dismantling, serving more than 90% of the world's LDT.

10.6.2 Tool modules

The LCIA tool is a software application developed in Microsoft's Excel spreadsheets. Overall, the LCIA tool consists of 25 spreadsheets. Spreadsheet 1, is for inserting generic ship input, required to perform calculations of the tool. Spreadsheets 2 to 24, include the calculations for the establishment of the LCI (i.e. the calculation of the quantities of pollutants). Finally, in spreadsheets 25 and 26, the calculations of the LCIA 2008 Recipe are performed. In summary, the spreadsheets of the LCIA Tool are as follows:

1. Spreadsheet 1: Input data,

2. Spreadsheets 2-7: Shipbuilding phase,

3. Spreadsheets 8-17: Ship operation,

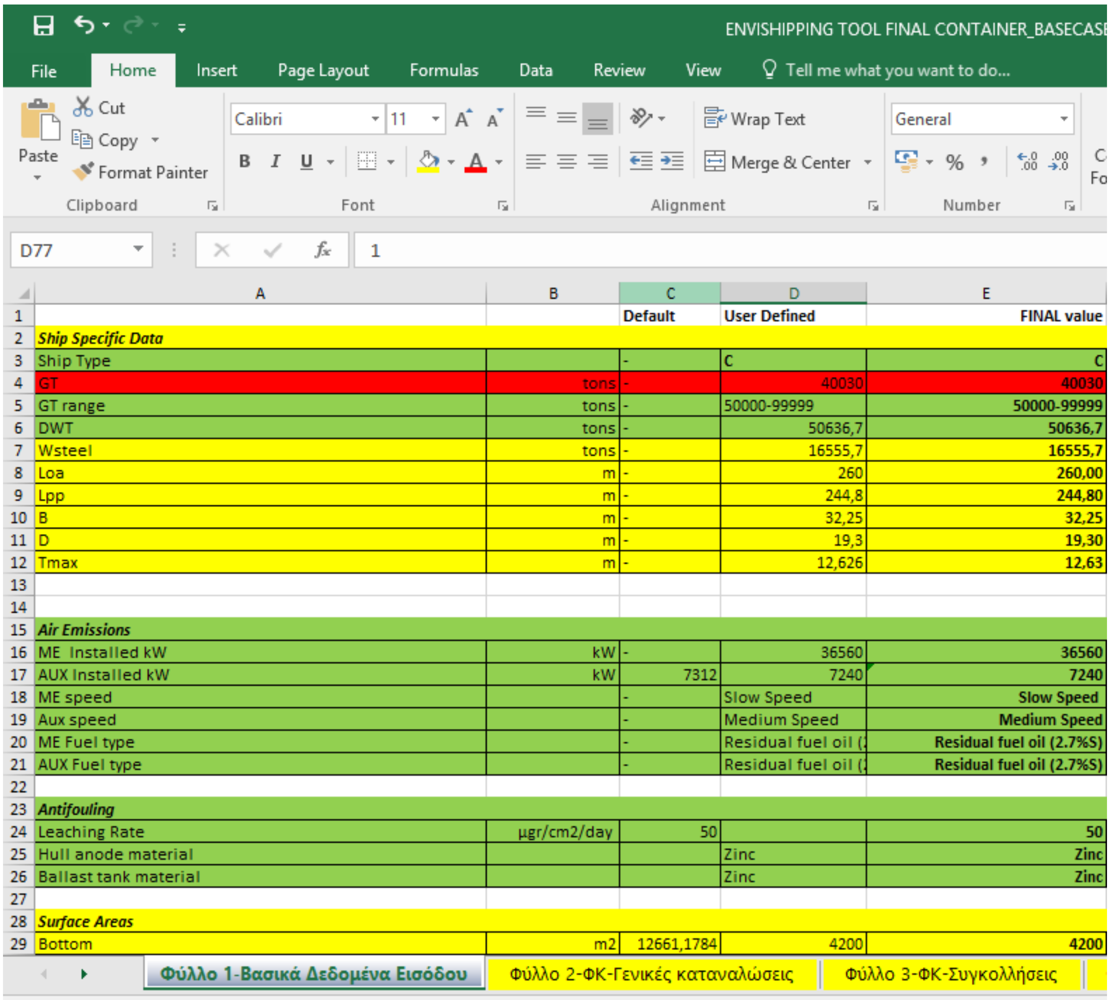
4. Spreadsheets 18-20: Ship maintenance,

5. Spreadsheets 21-24: Ship dismantling/recycling, and

6. Spreadsheets 25-26: Impact assessment with ReCiPe 2008.

The general info inserted in Spreadsheet 1 follows:

Length overall, (Loa), Length between perpendiculars, (Lbp), Breadth, (B), Depth, (d), Draught, (Tmax), deadweight, (DWT), gross tonnage, (GT), lightship weight (LDT), lightship steel weight, main engine installed power, main engine speed (low, medium, high speed or turbine), auxiliary engines power, main engine fuel type (selection from drop down list), antifouling and surface areas.



	A	B	C	D	E
1			Default	User Defined	FINAL value
2	*Ship Specific Data*				
3	Ship Type		-	C	C
4	GT	tons	-	40030	40030
5	GT range	tons	-	50000-99999	50000-99999
6	DWT	tons	-	50636,7	50636,7
7	Wsteel	tons	-	16555,7	16555,7
8	Loa	m	-	260	260,00
9	Lpp	m	-	244,8	244,80
10	B	m	-	32,25	32,25
11	D	m	-	19,3	19,30
12	Tmax	m	-	12,626	12,63
13					
14					
15	*Air Emissions*				
16	ME Installed kW	kW	-	36560	36560
17	AUX Installed kW	kW	7312	7240	7240
18	ME speed		-	Slow Speed	Slow Speed
19	Aux speed		-	Medium Speed	Medium Speed
20	ME Fuel type		-	Residual fuel oil (	Residual fuel oil (2.7%S)
21	AUX Fuel type		-	Residual fuel oil (	Residual fuel oil (2.7%S)
22					
23	*Antifouling*				
24	Leaching Rate	μgr/cm2/day	50		50
25	Hull anode material			Zinc	Zinc
26	Ballast tank material			Zinc	Zinc
27					
28	*Surface Areas*				
29	Bottom	m2	12661,1784	4200	4200

Figure 79: Screen shot from the LCIA Tool software (Spreadsheet 1)

Other information which has to be includes specific parameters for the construction of the ship

Typical parameters of construction that need to be inserted in Spreadsheet 1 include estimates of the surface area of the hull, superstructure, cargo and ballast tanks, etc. the length of welding, material and energy consumption for steel cutting. In addition, the location of the shipbuilding yard is defined (United States of America, Japan, EU-27), in order to calculate the air pollutants from electricity consumption during the construction, according to the energy mix of the respective country.

The ship's construction phase includes all the processes carried out in the area of the yard. The environmental impacts associated with materials beyond this limit will not be considered. Therefore, the key processes that take into account are: overhead, steel welding, steel cutting and painting inside the yard.

10.6.3 Update of LCI algorithms

The tool includes some new algorithms that are different with those included in the Life Cycle Framework as were presented in Chapter 4. For example the algorithms for steel cutting are now include two cutting methods. Also the overhead estimation for shipyard are now country specific. The LCI processes that have been updated are presented below.

Overhead

Almost all processes in shipbuilding have requirements in electric power. In addition, power is needed for the functioning of the offices within the yard, lighting, heating, etc. Even if this does not necessarily involve direct environmental impacts in the area of the yard, power consumption contributes to the emission of air pollutants from power plants. The quantity and composition of emissions depends on the country's energy mix. For this reason, the LCIA Tool offers the ability to choose the location of construction of the ship (United States of America, Japan, EU-27) and uses data for emission factors of pollutants (CO_2, CO, CH_4, N_2O, NOx, NMVOC, SO_2), from electricity use according to the annual reports of organizations United Nations Framework Convention for Climate Change UNFCC and International Energy Agency IEA electricity various countries annual consumption.

These processes are described in separate worksheets of the Tool (Spreadsheets 2-6), while the results are clustered in the Spreadsheet 7.

Sea trials and transport activities of raw materials are not taken into account. Transport practices are not included in the analysis, because they differ greatly between shipyards and, therefore, any generalisation would introduce uncertainty. Sea trials, have minimal impact in the environmental footprint of the ship during her life cycle.

Welding

The most common methods of welding in shipbuilding are [Eyres & Bruce, 2012],

- Flux core arc welding, FCAW),
- Shielded metal arc welding, SMAW,
- Gas metal arc welding, GMAW,
- Submerged arc welding, SAW.

All methods require the use of electrodes (wire/rod), electricity and, depending on the method, protective gases. Therefore, all calculations of pollutants during welding based on electrode consumed quantity and the type of welding. In addition, there are used semi-empirical mathematical relationships from shipyards in accordance with their practices and experience [Roh & Lee, 2007].

The electrodes usually contain minerals (chromium, hexavalent chromium, manganese, nickel, lead) for improving the welding. When melting the electrode, a quantity of the minerals is released into the atmosphere as emissions of particulate matter (PM_{10}).

Protective gases used in SMAW and FCAW methods. The protective gas is either a noble gas (argon), or carbon dioxide (CO_2), or a mixture of them.

The LCIA Tool, estimates the quantity of electrodes as a function of the weight of the steel structure. The relevant results are given in spreadsheet 3.

Steel cutting

The most common cutting methods in shipbuilding are (a) plasma arc cutting (plasma arc) and (b) the cutting oxygen (oxy-fuel flame).

The first of these methods is the most common, and usually is made by numerically controlled cutting automatic machines (Numerical control, NC). The second refers mainly to smaller range steel cutting and planning, which are made manually.

In the ARC plasma method, a stream of high-inert gas supply is converted to plasma in the presence of electrical arc. As a result, a significant amount of PM_{10} emissions can be released, when the cutting takes place in the open atmosphere. However, these emissions can be significantly reduced, if the process is done in water (Eyers and Bruce a, 2012).

In order to calculate the total emissions of pollutants from steel cutting in shipbuilding, it is necessary to estimate the cutting length. In this study, it was considered that the cutting length is a function of the welding length. In addition, it was considered that the total power required for steel cutting, is a function of the size of the ship and the methods applied by the yard. The relevant results are given in spreadsheet 4.

The LCIA Tool has been used in the second and third LCIA case studies (see Chapter 11).

10.7 Evaluation of impact assessment methods in the context of LCA

The Joint Research Centre (JRC) and institute of the European Commission, has formed the International Reference Life Cycle Data System (ILCD) with the aim to gather information to gather expertise and promote uniformity in the implementation of LCA, to meet the requirements of ISO Standards and the use of reliable and quality data for life cycle assessments (EC-JRC, 2011). This initiative has developed a guide with the basic characteristics of impacts (intermediate and final breakdowns) that should be included in the assessment.

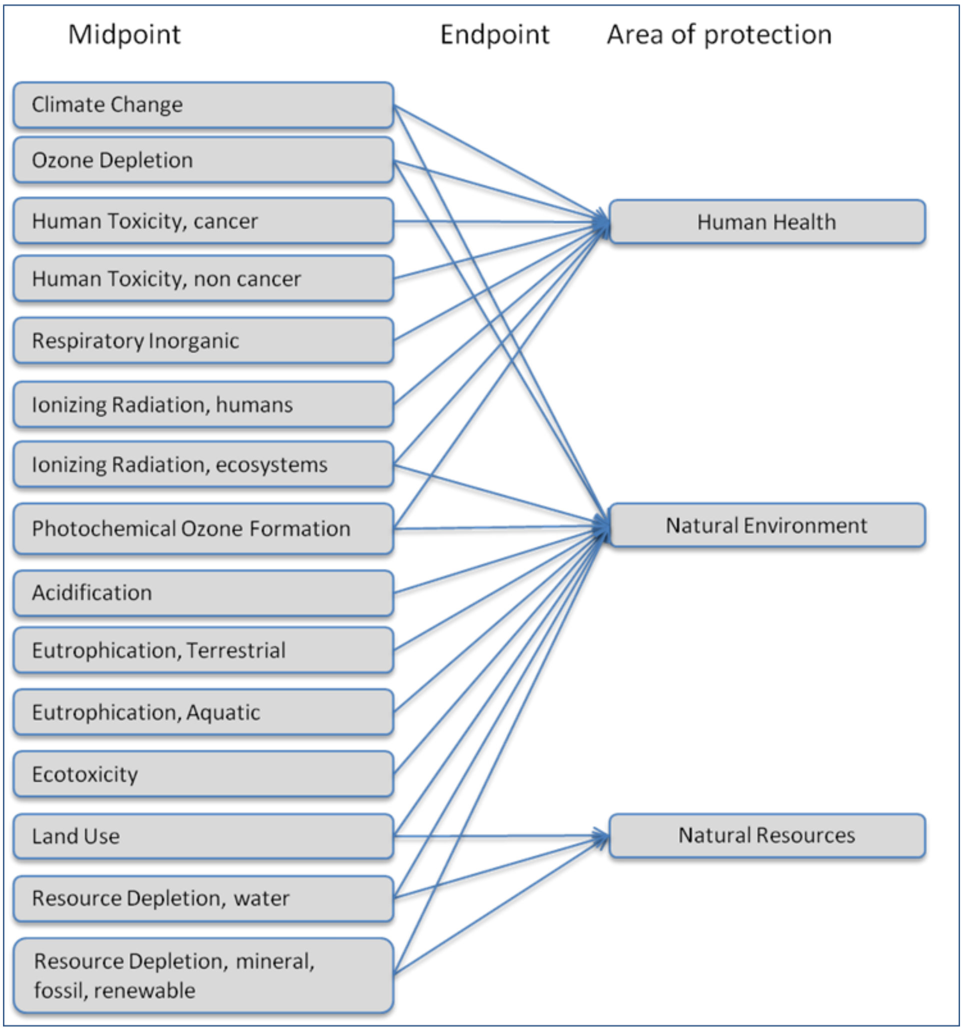


Figure 80: International Reference Life Cycle Data System, ILCD, framework of EC for the impact assessment in the context of LCA (adjusted from Hauschild et al, 2013)

Evaluations performed in the context of the JRC framework identify the impact categories which can be safely used both in the middle (midpoint level) and final level (level endpoint), on the basis of criteria related to the scientific completeness and adequacy of the method, the transparency and the precision of characterisation factors (Hauschild et al, 2013). The JRC work reflects the EU's positions on the LCA methodologies. For the final level of damage assessment (endpoint impact categories), only three LCA methods have been evaluated as satisfactory for use in the context of ILCD.

10.7.1 Uncertainty

The uncertainty observed in the impact assessment of an LCA analysis is attributed to the data accuracy of the Life Cycle Inventory (objective uncertainty), and in the accuracy of the impact model used (subjective uncertainty). The objective uncertainty has been already discussed previously in this thesis, in the development of the life cycle inventory. The subjective uncertainty is attributed to the diversity of interpretations with regard to the importance of a specific impact.

This diversity is subject to the knowledge level of the analyst, the perception of the society about environmental problems, and the time horizon that is chosen every time for the impact measurement.

In Eco-indicator 99, the subjective uncertainty is treated by taking into account principles borrowed from the so-called Cultural Theory (Hofstetter, 1998). According to this theory, the way that a person fits in a society can be formatted in a system of axes, where the horizontal dimension corresponds to the degree of the person’s integration in a group (group axis) and the vertical, to the extent that the person's life is limited by external influences (grid axis), (De Schryver, 2010). The possible combinations of positions in this two-dimensional system, separate the character of the person in five "archetypes" which essentially describe the personal lifestyle. The impact assessment in the Eco-indicator 99 method, utilizes the archetypes of the individualist, of the egalitarian and the one of the hierarchist.

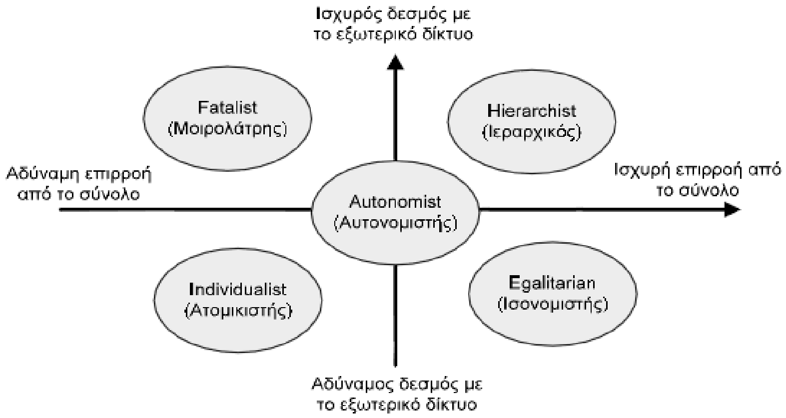


Figure 81: The different human archetypes according to the Cultural Theory (source: Theodosiou, 2008)

Predictions for the perceptions of these archetypes in relation to values that determine views on environmental issues is given in the next table. From these predictions, are made available three different sets of values and consequently three different choices of models for environmental damage within the LCA. Thus, for any system, product, or process to which the Eco-Indicator 99 method applies, it can be introduced in this way, the subjectiveness in the environmental impact assessment.

Table 53: The three archetypes involved in environmental impact assessment in LCA (adapted from Theodosiou, 2008, and De Schryver, 2011)

Believes/Archetypes	Individualist	Hierarchist	Egalitarian
Natural Environment	Not in danger	With limits	Fragile
Generational	Present > Future	Present = Future	Present < Future
Development	Development with market terms	Development with environmental terms	Development with equity terms
Management	Priority	Proportionality	Equity
Knowledge level	Justified impacts	Potential impacts	All known impacts

10.8 Impact Assessment using External Cost

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 always consistent (Psaraftis and Contovas, 2011). 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.

Using the aforementioned approaches, various forms of external transport costs have been calculated in studies and research projects in the past, such as the ExternE, NEEDS, UNITE, CAFE, HEATCO, RECODIT and GRACE (Bickel and Friedrich, 2005), (Holland et al., 2005), (Bickel et al., 2006, (Black et al., 2003), (Nash et al., 2008), (JRC, 2008).

The literature review revealed that usually the studies for the estimation of the maritime transport external cost cover certain categories of this cost (usually the cost of air emissions). None of the studies collected is covering the external cost in the final stage of the ship’s life. Usually, the impact of liquid wastes other than oil is excluded from the impact assessment since it is considered not important from an environmental perspective.

10.8.1 The concept of External Cost

The concept of external cost has emerged and expanded primarily by Arthur Cecil Pigou during the 1920s. External cost is the cost from an economic activity that is transferred to third parties without being counted in the overall cost of this activity, (Bickel and Friedrich, 2005).

According to Denisis (2009) the external cost can be either positive or negative. In his PhD thesis Denisis, argues that the external cost is identical with the definition of externality. The externality occurs when the economic activity of a person (or a group of persons) creates costs or benefits to other groups of people who are not involved in this activity. Externality is the state where the recipient of the impact of an activity is not compensated (in case that he faces a negative impact) or does not pay a fee (in case he receives a benefit).

Private cost is the cost sustained by an activity due to the commitment of labour, raw materials, energy, and other cost for the production of a good. The social cost is the sum of the private cost and the external cost.

Social Cost=Private Cost+External Cost

In an ideal functioning of the market, the social cost should follow the principle of equity. Therefore, the price of a good or a service is determined by the supply and demand. In real life however, the production never corresponds to the actual social optimum. It is more often that the value of a commodity will not take into account the total environmental cost creating this way an external cost. It is also usual that the marginal cost of production does not incorporate the actual cost transferred to the society during the production process (Kalampiakos and Damigos, 2008).

In a market without social protection measures, a producer tends to ignore the external costs to third parties. Therefore, the production quantity will be set at Q1 (where Demand equals to the Supply). This is socially inefficient because the social marginal cost (SMC) is greater than the social marginal benefit (SMB). The social efficiency occurs when the production quantity is set at Q2, where SMC = SMB.

Looking at the diagram of prices (P) and production quantities (Q), of Fig. 82, and using as an example of production the transport work, we can assume that the curve of demand (D=PMB) represents the willingness to pay for the transport work, whereas the supply curve represents the marginal cost for the production of that transport work. In Fig. 82 there are shown two supply curves; the first one is the supply curve using the marginal social cost (SMC) and the second one the supply curve using the marginal private cost (PMC). When the market functions under an optimal social equilibrium, the amount of transport work is set at quantity Q2, which takes into account the total social cost (sum of private and external cost).

In case that the amount of transport work increases (Q1), there is a new state, called private equilibrium that takes into account mainly the private cost of the transport work (e.g. salaries and consumables), which corresponds to more production than the actual demand, while there has been resource expenses (e.g. use of fossil fuels) not included in the final cost that lead in the creation of external cost (i.e. reduction of social wellbeing due to air emissions of the subject transport work). The red triangle is the area of social wellbeing loss and essentially indicates the area of oversupply of transport work.

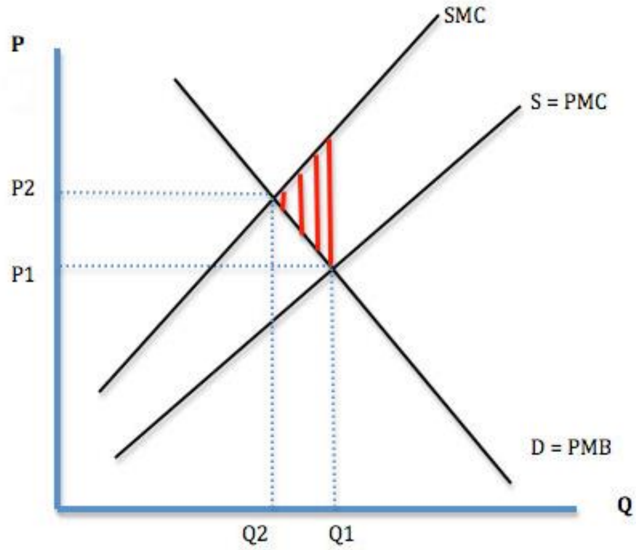


Figure 82: External vs Internal Cost (source: Economicshelp.org, 2014)

Unlike the welfare loss deriving from the reduced productivity or consumption, which is feasible to estimate since it has a certain monetary value, the loss of environmental and social goods (e.g. deterioration of quality of the atmosphere due to air pollution), it is not always easy to quantify.

Transport's external cost may be assessed by following two different approaches; the bottom-up and the top-down, both having advantages and pitfalls. The estimation of marginal costs is usually based on bottom-up approaches which consider specific transport conditions (by referring to case studies) (JRC, 2008). This work follows the approach of bottom-up for the assessment of external cost in a life cycle perspective at the ship level. The transport conditions input derives from the Panamax tanker case study which has been conducted in previous work within this Task.

Various research projects have made assessments of external costs for transport. The literature survey allocated projects having external cost estimations in particular for air emissions. The list of these projects is as follows: ExternE, NEEDS, UNITE, CAFE, HEATCO, RECODIT, and GRACE (Bickel and Friedrich, 2005), (Holland et al., 2005), (Nash et al., 2008), (EC-JRC, 2009).

Estimations on the external cost of transport activities in the above studies are significantly diverse making comparisons difficult. This diversity is mainly attributed to the variations in model assumptions, cost categories, emission factors and unit values adopted.

10.8.2 External cost of transport

Many transport activities result in external cost creation (either positive or negative). The usual categories of negative external cost from transport activities are the following (JRC, 2008):

1. Congestion cost
2. Accidents cost
3. Emissions to air
4. Noise effect

5. Effects on climate change

In another relevant study, the externalities created by transport have additional categories to cover the amount of land captured for the development of transport infrastructure (Maibach et al., 2008).

For the transport sector, there is prevailing direction inside EU that instantly promotes strategies and measures for the internalisation of external cost. In the official policy of the EU (EU, 2008) it is considered that there should be a different pricing enforcement to the various categories of external costs from transport to address the locality phenomena and the fluctuations in relation to the use of transport systems and infrastructures. This is more relevant for the road transport sector and it happens for example in the case of congestion. However, it may be also applicable to other forms of external cost, as for example for the effects of air pollution, noise and accidents, which have a strong local dimension and may vary with time, place and transport network. The locality parameter in the external cost caused by maritime transport will be further elaborated in the next section.

On the contrary, for the climate change effects of transport it is widely accepted that the time and place the greenhouse gas emissions occur are not important parameters. Therefore, it is considered that differentiated cost figures are not necessary; however, there is a general trend to introduce in all transport sectors, market mechanisms directly connected with the consumption of fuels such as taxation on fuel or even a market system for CO2 emissions (EU, 2008) in order to attain the objective of internalizing the external cost of climate change from transport activities.

Overall, the benefits from the internalization of external cost can be the following (van Essen et al., 2007):

1. Improve transport overall efficiency
2. Ensuring the equity between different transport modes (through fair pricing and accessible transport activities),
3. Enhanced safety and security in the movements of people and goods,
4. Reduce the environmental impact of transport.

Illustrated example of a fair strategy for the internalization of external cost is “the polluter pays” principle, which is integrated in the transport regime of the majority of the developed countries. This principle applies traditionally to international shipping as well. An administration has in general three different options to limit the external cost of transport:

1. Command-and-control regulations: The administration sets emissions limits, or regulate specific measures for the handling of wastes and garbage.
2. Pricing methods: Includes taxes for the produced quantities of transport emissions and wastes, fees for the use of infrastructure etc.
3. Cap-and-trade. Financial measures permitting the exchange of emission rights within the transport sector, between different transport sectors or between countries.

10.8.3 External cost of climate change

The uncertainty over the valuation of the external costs of climate change, due to the greenhouse gases, is very large. The Intergovernmental Panel on Climate Change (IPCC) does not suggest any particular range of values for the marginal damage of CO_2 emissions on climate change. The IPCC emphasizes that estimates of the social costs of climate change have a wide range of uncertainty because of the limited knowledge of impacts, uncertain future of technological and socio-economic developments, and the possibility of catastrophic events or surprises (Denisis, 2009).

Two different ways of assessing the climate change external cost exist; the first is based on the avoidance cost of CO2, and the second on the damage cost of CO_2. A very large variety of costs values exists between these two options and inside each option as well. A broad overview of avoidance and damage cost estimates is presented in the IMPACT study (Maibach et al., 2008). For example, this study estimates that the damage cost of climate change for the year 2030, is expected to be between 20 and 100 Euros/ton CO_2 eq.

Denisis (2009), in his PhD thesis collected data which reveal that the CO_2 external cost range (using year 2009 as basis) may be between 5 and 135 Euros/ton as shown in the following figure.

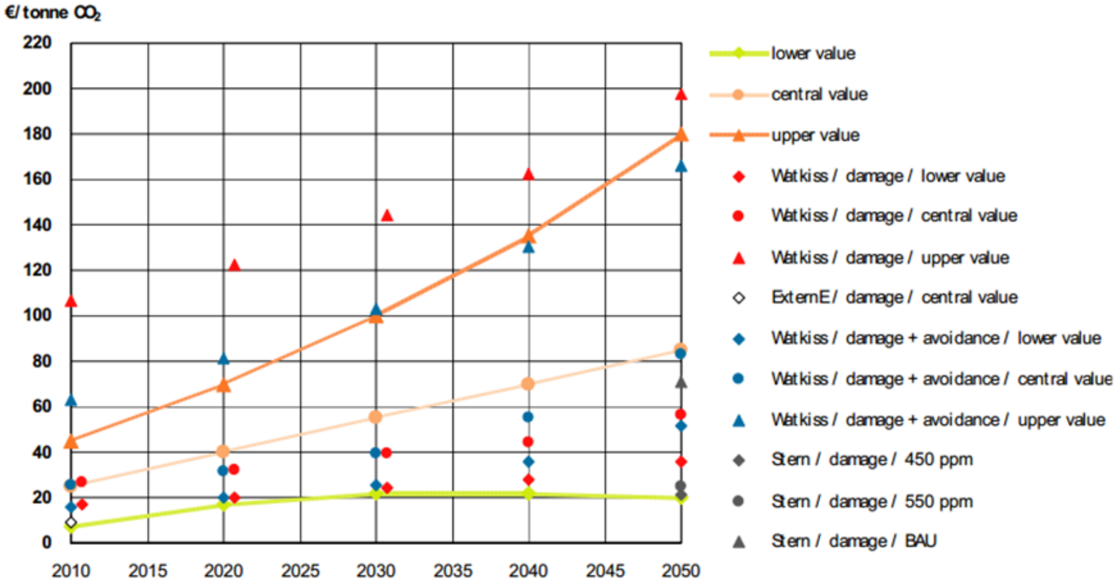
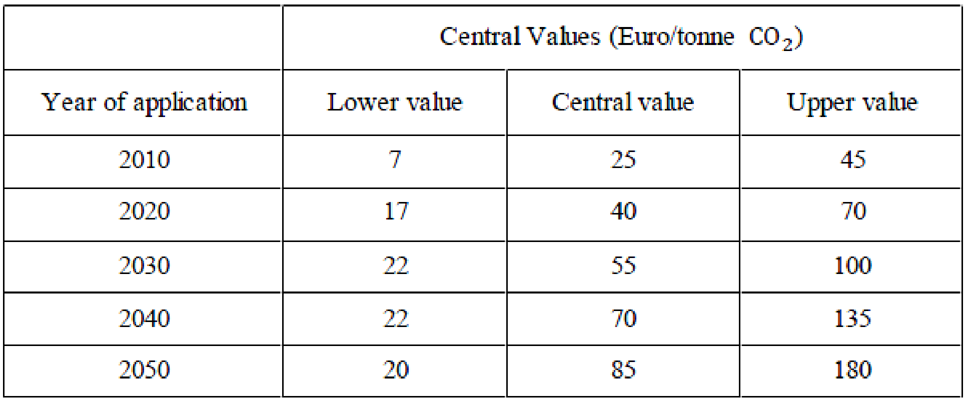


Figure 83: CO2 external cot range (Denisis, 2009)

In the updated study for 2008 on the external cost of transport in EU (Van Essen et al., 2011), the authors prefer to use avoidance cost rather than damage cost, for measuring the external cost of climate change. Damage cost is preferred only as an upper bound in case its value is higher than the avoidance cost value for the same period. It is noted that all the aforementioned cost estimations are for the EU transport sector in general.

For reasons of consistency (since in the context of LCA the impact is measured in damage), the damage approach is preferred for the calculations of climate change external cost. Nevertheless, it would be misleading for the present work to select only one value for the cost of climate change of maritime transport. Maibach et al, (2008) have reviewed studies of external costs for EU transport modes and presented suggested values of external costs of climate change for maritime transport in EU. These have been used for the calculations of climate change costs in the case study of the Panamax tanker.

Table 54: Maritime Transport external costs distribution in EU waters (Sieber & Kummer, 2008)



	Central Values (Euro/tonne CO_2)		
Year of application	Lower value	Central value	Upper value
2010	7	25	45
2020	17	40	70
2030	22	55	100
2040	22	70	135
2050	20	85	180

10.8.4 External cost of air pollution

Health and environmental impacts of air pollutants are very dependent in the proximity of the emission source to the receptors. It is expected that, at least a portion of ship emissions have lower health and environmental impacts since they are released sometimes far from populated areas or sensitive ecosystems. Moreover, the mechanisms of emission spreading sometimes are different in the marine environment. For example, NOx emissions from shipping are transported much less efficiently upward than road traffic emissions because there is much less convection over the oceans than over land.

However, in port cities ship emissions are in many cases a dominant source of urban pollution and need to be addressed, especially with respect to specific emissions such as particulate matter (PM). Furthermore, the emissions from ships can be transported in the air and thus can cause environmental and health problems in areas very far away from the emission source. This pathway is especially relevant for the NOx and SOx emissions (Cofala et al., 2007).

Following what has been done in other modes of transport to monetize the external impacts of maritime transport (with reference to air pollutants) through a bottom-up approach, the following tasks should be carried out:

- estimation of ship emissions;
- estimation of ships contribution to pollutant concentration;
- estimation of exposure of receptors;
- application of dose-response functions to determine various impacts;
- monetization of these impacts.

Best available external cost factors originate from the projects CAFE (Holland et al., 2005) and HEATCO (Bickel et al., 2006) both based on the IPA methodology (Maibach et al., 2008). In CAFE, damage values of NOx και SO_2 are provided in country level. For particulates damage values the model created within the project HEATCO delivers better results. An illustrated selection from the aforementioned studies has been made by Kronbak (2012) for the estimation of damages in different ship operations (i.e. at berth and on route). This study has used a mix of damage costs derived from the aforementioned studies which is shown in the table below.

Table 55: Selected cost factors of air pollutants in EU for year 2010 (reproduced from Maibach et al., 2008)

	Damage cost factors in 2010 prices (Euro/ton)				
Pollutant	***NOx***	***SO2***	***Particulate Matter***		
Source of data	***CAFE***	***CAFÉ***	***HEATCO***	***HEATCO***	***HEATCO***
Local environment			***Metropolitan***	***Urban***	***Country***
Greece	1,090	19,083	338,992	109,181	47,707
France	9,235	9,595	470,377	151,475	94,027
Germany	10,586	12,130	423,985	136,734	82,702
Norway	2,457	3,071	447,890	122,348	43,545
Italy	7,117	7,617	464,004	149,965	84,410
UK	4,949	8,376	493,784	159,001	77,031
Euro area	5,290	6,733			31,260
Baltic Sea	3,126	4,448			14,428
Mediterranean Sea	601	2,405			6,733
North East Atlantic	1,924	2,645			5,771
North Sea	6,132	8,296			33,664

After the conclusion of the analysis in the context of this thesis in 2014, an update of the study for the external cost of transport in Europe was published by DG-MOVE (Update of the Handbook on External Costs of Transport). The revised values for external cost of maritime transport are reported in Appendix 3.

10.8.1 External cost methodologies

Although there exist many uncertainties in the valuation of external cost, there is a wide consensus on the major methodological issues. For air pollution costs, the impact pathway approach is broadly acknowledged as the preferred methodology. Moreover, the health cost estimates from air pollution are based on the willingness to pay concept (DG Move, 2014). For the GHGs which mainly call for long-term reduction targets, the abatement cost approach (in contrast to the damage cost approach used for other environmental impacts) is the best practice for estimating climate cost. There exist other external costs, e.g. costs related to the dependence in energy, which however lack from scientific consensus and as such they are difficult to evaluate (DG Move, 2014).

Impact Pathway Approach (IPA), was developed in the context of EC research projects in the decade 2000 – 2010 and is suitable for the calculation of the external cost of air emissions. (Denisis, 2009). IPA follows the emissions pathway from the emission source to the areas, and measures impacts to people, ecosystems and infrastructure (Bickel and Friedrich, 2005). The steps of the method are as follows:

1. Estimation of emissions quantity at source (Burden)
2. Estimation of the dispersion of air pollutants (Dispersion) around the source including a possible chemical transformation in the environment. For the

spreading of emissions, there are various models that can be used. However the IPA used the following two models:

   b. Gauss dispersion models for range between 50 - 100 km
   c. Lagrange dispersion models for greater distances, which take into account chemical reactions between pollutants.

3. (Exposure). The result illustrates the extent to which the population at risk is exposed to the imposed emissions.
4. (Impact) Estimation of natural impacts to the recipient using dose response functions originating from epidemiology studies
5. Monetary valuation with translation of the natural impact to its monetary equivalent (Damage):
   a. For market goods by following market values
   b. For non-market goods (π.χ. human health) by using impact assessment techniques

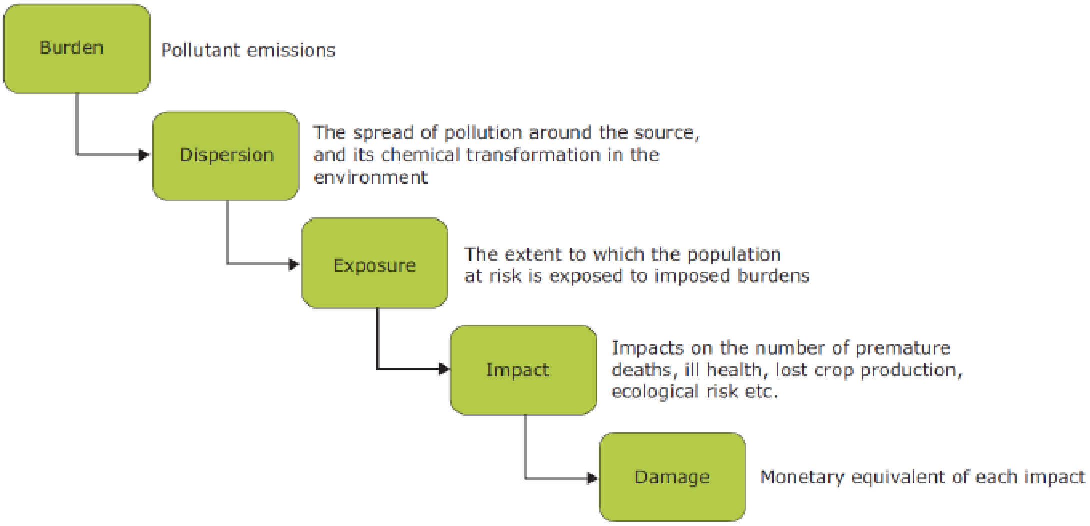


Figure 84: The steps of Impact Pathway Analysis (source: (EEA, 2011)

For example, let the objective be the calculation of the external cost of NOx emissions from a power plant. Then the steps of the IPA could evolve as follows:

1. Source: Determination of emissions from the activity. Calculation of NOx emission quantities per GWh of produced energy, from the specific power plant.
2. Dispersion: Apply dispersion models to determine the ozone formation from NOx.
3. Exposure: Estimate the population under risk.
4. Dose-Response Function: Determine the natural impact from the increase in concentration of NOx and the formation of ozone using conversion models (e.g. number of asthma cases due to the ozone increase in the atmosphere in the broader area).

5. Monetary Valuation: Calculation of the overall cost from the natural impacts estimated in the previous step (e.g. multiplying the cost of one asthma case by the total number of asthma cases).

IPA is more effective when the emission source is stable (i.e. a power plant). However, the calculation in the source is not always possible for the case of a moving emission source (i.e. the ship) and inevitably, some assumptions may be considered.

10.8.2 Literature on Maritime Transport External Cost

In a top-down study for the external cost of maritime transport in Europe carried out on behalf of the EC the following three main external cost factors have been considered (Trasporti e Territorio Srl, TRT, 2007):

- marine pollution (discharges into the sea);
- air quality (atmospheric emissions);
- climate change (greenhouse gases).

Costs of climate change have been calculated by applying an average value of 75 €/tonne CO_2 (in line with the Stern Review, 2006). For other air emissions the costs have been calculated using the model of project CAFÉ (Holland et al., 2005).

The study concluded that the external costs, in year 2006, amount to EUR 260 billion for the world fleet and EUR 57 billion (22%) for the EU fleet. The study has also calculated the cost of illegal activities related to oil spills in EU. Adding to these costs the ones due to illegal oil spills worldwide, whose cost estimates are about EUR 39 billion (13% of the total external costs), gives an overall external cost of EUR 299 billion for the world fleet. This estimate does not include the external costs of resources consumptions, solid (garbage) and liquid (sludge) waste, for which monetary valuations are not available. The complete external costs 'bill' to world citizens and environmental resources due to maritime transport is about EUR 300 billion per year (2006), 21% of which is from the EU fleet (64 billion). The figure below shows the external cost of the EU ocean-going fleet, divided by ship type and cost category (Trasporti e Territorio Srl, TRT, 2007).

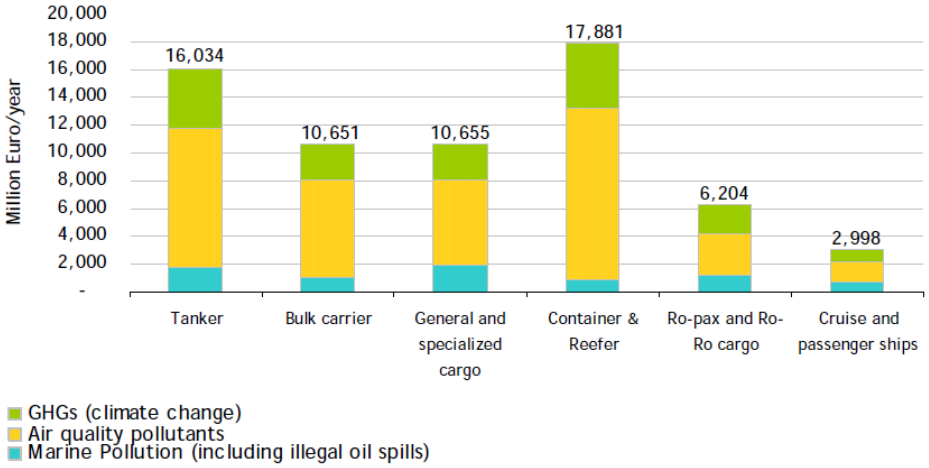


Figure 85: Total external costs for the year 2006, EU ocean-going fleet by ship and cost category (Including illegal oil spills) (Trasporti e Territorio Srl, TRT, 2007)

Sieber & Kummer (2008) calculated the external cost of maritime transport emissions (CO2, PM2.5, NOx, SOx) in EU at 19.6 billion Euros/year and the marine pollution external costs at 24 billion Euros/year. They use information on cost estimation techniques from the projects ExternE και UNITE. The following average values have been used in this study:

- Cost of 1 ton of marine pollution: 24,000 Euros
- Cost of 1 ton CO_2: 22 Euros

The costs of airborne emissions in European waters have been assessed with application of the Impact Pathway Approach (IPA) method. This method has been developed in the ExternE project series and is acknowledged as the best bottom-up methodology in this respect (Van Essen et al., 2007), (Maibach et al., 2008). The essential feature of this approach is the modelling of the path from air pollutant emissions to impacts on receptors (e.g. human, nature, material and crops) and the final expression of these effects in monetary units (Bickel and Friedrich, 2005).

Sieber & Kummer (2008) provided maritime transport external costs results distributed around Europe. According to the authors, 44% of the costs occur in the Mediterranean and 33% in the North Sea. The share per pollutant ranges between 21% for CO_2 and 29% for $PM_{2.5}$.

Vanherle and Delhaye (2010) assessed the maritime transport externalities by considering three main impact areas: marine pollution into the sea, air quality and climate change. Interesting result of this study is the remarkable difference of external cost between bulk transport (about 0.3 cent Euro/t-km), container transport (0.5 cent Euro/t-km) and the Ro-Ro transport (3.2 cent Euro/t-km).

Another study has used the top-down approach for the estimation of external cost of international and domestic maritime transport in Greece (cost of CO_2, NOx, SO_2, PM) at the period between 1984 – 2008. The study has used fuel-based data for the Greek coastal shipping sector and activity based data for the international shipping (Tzannatos, 2010). The same author has estimated in another study the external cost of emissions in the port of Piraeus (Tzannatos, 2010b).

Denisis (2009) in his PhD thesis justifies the superiority of intermodal short sea shipping in terms of lower external costs compared to the all-truck transportation. In addition, he argues that traditional top-down or bottom-up methodologies reveal the vagueness, imprecision, and subjectivity in the valuation of environmental externalities. He suggested a fuzzy logic model to solve the problem, which can be handled in a rigorous but also simply way. This thesis contributes to the literature by providing a precise and site-specific estimation.

Another study (Lee et al., 2010) explored the external costs of domestic container transportation in Taiwan with respect to the air pollution and climate change impact categories. The study provides a good comparison between truck and short-sea shipping (SSS), and found that the external costs of SSS are considerable lower than for truck transport. The emission amount (air pollutants and GHG) is calculated by taking a comprehensive consideration of transport activity intensity and emission factors.

For the case of shipping, air pollution is the external cost driver creating considerable impacts to human health and the environment (ExternE, 2005). Since there is no consensus yet, on the figures of external cost created by emissions contributing to climate change, this study is not dealing with climate change external costs.

Various studies in the literature have made estimations of the external cost of ship emissions. ExternE (2005), estimated the external cost of air pollution from shipping in the port of Venice at 24 million Euros. Friedrich and Bickel (2001) estimated the external cost of inland shipping for Netherlands and found at 321 million Euros and the cost in euro per 100 vkm due to airborne emissions of container ships on different routes: In Piraeus 9300 €/vkm, in Iraklio 900 €/vkm, in the Aegean Sea 1000 €/vkm, in the trip Felixstowe–Rotterdam 1200 €/vkm and in the trip Rotterdam–Felixstowe 1050 €/vkm. CAFÉ project series (2005), calculated for the European Seas the external cost of air pollution from maritime transport at 45 billion euro.

Maffii et al. (2007) estimated the total external costs of air pollution for 2006 for the EU ocean-going fleet and the world fleet and found them to be 40 billion euro and 184 billion euro respectively.

In external cost estimations for a specific case of a container ship sailing between Rotterdam and Gothenburg, Lee et al. (2010) found that the round trip would create 399,498 euro of air pollution external costs. Nash et al. (2008) calculated the air pollution costs of inland water transport for two selected trajectories on the Rhine and the Danube and found that environmental costs range between 0.17 and 0.41 cent per tonne and kilometre (tkm). For the inland waterway transport from Basel to Rotterdam, Schmid et al. (2001) estimated for a vessel carrying 200 TEU the external costs of air pollution depending the upstream–downstream shipping and the results are for air pollution downstream:18.54 €/LU (loading unit), upstream: 4.95 €/LU.

Gallagher (2005) analysed the total emissions and the economic costs of shipping emissions in the United States from 1993 to 2001 and found that the economic costs of SOx pollution range from $697 million to $3.9 billion and the costs from NOx emissions are $3.7 billion. Berechman and Tseng (2012) estimated the costs of key exhaust pollutants from shipping in the port of Kaohsiung in Taiwan at 119 million $.

11. IMPACT ASSESSMENT CASE STUDIES

Summary

This chapter presents four case studies conducted for assessing the environmental impact ships.

The details and specific features of these case studies are shown in the following table.

Case Study	Scope	Sample ship	Specific features
No1	a. Impact in the context of LCA b. Impact using the external cost approach	Panamax Oil Tanker	Adapt Eco Indicator 99 technique for ship emissions impacts External cost range of CO2
No2	Assessment in the context of LCA, using the LCIA Tool	Cement carrier	The Recipe 2008 damage model is used Scrubbers and MDO solutions are assessed in LCIA
No3	Assessment in the context of LCA, using the LCIA Tool	Passenger ship	The Recipe 2008 damage model is used
No4	Assessment in the context of LCA, using the LCIA Tool	Containership	The Recipe 2008 damage model is used Impact per life cycle stage

Acknowledgments

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2. Part of the work included in this chapter was conducted in the context of the research project "EnviShipping: Environmental Footprint of Ships from a Life Cycle Perspective", a multi – partner project funded by the General Secretariat of Research and Technology.

Publications related to this Chapter

1. **Chatzinikolaou, S. and Ventikos, N.P., (2014) "** Assessing Environmental Impacts of Ships from a Life Cycle Perspective", In Proceedings of the 2^{nd} International Conference on Maritime Technology and Engineering , MARTECH 2014, 15-17 Oct 2014, Lisbon Portugal.

2. **Chatzinikolaou S.D., Ventikos N.P. (2013), "**Lifecycle Impact Analysis for Ships", Proceedings of the 2013 Annual Meeting of the Hellenic Institute of Marine Technology: The Book of Marine Technology, Piraeus, Greece, pp. 71-82

11.1 Case Study 1: Impact Assessment of air emissions from a Panamax tanker

Utilizing the developed LCI of the hull subsystem of the Panamax tanker (see par. 6.2 Case study 1) an impact assessment has been conducted with the application of the Eco-Indicator 99 damage assessment method. Illustrative results of these calculations are presented in this paragraph.

The inventory of this study includes information on the following air emissions: CO_2, CH_4, SOx, NOx, PM, VOCs, NMVOC, and CO). The allocation of emissions to midpoint impact categories follows the damage model of Eco-Indicator 99, which is a widely used impact assessment method in the context of LCA. According to this model, CH_4 is an important GHG and its impact pathway matches with the pathway of CO_2. NMVOCs are non-methane volatile compounds that are treated in the same manner as the VOCs in the Eco-Indicator 99. The land use and land conservation impacts have no relevant input. Although it is acknowledged that using non-renewable resources (steel, fuels) during the ship's life cycle might have an important contribution to the environmental impact this is not considered in this particular impact assessment scenario.

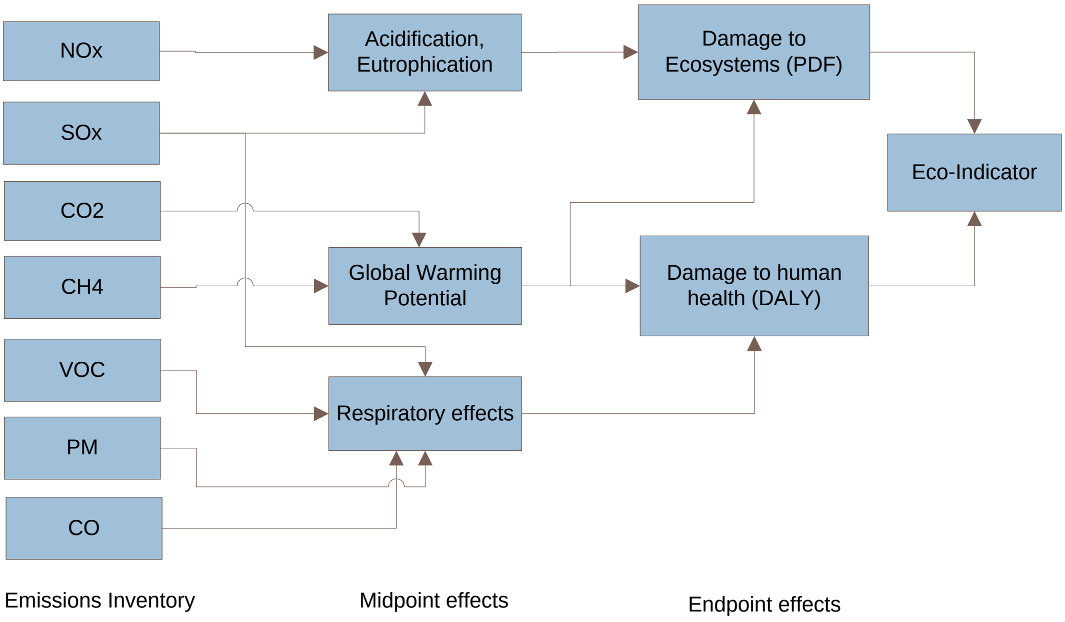

Figure 86: Damage model for the Life Cycle Impact Assessment of ship emissions

The inventory provides information for the emissions produced per process, subsystem (hull, machinery) and life cycle stage.

The following table presents the inventory of emissions for the hull subsystem of the examined ship. The hull subsystem has been selected because it reflects industrial processes near populated areas, which matches with the impact assessment in the framework of LCA.

Table 56: Hull subsystem of the Panamax tanker–Life cycle emissions inventory

Emissions	Shipbuilding	Operation	Maintenance	Dismantling	TOTAL	
CO2	2571.40	-	7966.33	4031.81	14569.53	tons
CO	44.94	-	74.75	378.94	498.63	tons
CH4	0.46	-	1.34	1.03	2.83	tons
NOx	22.70	-	111.58	52.16	186.44	tons
PM (all)	2.64	-	3.99	11.06	17.69	tons
SO2	19.28	-	92.20	62.74	174.23	tons
SOx	3.50	-	5.48	3.74	12.72	tons
VOC	19.84	-	77.62	0.15	97.62	tons
NMVOC	0.18	-	0.31	0.13	0.62	tons

11.1.1 Impact calculations within the LCA context

The example of air emissions impact assessment considers only the emissions of the hull subsystem inventory. These emissions occur at shipbuilding, ship repair and recycling yards; therefore, it can be assumed that they are similar to emissions of industrial land based sites for which the available LCIA techniques such as the Eco-Indicator 99 have been developed. The impact of air emissions produced during the operational phase of the ship's life cannot be assessed by any LCIA technique in their present form. For example, the contribution of air pollutants of ships such as NOx and SOx to the acidification is not comparable to the impact from land based air pollutants. Currently, in the context of LCA there is no available damage model to cover the environmental impact of ship air pollutants (NOx, SOx, PM, VOC). This is in fact an area where future research should focus on. The development of LCA damage models explicitly for the case of maritime transportation would allow incorporating the emissions occurring away from land (in open sea) to the impact assessment procedure.

The emissions are first allocated to midpoint impact categories according to the damage model presented in Figure 86, and then the characterization calculations are performed to arrive at the Impact Score (IS). Table 57 summarizes the results of the impact assessment of the ship hull subsystem. Normalisation and final weighting to a single score has been also performed.

Table 57: Impact of GHG using the Eco-Indicator 99

CLIMATE CHANGE (human health)					
	Inventory	**units**	**CF**	**IS**	**units**
CO2	2.64E+07	kg	4.00E-07	1.06E+01	DALY
CH4	4.77E+03	kg	8.00E-06	3.81E-02	DALY
			TOTAL	1.06E+01	DALY

The results reveal that the climate change impact of the emissions produced by the hull subsystem during the life cycle of the ship equals to 10.6 years of years of human life lost. This figure aggregated with the impact of respiratory effects presents the total impact on human life of the hull subsystem over the twenty five years of ship life which is 58.7 years of human life lost.

Table 58: Impact of air pollutants using the Eco-Indicator 99

RESPIRATORY INORGANICS						
	Inventory	units	CF		IS	units
CO	8.78E+05	kg	7.31E-07		6.42E-01	DALY
NOX	2.56E+05	kg	8.91E-05		2.28E+01	DALY
PM(all)	2.87E+04	kg	3.75E-04		1.08E+01	DALY
SO2	2.37E+05	kg	5.46E-05		1.29E+01	DALY
SOX	1.65E+04	kg	5.46E-05		8.99E-01	DALY
				TOTAL	4.81E+01	DALY
RESPIRATORY ORGANICS						
	Inventory	units	CF		IS	units
CH4	4.77E+03	kg	1.28E-08		6.10E-05	DALY
VOC	9.78E+04	kg	6.46E-07		6.32E-02	DALY
NMVOC	7.54E+02	kg	1.28E-06		9.65E-04	DALY
				TOTAL	6.42E-02	DALY

The optional step of normalization and final weighting, between the three areas of protection (damage categories) has been also performed and the outcome is given in the following table. The impact in the category of land use reflects the extra energy for future mining of iron, which is assumed equal to the quantity needed for the steel of the ship.

It is obvious that these two steps share the largest uncertainty due to the limited knowledge of the contribution and relative importance of the impact categories. The single score however, allows the aggregation of different effects making the results of the LCA study more understandable to decision makers (EC-JRC, 2011).

Table 59: Impact in Single Score using the Eco-Indicator 99

Damage Categories	*IS results*	*units*	*Normalization factor*	*Normalization result*	*Weighting Factor*	*Single Score*
Human Health	5.41E+01	DALY	6.51E+01	3.52E+03	400	1.54E+06
Ecosystem Quality	1.73E+06	PDF×m^2/yr	1.95E-04	3.37E+02	400	
Land Use	435662.6	Mjsurplus	1.19E-04	5.18E+01	200	

Considering that according to the Eco-Indicator 99 method, one point (1Pt) corresponds to the 1/1000 of the yearly environmental load caused by the average European inhabitant the result can be translated as follows: the impact of emissions produced by the ship hull during a twenty five years of life cycle, is of equal magnitude to the impact produced by a small European town of 1540 inhabitants in one year.

Another interesting result is that the hull subsystem’s impact is distributed in the three life cycle phases of this subsystem. Shipbuilding is responsible for 40 percent of the total; maintenance and recycling phases are responsible for 35 and 25 percent respectively.

11.1.2 Impact calculations using the external costs framework

Cost factors have been allocated for GHG emissions (CO_2 eq.), and air pollutants (SO_2, NOx, PM). The inventory of emissions produced in previous work within this task has been used as input. The external costs have been calculated for different countries and geographical areas around Europe for which cost factors were available. The results of external costs have large variations demonstrating the difficulties and uncertainty in such estimations.

The first case study examined in this respect is the hull subsystem of the Panamax oil tanker. The life cycle external costs of this system greatly differ subject to the country or the region these costs are calculated for. Lower overall external costs derived for countries such as Norway, where some internalization measures have been adopted recently (i.e. ECA areas).

There is a great difference of external cost distribution per emissions type from country to country. For example, the NOx emissions in Greece have a very low cost factor (for reasons unknown to the authors) which consequently offers a small contribution of this emission type to the country's total result. This is not the case for other countries (e.g. France, Germany) for which the external cost of NOx emissions has significant contribution to the country's result. The cost of PM emissions has smaller variations among the countries examined. However, PM impacts are extremely proportional to the proximity of the emission source to the people affected. To some extent, this is covered in the present calculations using the information provided by Maibach et al. (2008).

The results per country are given in the figure below. The life cycle external cost of the hull sub-system for the Panamax tanker (75,000 tonnes of dwt) case study may be from 4 million Euros (using cost values for Norway) up to approximately 10 million Euros (using cost values for Germany).

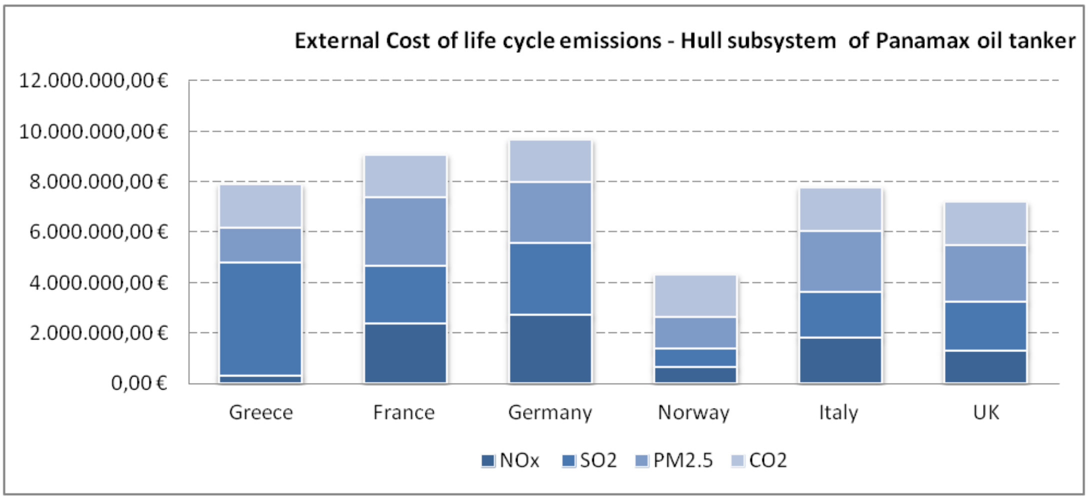

Figure 87: Life cycle external cost in different EU countries– Hull subsystem of Panamax oil tanker

Variations are also recorded in the calculations of external costs for different areas around Europe. The higher external costs are shown in North Sea (6.2 million Euros) and the lower in Mediterranean Sea (2.6 million Euros). The external cost of the life cycle emissions of the hull subsystem of the Panamax oil tanker in the Euro area (for which a separate cost factor was available) has been estimated at 5.5 million Euros.

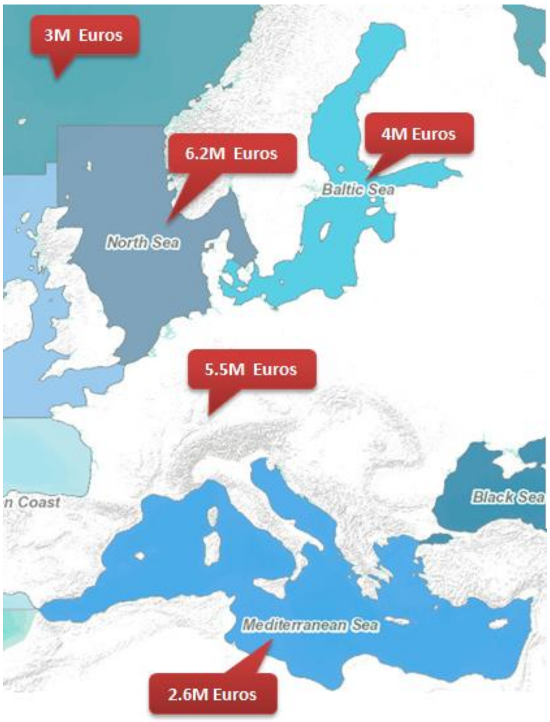

Figure 88: External cost of CO2 in different areas around EU – Hull subsystem of Panamax oil tanker

The external cost of CO_2 for the ship of the case study has been calculated per year of the life cycle using cost factors for Europe derived from previous studies. The results illustrate the wide range of uncertainty existing in the estimation of such costs. This is due to the limited knowledge of impacts and uncertain future of technological or socio-economic developments and other events that may significantly alter the magnitude of these costs.

The total cost of CO_2 over the life cycle of the ship ranges between 16 – 65 million Euros. It is noted that this is the result for the whole ship system (hull and machinery life cycle emissions are included). A rational approximation (using medium cost factors) is that the external cost per year has the trend to double over the years of the ship's life from one million Euros (in year one) to over two million Euros (in year twenty-five).

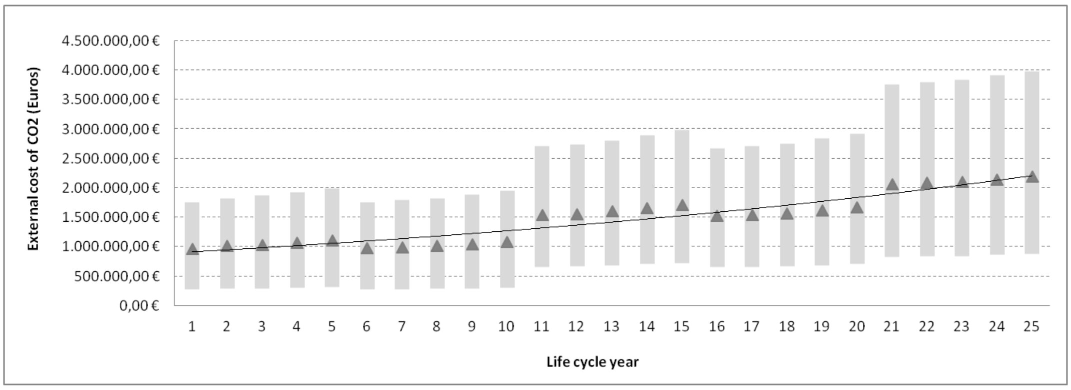

Figure 89: External (damage) cost of CO_2 per life cycle year of a Panamax type oil tanker

11.1.3 Conclusions

This study has elaborated the following two separate approaches for the impact assessment of ship emissions in a life cycle perspective:

The first approach is the Life Cycle Impact Assessment (LCIA), a standardized method through the ISO framework for LCA. This approach does not make use of monetary values and has specific units for the measurement of impacts.

The second approach evaluates the impacts in terms of monetary values utilising the concept of external costs.

Both approaches have been tested against scenarios originated from the Panamax tanker life cycle (for which emissions inventories are available from previous work (Chapter 6) and illustrative results are presented and discussed in this report. The most illustrative findings of the first approach (impact assessment of ship emissions in the framework of LCA) are the following.

- The LCA framework provides a rational approach for modelling the pathway from the emission to the final impact.
- The normalisation and weighing steps illustrate the greater uncertainties because they entail selection of factors which are generic and subjective.
- The hull sub system of the examined ship (Panamax tanker) has relative low life cycle impact which is equal to the impact produced in one year by 1540 EU inhabitants.
- Shipbuilding is responsible for 40 percent of the total impact of the hull subsystem; maintenance and recycling phases are responsible for 35 and 25 percent respectively.

The main findings from the application of the second approach, which assesses emissions impact with the external cost approach, are the following:

- Great uncertainty and a large variation in available cost factors exist for the external cost of greenhouse gases.
- A conservative selection of cost factors ends up with a yearly external cost of CO_2 which is expected to double over the years of the ship's life cycle; from one million Euros (in year one) to over two million Euros (in year twenty five).
- Significant external cost is attributed to air pollutants due to the impact of these emissions on human health. Variations exist in the calculations of external cost for different countries and regional areas around Europe.

In conclusion, it is without any doubt that the assessment of shipping impacts in a life cycle perspective can be a useful tool for ship designers, ship operators and policy makers who are working towards the improvement of the environmental footprint of maritime activities.

11.2 Case Study 2: Life Cycle Impact Assessment of Cement Carrier

With the help of Recipe 2008 damage model, a full LCIA study is applied to the cement carrier with the following particulars.

Table 60: Main particulars of the cement carrier LCIA study

Main Particulars – Cement Carrier		
Gross Tonnage. GT	tons	4940
Deadweight. DWT	tons	6000
Steel weight	tons	3043
Length overall. Loa	m	112
Length between perpendiculars. Lbp	m	106.80
Breadth. B	m	16.30
Depth. D	m	8.70
Maximum Draft. Tmax	m	6.62

Machinery – Cement Carrier		
Main engine		Wartsila Finland Oy 9L20
Auxiliary engines		Wartsila Finland Oy 4L20
Installed power ME	kW	2X1620
Installed power AE	kW	648
SFOC ME	kg/kWh	190
SFOC AE	kg/kWh	194
ME fuel		Residual fuel oil 2.7%S
AE fuel		Marine diesel oil 0.7%S

Operational data – Cement Carrier		
Trips pattern	Round trips / year	50
Port calls	Calls / round trip	2-3
Crew and passengers	persons	16
Life cycle	years	25
Distance covered	nm/round trip	1000
Average speed	knots	11
Duration of round trip	hours/round trip	120
Manoeuvring time	hours/ round trip	2
Time at port	hours/ round trip	50

11.2.1 Reduction of the environmental impact

In this paragraph two alternative solutions for the reduction of Sulphur emissions are analysed with using the life cycle environmental impact tool:

- Solution 1 – Installation of a Wet scrubber unit
- Solution 2 – Use of Marine Diesel Oil with low sulphur content (0.1%).

To evaluate the overall environmental impact in the operational phase of the ship the following assumptions are taken:

- An increase of 1 – 5 percent in the energy demand due to the needs of the scrubber unit.
- The ship uses the scrubber unit at all times (100 percent use at port and at sea)
- The scrubber unit is capable of reducing the SOx by 95 percent and the PM by 80 percent.
- The parasitic loads from scrubber operation are covered by the auxiliary engines.

Results

The application of the two solutions is altering the operations part of the life cycle inventory. It is considered that the other life cycle stages are not considerably affected.

Table 61 presents part of the Life Cycle Inventory which corresponds to the air emissions (during the operational life of the ship). The table includes the emissions from a. the initial scenario of operation, b. the operation with using the scrubber solution, and c. the operation with using the MDO fuel solution.

Table 61: Life Cycle Impact Assessment of the cement carrier

Environmental phenomenon	Shipbuilding	Operation Maintenance	Recycling	Total
Marine eutrophication [kg P_{eq}]	1.23	96361.02	0.00	96362.25
Climate change [kg $CO2_{eq}$]	27823.62	151685394.37	550179.36	152263397.36
Ozone depletion [kg CFC 11_{eq}]	0.00	0.00	0.63	0.63
Terrestrial acidification [kg SO2 eq]	74.40	3608348.73	0.00	3608423.12
Photochemical oxidant formation [kg $NMVOC_{eq}$]	2400.58	2773432.65	0.00	2775833.22
Particulate matter formation [kg $PM10_{eq}$]	18.29	1275095.91	0.00	1275114.20
Freshwater ecotoxicity [kg 1.4 DB_{eq}]	0.00	0.00	0.00	0.00
Human toxicity [kg 1.4 DB_{eq}]	0.00	91447.30	10.14	91457.43
Marine ecotoxicity [kg 1.4 DB_{eq}]	0.00	504442.22	0.00	504442.22
Terrestrial ecotoxicity [kg 1.4 DB_{eq}]	0.00	0.00	0.00	0.00

Table 62: Emissions inventory (initial scenario – Scrubber solution – MDO fuel solution)

Emission	units	Initial	Scrubber	MDO
PM	kg	286545	62873	48743
CO_2	kg	149355423	151658514	153207144
CH_4	kg	2389	2425	2389
N_2O	kg	7587	7695	7168
NO_X	kg	2470725	2505896	2339682
CO	kg	119947	121750	119947
NMVOC	kg	111345	113019	111345
SO_2	kg	2224692	127727	124248

The new environmental footprint resulting from the application of the two solutions reveals that:

1. The SO_2 and PM emissions are drastically reduced with both solutions; however the scrubber solution has the largest reduction from the two alternatives
2. Due to the parasitic loads of the scrubber unit the fuel consumption in auxiliary engines is increased which increases the GHG emissions
3. The MDO solution is also increasing the GHG emissions (due to the higher emission factor of this fuel in comparison to the emission factor of the HFO).

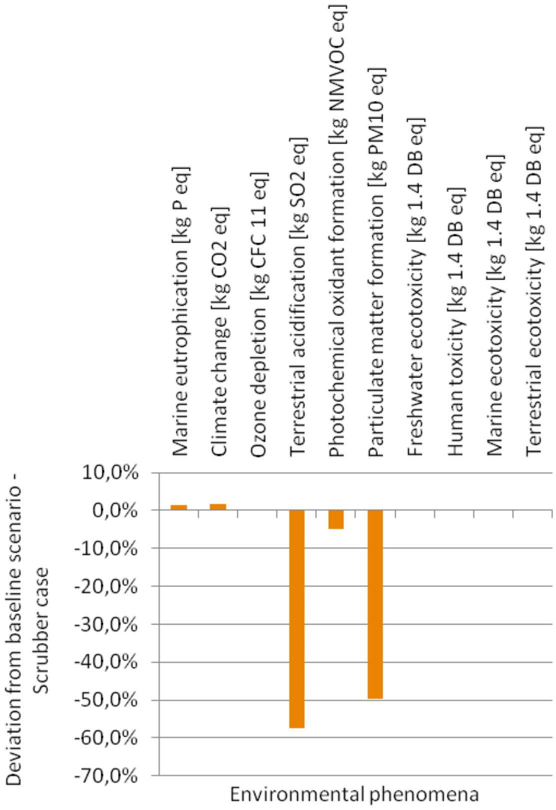

Figure 90: Scrubber - Environmental impact assessment

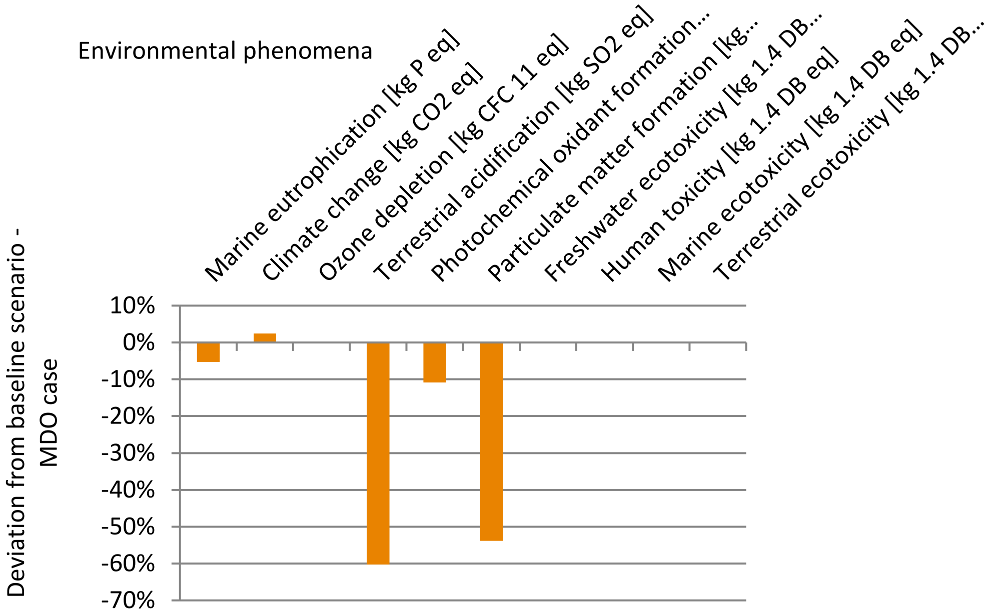

Figure 91: MDO – Environmental impact assessment

11.3 Case Study 3: Life Cycle Impact Assessment of a passenger ship

The ship is operating in a domestic coastal shipping line. Operations data as well as data for wastes production have been made available by the shipping company.

The objective of the case study is to extract the life cycle inventory of the ship and perform a life cycle impact assessment with the use of the LCIA Tool. The study took into account all waste streams (oil and non-oil liquid wastes, garbage) and air emissions, created throughout the life cycle of the ship. Data have been available also for the ship port interface.

The improvement of the environmental footprint for this particular case study is not examined with the use of the life cycle impact assessment tool. In Chapter 7, this particular passenger ship is the case study ship of the comparative life cycle analysis of two fuel alternatives; namely the HFO and the LNG.

Table 63: LCIA case study – Passenger ship details

Main Particulars – RoPax Ship		
Year of built/major conversion		1996/2007
Shipbuilding country		Japan
Deadweight. DWT	tons	6174
Length overall. Loa	m	196
Breadth. B	m	27
Speed	knots	27.5
Passengers		1845
Vehicles		560

Table 64: LCIA case study – Passenger ship operating profile

Initial Scenario		
Ship type	Ro-Ro	
Fuel	Low sulphur HFO	
	value	unit
Speed	20.5	knots
Engine	34377	KW
Engine Load	85%	% MCR
DWT	6174	ton
Piraeus – Island X	206	nm
Duration	10.05	hr
Load Factor	0.9	
Pay Load	0.75	

The following table includes the results of the LCIA using the Recipe 2008 impact methodology. The results are presented per category of environmental damage and life cycle stage.

Table 65: Life Cycle Impact Analysis – Passenger Ship case study

Environmental phenomenon	Construction	Operation	Repair	Scrapping	Grand Total
Marine eutrophication [kg P eq]	1,23	97576,35	2,76	0	97580,34
Climate change [kg CO2 eq]	27823,62	151920084,9	9367,12	550179,36	152507455
Ozone depletion [kg CFC 11 eq]	0	0	0	0,6336	0,6336
Terrestrial acidification [kg SO2 eq]	74,39	1836883,48	51,23	0	1837009,11
Photochemical oxidant formation [kg NMVOC eq]	2400,57	2654727,90	5487,64	0	2662616,12
Particulate matter formation [kg PM10 eq]	18,29	959398,78	52,86	0	959469,94
Freshwater ecotoxicity [kg 1.4 DB eq]	0	1,12E-19	0	0	1,128E-19
Human toxicity [kg 1.4 DB eq]	0	91447,29	0	10,13	91457,43
Marine ecotoxicity [kg 1.4 DB eq]	0	504442,21	0	0	504442,21
Terrestrial ecotoxicity [kg 1.4 DB eq]	0	1,21E-18	0	0	1,21E-18

11.4 Case Study 4: Life Cycle Impact Assessment of a Containership

The initial scenario of operation for the containership case study is formulated with introducing, in the LCIA Tool, the input provided by the shipping company. This input can be found in Appendix 4.

Then the LCI of the initial scenario is developed which corresponds to the “business as usual” operating profile of the ship. This LCI can be also found in the Appendix xx.

The LCIA is then conducted using as input the LCI. The LCIA tool developed in the context of the EnviShipping project is used for that purpose.

11.4.1 Life Cycle Impact Assessment

The LCIA provide the impact assessment results per category of impact. The categories are those of Recipe 2008.

The results are available per life cycle stage and per process and can be comparatively presented in order to identify the process with the largest contribution in the damage categories.

The results the LCA tool per life cycle stage are presented in Appendix 4.

Here only the most illustrative of the results of the impact assessment are provided.

- The CO_2 emissions from the shipbuilding phase are 0.8 percent of those created during the operational phase. It is reminded that specific boundary conditions are foreseen in the LCIA Tool. Probably with altering these conditions the results in this life cycle stage would be different.
- It is obvious that the life cycle stage of operation produces the largest environmental impact. As the following figure shows the operation (red columns) has the main contribution nearly in all damage categories of the Recipe method.
- The GHGs are the main environmental driver in the operational phase. Of these the CO2 is the dominant one. For this specific containership and the given (by the shipping company) operational profile the calculated, by the method, CO_2 emissions are 0.134kg/TEU nm.

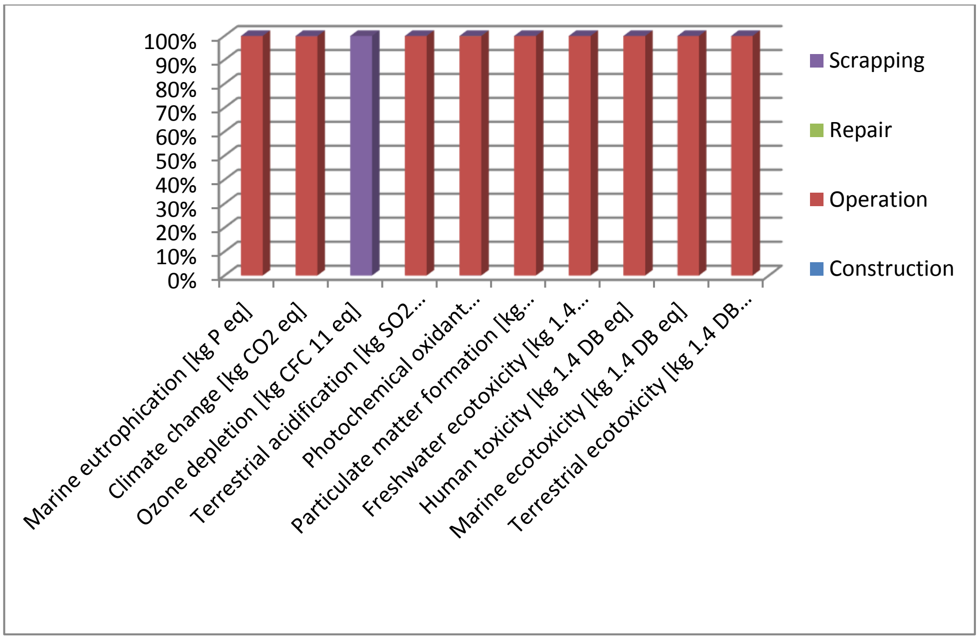

Figure 92: Contribution of life cycle stages in the categories of impact – Containership

Table 66: LCIA results per life cycle stage – Containership case study

Environmental Phenomenon	Shipbuilding	Operation	Maintenance	Scrapping	TOTAL
Marine eutrophication [kg P_{eq}]	8.96	2249533.68	14.71	0.00	2249557.34
Climate change [kg $CO2_{eq}$]	202369.70	2402297526.46	47534.83	2982465.36	2405529896.35
Ozone depletion [kg CFC 11_{eq}]	0.00	0.00	0.00	0.63	0.63
Terrestrial acidification [kg SO2 eq]	541.12	72377816.08	267.93	0.00	72378625.14
Photochemical oxidant formation [kg $NMVOC_{eq}$]	10890.54	63310270.01	46361.41	0.00	63367521.96
Particulate matter formation [kg $PM10_{eq}$]	133.03	25992709.27	282.42	0.00	25993124.73
Freshwater ecotoxicity [kg 1.4 DB_{eq}]	0.00	0.00	0.00	0.00	0.00
Human toxicity [kg 1.4 DB_{eq}]	0.00	1136275.35	0.00	10.14	1136285.49
Marine ecotoxicity [kg 1.4 DB_{eq}]	0.00	6267929.97		0.00	0.00
Terrestrial ecotoxicity [kg 1.4 DB_{eq}]	0.00	0.00		0.00	0.00

Two different options for improving the environmental impact of the initial scenario have been examined; namely slow steaming and use of alternative fuel (MDO with 0.1 sulphur content). The improved environmental impact outcome is presented below.

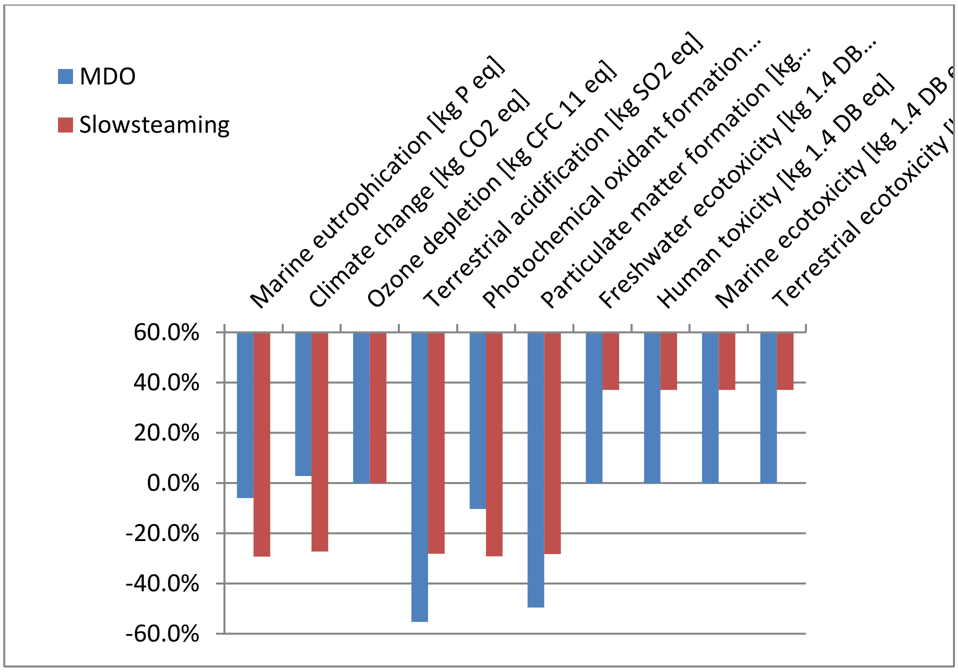

Figure 93: Containership case study – MDO and slow steaming environmental impact assessment

12. IMPACT OF SHIP EMISSIONS IN PORT AREAS

Summary

This chapter presents two case studies with assessments of the external cost (in human health) of passenger ships and cruise ships approaching the port of Piraeus.

For this assessment the Impact Pathway Assessment (IPA) methodology. Health cost from ships at port has been estimated at both local (greater Athens area) and regional level (entire territory of Greece). Results show that higher costs occur at the local level. The dominant pollutants creating this cost are particulate matter ($PM_{2.5}$, and PM_{10}). Overall, the results indicate that the health impact of ship port emissions in Piraeus is not negligible; however it is considerably lower than the corresponded cost deriving from other sectors (i.e. the road transport and the land based industries of the Athens regional area) for which comparisons are available.

Acknowledgments

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2. Part of the work included in this chapter has been carried out in the context of the research activities of the Centre of Excellence in Ship Total Energy-Emissions-Economy of the National Technical University of Athens, School of Naval Architecture and Marine Engineering. The Centre has received financial support by the Lloyds Register Foundation (LRF) which is gratefully acknowledged. LRF helps to protect life and property by supporting engineering.
3. Part of the work included in this chapter was conducted in the context of the research project “EnviShipping: Environmental Footprint of Ships from a Life Cycle Perspective”, a multi – partner project funded by the General Secretariat of Research and Technology.

Publications related to this Chapter

1. **Chatzinikolaou, S., Oikonomou, S., and Ventikos, N.P. (2015)** "Health Externalities of Ship Air Pollution at Port-Piraeus Port Case Study" in Transportation Research Part D: Transport and Environment, 40 (2015) 155–165.

12.1 Intro - Motivation

Air pollution has become a major threat to both human health and the environment. The World Health Organisation (WHO) considers the exposure to air pollution as the world’s largest single environmental health risk, causing 1 in 8 of total global deaths, or 7 million deaths in year 2012 (WHO, 2014). Maritime transport activities are contributors to air pollution problems especially with respect to the emissions resulting from the combustion process in marine engines (i.e. sulphur and nitrogen oxides and particulate matter). Hence, since the large portion of international ship traffic occurs not far from the coastline (Endresen et al., 2003) air pollution from ships can also have impacts on human health. There is evidence showing that particulate matter (PM) emissions from shipping are responsible for approximately 60,000 premature deaths annually (Corbett et al., 2007), most of them occurring near populated coastlines in East Asia, Europe and South Asia. In response, the International Maritime Organisation (IMO) has recently adopted specific regulations for reducing air pollution in specific areas around the world (the so called Emission Control Areas, ECA). European counties have also put in force specific measures for the reduction of ship air pollution in harbour areas.

It is important to note that currently air quality represents the first environmental priority in port areas. This is illustrated in the recently published ESPO / EcoPorts Port Environmental Review 2016 (ESPO, 2016). EcoPorts is a major environmental initiative of the European port sector which aims to create a level playing field on environment through cooperation and sharing of knowledge between ports. It was initiated by a number of proactive ports in 1997 and has been fully integrated into the European Sea Ports Organisation (ESPO) since 2011. ESPO and EcoPorts have been monitoring the top environmental priorities of the European port sector since back in 1996 through regular respective surveys. Air quality which was not included in the list of environmental priorities in port areas in the review of the year 1996 is pointed out as the current top environmental priority by the European port sector as a whole. This reflects the priority given to issues related to human health, especially the health of people working or living in the proximity of ports. This is also in line with the European political agenda as depicted in the EU Air Quality policy.

IMO recently published a study on emission control in port areas in which the importance of air pollution in the ship-port interface is highlighted (IMO, 2015). The study identified measures and practices that should be taken into consideration for reducing air emissions and improving overall energy efficiency inside the port area.

Air pollution constitutes one of the most significant environmental problems for Athens, the capital city of Greece, with its four million inhabitants and over 9000 industrial installations (Mirasgedis et al., 2008). Piraeus port is one of the most important installations in the Athens area, since it constitutes the largest port infrastructure of Greece and one of the busiest passenger ports in Europe. Piraeus port has multiple functions (bulk cargo, container, passenger and cruise terminals) and heavy sea traffic which has increased through the years owing mainly to an expansion of the containerships terminal but also to the continuous growth of cruise ship market in recent years and a non-declining need for coastal passenger transportation due to the unique landscape of the country with hundreds of islands in the Aegean Sea. Especially the passenger port facilities are very close to Piraeus city which is built-in the greater Athens area.

Figure 94: Top 10 environmental priorities of European ports for 2016 (ESPO, 2016)

12.2 Literature Review

Air emissions of shipping may be grouped, subject to their general impact, to: emissions causing air pollution and emissions contributing to the climate change phenomenon. The first category includes mainly emissions such as SO_x, NO_x, PM, CO and VOC whereas the second one includes the so-called greenhouse gases such as CO_2, HCFC, and CH_4 and others.

The focus of the work in this chapter is on the health impacts of ship air emissions. Ship emissions having human health impacts may be further categorized in primary and secondary pollutants. The primary pollutants are emissions that have immediate effects in the proximity of the emission source (local effects). Secondary pollutants derive when emissions are transformed during their distribution in the atmosphere to produce other pollutants. This transformation is subject to chemical reactions and may take place far away (some hundreds of kilometres) from the emission source.

12.2.1 Air Emissions with Health Impacts

Particulate Matter (PM)

Particulate Matter (PM) emissions represent the most significant source of health damage costs (Rabl A., 2001). PM has various type and components however they are usually divided in $PM_{2.5}$ and PM_{10} subject to the particle size (diameter). There is sufficient evidence that there exist a link between particle levels and hospital admissions and emergency room visits, even death from heart or lung diseases (Denissis, 2009). WHO (2013) concluded that "*the evidence for a causal link between PM2.5 and adverse health outcomes in humans have been confirmed and strengthened and, thus, clearly* *remain valid*". PM emissions are mostly primary pollutants and their impact on human health is experienced in the proximity of the source hence they have local impacts.

Nitrogen Oxides (NO_x)

Most nitrogen oxides (NOx) emitted in the form of NO which is rapidly oxidized in the atmosphere to NO_2 and then to nitric acid and other nitrates. NO is usually considered harmless as it is a reducing and not an oxidizing agent (Rabl, 2001). NO_2 primary affects the respiratory system (EEA, 2013). Short-term exposure to NO_2 can change the lung function in sensitive population groups and long-term exposure can lead to more serious effects such as increased susceptibility to respiratory infection (EEA, 2013). Epidemiological studies have shown that long-term exposure to NO_2 is possibly associated with an increase of symptoms of bronchitis in asthmatic children. NO_2 is also correlated with other pollutants (especially PM), making it difficult to distinguish the effects of NO2 from those of other pollutants (EEA, 2013). The main health damage of NO_x is the result of its second pollutants, O_3 and nitrate particles. Especially the nitrate particles may be transported in long distances by winds and inhaled deep into people's lungs increasing illness and premature death (from asthma and bronchitis), (Rabl, 2001).

Sulphur Oxides (SO_x)

Oxidation of SO2 forms acidic deposition also known as acid rain, which can cause adverse effects on ecosystems through acidification (EEA, 2013). SO_2 as a primary pollutant can contribute to respiratory problems, particular in children and elderly, and aggravate existing heart and lung diseases (Denisis, 2009). According to epidemiological studies SO_2 can affect the respiratory system and lung functions, and cause irritation of the eyes (EEA, 2013). Overall, sulphur oxides as nitrogen oxides have some immediate effects on human health but can harm human health even at the regional level since they are transformed into secondary pollutants (sulphates and nitrates respectively) far away from the emission source.

Other air pollutants

Apart from the aforementioned emissions there are other ship air pollutants having health effects, such as carbon monoxide (CO), volatile organic compounds (VOC) and ozone (O_3). For CO, there is evidence that its direct impacts appear to be statistically significant, however the estimated damage costs are low, even for the transport sector (Rabl, 2001). VOC contain hydrocarbons (HC), some of which are carcinogenic. Other harmful components of VOC are the polycyclic aromatic hydrocarbons (PAHs) which are ubiquitously distributed human mutagens and carcinogen (Choi et al., 2006). Epidemiological studies have proven that daily exposures to ozone increases mortality and respiratory morbidity rates and other health effects from long-term exposures, however these results are not conclusive and will need further confirmation (WHO, 2008).

In response to the effects of ship air pollution, the International Maritime Organisation (IMO) which is the formal regulating body of the maritime sector has recently adopted (2010 and 2011) specific regulations for reducing air pollution from PM (IMO, 2015) as well as sulphur and nitrogen oxides in specific areas around the world, the so called

Emission Control Areas (ECA). European counties have also put in force specific measures for the reduction of ship air pollution in harbour areas (European Commission, 2015).

12.2.2 Port emissions regulations

Air emissions are regulated at the EU level through directives and then transposed into members' states national law. Ships are also regulated by the International Maritime Organization (IMO) which formulates new maritime laws which have to be transposed into the national law through a ratification process which should reach a certain threshold in order for the regulation to take global effect.

In December 2013, the European Commission published the so called Clean Air Policy Package and revised the National Emission Ceilings (NEC) Directive. The NEC defines the maximum permissible levels of national air emissions (PM, SOx, and NOx) per EU member state. Port emissions are partially covered in this regulation since only domestic shipping activity is counted in the national air emission inventories. Ships of foreign flags that call an EU port are not included in the national inventories and thus are not covered by the NEC Directive.

Another relevant regulation by the EC is the Air Quality Directive (AQD) (2008/50/EC), which regulates ambient concentrations of air pollution by defining limit values for air pollutants such as SO2, NOx, PM10 and PM2.5. As ports are often located in or around urban areas or, they sometimes contribute significantly to local air pollution, which may result in breaches of the limit values.

Specific regulations for ship air emissions are in force at global and regional (EU) level which cover the port time as well as the time that the ship sails near sensitive areas. The focus of these regulations is in the quality of marine fuels and in particular at the sulphur content. At global level the regulation covering ship emissions (greenhouse gases and specific air pollutants) is MARPOL and in particular the Annex VI. MARPOL has identified sensitive areas (the so called Emission Control Areas, ECAs) for ship emissions in which stringent standards are in place for the sulphur content. At the EU level, SOx and PM emissions of ships are regulated by the Sulphur Directive (2012/33/EU) which transfers the IMO regulations into the European level. Specifically for the port area the directive requires that ships should use marine fuels with not more than 0.1% sulphur content during their stay at a European port (if this stay takes two hours or more). Alternatively, ships may implement other measures to meet the requirements set (i.e. use of scrubber technology to grasp SOx in the funnel or use liquefied natural gas or other alternative fuels which do not contain sulphur).

Table 67: Maximum Sulphur content in marine fuels

Global Regulations		**Regional Regulations: EU Directive 2012/33**		
MARPOL ANNEX VI		All ships	Passenger ships	Ships in EU ports
Outside SECAs	3.5% after 1.1.2012	3.5% as from 18.6.2014	1.5% until 1.1.2020	

	0.5% after 1.1.2020	0.5% as from 2020	0.5% as from 1.1.2020	0.1% already in effect since 1.1.2010*
Within SECAs	1% after 1.7.2010	1% until 31.12.2014	1% until 31.12.2014	
	0.1% after 1.1.2015	0.1% as from 1.1.2015	0.1% as from 1.1.2015	
* except if they are at berth for less than two hours or they use shore side electricity				

There are no specific regulations for ships that restrict NOx emissions or CO2 emissions inside port areas. Regulation 13 of MARPOL VI, regulates NOx emissions and imposes new ships (with a keel-laying date on or after January 1st 2016) to meet Tier III requirements inside the North American and US Caribbean ECAs (so-called NECA areas).

12.3 Ship emissions in port areas

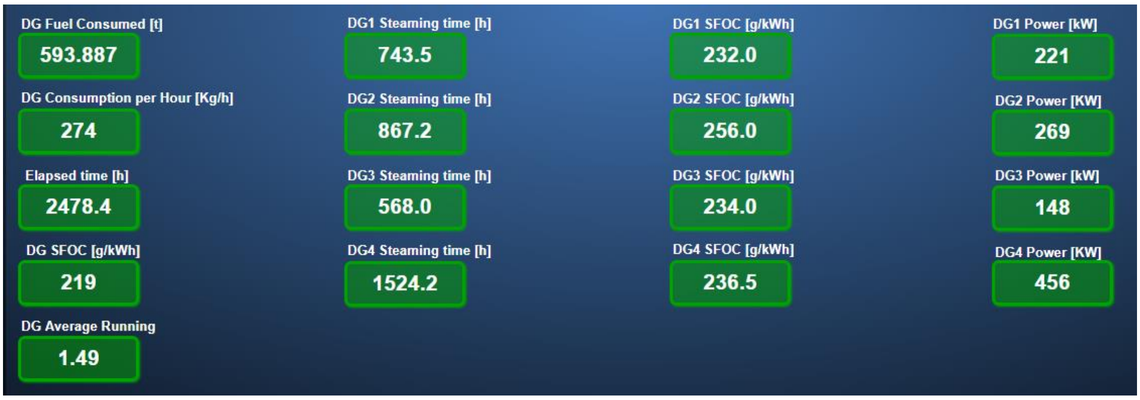
The data presented in this paragraph extracted from a commercial continuous monitoring and performance analysis system (InfoShipEGO©) which is capable of acquiring data from ship operation every five minutes and providing with various performance analysis results suitable for decision making with respect to energy optimisation on-board. Consumption data are acquired in this performance tool directly from on-board flow meters (one for the main engine and one for the auxiliary engines).

12.3.1 Short sea shipping cargo ship

According to the EU (COM (1999), 317 FINAL), Short Sea Shipping is defined as “the movement of cargo and passengers by sea, between ports situated in geographical Europe or between those ports and ports situated in non-European countries having a coastline on the enclosed seas bordering”.

The cargo ship presented here is a container ship (64000 GT) carrying 4,000 TEU. The subject ship in the examined period (June 2016 – June 2017) has been operating mostly around Europe. With the help of the tool, investigation of the ship routes is available, which reveals that the ship has been working entirely in short sea-shipping voyages in the aforementioned period. The ship spent 28% of her operating time (103 days in one year) inside port areas and the fuel consumption of the diesel generators inside port areas was 593.89 tonnes in total. The average number of diesel generators running was 1.49 (the vessel has four diesel generators with 1775 Kw, each). The voyage phases share is as follows:

- at port: 27,96 %
- manoeuvring: 16.43%
- at sea: 55.61%



DG Fuel Consumed [t] 593.887
DG Consumption per Hour [Kg/h] 274
Elapsed time [h] 2478.4
DG SFOC [g/kWh] 219
DG Average Running 1.49
DG1 Steaming time [h] 743.5
DG2 Steaming time [h] 867.2
DG3 Steaming time [h] 568.0
DG4 Steaming time [h] 1524.2
DG1 SFOC [g/kWh] 232.0
DG2 SFOC [g/kWh] 256.0
DG3 SFOC [g/kWh] 234.0
DG4 SFOC [g/kWh] 236.5
DG1 Power [kW] 221
DG2 Power [KW] 269
DG3 Power [kW] 148
DG4 Power [KW] 456

Figure 95: Fuel consumption data at port of short sea shipping container ship (source: RINA)

12.3.2 Open sea cargo ship

The cargo ship in this case is a container ship operating between North and South America. The ship is 84,900 tonnes deadweight and has a capacity of 6,750 TEU. The data presented below have derived from the same performance monitoring tool and cover the same period as before (June 2016 – June 2017). In this period, the subject ship spent 19.50% of its operating time at port area (73.5 days). The ship has four diesel generators and the average number of running units at port is 1.20. The fuel used in diesel generators is MGO with sulphur content 0.1%.

DG Fuel Consumed [t] 23023.361
DG Consumption per Hour [Kg/h] 13062
Elapsed time [h] 1763.9
DG SFOC [g/kWh] 10,758
DG Average Running 1.20
DG1 Steaming time [h] 635.4
DG2 Steaming time [h] 415.2
DG3 Steaming time [h] 163.5
DG4 Steaming time [h] 901.2
DG1 SFOC [g/kWh] 247.4
DG2 SFOC [g/kWh] 22401.8
DG3 SFOC [g/kWh] 219.2
DG4 SFOC [g/kWh] 17088.4
DG1 Power [kW] 382
DG2 Power [KW] 227
DG3 Power [kW] 88
DG4 Power [KW] 522

Figure 96: Open sea cargo ship. Fuel consumption at port (source: RINA)

Overall, the total CO2 emissions inside the port areas are 72,355.59 tonnes. The tool calculates SOx and NOx emissions, which are 514.51 tonnes and 12,850.49 tonnes respectively.

CO2 [t] 72355.59
ME CO2 [t] 650.84
DG CO2 [t] 71205.17
SOx [t] 524.00
ME SOx [t] 4.69
DG SOx [t] 514.51
NOx [t] 26842.19
ME NOx [t] 6483.88
DG NOx [t] 12850.49

Figure 97: Open sea cargo ship. Port emissions (source: RINA)

12.4 Port Emissions Case Study

12.4.1 Description

The goal of the case study is to apply the IPA methodology in order to estimate the external health costs of primary ($PM2_{.5}$, PM_{10} NO_x and SO_x) and secondary pollutants (nitrates and sulphates) emitted from coastal passenger ships and cruise ships approaching the port of Piraeus. The port of Piraeus is the largest port in Greece and holds the seventh highest passenger traffic in Europe, servicing about 9 million passengers annually (European Commission, 2013). The passenger terminal is part of the city of Piraeus while the freight terminals of the port of Piraeus are not urbanized (Tzannatos, 2010).

Table 68: Case Study – Overview

Case study: External health cost of coastal ferries and cruise ships at Piraeus Port	
Time period	(Annual estimation – port stay, manoeuvring)
Ships included	124 cruise and 59 coastal passenger ships
Emissions Inventory	Based on Tzannatos (2010)
Pollutants into consideration	PM10 , PM2.5 , NOx , SO2 ,nitrates and sulphates
Meteorological data	National Observatory of Athens
Range of local area examined	≈56km (metropolitan Athens area)
Range of regional area examined	+500 km (Greece)
Local population data (400 cells)	ELSTAT (Hellenic Statistical Authority)
Exposure-Response Functions (ERF)	ExternE (values as of September 28th 2004)
Unit damage costs	ExternE (€)

12.4.2 Inventory - Emissions Data

Using an in-port ship activity-based methodology, Tzannatos (2010) estimated the emissions of 124 cruise and 59 coastal passenger ships for the passenger port of Piraeus during a twelve-month period (2008–2009). The ship operations considered are: berthing time, manoeuvring time and finally the arrival and departure time (one hour each). The total NO_x emissions were 1790 tons, and SO_2 and $PM_{2.5}$ emissions were 722 and 99 tons, respectively. Emissions of $PM_{2.5}$ are a portion of PM_{10} emissions. More explicitly, it is considered that the emission of $PM_{2.5}$ is equal to 0.92× M_{10} (EPA, 1999, 2009), and $PM_{2.5}$ ERF values derive from PM_{10}, scaled by 1.67 (Spadaro, 2004).

12.4.3 Meteorological data

Detailed meteorological data are needed for the local level pollutant dispersion modelling. Hourly values of wind speed, direction and ambient temperature for the period 4/6/2012–30/11/13 (19 months in total) recorded in the nearest meteorological station (located 5 km from Piraeus port) were obtained from the National Observatory of Athens.

12.4.4 Pollutants and emissions source characteristics

The basic assumption is that there is constant emission source located at the centre of the port, which is reasonable since the port has non-stop passenger traffic throughout the year and the berthing locations are spaced 500 m or less from each other inside a 2 by 2 km cell. The stationary source is assumed to be at the centre of that cell. This assumption is required in order to use the Gaussian model of the QUERI algorithm (stationary source with a constant emission through the year).

Finally, typical values of a passenger/cruise ship have been used as input at the optional data: stack height, stack diameter, flow velocity and gas temperature. Emission rate (tons/yr) and deposition velocity (cm/s) are inputs for the dispersion calculations. The deposition velocity is an indicator of the atmospheric pollutant removal rate. Emission rate are those estimated by Tzannatos (2010).

Mean values for Europe were used for the deposition velocity (k) as reported by Spadaro (2004).

The emission source coordinates are: 23.63706 (longitude) and 37.94222 (latitude). The optional data values of the emissions source that are required by the software typical values are:

a. Stack height: 25 m, (General Arrangement of typical coastal passenger vessel)
b. Stack diameter: 5 m, (General Arrangement of typical coastal passenger vessel)
c. Flow velocity: 10 m/s, (EIA report, 2013)
d. Gas temperature: 600 K, (Kyrtatos, 1993)

12.4.5 Receptors (at local and regional level)

The distribution of inhabitants per square cell (400 cells in total) was set up using available population census released by the Hellenic Statistical Authority (ELSTAT, 2001, 2011). The local domain has an effective radius of 56 km equivalent to a square-shaped (cells) domain, with sides equal to 100 km as proposed by Spadaro (2004). This area covers approximately the entire greater metropolitan Athens area where almost half of the country’s population is located. The regional radius is 500 km, which covers a large portion of the total territory of Greece.

12.4.6 Exposure response functions (ERF) and monetary values

The ERF (values as of September 2004) and unit damage costs (in Euro) of the ExternE project were used for emissions of PM10, SO2 and NOx. The ERF values for PM2.5 have been calculated as function of the PM10 values (according to ExternE). The health impacts implemented at that these ERF functions are:

1. <u>Mortality</u>, expressed in Years of Lost Life (YOLL), per person per µg/m^3 of pollutant per yr. As the ERF for long-term mortality are not available for SO2, only the acute mortality contribution is calculated.
2. <u>Chronic bronchitis,</u> expressed in cases chronic bronchitis per person per µg/$m^3$of pollutant per yr.
3. <u>Net restricted activity days (net RADs),</u> expressed in net RADs per person per µg/$m^3$of pollutant per yr. It is assumed that the days in hospital for respiratory admissions (RHA), congestive heart failure (CHF) and cerebrovascular conditions (CVA) are also restricted activity days (RAD).
4. <u>Respiratory hospital admissions (RHA),</u> expressed in RHA per person per µg/$m^3$of pollutant per yr.

5. Cerebrovascular hospital admissions, expressed in cerebrovascular hospital admissions per person per μg/$m^3$of pollutant per yr.
6. Chronic cough in children, expressed in cases chronic cough in children per person per μg/$m^3$of pollutant per yr.
7. Congestive heart failure in elderly, expressed in cases congestive heart failure in elderly per person per μg/$m^3$of pollutant per yr.
8. Cough in asthmatic adults, expressed in cases cough in asthmatic adults in elderly per person per μg/$m^3$of pollutant per yr.
9. Bronchodilator use in asthmatic adults, expressed in cases Bronchodilator use in asthmatic adults per person per μg/$m^3$of pollutant per yr.
10. Lower respiratory symptoms in asthmatic adults, expressed in cases lower respiratory symptoms in asthmatic adults per person per μg/$m^3$of pollutant per yr.
11. Cough in asthmatic children, expressed in cases cough in asthmatic children in elderly per person per μg/$m^3$of pollutant per yr.
12. Bronchodilator use in asthmatic children, expressed in cases bronchodilator use in asthmatic children per person per μg/$m^3$of pollutant per yr.
13. Bronchodilator use in asthmatic children, expressed in cases bronchodilator use in asthmatic children per person per μg/$m^3$of pollutant per yr.
14. Lower respiratory symptoms in asthmatic children, expressed in cases lower respiratory symptoms in asthmatic children per person per μg/$m^3$of pollutant per yr.

12.4.7 Results

Concentration contours

Concentration contours per air pollutant were developed with the help of the concentration profiles. The contours illustrate how the pollutants spread within the local domain. The red colour indicates the area with the highest concentrations.

Even the highest concentrations of air pollutants in the case study are well below the highest permitted limit values for Greece (for example: the limit value for $PM_{2.5}$ is 26μg/m^3 which is an order of magnitude higher than the highest calculated value of the case study).

The area in which pollutants reach their highest concentration is located at Neo Ikonio, Perama (coordinates from emission source (X, Y) = (-2.5 km, 2.5 km)).

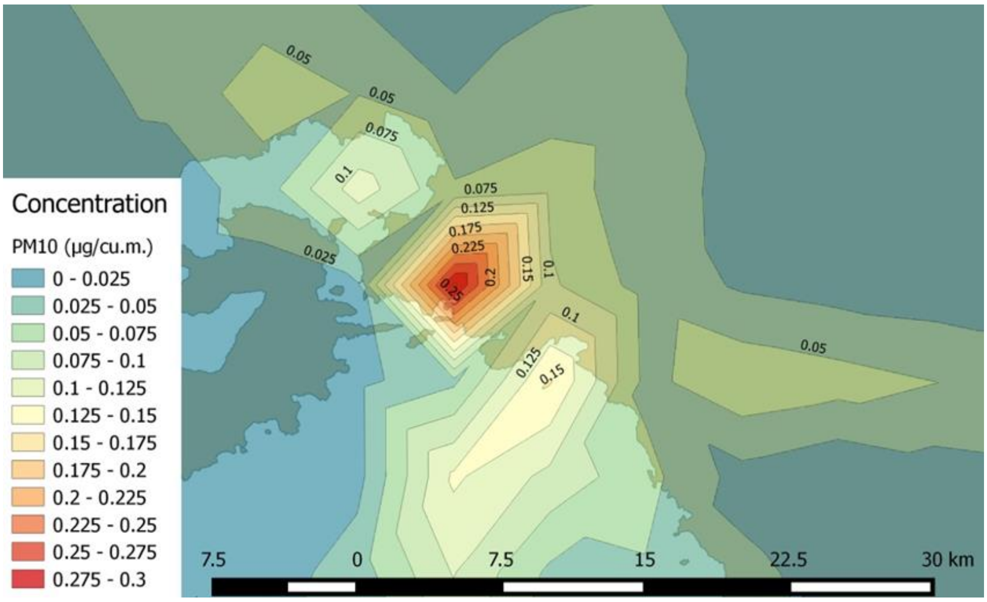


Figure 98: PM$_{10}$ concentration in local area

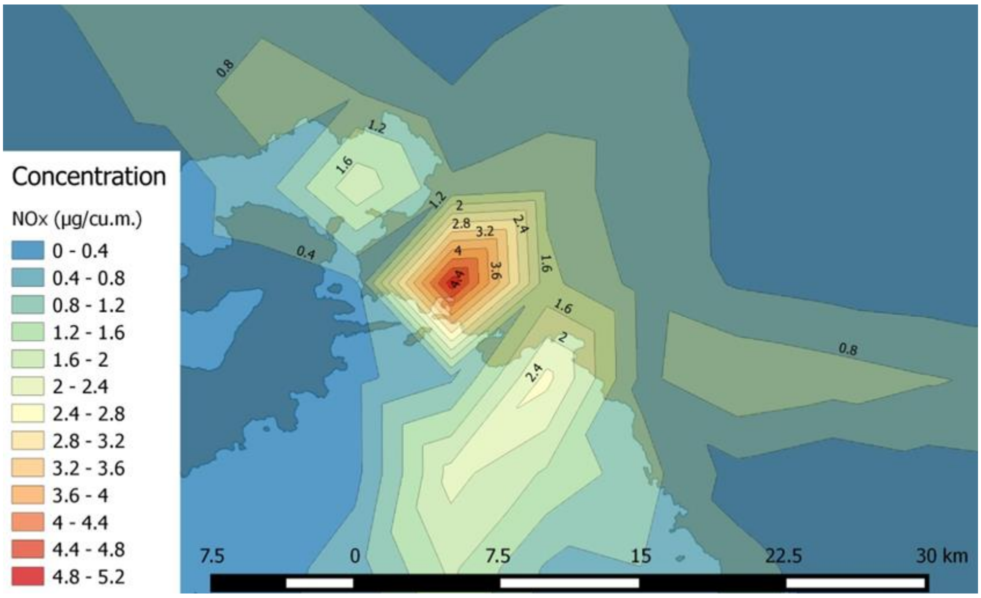


Figure 99: NO$_x$ concentration in local area

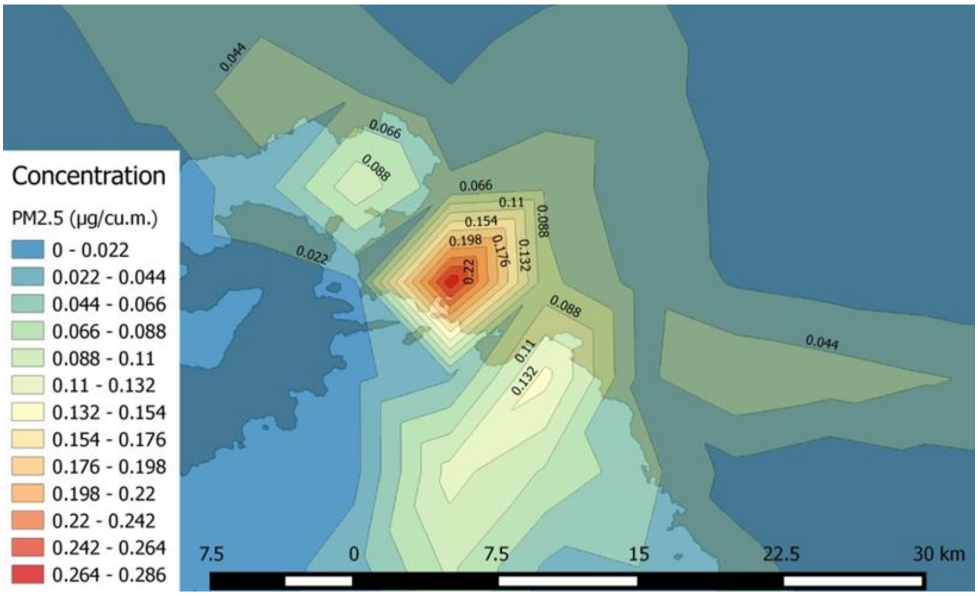


Figure 100: PM$_{2.5}$ concentration in local area

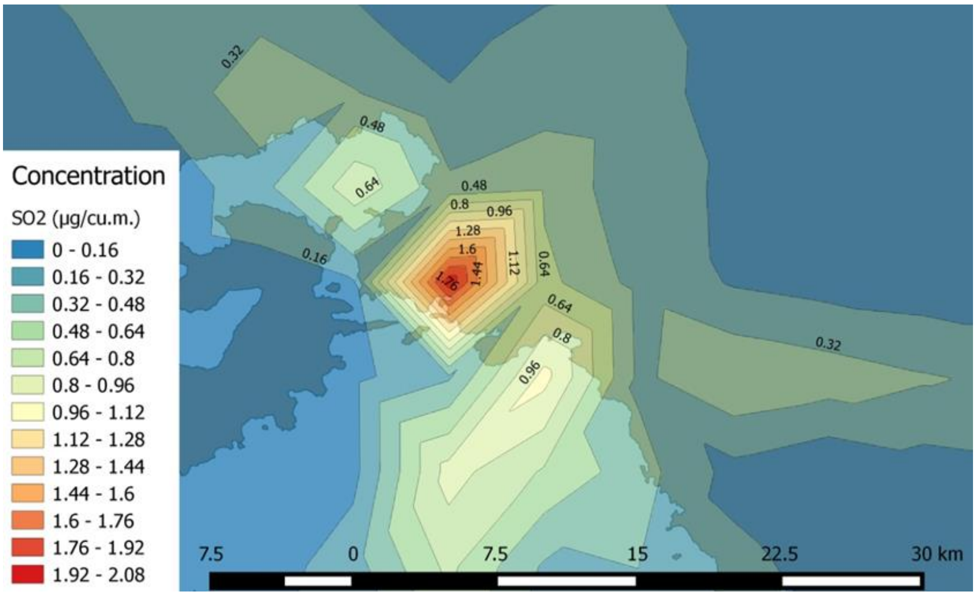


Figure 101: SO$_x$ concentration in local area

External (Health) Cost

The case study estimates the external cost in health resulting from air pollutants emitted by coastal passenger ships and cruise ships calling at the port of Piraeus in one year (2008–2009). The total external cost in health is 26.314.700 Euro, which derives from the combination of the external costs of all air primary and secondary pollutants under examination: PM$_{10}$, PM$_{2.5}$, NOx, SO$_2$, sulphates and nitrates.

Results per pollutant are provided in the following figure. The estimated health cost is not negligible at the local level (Athens metropolitan area). Particles cause the higher external health cost, 61% of the total (PM$_{2.5}$ is the most important contributor). NO$_x$ emissions have no external cost in health as primary pollutants but are the primary contributors to health cost at the regional level (overall they are responsible for 25% of the total health cost) (see Fig. 101).

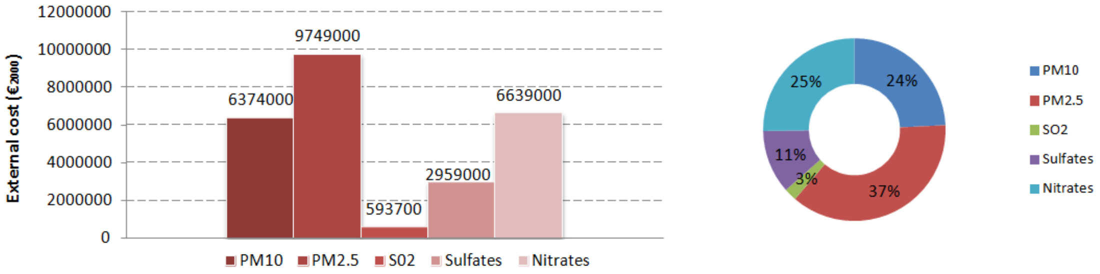


Figure 102: Results of health external cost per pollutant

Mortality cost (which illustrates the willingness to pay for protecting the value item of life), dominate the overall health cost. The presentence of mortality and morbidity costs in the overall external cost are 67% and 33% respectively. The pollutant with the biggest mortality external cost as well as the biggest morbidity external cost is $PM_{2.5}$ (6.5 m € and 324.000,00 € respectively). Nitrates and sulphates have only regional impacts, while PM_{10}, $PM_{2.5}$ and SO_2 have both local impacts and regional impacts. However, the contribution of particles to external health cost is observed mainly at the local level (85% of their external cost is local).

Figure 102 shows the yearly external cost in health per receptor at local and regional level. The local radius is 56 km the local area is covering approximately the entire greater Athens metropolitan area (3.8 million inhabitants according to country's census 2011). Moreover, the regional level (radius over 500 km) corresponds to roughly the entire Greek territory. Port emissions of PM2.5 add 2.2 € to the annual external (health) cost of an Athens inhabitant, emissions of PM10 add 1.4 € and emissions of SO2 add another 0.1€. The total annual external cost in health for one Athens inhabitant due to port emissions is nearly four euros (€). Nitrates and sulphates are not contributors to the aforementioned cost since their total impact occurs at the regional level. At the regional level, nitrates represent the largest contributing category of air pollutants with an annual external cost of one € per person followed by the sulphates 0.4 €. The total external cost per year in health outside the greater Athens area is 1.7 € per inhabitant.

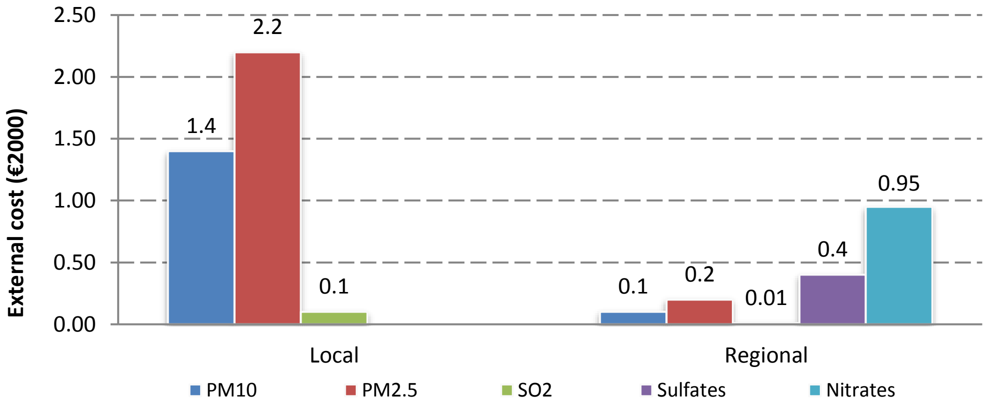


Figure 103: External cost per person (at local and regional level).

There is a great uncertainty of health in cost evaluations as Figure 103 displays (an order of magnitude is a typical range in the final health cost estimation). Uncertainty is due to data, modelling and ethical variations. However, the results are still useful especially for comparison (i.e. cost of different sectors) and decision-making purposes.

The uncertainty of economic valuation for the damage category of mortality and for all the pollutants is shown in Figure 104 below.

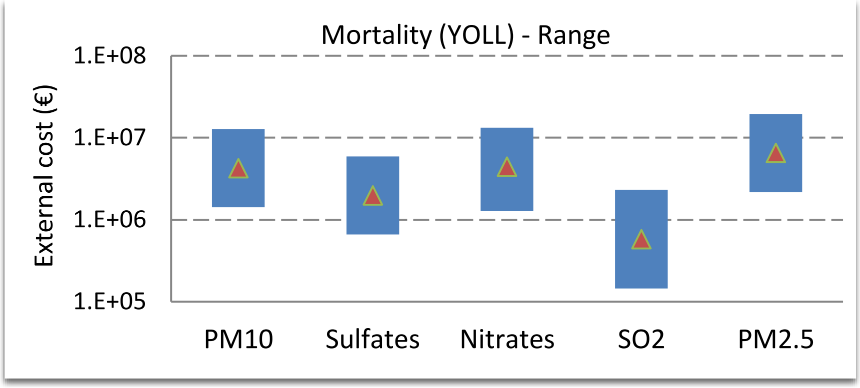


Figure 104: Uncertainty range – Mortality category

12.4.8 Discussion

In order to obtain an evaluation of the results derived from the present work two different comparisons have been made with other dominant emission sources.

The first comparison is between external costs of PM_{10} emissions of the present study and the corresponded costs of the industrial sector in the metropolitan area of Athens. According to the Institute for Environmental Research and Sustainable Development (IERSD), (2007), the air pollution impacts of the land based industrial activity in the Athens metropolitan area are mostly attributed to emissions of PM_{10}. These emissions are responsible for about half of the externalities created from human activities in the region, reaching a total annual cost of 94.3 m €. Since the aforementioned study refers only to emissions of PM_{10}, this emission category is used as the comparison basis with the present work. It is noted that the results of the present study also depict that this particular category of port emissions is the main contributor to external cost creation. The comparison unit is the annual external (health) cost of PM_{10} per person living in Athens area. According to the IERSD study, the industrial sector corresponds to a 25.9 annual external cost per Athens inhabitant, while the passenger port emissions of Piraeus correspond to a 1.4 € (which is 5.7 percent of the industrial sector cost). It is however noted that the industrial sector in Athens according to IERSD includes nearly 9000 land based industries while the emissions data in the port of Piraeus derive from a data sample of only 183 ships. This indicates that the external cost obtained in the present study is not negligible and should be interpreted accordingly by decision makers.

The second comparison that has been made is with the road transport sector's emissions in the area of Athens. Friedrich & Bickel (2001) have estimated for Athens the external cost of $PM_{2.5}$ (dominated completely by health cost), for a EURO II petrol car at 1.32 € per 100 vkm (vehicle kilometers). The comparison unit is the same as before (annual external cost in health) but the emissions category this time is o $PM_{2.5}$. In order to arrive to a comparative figure a simplistic and reasonable assumption is made which accepts that the 1500000 cars of Athens, (nearly all of them are petrol cars because of the ban of the diesel cars that was in force until 2011) travel approximately 5000 km within the examined area in one year. With this assumption, the annual external cost of road transport's $PM_{2.5}$ emissions is 99m €. The resulted health cost per person living in Athens for the road transport sector is estimated then at 25.9 €. Therefore, it is resulted that the health cost per person living in Athens from $PM_{2.5}$ emissions of coastal passenger ships and cruisers is 8.5 percent of the corresponded cost from road transport.

From the two comparisons it can be concluded that the health cost contribution of industrial and road transport sectors are of equally importance. This result is in line with the Organization of Economic Cooperation and Development (OECD) (2014) which argues that "*The available literature, read with care, suggests that, in the EU24, road transport's share of the economic cost, properly calculated, is likely to be ≈50%*". The results of the comparisons made in are shown in the following Figure 105.

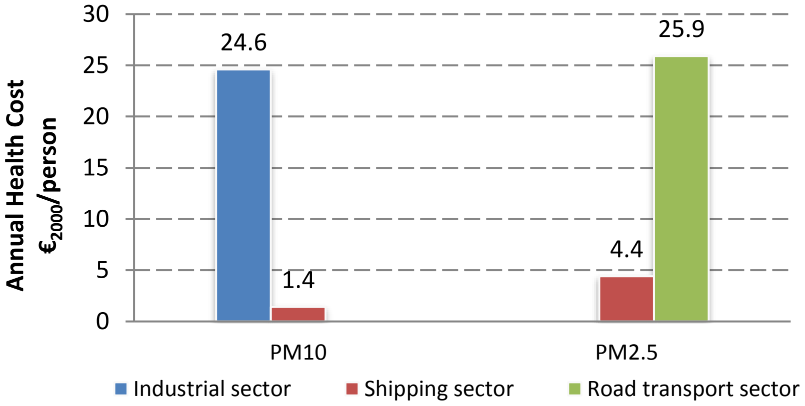


Figure 105: Comparison between ship port emissions and other sectors

12.5 Conclusion

Large portion of the air pollution external cost falls in the category of health cost. This study has developed a methodology for making assessments of health cost from ships at port. The methodology is based on the Impact Pathway Assessment (IPA), which has been used by the ExternE, a series of research projects funded by the European Commission, Directorate-General (DG) Research.

The results show that the health impact of ship port emissions in Piraeus is not negligible although it is much less than costs from other sectors for which comparisons have been available. The overall external cost in health caused by air pollutants emitted from all coastal passenger ships and cruise ships in the port of Piraeus (first case study) reach a total of 26 million €. Health costs were calculated at the local (greater Athens area) and regional level (entire territory of Greece). Particulate Matter are responsible for the higher health costs occurring at the local level.

Future improvements that would increase the validity of health cost estimation in shipping mainly concern the treatment of data and methodological uncertainties.

Detailed and robust inventories of ship emissions at port might be available by the use of ship movements inside the port area (i.e. utilizing the Automatic Identification System, AIS). Accurate emission factors are also needed which would reflect the actual loading condition of ship engines, the real operating profiles (time at port, at manoeuvring, sailing time) and the type and quality of fuels used.

There exists great uncertainty (data, modelling, ethical) in the estimation of this external cost. Methodological uncertainties involve mainly the accuracy of the dispersion models used. Therefore, a new dispersion model explicitly developed for air pollutants emitted by the ship funnel taking into also account analytical meteorological data and most importantly the ship movements (manoeuvring in port or travelling in open sea) would increase the validity of impact assessment and corresponding results. Finally, it would be interesting to explore possible changes in the external health costs from the application of different technologies (like cold ironing) or emission reduction solutions for shipping.

In concluding, it is noted that health impact assessments illustrate a sound basis for decision support and should be further exploited. The interest in health cost estimates is expected to grow in the future since at least at European level there are official strategies promoting the introduction of measures to internalise the external cost of transport into market transactions.

13. DISCUSSION

In the discussion chapter the objective is to summarise and evaluate the main results of this thesis. Since the last lines of this thesis are written in June 2018, the scope of this chapter is also to give an updated view of international shipping, with particular focus on the current environmental agenda of this sector. Especially with respect to ship air pollution and GHG which have been the main focus areas of this study there is extensive activity from policy makers at both regional (EU) and global (IMO) level. New regulations and standards are forcing the systematic measurement of ship air emissions and provide with robust reports at ship and fleet level in order for the decision makers to identify the most suitable measures for reducing the environmental impact of ships. Thus, the results of the study especially those concerning the methods and tools for assessment of emissions and their impacts could serve as valuable contribution to this direction.

13.1 Main contributions

13.1.1 Contribution No1: Defining maritime transport sustainability

The first goal (and first research question) of this PhD thesis was to provide a definition for what means a sustainable maritime transport system.

To proceed to the definition the author carried out an extensive literature survey and identified the following three principles that a sustainable transport system should observe.

A sustainable transport system should observe the following principles:

1. *Accessibility: the ability to obtain or have access to desired goods, services, activities and destinations*
2. *Resource constrains: the acceptance of natural (e.g. for fossil fuels) and social limits (e.g. in safety)*
3. *Equity: the balanced distribution of transport benefits and costs among people and between generations*

The proposed definition for a sustainable maritime transport system is the following:

'A Maritime Transport System is sustainable when it has the capability to offer and maintain non-declining and efficient accessibility by observing the principles of equity and resource constrains' (Chatzinikolaou and Ventikos, 2011)

The study that covered this first question of the thesis was concluded in 2011 and the results were presented in an international peer reviewed conference (IMAM, 2011). The definition is consistent with the definition of sustainability as proposed in 1987 by the so-called “Brundtland Report” which has set the original notion for this concept: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.

Later, in 2013, the perspective of IMO for what means sustainability in the maritime transport sector was launched. This mainly involves a set of seven actions towards a sustainable maritime transport system. Actions identified are for energy efficiency, safety, and energy supply among others (see Chapter 2).

Recently, Holden et al., (2017) in their book ‘The imperatives of Sustainable Development: Needs, Justice, Limits’ proposed a similar concept to the three principles presented in this thesis. The authors of this book are seeing sustainable development as an ethical statement from which three equally important moral imperatives derive: a) satisfying human needs, b) ensuring social justice and c) respecting the environmental limits. The authors argue that these imperatives constitute constraints in human behaviour. There is an obvious link between the aforementioned imperatives and the principles for sustainable transport system proposed in this thesis. Drawing the obvious parallel for the maritime transport sector it can be stated that the principles of a maritime transport system sustainability should constitute equally important constraints (at an operational level) for ships.

An illustrative industrial perspective by SSI is also lacking a definition of sustainability for maritime transport. The SSI identifies selected areas of actions to be taken by the industry until 2040 in order for shipping practices to be less unsustainable.

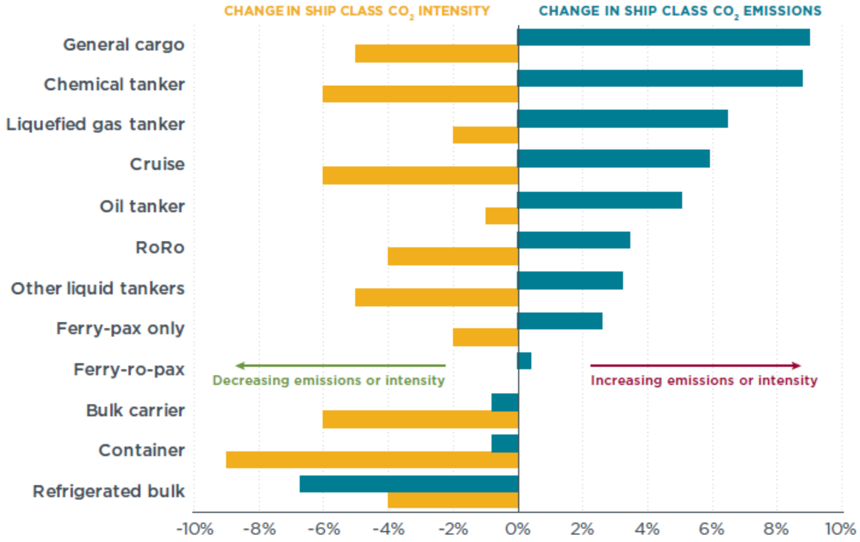


Figure 106: Change in CO2 emissions and CO2 intensity for key ship types (International Council on Clean Transportation, 2017)

It is clear that any transportation system using fossil fuels will never be sustainable since the rate of extracting fossil fuel volumes is more than the capacity of the earth to replace these volumes. Such transport systems do not observe the principle of resource constrains.

Moreover, there is evidence that with the current methods and technologies used for energy efficiency there have been some increases in efficiency which however are not enough to reduce the absolute CO2 emissions from shipping. This is clearly demonstrated also in a recent ICCCT report (2017), see also Figure 106.

3.1.1.1 Example of a sustainable maritime transport system

The proposed research project was submitted for funding in the Greek Secretariat for Research and Development in 2017. The project entitled “Sustainable Short Sea Shipping” (S^4Life) aims at the sustainable integration of renewable energy in Short Sea Shipping (SSS), through the development of cutting-edge technologies. The project’s main research challenge is the development and pilot application of a Portable Unit for Renewable Ship Energy (thereafter PURE-Ship), which will be able to receive, carry and deliver renewable energy for use on-board ships. The PURE-Ship unit uses a combination of battery and fuel cell technologies, together with a reformer that produces hydrogen from gas biofuel, all fitted in a compact and easily transportable package (suitable to be transferred in a small track).

The project will also develop a logistics schedule which will facilitate the rapid replacement of the PURE-Ship unit during the vessel’s berthing, so that it will not be necessary for the ship to produce and store electricity. The design of the unit will enable a low retrofitting cost onboard, for coupling the unit with the existing power system.

For the PURE-Ship unit, the storage capacity, the specific mixture of renewables, as well as the logistics schedule, will be parametrically assessed in three distinct utilization scenarios, namely:

- Main propulsion on a vessel serving a short ferry line between two ports
- Auxiliary power on a passenger vessel
- Shore side electricity supply at port (cold ironing)

In the above scenarios, the project will study and optimize the system: renewable energy uptake from land – energy transportation – energy use on-board - replacement - recharging. This optimization will be carried out using methods for Life Cycle Sustainability assessment developed by project partners (NTUA, RINA), with the ultimate goal of an overall positive external cost balance of the system (economic viability, positive social impact and zero emissions).

The expected main results of the project are: a) the design of the PURE-Ship unit and the retrofit of the ship in order to receive this unit, b) the construction of a scaled prototype of the PURE-Ship unit and its pilot application, c) the life cycle sustainability analysis (economic, environmental and social) of the system, and d) the dissemination of the results and the investigation of the commercial exploitation of the unit. The consortium brings together leading research organizations, namely the National Technical University of Athens - NTUA (School of Naval Architecture and Marine Engineering) and the Centre for Research & Technology Hellas - CERTH (Aerosol and Particle Technology Laboratory), and high expertise private companies: RINA (Class Society), Hellenic Sea Ways (shipping company), SUNLICHT (batteries/energy storage systems), HELBIO (hydrogen technology/fuel cells), and the Hellenic Marine Environment Protection Association (HELMEPA). The project has the support of the Hellenic Shortsea Ship-owners Association (HSSA).

13.1.2 Contribution No2: LCA framework for assessing air emissions

Pioneer life cycle studies within the maritime transport conducted in the 1990s, have demonstrated that studying industrial systems from a life cycle perspective may offer important benefits, such as avoiding the shifting of environmental impacts from one stage of the life cycle to another or enabling the identification of weak environmental processes within the life cycle chain. The LCA method, as proposed in the relevant ISO standard, has not been particularly developed for the case of ships and most of its features match better to land based products and services. It is therefore essential to adapt the method before conducting an LCA study for a ship system.

This thesis proposes a unique framework for studying ship emissions in a life cycle perspective. The Life Cycle Framework main capabilities are the following:

1. *Inventory of air emissions from any identified process*
2. *Emissions covered: CO2, CO, SO2, NOx, PM (all), CH4, VOCs*
3. *Air emissions are available per life cycle stage, process, system element, subsystem, and total*
4. *Annual air emissions analysis*
5. *Emission comparisons between different operational ship profiles*

The proposed life cycle ship framework considers the ship as a system that may be detailed into first into sub-systems and then further into system elements for which: (a) inputs, (b) processes, and (c) outputs, are identified and elaborated. Important ship life cycle stages taken into account in this model are: the shipbuilding stage, the ship operation including major maintenance activities, and the stage of ship dismantling/recycling.

At the process level the emissions are calculated using theoretical or empirical mathematical modelling. The information derives from previous LCA studies, manufactures data, data from shipbuilding, and ship repair operations and the general literature. The framework also includes an algorithm for calculating the activity data after basic input has been provided by the user (i.e. days at port, at sea, manoeuvring etc.).

A software (in MATLAB environment) has been developed which models all elaborated processes of the LCA framework, with their equations and algorithms (in Chapter 5).

The LCA Framework and the LCA software contribute in the field of reporting and monitoring of ship air emissions by proposing a systematic way of collecting and elaborating data for various ship system elements and processes

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The software can be used also for supporting decisions in the long term since it can estimate emissions results per year or make projections about air emissions during the life cycle of the ship.

A number of case studies were conducted with the use of the proposed LCA framework. In the process of conducting the case studies the framework has been reviewed and updated with new features. This work is spread in Chapters 4, 5, 6, and 8.

The following table summarises the case studies conducted with application of the LCA framework.

Table 69: Case studies conducted with application of the proposed LCA Framework

Case Study	Scope	Sample ship	Specific features
No1	Emissions Life Cycle Inventory	Panamax Oil Tanker	Modelling shipbuilding emissions Fixed ship operation scenario
No2	Annual Emissions Inventory	Panamax Oil Tanker	Activity data for fuel consumption of main engines Added resistance due to marine growth Fuel consumption and emissions from boilers
No3	Alternative operational scenarios' to accomplish the same transport work	Panamax Oil Tanker, Suezmax Oil Tanker	Effect of slow steaming Effect of speed limit Effect of fleet distribution
No4	Emissions from coating operations	General cargo 30,000 dwt	VOC emissions in shipbuilding, ship repair

Moreover, in Chapter 8, two important parameters that greatly affect the emissions inventories are discussed; namely the speed parameter, which is used as a design as well as an operational measure for energy efficiency, and the parameter of fuel consumption estimation and the uncertainty in relation to its monitoring and reporting. Calculations have been conducted to demonstrate the influence of speed in the EEDI. It is well known that the EEDI reference line has been calculated by using data from Lloyd's fairplay database. This database contains information for the speed; however it is not clear which exact speed is reported in the database. The calculations conducted in this thesis demonstrate the great influence of slight changes in speed (in the order of 15 percent max) to the reference line of EEDI. It is noted that the author has contributed in the work submitted by the Greek delegation to IMO for an alternative EEDI which would

The probabilistic model developed is able to:

1. *Develop probabilistic distributions of fuel consumption coming from noon reports*
2. *Compare the fuel consumption estimates of the model with fuel consumption info from activity data.*
3. *Apply a robustness analysis to the model developed for fuel consumption*
4. *Calculate emissions of CO2, NOx, SOx from the fuel consumption data*

The proposed probabilistic model can be used to evaluate the information provided by the ship reporting system and can support the compliance with the European MRV and/or the IMO DCS regulations.

13.1.3 Contribution No3: Comparative LCA study/ LNG vs. HFO

The LNG is considered a promising alternative for marine applications particularly because the burning of this fuel results in limited air emissions (of SOx, NOx, and particulates). Although there is experience from using LNG as fuel (i.e. use of boil-of-gas in LNG carriers), the LNG – fuelled ships are relatively short in numbers. There are some important parameters for this, the infrastructure, regulatory framework, and lower energy density and higher price compared to conventional fuel oil, being the dominant ones. Overall, the LNG remains the most expensive of the three alternative solutions to respond to the so called 2020 Sulphur limit imposed by international regulations. The three alternative options are shown in the following figure.

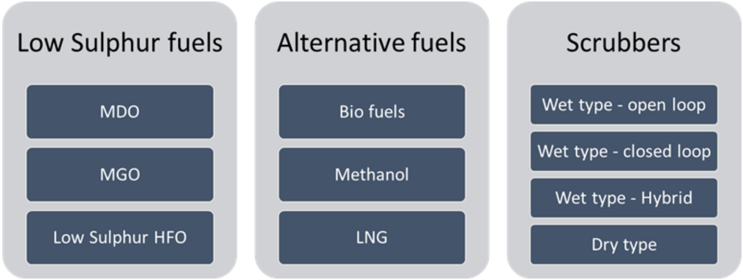

Figure 107: Alternative options to meet the 0.5 percent Sulphur limit imposed by international regulations

Burning of one tonne of LNG in marine engine results in 2.75 tonnes of CO2 emissions which is approx. 30 percent lower than the respective numbers for HFO. How different would be this figure if the whole life cycle of the LNG is to be taken into account? This questions has been the motivator to perform (in Chapter 7 of the thesis) a comparative LCA study for two marine fuel alternatives (LNG and 1% sulphur HFO). The life cycle of fuels has been taken into account; namely, production, transportation, storage, and combustion of the fuels on-board ships. For the stage of on-board combustion the case of a passenger vessel operating in a fixed round schedule between the port of Piraeus and an island port in the Aegean Sea is considered. The study compared the environmental impact of main air emissions produced during the entire life cycle of the two alternatives.

The results show that for both fuels there is an obvious dominance of the combustion stage in emissions and environmental impacts. The comparative LCA justifies the benefits in air pollution reduction with the use of LNG. However, with respect to the climate change impacts, the benefits of LNG are not that obvious.

The results of the **comparative LCA study** (**LNG vs. low sulphur HFO**) show that in greenhouse gas equivalents, the life cycle impact of the two fuel alternatives are marginal **(the life cycle of LNG has 9 percent less CO2 – eq).** Moreover, it has been demonstrated that the **LNG supply chain produces five times more CH_4 emissions than the supply chain of HFO.**

Emissions during ship operation

As clearly depicted in the results of the cases studies conducted, the operation of ship engines is the main contributor of the ship emissions inventory. This thesis has used three different methods for the calculation of ship emissions during the operation phase of the ship, namely:

1. The fuel consumption method: The method is mainly based on the fuel consumption data. In case these data are accurate this method offers high precision at the ship level and can be preferred to get more realistic emissions estimations. The fuel consumption data is the main query of the MRV Regulation of the EU. According to this regulation, fuel consumption data may be obtained from a) noon reports forwarded every day from ship to shore (noon reports have been used in the uncertainty analysis, Chapter 8) , b) bunker delivery notes (BDN) which feature the official bunkers quantity the ship has received in a bunker operation, and periodic stocktakes, and c) from flow meters which are installed in the fuel system to monitor the fuel consumption of different energy sources onboard (this implies that a continuous monitoring system is installed onboard) and d) from direct measurements of exhaust gases. If methods a – c are applied then emission factors, which are subject to the specific fuel, should be used to convert fuel consumption into emissions.
2. The engine power method. This method could be used in the case of absence of fuel consumption data. The engine power, engine load and the working hours have to be also considered for this calculation. The life cycle framework developed in this thesis has used formulae for engine power estimation.
3. The energy method. This method is not an independent one, since it is totally related to the fuel consumption. In order to perform the calculation, the fuel consumption data is needed. Then, the total energy produced by burning these fuels is calculated by using the calorific values of the various fuels used onboard. For example calorific values for HFO and MDO are 40.6 and 42.7 TJ/ton, respectively. An application of the energy method was made in the comparative LCA study between LNG and HFO, (in Chapter 7).

It is not in the scope of the thesis to comment on the effectiveness or accuracy of the above methods in the estimation of ship emissions. Reliable data are needed in all methods. Information on the fuels consumed onboard ships are in the hands of shipping companies, and often considered a sensitive information. The engine power method which is mainly used in the absence of real data, may involve assumptions that can result in emissions inventories that may be difeerent from the ship reality. In this thesis, the choice for employing the method was driven by the availability of information. However, the Life Cycle Tool, has been developed to use the fuel consumption method and requires the user to provide the input concerned.

In the context of this thesis, the author has not had the chance to elaborate data coming from continuous monitoring systems. Only after the completion of the work, and in his current position he had the chance to work with a commercial software that enables the continuous monitoring (every 5 min) of important ship data to perform environmental assessments and provide decisions assistance for enhancing the energy efficiency onboard. From this experience it can be stated that there are some clear advantages in the use of continuous monitoring systems which are mainly connected with the proper exploitation of big data. In Chapter 8, an example of the accuracy offered by exploiting big data is shown, which concerns the estimation of the ship power and speed curve.

13.1.4 Contribution No4: Life cycle Impact assessment of ship emissions

The impact assessment of ship air emissions has been studied in Chapters 9, 10, and 11. Studies covering the impact of ship emissions are not widely available.

Ship air emissions were mainly examined in the impact assessment studies. The drivers jointly determining the impact of an emission are: a. the emission quantity, b. the properties of the substance emitted, c. the characteristics of the source of the emission, and d. the features of the receiving environment.

The majority of impact assessments available today (including impact assessments within the LCA framework) take into account only the first two impact drivers of the above list. This is not problematic when addressing impacts at global scale (e.g. climate change), since the impact is independent of where the emission occurs. However, for air pollution impacts (e.g. acidification, eutrophication, human health effects etc.) which have local or regional characteristics, the situation can be very different and all four drivers of the impact should be adequately considered in order to arrive at reliable results.

The impact of GHGs is not easily measurable which is depicted by the wide range of monetary values collected in the literature review (see Chapter 10). However, the health and environmental impacts of air pollutants are subject to the proximity of the emission source to the receptors and therefore can vary significantly.

Two separate approaches were used in the ship impact assessment namely: the Life Cycle Impact Assessment (LCIA), a standardized method through the ISO framework for LCA and the external cost approach.

This thesis proposes a life cycle impact tool for ships based on principles of the ISO standards for LCA, and validated damage models. The main objectives of the tool are:

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1. *To record all pollutants (oil and non-oil liquid wastes, garbage, air emissions), generated by the various ship related processes and*
2. *To assess their environmental impact throughout the ship's life cycle.*

The results show the wide range of uncertainty in the estimation of emissions impact and associated costs. The total external cost of CO2 over the life cycle of the ship ranges between 16 – 65 million Euros. It is noted that this is the result for the whole ship system (hull and machinery life cycle emissions are included). For **the case study of the Panamax oil tanker**, examined in this thesis, **the external cost per year has been estimated to double over the years of the ship's life**, **starting from (an average of) one million Euros to account for two million Euros (in year twenty-five**).

13.1.5 Contribution No5: Impact of ship emissions in port areas

Health impacts of ship air emissions in port areas have been examined in Chapter 12. The methodology (the impact pathway approach) considers ship emissions at port as similar to emissions from stationary sources. Then it uses meteo data for modelling the dispersion of air pollutants together with population data and exposure response functions to assess the external cost in human health. Open-source software has been used for modelling the dispersion of air pollutants. The results are monetary values of the annual impact of ships to human health.

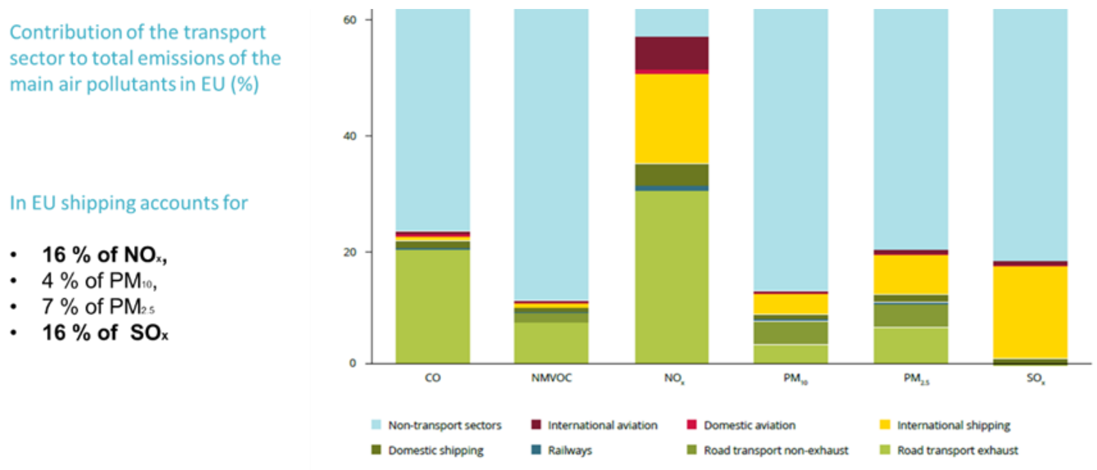
One important finding of the port emissions study (for Piraeus port) is that ship emissions are not negligible.

The ship air pollutant with the biggest mortality external cost as well as the biggest morbidity external cost is PM_2.

The results show that **the health impact of ship port emissions** in Piraeus **is not negligible** although it is much less than costs from other sectors for which comparisons have been available (**8 percent of the external cost from road transport**).

The literature indicates that the **broader industrial sector impose an annual external cost of 25.9 € to an Athens inhabitant**, and according to the results of the study, **the port emissions of Piraeus add only a 1.4 €**.

Recent studies show that the contribution of shipping in air pollution is increasing. This is partially attributed to the quality of marine fuels which contain higher sulphur content and particulates compared to other transport modes. The TERM 2017 report of EEA reveals that shipping in EU is responsible for 16 percent of SOx and 16 percent of NOx emissions (see Figure 108).



Contribution of the transport sector to total emissions of the main air pollutants in EU (%)

In EU shipping accounts for

- **16 % of NO_x,**
- 4 % of PM_{10},
- 7 % of $PM_{2.5}$
- **16 % of SO_x**

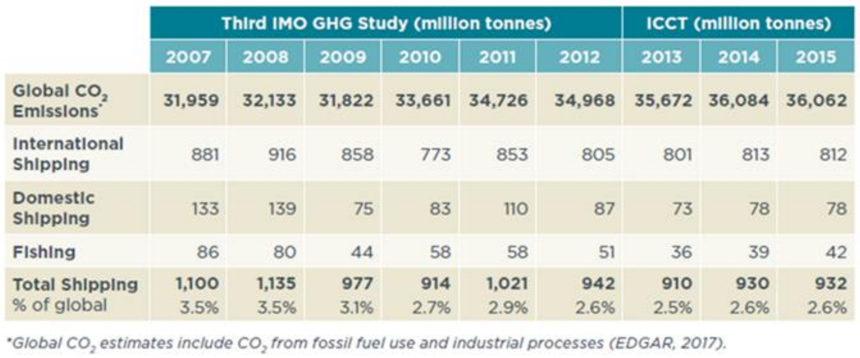
Figure 108: Aviation and shipping — impacts on Europe's environment TERM 2017: Transport and Environment Reporting Mechanism (TERM) report (European Environmental Agency, 2018)

Since SOx, NOx, and PM emissions, are responsible for increasing the health (external) cost, the combating of these emissions is getting more and more important at European level and global level. The so called Sulphur Cap which enters into force in 2020 is one of the most well-known policies at global level to internalise the external cost of shipping.

13.2 Policy update

An update on the recent policy developments in the field of ship air emissions is provided in this paragraph. From 2016, where the work of this thesis was finalised there are some important developments in the policy level that make this update essential.

An update on the GHG emissions from International shipping comes first (see Figure 109). Currently International shipping emits less than 1000 million tonnes of CO2 annually and is responsible for about 2.6% of global greenhouse gas emissions (ICCT, 2017).



	Third IMO GHG Study (million tonnes)						ICCT (million tonnes)		
	2007	2008	2009	2010	2011	2012	2013	2014	2015
Global CO_2 Emissions*	31,959	32,133	31,822	33,661	34,726	34,968	35,672	36,084	36,062
International Shipping	881	916	858	773	853	805	801	813	812
Domestic Shipping	133	139	75	83	110	87	73	78	78
Fishing	86	80	44	58	58	51	36	39	42
Total Shipping % of global	1,100 3.5%	1,135 3.5%	977 3.1%	914 2.7%	1,021 2.9%	942 2.6%	910 2.5%	930 2.6%	932 2.6%

**Global CO_2 estimates include CO_2 from fossil fuel use and industrial processes (EDGAR, 2017).*

Figure 109: Update on Global shipping GHG emissions (ICCT, 2017)

Yet, shipping GHG emissions are expected to increase between 50% and 250% by 2050 – depending on future economic and energy developments. This is not compatible with the internationally agreed goal adopted in 2015, the so-called Paris Agreement that has set the specific goal of holding global warming to well below 2 degrees Celsius (°C) compared to pre-industrial levels, and of pursuing efforts to limit it to 1.5°C (UNEP, 2017). To meet these targets the shipping sector will have to cut in half the worldwide GHG by 2050 (compared to 1990 levels).

In October 2016, the Marine Environment Protection Committee (MEPC) of IMO adopted a Global Data Collection System (DCS), in Regulation 22A entitled "Collection and reporting of ship fuel oil consumption data" as part of MARPOL Annex VI. The regulation applies to ships above 5000 GT on international voyages and it has many similarities with the MRV regulation of EU. From 01 January 2019, all ships, to which this regulation applies, have to collect and report to their administration the following data

- Fuel consumption, by fuel type, in metric tonnes
- Methods used for collecting fuel consumption data
- Distance travelled
- Hours underway

The timeline and responsibilities of ships and verification bodies as set in the DCS are shown below (Figure 110).

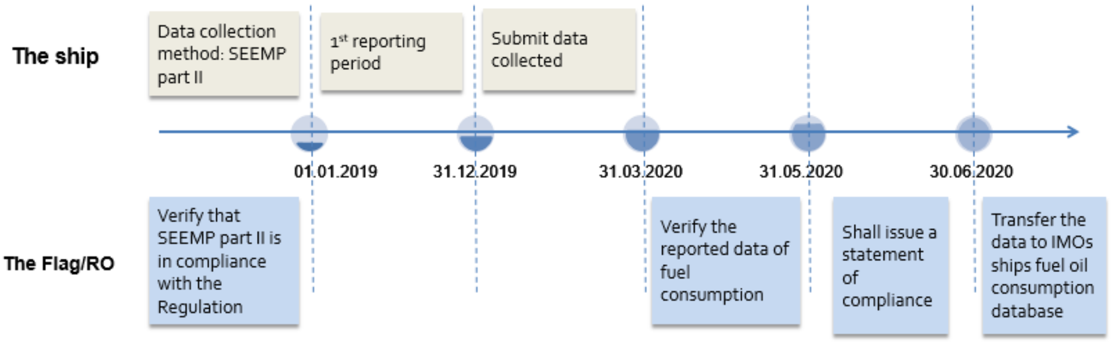
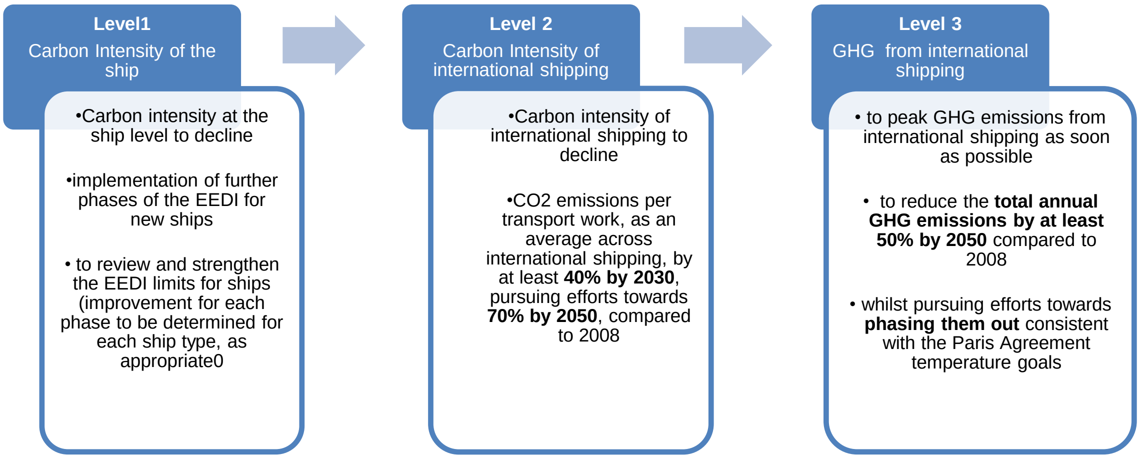


Figure 110: Timeline and responsibilities for the Data Collection Scheme, DCS of IMO.

In April 2018, IMO set an Initial Strategy on the reduction of greenhouse gas emissions (GHG) from shipping as the outcome of MEPC 72. With the information obtained from the implementation of the Data Collection System of IMO, this strategy will be reviewed and finalised until 2023.

The main points of this strategy are categorised in three levels of ambition as follows (see also Figure 111):

- The energy efficiency design requirements for ships are to be reviewed and strengthened (by 2023)
- The total annual GHG emissions to be reduced by at least 50% by 2050 compared to 2008, whilst pursuing efforts towards phasing them out, thus decarbonizing international shipping (by 2050)
- The strategy includes candidate short-, mid- and long-term measures with respective timelines



Level1
Carbon Intensity of the ship

- •Carbon intensity at the ship level to decline
- •implementation of further phases of the EEDI for new ships
- • to review and strengthen the EEDI limits for ships (improvement for each phase to be determined for each ship type, as appropriate0

Level 2
Carbon Intensity of international shipping

- •Carbon intensity of international shipping to decline
- •CO2 emissions per transport work, as an average across international shipping, by at least **40% by 2030**, pursuing efforts towards **70% by 2050**, compared to 2008

Level 3
GHG from international shipping

- • to peak GHG emissions from international shipping as soon as possible
- • to reduce the **total annual GHG emissions by at least 50% by 2050** compared to 2008
- • whilst pursuing efforts towards **phasing them out** consistent with the Paris Agreement temperature goals

Figure 111: The levels of the GHG strategy of IMO as agreed in MEPC 72.

Candidate measures that have been discussed in MEPC 72 and proposed by IMO for the three levels are shown below (IMO, 2018):

1. Short term measures (2018 – 2023)
    - Energy efficiency with focus on EEDI and SEEMP
    - Progress energy efficiency measures for new and existing ships
    - Analyse the use of speed reduction/speed optimisation as measure
    - Address the methane emissions and further address VOCs
    - Boost R&D to address marine propulsion and innovative technologies
    - Incentives for first movers to take-up new technologies
    - Undertake additional GHG studies to inform policy decisions

2. Mid-term measures (2023 – 2030)
    - Effective uptake of alternative low-carbon and zero carbon fuels
    - New emission reductions mechanisms, including market based measures
    - Enhance energy efficiency performance through operational energy measures

3. Long term measures (2030 and beyond)
    - Pursue the development of zero-carbon or fossil-free fuels in order to reach the goal of de-carbonization in the second half of the century
    - Consider other possible new/innovative emission reduction mechanisms

14. CONCLUSION

This thesis launces a definition for what means a sustainable maritime transport system and links this definition with three essential principles that this system has to observe (efficient accessibility, resources constrains, and equity). The aim is to contribute in the discussion for redefining the sustainability concept for the maritime transport sector, by following the initial notion of this concept. The definition was compared to other similar definitions that were launched later (two years after the publication of the author's work in the field), by IMO and other industry initiatives. It is evident that this discussion is ongoing since the concept of sustainability is receiving additional attention recently, especially now that the UN have adopted, a new strategy for the global sustainable development (effective from 2016).

From the three pillars (or areas of protection) of sustainability, this thesis mainly elaborated on the environmental pillar. The economic pillar is covered partially in the impact assessment chapters with the external cost approach. The societal pillar is covered partially in the impact assessment (i.e. estimation of health external cost produced by ship emissions). Overall, the sustainability of maritime transport, has been discussed in a theoretical context in this thesis, and methods and tools for assessing the different pillars of sustainability have been developed. At the best knowledge of the author, no framework for an integrated sustainability assessment exists for the time being. Hence, this is an area that future research should focus on.

The Life Cycle Thinking approach represents a transition from traditional environmental protection strategies towards the concept of sustainability. Life Cycle Thinking also reflects the growing awareness of modern societies about the real life cycle impacts of products and services. The full life cycle of the system, (i.e. the ship) has to be considered in such an analysis: from raw material production, through transportation, assembly, operational life, up to the recycling and final disposal of wastes. The importance of the life cycle thinking in environmental assessments is highlighted by the inclusion of Life Cycle Thinking as the most important amendment in the revised ISO 14001:2015, which was launched in September 2015 and in other initiatives worldwide.

A new Ship Life Cycle Framework was developed in this thesis, which observes the principles of the Life Cycle Assessment method together with a software that can handle these calculations for different ships and various operating profiles. Ship LCA is time-consuming and needs a large amount of input data in order to be effective. Shipbuilding and ship recycling have pointed out as the weakest areas in this respect.

Four case studies conducted which have made use of the life cycle framework to develop Life Cycle Inventories of ship emissions. The uncertainty in such estimations was examined and the outcome is a probabilistic model which approaches in a satisfactory way the real fuel consumption of the ship (compared to real noon report data). This work may be appropriate to assist shipping companies complying with new regulations (the EU MRV, and the IMO DCS), that require the accurate reporting of fuel consumption and emissions from ships.

One of the main contributions of this thesis is in the area of the impact assessment of ship emissions. Impact assessment studies are not widely available for the case of ships. Studying the impact of air emissions, is in line with the European official policy that asks for a better understanding on how air pollution is affecting humans, ecosystems and the climate and subsequently the society and the economy.

This thesis has elaborated two separate approaches for the impact assessment of ships. The first approach is the Life Cycle Impact Assessment (LCIA), which has extensive applications in other industrial sectors and uses specific methodologies for the calculation of impacts. The second approach evaluates the impact of ship emissions with the concept of external cost.

Ship air emissions may have local and global effects to human health and ecosystems and these were handled in the impact assessment work. In this context, a study conducted for the impact assessment of ship emissions in port areas. The study took into account the characteristics of the emissions but also the specific features of the area where these occurred as well as the receptors affected by these emissions.

The evaluation of external cost of ship emissions remains a challenge especially for the case of GHG emissions. The wide range of existing monetization values for CO_2 emissions is illustrative in this respect. This thesis has made estimates for the annual external cost of CO_2 which range from 1 to 2 million Euros for a typical panamax oil tanker. New regulations (i.e. the EU MRV) will support policy makers to eventually enforce market based measures for shipping. Sound inventories of emissions will be essential to support the introduction of these market based measures. Data will be soon available due to the MRV and DCS, and the shipping industry, the shipping companies, and class societies, will have to exploit them in order to perform more robust assessments. In response, shipping companies are starting to install automated systems for continuously monitoring energy related info onboard their ships. These systems create big data which can be analysed to provide robust emissions inventories at the ship level and improve the environmental performance of ships. The digitalisation era which shipping is entering into, will soon assist these developments.

International shipping has seen its environmental agenda growing rapidly in recent years. Within six years from now (Dec 2018), the international shipping industry will have to face the enforcement of new regulations that cover different environmental drivers (sulphur emissions, ballast water, hazardous materials in recycling, and GHG to name only the confirmed ones). To comply with these regulations, ships will have to be retrofitted with expensive equipment, use more expensive fuels, or change their operating profile among other solutions. Yet, this “greening” process has to be in harmony with the economic performance of ships, and shipping companies, therefore the quest is for win-win solutions (Psaraftis, 2016). This extreme pressure to shipping, needs to be better supported from sound evidence about the real pressures posed by ships to the environment and human health. In this direction, substantial support can be offered from impact assessment studies similar to those conducted in this thesis. Finally, the timeline of enforcement of new regulations would be probably more justifiable if a prioritisation of the importance of ship environmental drivers would be made feasible. The above illustrate the necessity for additional emphasis on ship environmental impact assessments in the future.

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15. APPENDIX 1 – EEDI BASELINE CALCULATION

15.1 EEDI Assumptions as per IMO/MEPC 60

In MEPC 60 new assumptions were agreed regarding the method for calculation of EEDI baselines for different ship types. To calculate the exact index value for each ship, the following assumptions should be made[3]:

1. Carbon emission factor is constant for all engines, i.e. $C_{F\text{-}ME} = C_{F\text{-}AE} = C_F = 3.1144$ g CO2/g fuel (previous value: 3.14 g CO2/G fuel);
2. The specific fuel consumption for all ship types is constant for all main engines, i.e. $SFC_{ME} = 190$ g/kWh.;
3. The specific fuel consumption for all ship types is constant for all auxiliary engines, i.e. $SFC_{AE} = 215$ g/kWh (previous value: 210 g/kWh);
4. $P_{ME(I)}$ is 75% of the rated installed power (MCR) for each main engine without any deduction for shaft generator
5. For main engines with a rated installed power (MCR) below 10,000 kW, PAE is expressed as 5% of the main engine MCR.

$$P_{AE(MCRME<10000KW)} = 0{,}05 \times \sum_{i=1}^{nME} MCR_{MEi}$$

6. For main engines with an MCR of 10,000 kW or above, P_{AE} is expressed as 2.5% of the main engine MCR plus a constant hotel load.

$$P_{AE(MCRME>10000KW)} = \left(0{,}025 \times \sum_{i=1}^{nME} MCR_{MEi}\right) + 250\,;$$

7. All correction factors f_j, f_i and f_w are set to 1;
8. Innovative mechanical energy efficiency technology, shaft motors and other innovative energy efficient technologies are all excluded from the baseline calculation, i.e. $P_{AEeff} = 0$, $P_{PTI} = 0$, $P_{eff} = 0$.

The equation for calculating the estimated index value should be as follows:

$$Estimated\ Index\ Value = 3.11 \cdot \frac{190 \cdot \sum_{i=1}^{NME} P_{MEi} + 215 \cdot P_{AE}}{Capacity \cdot V_{ref}}$$

The 60th MEPC concluded that in light of the changes made in the assumptions of the EEDI simple formula, new calculations should be conducted and submitted for the establishment of the EEDI baselines for new ships.

Regarding the applicability of the EEDI it is widely acknowledged that the current approach could be feasible, with certain reservations, for oceangoing cargo ships which have uniform design criteria. In practice this means tankers, bulk carriers,

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[3] Doc MEPC 60/WP9 Annex 4

containerships, LNG-carriers, LPG carriers, RoRo vehicle carriers and largest general cargo ships. It is reasonable to set CO2 limits firstly for these ship types since they account for the vast majority of emissions from shipping.

In the context of a research synergy with ABS Class Society, the author has performed new EEDI baseline calculations for the three major ship types i.e. tankers, containerships, and dry cargo carriers (bulk carriers). The results are presented and discussed in this appendix.

15.2 Updated EEDI for Containerships

As regards containerships, MEPC 59 approved a change in the capacity factor to be utilized in the EEDI formula, from 75% DWT to 65% DWT, for reasons of targeting ship optimization at a value that better reflects normal operating conditions in the container trades. This has been incorporated in our analysis. This analysis has utilised the Lloyd's Fairplay (SeaWeb) database and the containerships included are of fully cellular type in accordance with the definitions of ship types given in MEPC.1/Circ.68. The data sample concerns relatively new designs (built 1999 – 2009) and the harvested information includes vessel's details such as:

1. DWT,
2. Displacement,
3. Service speed,
4. Number and Type of main engine(s) (2-stroke, 4-stroke),
5. Total main engine(s) installed power,
6. Total daily fuel consumption (main and auxiliary engines),
7. L_{BP}, B, T_{MAX}, D, and
8. TEU capacity.

The following table summarises the initial and final utilised containerships data sample for the calculation of the EEDI baseline. From the initial number of 2520 ships obtained, 40 ships excluded due to inadequate or missing data. The final EEDI baseline curve has derived by excluding another 109 ships, which considered outliers (with more than two standard deviations from the baseline).

Figure 112: Containerships data sample for the EEDI baseline calculations

Containerships fleet: +400 gt (built 1999 – 2009)	
Initial	2520
Utilised	2480 (40 with missing data)
EEDI baseline	2371 (109 outliers)

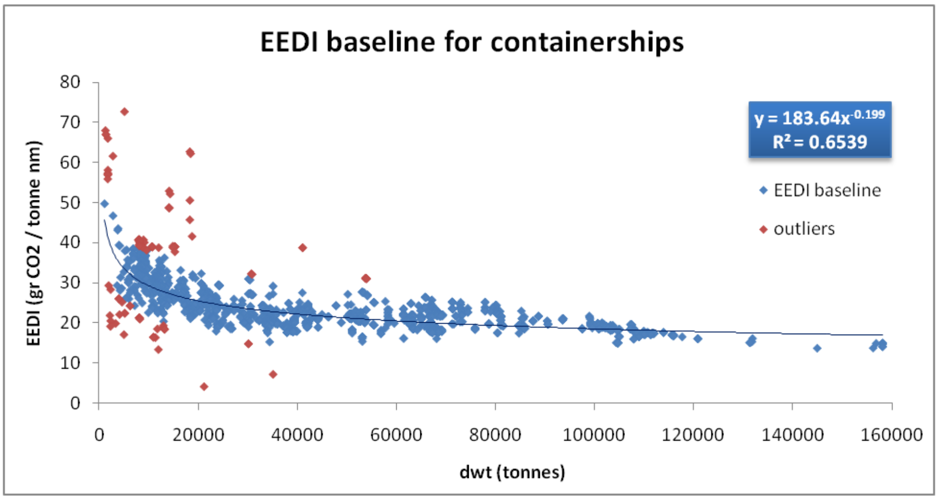

Figure 113: Updated EEDI baseline for containerships

The final EEDI baseline curve is shown in the Figure above. This is very close to other submitted proposals for EEDI baselines. For example, the collaborative submission of Denmark, the Marshall Islands and the World Shipping Council[4], resulted in the curve described by the equation: $y = 214.44\ x^{-0.216}$ ($R^2 = 0.6565$). It is noted that the aforementioned study has utilised slightly different data sample. Our analysis (in accordance to MEPC 60 recommendations) has included container vessels of 400+ gt built within the period 1999 – 2009, whereas the collaborative submission included container vessels with 400+ gt built within the period 1998 – 2007.

15.3 Updated EEDI for Tankers

The updated EEDI baseline curve for the tankers fleet is shown in Figure 79. The red points are outliers i.e. points with two or more standard deviations that were excluded from the final EEDI regression formula. According to MEPC.1/Circ.68**,** all the following tanker types should be included in the calculations: oil tankers (i.e. crude, product, asphalt, coal, unspecified), chemical (i.e. chemical/products, molten sulphur, wine, vegetable oil, edible oil, beer, latex, fruit juice, and parcels), and other liquids (i.e. water, molasses, glue, alcohol). Table 70, shows the initial tankers data sample, the utilised sample and the final sample from which the baseline has derived. All ships in the sample concern relatively new designs (built: 1999 – 2009).

Table 70: Tankers data sample for the EEDI baseline calculations

Tankers fleet: +150 gt (built 1999 – 2009)	
Initial	4387
Utilised	3839 (548 with missing data)
EEDI baseline	3729 (110 outliers)

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[4] Doc MEPC 60/4/14 submitted by Denmark, the Marshall Islands and the World Shipping Council

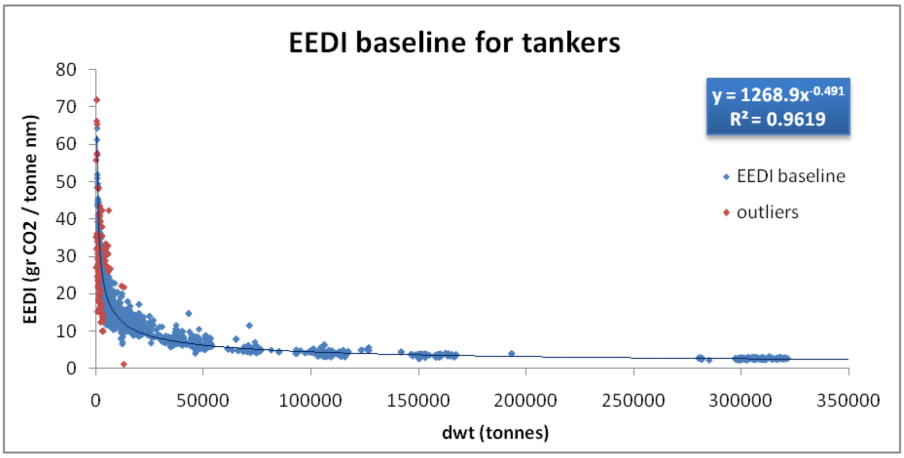

Figure 114: Updated EEDI baseline for tankers

The results show that for the tankers of size lower than 25,000 dwt, there is big scatter in the index values. Actually all outliers are ships with dwt lower than 25,000 tonnes. This size category includes tankers with high variations in design, (i.e. product tankers, chemical tankers, shuttle tankers, other special purpose tankers), speed and installed power leading the basic approach of EEDI to be less feasible for these tankers. The applicability of the EEDI baseline formula in the lower dwt ranges has been widely debated[5,6] and proposals have been made to IMO to avoid including vessels with dwt lower than 20,000 tonnes in the baseline standards.

For the formulation of baselines for tankers, it should be considered whether the baseline should be defined separately for the different size classes such as Panamax, Suezmax, and VLCC's. This is since in the current definition of baselines ships bigger or smaller than the examined category effect on baseline value. This could make the requirement too easy or too tight in some cases.

15.4 Updated EEDI for Bulk Carriers

The ship types that should be included in this category according to MEPC.1/Circ.68 are those described as dry cargo carriers. A dry cargo carrier may be found in the SeaWeb database as: single deck bulk carrier, ore carrier, bulk carrier self-discharging, cement carrier, wood chips carrier, urea carrier, aggregates or sand carrier, and limestone carrier. Newly built ships were included (1999 – 2009) and the sample is given in the following Table 71. The updated regression formula is shown in Figure 115. Red coloured points in this Figure illustrate the outliers that excluded from the final regression formula (two or more standard deviations).

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[5] GHG-WG 2/2/1. Input to further development of the Energy Efficiency Design Index. Submitted by the Netherlands

[6] Centre for Maritime Technology and Innovation, CMTI (2009). The IMO Energy Efficiency Design Index. A Netherlands Trend Study

Table 71: Bulk carriers' data sample for the EEDI baseline calculations

Bulk carriers fleet: +150 gt (built 1999 – 2009)	
Initial	2692
Utilised	2556 (136 with missing data)
EEDI baseline	2486 (70 outliers)

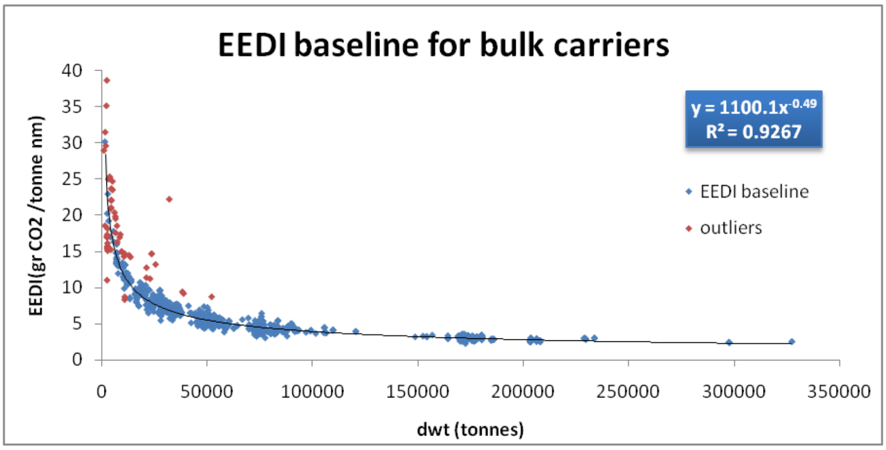


Figure 115: Updated EEDI baseline for bulk carriers

As stated previously within the bulk carriers' category several special sub-types differ in terms of lightweight, installed power and main particulars. This poses challenges in the formulation of the EEDI baseline and it should be further examined whether certain sub types should be excluded from the scheme, or special correction factors should be introduced for these ships. In modern bulk carriers, the optimization of design criteria has led to quite constant design speed of the vessels, which varies typically between 14 and 16 knots. The trend for ships smaller than 25,000 dwt is similar as with tankers. In smaller ships, the design speed varies from 11 to 16 knots and therefore installed engine power and thus the EEDI value have higher scatter (bandwidth). This is illustrated also by the fact that nearly all outliers are ships in this range of dwt.

15.5 Conclusion

The following table summarises the previous and latest EEDI Baseline results from the work that have been conducted in the context of the research synergy with ABS Class Society. The updated EEDI regression formulas show better fitting, with the containerships new formula being the most improved one.

Table 72: Comparison of EEDI baselines

	EEDI baseline (2009)		Updated EEDI baseline (2010)	
Tankers	$y = 591.84\,x^{-0.4816}$	$(R^2 = 0.9615)$	$y = 1268.9\,x^{-0.491}$	$(R^2 = 0.9619)$
Bulk Carriers	$y = 434.41\,x^{-0.4625}$	$(R^2 = 0.9056)$	$y = 1100.1\,x^{-0.490}$	$(R^2 = 0.9267)$
Containerships	$y = 20.119\,x^{-0.0952}$	$(R^2 = 0.1339)$	$y = 183.64\,x^{-0.199}$	$(R^2 = 0.6539)$

17. APPENDIX 2 – UNCERTAINTY IN FUEL CONSUMPTION CALCULATION

17.1 Uncertainty calculation in fuel consumption according to MRV

17.1.1 METHOD A - Bunker Delivery Note (BDN) and periodic stock takes of fuel tanks

Under existing MARPOL Annex VI regulations, the BDN is mandatory, is to be retained on board for three years after the delivery of the bunker fuel and is to be readily available. The periodic stocktake of fuel tanks on-board is based on fuel tank readings. It uses tank tables relevant to each fuel tank to determine the volume at the time of the fuel tank reading. The uncertainty associated with the BDN shall be specified in the monitoring plan. Fuel tank readings shall be carried out by appropriate methods such as automated systems, soundings and dip tapes. The method for tank sounding and uncertainty associated shall be specified in the monitoring plan.

The BDN has to contain at least the following information (MEPC.1/Circ.508):

1. name and IMO number of receiving ship;
2. port;
3. date of commencement of delivery;
4. name, address and telephone number of marine fuel oil supplier;
5. product name(s);
6. quantity (metric tons);
7. density at 15˚C (kg/m3);
8. sulphur content (% m/m); and
9. a declaration signed and certified by the fuel oil supplier’s representative that the fuel oil supplied is in conformity with regulation 14(1) or (4)(a)and Regulation 18(1) of MARPOL Annex VI.

To verify the reported fuel consumption data it should ideally be ensured that all BDNs that a ship has received are presented. According to Regulation 18 of MARPOL Annex VI, the bunker delivery notes have to be maintained on-board for a period of not less than three years following the delivery.

-A ship has received BDNs for all its bunkering operations.

-The BDNs presented are not falsified

The Period is the time between two port calls or time within a port.

Port of call is the port where a ship stops to load or unload cargo or to embark or disembark passengers; consequently, stops for refuelling, obtaining supplies, relieving the crew, going into dry-dock or making repairs to the ship and/or its equipment, stops in port because the ship is in need of assistance or in distress, ship-to-ship transfers carried out outside ports, and stops for the sole purpose of taking shelter from adverse weather or rendered necessary by search and rescue activities are excluded.

Quantity of fuel consumed for a period N is equal to the Quantity of fuel delivered in the period N minus the Quantity of fuel de-bunkered in the period N plus the difference between the Stock of fuel at the beginning of the period and the Stock of fuel at the end of the period.

The equation to calculate Q is as follows

$$\mathbf{Q=P-E+(S_b-S_{end})}$$

Where

Q	Quantity of fuel consumed for a period N
P	Quantity of fuel delivered in the period N
E	Quantity of fuel de-bunkered in the period N
S_B	Stock of fuel at the beginning of the period
S_{end}	Stock of fuel at the end of the period

According to EU MRV uncertainty means a parameter, associated with the result of the determination of a quantity, that characterises the dispersion of the values that could reasonably be attributed to the particular quantity, including the effects of systematic as well as of random factors, expressed as a percentage, and describes a confidence interval around the mean value comprising 95 % of inferred values taking into account any asymmetry of the distribution of values;

Under the assumption that no fuel oil is de-bunkered, the uncertainty can be expressed as follows:

$$u_Q = \frac{\sqrt{(U_S)^2 + (U_S)^2 + (U_{P1})^2 + .. + (U_{Pn})^2}}{P + (S_B - S_{end})}$$

Where

u_Q	total (relative) uncertainty associated with Q (in litres)
$\mathrm{U_S}$	(absolute) uncertainty of the stock level reading
$\mathrm{U_{Pn}}$	(absolute) uncertainty of the quantity delivered

Then the previous equation can be expressed as:

$$u_Q = \frac{\sqrt{(u_S \times S_b)^2 + (u_S \times S_{end})^2 + (u_{P1} \times P_1)^2 + .. + (u_{Pn} \times P_n)^2}}{P + (S_B - S_{end})}$$

$$u_Q = \frac{\sqrt{2 \times (u_S \times S)^2 + (u_{P1} \times P_1)^2 + .. + (u_{Pn} \times P_n)^2}}{P + (S_B - S_{end})}$$

Where

S is the max Quantity in the tank, which is equal to the capacity of the fuel tank.

Finally, as the activity data related to fuel consumption have to be expressed in tonnes, the density of the fuel has to be taken into account.

This can be expressed considering the following formula

$$u_{Qtonnes} = \sqrt{(u_d)^2 + \left(u_{Qlitres}\right)^2}$$

Where, u_d is the relative uncertainty density of fuel.

18. APPENDIX 3: UPDATED EXTERNAL COST VALUES FOR TRANSPORT AIR EMISSIONS

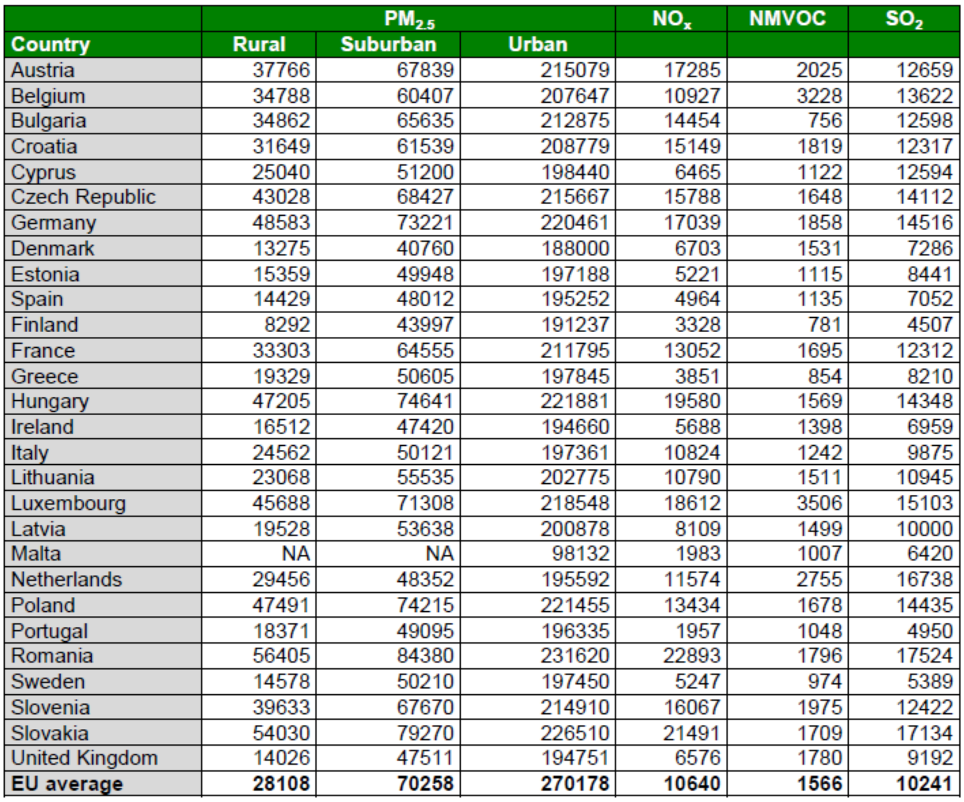
Update of the Handbook on External Costs of Transport

Report for the European Commission: DG MOVE

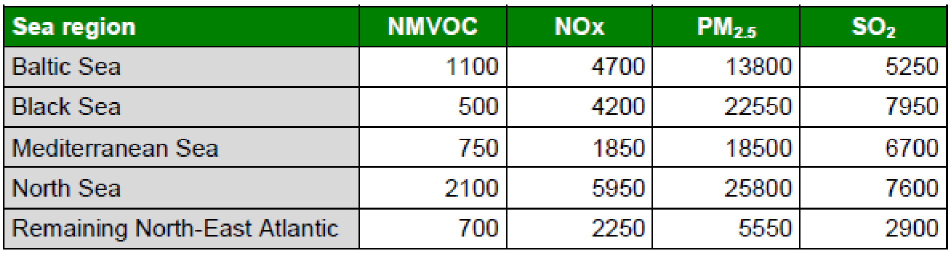
Ricardo-AEA/R/ ED57769 Issue Number 1

8th January 2014

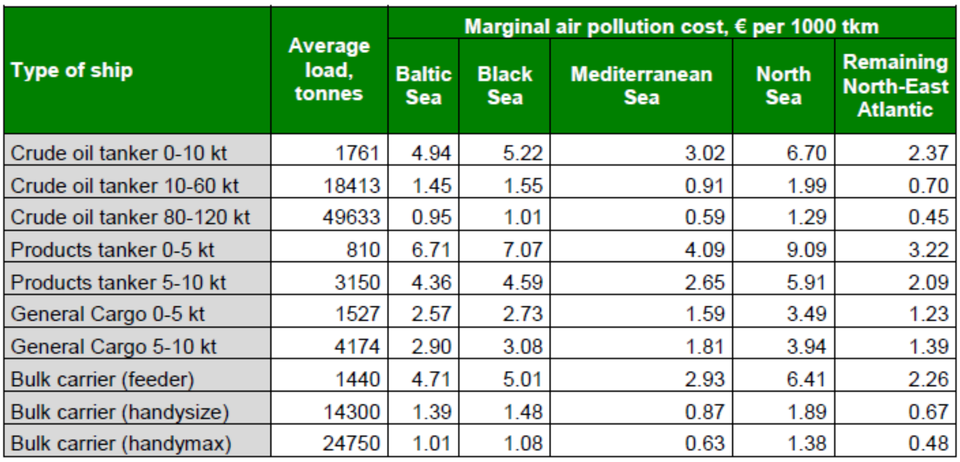
Damage costs of main pollutants from transport, in € per tonne (2010)



	$PM_{2.5}$			NO_x	NMVOC	SO_2
Country	**Rural**	**Suburban**	**Urban**			
Austria	37766	67839	215079	17285	2025	12659
Belgium	34788	60407	207647	10927	3228	13622
Bulgaria	34862	65635	212875	14454	756	12598
Croatia	31649	61539	208779	15149	1819	12317
Cyprus	25040	51200	198440	6465	1122	12594
Czech Republic	43028	68427	215667	15788	1648	14112
Germany	48583	73221	220461	17039	1858	14516
Denmark	13275	40760	188000	6703	1531	7286
Estonia	15359	49948	197188	5221	1115	8441
Spain	14429	48012	195252	4964	1135	7052
Finland	8292	43997	191237	3328	781	4507
France	33303	64555	211795	13052	1695	12312
Greece	19329	50605	197845	3851	854	8210
Hungary	47205	74641	221881	19580	1569	14348
Ireland	16512	47420	194660	5688	1398	6959
Italy	24562	50121	197361	10824	1242	9875
Lithuania	23068	55535	202775	10790	1511	10945
Luxembourg	45688	71308	218548	18612	3506	15103
Latvia	19528	53638	200878	8109	1499	10000
Malta	NA	NA	98132	1983	1007	6420
Netherlands	29456	48352	195592	11574	2755	16738
Poland	47491	74215	221455	13434	1678	14435
Portugal	18371	49095	196335	1957	1048	4950
Romania	56405	84380	231620	22893	1796	17524
Sweden	14578	50210	197450	5247	974	5389
Slovenia	39633	67670	214910	16067	1975	12422
Slovakia	54030	79270	226510	21491	1709	17134
United Kingdom	14026	47511	194751	6576	1780	9192
EU average	**28108**	**70258**	**270178**	**10640**	**1566**	**10241**



Sea region	**NMVOC**	**NOx**	**$PM_{2.5}$**	**SO_2**
Baltic Sea	1100	4700	13800	5250
Black Sea	500	4200	22550	7950
Mediterranean Sea	750	1850	18500	6700
North Sea	2100	5950	25800	7600
Remaining North-East Atlantic	700	2250	5550	2900



Type of ship	Average load, tonnes	Marginal air pollution cost, € per 1000 tkm				
		Baltic Sea	Black Sea	Mediterranean Sea	North Sea	Remaining North-East Atlantic
Crude oil tanker 0-10 kt	1761	4.94	5.22	3.02	6.70	2.37
Crude oil tanker 10-60 kt	18413	1.45	1.55	0.91	1.99	0.70
Crude oil tanker 80-120 kt	49633	0.95	1.01	0.59	1.29	0.45
Products tanker 0-5 kt	810	6.71	7.07	4.09	9.09	3.22
Products tanker 5-10 kt	3150	4.36	4.59	2.65	5.91	2.09
General Cargo 0-5 kt	1527	2.57	2.73	1.59	3.49	1.23
General Cargo 5-10 kt	4174	2.90	3.08	1.81	3.94	1.39
Bulk carrier (feeder)	1440	4.71	5.01	2.93	6.41	2.26
Bulk carrier (handysize)	14300	1.39	1.48	0.87	1.89	0.67
Bulk carrier (handymax)	24750	1.01	1.08	0.63	1.38	0.48

19. APPENDIX 4 - IMPACT ASSESSMENT CASE STUDY

19.1 Input - Operating profile of the ship

Table 73: Main particulars – Containership

Gross Tonnage, GT	tons	40030
Deadweight, DWT	tons	50636.7
Light Ship weight	tons	16555.7
Length overall, Loa	m	260
Lbp	m	244.8
Breadth, B	m	32.25
Depth, D	m	19.3
Maximum Draft, Tmax	m	12.626

Table 74: Machinery information – Containership LCA case study

Main Engine		Doosan-MAN B&W 8K90MC-C M
Auxiliary engines		Daihatsu 6DK-28
Installed power main engine	kW	36560
Installed power aux. engines	kW	4x1810
SFOC main engine	kg/kWh	171.9
SFOC aux. engines	kg/kWh	193
Fuel main engine		Residual fuel oil 2.7%S
Fuel aux. engine		Residual fuel oil 2.7%S

Table 75: Operational info – Containership LCA case study

Number of round trips	Round trips / year	7
Port calls	Calls / round trip	12
Crew and passengers	persons	22
Loading of main engine in maneuvering	%	15
Loading of aux engines in maneuvering	%	50
Loading of aux engines at port	%	50
Life cycle years	έτη	30
Distance covered in a round trip	nm/round trip	14570
Duration of a round trip	hours/round trip	1187.2
Maneuvering time	hours/ round trip	47.2
Time at port	hours/ round trip	172

Table 76: Maintenance info – Containership LCA case study

Frequency of hull painting	7.5 years (drydocking)
Frequency of painting for Topsides	7.5 years (drydocking)
Frequency of painting (Weather decks)	According to the specific needs
Frequency of painting (Superstructure)	
Frequency of painting (Cargo holds/tanks)	
Frequency of painting (Ballast tanks)	15 years

Frequency of anodes replacement	ς≥5χρόνια
Anodes weight (in ballast tanks)	1369.4 kg
Anodes weight (in hull)	442.4 + 35.2kg

Table 77: Coating surfaces – Containership

Wetted Surface	m^2	12245
Hull	m^2	4200
Topsides	m^2	4554
Weather decks	m^2	12748
Superstructure	m^2	3162
Cargo holds	m^2	59179
Ballast tanks	m^2	40522

Table 78: Wastes and garbage input – Containership

Sludge – Bilge – Grey/ Black waters - Garbage				
		Delivered to prf		***Produced onboard***
		Per port	Per trip	Per day
Sludge	m^3	-	48	0.8
Bilge	m^3	-	15	0.25
Liquid Oily	m^3	-	0.18	9.6
Solid Oily	ton	-	0.01	0.07
Black Water	m^3	-	0.3	18
Grey Water	m^3	-	7	350
Garbage*	ton	-	0.2	12

19.2 Life Cycle Inventory of the containership

Table 79: Life Cycle Inventory in Shipbuilding – Containership

Process	Area [7]	Pollutant	Unit	Quantity
Welding	Air	CO_2	kg	448
	Air	CH_4	kg	0.05
	Air	N_2O	kg	0.01
	Air	NO_X	kg	0.51
	Air	CO	kg	0.19
	Air	NMVOC	kg	0.02
	Air	SO_2	kg	0.92
Steel cutting	Air	CO_2	kg	48420
	Air	CH_4	kg	5.36
	Air	N_2O	kg	1.04
	Air	NO_X	kg	55.47
	Air	CO	kg	20.69
	Air	NMVOC	kg	2.30

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[7] Area of the life cycle impact

	Air	SO_2	kg	99.60
Coatings	Air	CO_2	kg	35616.54
	Air	CH_4	kg	3.94
	Air	N_2O	kg	0.77
	Air	NO_x	kg	40.80
	Air	CO	kg	15.22
	Air	NMVOC	kg	10615.42
	Air	SO_2	kg	73.26
Electricity	Air	CO_2	kg	116044
	Air	CH_4	kg	12.85
	Air	N_2O	kg	2.50
	Air	NO_x	kg	132.94
	Air	CO	kg	49.58
	Air	NMVOC	kg	5.51
	Air	SO_2	kg	238.70

Table 80: LCI in operation – Containership

Process	Area	Pollutant	Unit	Quantity
Engines operation – air emissions	Air	PM	kg	5287668
		CO_2	kg	2364965256
		CH_4	kg	44845
		N_2O	kg	121514
		NO_x	kg	57680351
		CO	kg	2084907
		NMVOC	kg	2284904
		SO_2	kg	40076820
Wastes	Ship-port	Sludge	litres	3789625
		Bilge	litres	9095100
		Liquid Oily	litres	606340
		Solid Oily	kg	113689
		Black Water	litres	4168588
		Grey Water	litres	34599276
		Garbage	kg	250115
Hull protection	Water	Anticorrosion material in sea	kg	33174
Ballast	Water	Water ballast	kg	1.00×10^9
Anodes	Water	Zinc	kg	90085
		Aluminum	kg	14175

Table 81: LCI in maintenance – Containership

Process	Area	Pollutant	Unit	Quantity
Sand blasting	Air	PM	kg	188.11
	Air	CO_2	kg	31947
	Air	CH_4	kg	0.40
	Air	N_2O	kg	1.49
	Air	NO_x	kg	359.93
	Air	CO	kg	23.72
	Air	NMVOC	kg	17.54

	Air	SO_2	kg	25.91
Coatings	Air	CO_2	kg	14994.64
	Air	CH_4	kg	1.66
	Air	N_2O	kg	0.32
	Air	NO_X	kg	17.18
	Air	CO	kg	6.41
	Air	NMVOC	kg	24512.74
	Air	SO_2	kg	30.84

Table 82: LCI in ship recycling – Containership

Process	Area	Pollutant	Unit	Quantity
Scrapping	Air	CO_2	kg	2980026
		Asbestos	kg	38028
		Ozone depleting substances	kg	69748

19.3 Life Cycle Impact Assessment Results

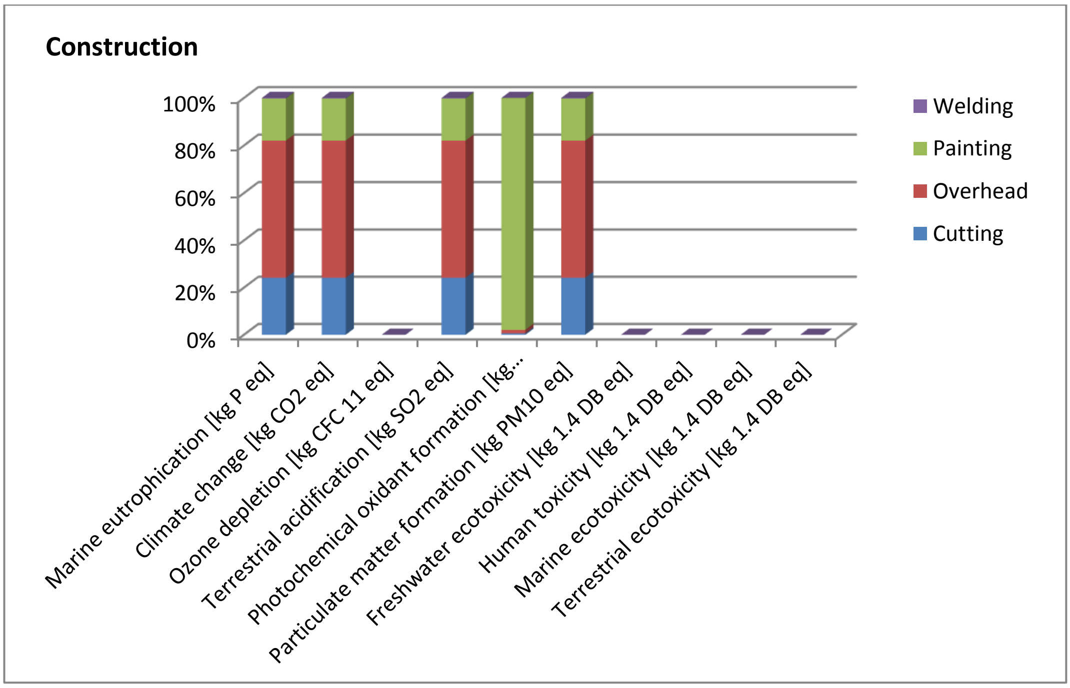

Figure 116: LCIA in shipbuilding - Containership

Table 83: Impact assessmenrt in shipbuilding per process – Containership

Environmental Phenomenon	Cutting	Electricity	Coating	Welding	TOTAL
Marine eutrophication [kg P_{eq}]	2.16	5.18	1.59	0.02	8.96
Climate change [kg $CO2_{eq}$]	48864.19	117109.95	35943.56	452.00	202369.70
Ozone depletion [kg CFC 11_{eq}]	0.00	0.00	0.00	0.00	0.00
Terrestrial acidification [kg SO2 eq]	130.66	313.14	96.11	1.21	541.12

Photochemical oxidant formation [kg NMVOC$_{eq}$]	66.84	160.19	10662.89	0.62	10890.54
Particulate matter formation [kg PM10$_{eq}$]	32.12	76.99	23.63	0.30	133.03
Freshwater ecotoxicity [kg 1.4 DB$_{eq}$]	0.00	0.00	0.00	0.00	0.00
Human toxicity [kg 1.4 DB$_{eq}$]	0.00	0.00	0.00	0.00	0.00
Marine ecotoxicity [kg 1.4 DB$_{eq}$]	0.00	0.00	0.00	0.00	0.00
Terrestrial ecotoxicity [kg 1.4 DB$_{eq}$]	0.00	0.00	0.00	0.00	0.00

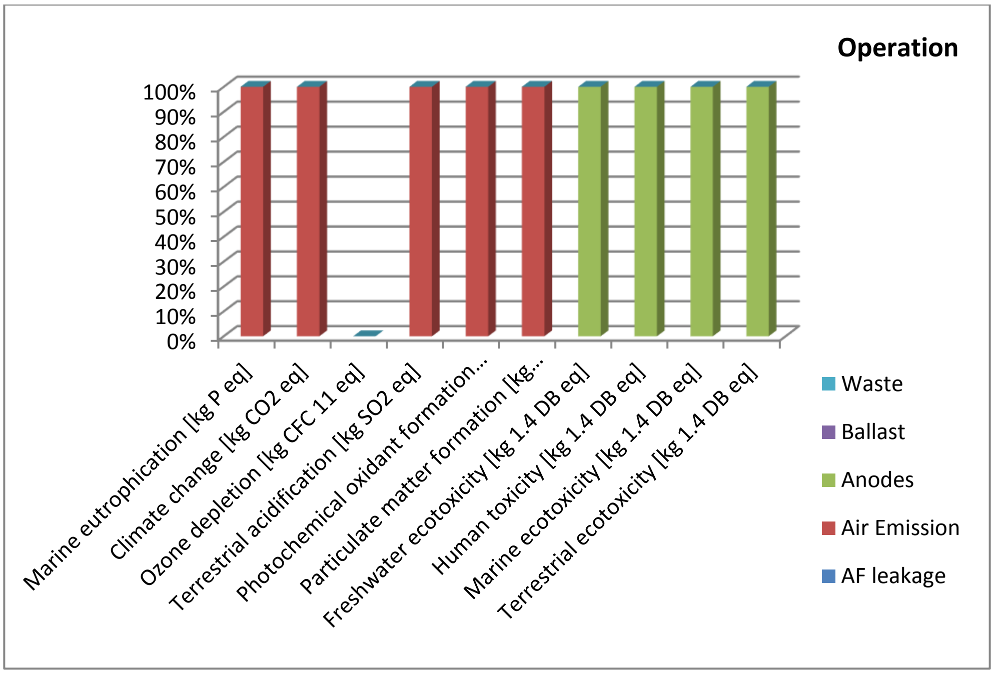

Figure 117: LCIA in operation – Containership

Table 84: Impact per process in operation – Containership

Environmental Phenomenon	**Air emissions**	**Anodes**	**TOTAL**
Marine eutrophication [kg P$_{eq}$]	2249534	0	2249534
Climate change [kg CO2$_{eq}$]	2402297526	0	2402297526
Ozone depletion [kg CFC 11$_{eq}$]	0	0	0
Terrestrial acidification [kg SO2 eq]	72377816	0	72377816
Photochemical oxidant formation [kg NMVOC$_{eq}$]	63310270	0	63310270
Particulate matter formation [kg PM10$_{eq}$]	25992709	0	25992709
Freshwater ecotoxicity [kg 1.4 DB$_{eq}$]	0	0	0
Human toxicity [kg 1.4 DB$_{eq}$]	0	1136275	1136275
Marine ecotoxicity [kg 1.4 DB$_{eq}$]	0	6267930	6267930
Terrestrial ecotoxicity [kg 1.4 DB$_{eq}$]	0	0	0

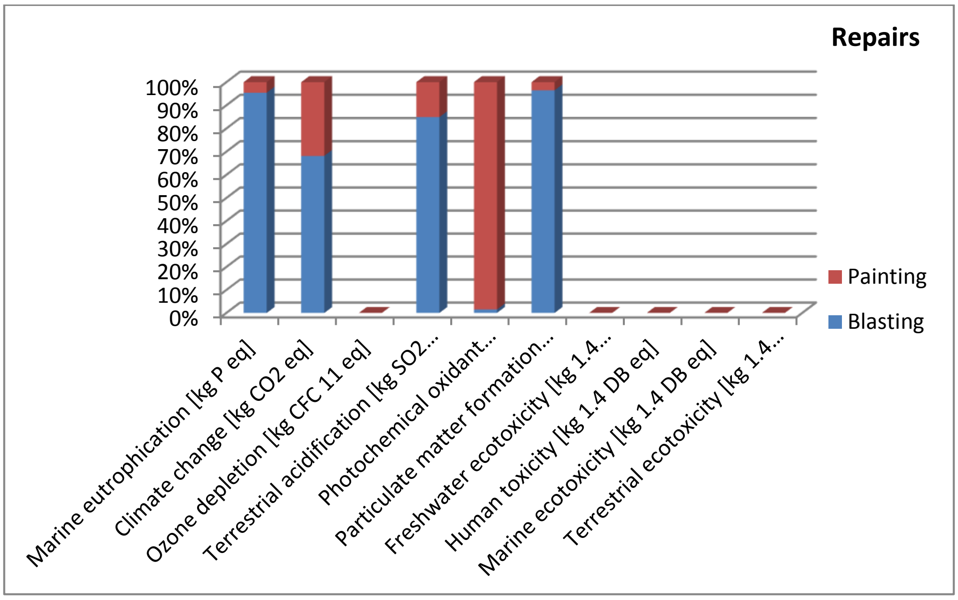

Figure 118: LCIA in srepairs - Containership

Table 85: Impact pr process in repairs – Containership

Environmental Phenomenon	Sandblasting	Coating	TOTAL
Marine eutrophication [kg P_{eq}]	14.04	0.67	14.71
Climate change [kg $CO2_{eq}$]	32402.51	15132.31	47534.83
Ozone depletion [kg CFC 11_{eq}]	0.00	0.00	0.00
Terrestrial acidification [kg SO2 eq]	227.47	40.46	267.93
Photochemical oxidant formation [kg $NMVOC_{eq}$]	380.65	45980.76	46361.41
Particulate matter formation [kg $PM10_{eq}$]	272.47	9.95	282.42
Freshwater ecotoxicity [kg 1.4 DB_{eq}]	0.00	0.00	0.00
Human toxicity [kg 1.4 DB_{eq}]	0.00	0.00	0.00
Marine ecotoxicity [kg 1.4 DB_{eq}]	0.00	0.00	0.00
Terrestrial ecotoxicity [kg 1.4 DB_{eq}]	0.00	0.00	0.00

Table 86: Impact per process in recycling – Containership

Environmental phenomenon	TOTAL
Marine eutrophication [kg P_{eq}]	0.00
Climate change [kg $CO2_{eq}$]	2982465.36
Ozone depletion [kg CFC 11_{eq}]	0.63
Terrestrial acidification [kg SO2 eq]	0.00
Photochemical oxidant formation [kg $NMVOC_{eq}$]	0.00
Particulate matter formation [kg $PM10_{eq}$]	0.00
Freshwater ecotoxicity [kg 1.4 DB_{eq}]	0.00
Human toxicity [kg 1.4 DB_{eq}]	10.14
Marine ecotoxicity [kg 1.4 DB_{eq}]	0.00
Terrestrial ecotoxicity [kg 1.4 DB_{eq}]	0.00