A NOVEL APPROACH TO ENVIRONMENTAL ASSESSMENT OF SHIPS – DEVELOPMENT OF A PERFORMANCE INDEX FOR SHIP OPERATION

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Abstract

Shipping has a considerable impact on the environment due to operational and accidental pollutant releases. Maritime environmental legislation has tightened in recent years since the introduction of the MARPOL 73/78 regulations, however there is often a significant time gap between when the regulations are adopted and when they legally enter force. The emergence of private voluntary initiatives has occurred in an attempt to bridge this gap, reduce environmental impacts and raise the environmental profile of ships. However, there are inconsistencies in the methodologies used to define ship performance, while the number and diversity of initiatives available for use can cause confusion, hindering progress towards greater sustainability.

A critical analysis of existing environmental initiatives in the shipping industry has been conducted, highlighting limitations with regards to applicability, scope, ambition, and integrity of the methodologies adopted. Many of the existing initiatives lack the flexibility to be ship specific and show bias towards certain environmental indicators, and lack the ambition to set stringent standards. Many of the schemes use proxy indicators based on design criteria as a measure of environmental performance rather than actual emissions and discharges.

An alternative approach to environmental assessment of ships is proposed which offers a holistic method of assessment, can be applied to multiple vessel types using a broad, relevant scope based on environmental impacts, and assesses performance based on actual emissions and discharges of pollutants to the environment. The proposed method, the VEP index, adopts a risk assessment based methodology and is intended as a holistic framework for assessment of ship environmental performance. The VEP index is rigorously tested using operational data from two case study vessels. The results clearly distinguish which of the vessels performs better environmentally, and highlight the suitability of the index for comparing vessel environmental performance. When compared with other indices used in the shipping sector, the VEP index provides a more accurate assessment of environmental performance based on ships' operational emissions.

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My PhD journey has transcended a period of significant change in my life, in which I have overcome many challenges, and enjoyed some of the proudest moments in my life to date. On completion of this thesis, I look forward to exploring new ventures, and feel a sense of excitement as to what the future holds.

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Glossary of Terms

AFS	Anti-fouling Systems
BWM	Ballast Water Management
CCN	Cloud Condensation Nuclei
CCNR	Central Commission for the Navigation of the Rhine
CCWG	Clean Cargo Working Group
CDEM	Construction, Design, Equipment and Manning standards for ships
CFCs	Chlorofluorocarbons
CH_4	Methane
CLINSH	Clean Inland Shipping
CNSS	Clean North Sea Shipping
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2 eq.	Carbon dioxide equivalent
CSI	Clean Shipping Index
EAS	Environmental Assessment System
EC	European Commission
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EF	Emission Factor
EMS	Environmental Management System
ESI	Environmental Ship Index
EU	European Union
EVDI	Existing Vessel Design Index
GHG	Greenhouse Gas
GHS	Global Harmonised System
Gt	Gigatonne
GT	Gross tonnage
GWP	Global Warming Potential
HCFCs	Hydrochlorofluorocarbons

HFO	Heavy Fuel Oil
HNO_3	Nitric acid
HNS	Hazardous and Noxious Substances
H_2SO_4	Sulphuric acid
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
ISO 14001	International Organisation for Standardisation - Environmental Management Systems: Requirements with guidance for use
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MSDS	Material Safety Data Sheet
MRV	Monitoring, Reporting and Verification
NECA	NO_X Emission Control Area
NMVOCs	Non-methane Volatile Organic Compounds
NO	Nitrogen monoxide
NO_X	Nitrogen oxides
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
ODP	Ozone Depleting Potential / Ozone Depleting Substances
OILPOL	International Convention for the Prevention of Pollution of the Sea by Oil
pH	Logarithmic scale for assessing acidity of alkalinity of a solution
PM	Particulate matter
PN	Particle number
SCC	Shipping in Changing Climates
SECA	SO_X Emission Control Area
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific Fuel Consumption
SO_X	Sulphur oxides
SO_2	Sulphur dioxide

SO_3	Sulphur trioxide
S-P-R	Source Pathway Receptor analysis
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
VEP	Vessel Environmental Performance
VEP Index	Vessel Environmental Performance Index
VEP_n	Normalised VEP
VOCs	Volatile Organic Compounds

Dissemination, Publications and Research Impact

The research carried out in this thesis has led to a number of publications at conferences and through journal and conference papers. The work has also made a significant contribution to the European Life programme funded Clean Inland Shipping (CLINSH) project, and has been disseminated through internal documents, workshops and consortia meetings hosted by the project. The research has been partially funded by Lloyds Register (LR), and mid-term outputs from the project were reported at progress meetings and through progress reports. The research has also been presented at Newcastle University through the annual Marine Technology PGR conferences. The following presents a list and brief description of outputs from the research, related to specific chapters of the thesis:

Conferences and Journals

- Article published in Journal for Transportation Research: Part D, June **2019**: Gibson, M. Murphy, A. J. Pazouki, K. (2019). Evaluation of environmental performance indices for ships. *Transportation Research Part D: Transport and Environment.* Vol. 73 pp. 152-161. Relates to Chapter 3 of thesis.

- Full scale ship performance conference (RINA), October **2018**, London. Conference paper: ‘Ship performance: using the real world as a laboratory’. Paper relates to Chapter 4 of thesis.

- Shipping and the Environment conference, 24-25th October **2017**, Gothenburg. Presented work on ‘A novel approach to holistic environmental assessment of ships’ (presentation and abstract), relating to Chapter 4 of thesis.

- Shipping in Changing Climates conference, 4-5th September **2017**, London. Presented work on ‘A novel approach for holistic environmental assessment of ships’ (presentation and extended abstract), relating to Chapter 4 of thesis.

- Shipping in Changing Climates conference, 10-11th November **2016**, Newcastle. Presented work on ‘A novel approach for holistic environmental assessment of ships’ (Presentation and extended abstract). This relates to Chapter 3 of the thesis.

Projects in industry, and other dissemination

- Green Award workshop, 3rd May **2018**, Newcastle. Presented work on ‘Vessel environmental scoring methodology’, relating to Chapters 4 and 5 of thesis.

- CLINSH programme consortium meeting, 11th April **2018**, Nijmegen. Presented work on ‘Vessel scoring and environmental initiatives’, relating to Chapters 4 and 5 of the thesis.

- CLINSH internal dissemination report (task D2.2), March **2018**. Report on ‘Regulations and initiatives in shipping’, relating to Chapter 3 of the thesis.

- CLINSH internal dissemination report (task D2.2), January **2018**. Report on ‘Environmental assessment methodology’, relating to Chapter 4 of the thesis.

- CLINSH task meeting, 17th March **2017**, Teleconference. Presented work on ‘Environmental initiatives in shipping’, relating to Chapter 3 of the thesis.

- Lloyds Register mid-term workshop, 31st January **2017**, Southampton. Presented literature review and proposed methodology to LR steering committee consisting of LR’s environmental manager, head of strategic research, senior specialist for strategic research, and principal specialist for fuels and emissions. The outputs of this exercise contributed towards the development of part A of the methodology presented in this thesis (Chapter 4), including the development of pollutant weighting factors referred to in Chapter 2 of the thesis.

Prior to commencement of this PhD research, some preparatory work was conducted as part of the Clean North Sea Shipping (CNSS) project, funded by The European Regional Development Fund. The following list presents the authors outputs from the CNSS project:

- Contribution to CNSS final report: key findings and recommendations, March **2014**, Bergen. Co-author of Chapter 3: Environmental Performance - Emission Indices.

- CNSS Final conference, March **2014**, Bergen. Presented work on ‘CNSS Emission Indices’, relating to background to PhD project.

- Low Carbon Shipping conference, September **2013**, London. Conference paper: ‘Modelling ship emission factors and emission indices’. Relates to Chapter 3 of thesis, and was conducted prior to the research outlined in this thesis.

1.0 Introduction

1.1 Introduction

The aim of this chapter is to introduce the purpose and focus of this research, and to provide the reader with an overview of the thesis. This chapter outlines the background to the research, the focus of the study, the contribution to the wider research field, the aims and objectives of the research, the research structure, and an overview of the thesis.

The thesis is presented in a series of chapters that address the research questions. Each chapter begins with an introduction to the topic and the purpose of the work, then provides a detailed description of the work carried out including any methods utilised and analyses of the findings, and ends with a summary of the outcomes.

1.2 Research background

The shipping industry is under increasing pressure to reduce its environmental footprint. Maritime legislation with regards to the environment has tightened in recent years with the introduction of international regulations such as MARPOL 73/78 and its annexes for controlling air emissions and discharges of oil, sewage, garbage and noxious substances to sea. Treaties such as the Ballast Water Management (BWM) and Anti-fouling Systems (AFS) Conventions regulate other pollutant discharges to water, and proposed agreements such as the Hong Kong Convention for ship recycling, and the Hazardous and Noxious Substances (HNS) Convention are yet to be ratified.

Many countries with a heavy reliance on the shipping industry recognise the need for improved air quality in ports and harbours, with increasing attention focussed on shipping sustainability through various international consortia such as CLINSH (Clean Inland Shipping), CNSS (Clean North Sea Shipping), and SCC (Shipping in Changing Climates).

Much of the focus of concern in the shipping sector has been on the impacts of air pollutants from vessels, while the effects of pollutant discharges to other aspects of the environment have received less attention. Ships are used to transport approximately two billion tonnes of oil around the world annually (Rodrigue *et al.*, 2009), and while the risk of spillage has decreased in recent years since the introduction of double hull tankers (Yip *et al.,* 2011), it is estimated that around 200,000 tonnes of oil are discharged to the environment during ship operation (Jernelov, 2010). Recreational shipping is responsible for discharging large quantities of sewage and grey water into the oceans, while the accumulation of toxic chemicals from antifoul coatings and discharge of untreated ballast water can have major impacts on the marine environment. It is therefore important that measures for controlling the effects of ships on the environment adopt a broad scope based on critical and rational assessment of impacts, rather than current political and regulatory concerns.

It has been suggested that the shipping industry is insufficiently regulated with regards to environmental protection due to the fragmentary nature of local, national, regional and international legislation (Lister *et al.,* 2015). The structure of international law requires a consensus based approach, which often results in stalled ratification of environmental conventions.

In response to the regulatory challenges, other approaches have been adopted to reduce the environmental impact of ships including the use of proactive environmental management strategies such as ISO 14001, to identify and control environmental risks by providing a framework for preventing and mitigating pollutant releases to the environment. Other environmental management techniques such as Life Cycle Assessment (LCA), scenario modelling and analysis, and environmental risk assessment are useful tools for estimating and quantifying the potential impact of pollutant emissions on the environment, however such activities are complex and require significant allocation of time, resource and expertise to be conducted.

An increasingly common approach to assessing and communicating the environmental performance of ships is through the use of voluntary environmental initiatives, which act as indicators of environmental performance and attempt to apportion cost to harmful emissions by offering incentives to cleaner ships. However, studies suggest that many of the indices developed focus heavily on emissions to air, without taking into consideration the interactions with the wider environment (Murphy *et al.,* 2013).

Numerous environmental indices have been proposed as methods to assess ships, approximately 50 were catalogued as part of the Clean Baltic Sea Shipping CLEANSHIP project (Fridell *et al.,* 2013), and additional studies identify numerous other initiatives used in the shipping sector (Svensson and Andersson, 2011; EMSA, 2007; Pike *et al.*, 2011; SSI, 2013; Stuer-Laridsen *et al.,* 2014).

Further to this, Murphy *et al.* (2013) conducted an in depth analysis of two of the more commonly used indexing systems for emissions to air; the ESI (Environmental Ship Index) and CSI (Clean Shipping Index). The previous studies provide some preliminary data with respect to the composition of green shipping initiatives, however there is a lack of analysis regarding the effectiveness of such schemes in improving the environmental performance of ships.

Additional research is required to investigate the methods used to rank vessel environmental performance, and assess the effectiveness of existing schemes in reducing pollutant emissions and discharges from ships. There is also a need for development of coherent strategies for assessing the impact of ship related pollutants on the environment using a quantitative approach.

The motivation behind this thesis is driven by the authors' interest in the environment and recognition of the importance of environmental preservation for future generations. Previous work in the fields of environmental science (Undergraduate) and environmental engineering (Masters) have fuelled this interest, while prior research into ship environmental indices (Murphy et al., 2013), to which the author of this thesis contributed, highlights the need for further exploration in this field.

1.3 Focus of study

It is proposed that this research seeks to establish a rational and coherent strategy for assessing and ranking the environmental performance of ships that is transparent and effective across all ship types and sizes. The thesis focuses on commercial ships, however the approach is to be flexible for adaptation to other types of fleet including recreational craft, fishing vessels and warships (excluding nuclear). This will be done through identification of the key impacts of shipping on the environment, and development of an appropriate system of assessment through investigation of current indices and assessment techniques. Furthermore, the proposed method will assess a ships environmental performance against realistic operating profiles, rather than under assumed test conditions, which is current practice. In order to truly measure performance, a ship must be ranked against the regulatory requirements, but also take into consideration the wider impacts on the environment. That is, a ranking system is required to assess a ships green credentials beyond simply meeting the regulations.

1.4 Research contribution

This thesis contributes to the wider research field by detailing the impacts of ship operations on the environment, and outlines the related regulatory and voluntary management and control mechanisms currently utilised in the industry. Summaries of the outputs are presented to help better understand the linkages between pollutant emissions and environmental threats, and the measures currently implemented to reduce such threats. This study also proposes a set of quantified pollutant weighting factors by assessing the severity of impacts of ship emissions and discharges to the environment.

The research builds upon the body of work conducted by Svensson and Andersson (2011), Fridell *et al.* (2013), Pike *et al*. (2011) and Stuer-Laridsen *et al.* (2014), examining the use of environmental performance indices in the shipping sector by providing in depth analyses of the transparency, scope, assessment rationale and flexibility of the existing schemes. The purpose of this is to understand their limitations, and develop the existing strategies into an accurate and rational approach for assessment of environmental performance based on realistic operational profiles of ships. An environmental assessment method for ships, the VEP index, is presented.

1.5 Aim and objectives

The aim of this research is to develop a clear and coherent method for assessing and ranking the environmental performance of ships using a holistic approach. The method must include ships interactions with the environment and consider actual as opposed to theoretical ship performance.

The objectives of this research are as follows:

- Comprehensive review of literature outlining the interactions and impacts of ships on the environment, along with the regulatory and voluntary mechanisms utilised for controlling ship related pollutants.

- Critical analyses of existing environmental rating and assessment systems, identifying the limitations with existing schemes.

- Development of a ship environmental assessment methodology (the VEP index) applicable across a range of ship types.

- Application of the methodology using actual performance data from case study vessels.

1.6 Overview of thesis

The thesis is divided into six chapters, with references and appendices presented at the end. It is recommended that each chapter is read in the order laid out, as the findings from each are referenced in the sections that follow, however the chapters can also be read independently. The content of each chapter is briefly outlined in the following sections.

1.6.1 Chapter 1.0 - Introduction

Chapter 1 provides an introduction to the research topic and explains how and why this study delivers a significant academic contribution. The aims and objectives of the research are clearly defined, and the thesis overview provides a brief explanation of the content and purpose of each chapter.

1.6.2 Chapter 2.0 - Environmental impacts of shipping

This chapter presents a review of ships' interactions with the environment, the types of pollutants emitted during ship operation, and the environmental consequences. The purpose of this chapter is to review existing scientific evidence on shipborne environmental impacts and to provide rationale for the development of pollutant weighting factors to be used in a ship environmental assessment method. The interactions with the environment, sources and pathways of pollutants, and subsequent impacts are summarised in this chapter, and an environmental impacts summary table is presented in Appendix A.

1.6.3 Chapter 3.0 - Environmental management, assessment and control in the maritime sector

Chapter 3 outlines the pathways and barriers to sustainable shipping through environmental regulation, management and assessment. The purpose of this chapter is to analyse the effectiveness and limitations of existing measures of environmental management and assessment in the maritime sector. This includes the role of national and international legislation in reducing the environmental impacts of shipping, the barriers to regulatory implementation, and the use of voluntary environmental schemes and initiatives to fill the void where regulation is considered ineffective.

1.6.4 Chapter 4.0 - Development of a holistic environmental assessment model

The purpose of this chapter is to outline the proposal for a framework for assessing ships' environmental performance. The method proposed in this research - 'the VEP index' - is holistic in scope, can be applied to all types and sizes of ship, and assesses environmental performance based on operational data. There are two parts to the methodology, A and B, each consisting of several steps. Part A defines the scope of the assessment and the weighting factors assigned to each pollutant, and part B outlines the vessel data collection procedure and how the data can be used to calculate vessel environmental performance scores.

1.6.5 Chapter 5.0 - Testing the methodology

The purpose of this chapter is to test the flexibility and sensitivity of the VEP index methodology to confirm its suitability for use across a range of vessels. Two case study vessels with similar design specifications and operating characteristics have been assessed to demonstrate use of the index. The method can clearly distinguish which of the two vessels performs better environmentally, based on voyage data. The case study vessels are also evaluated using the existing environmental initiatives evaluated in Chapter 3, and the results are compared with the VEP index results to highlight the benefits of the method over the existing indices.

1.6.6 Chapter 6.0 - Conclusions and recommendations for future work

The final chapter summarises the conclusions of the thesis on a per chapter basis. The contributions of the research to the wider field of study are also summarised, along with the limitations encountered, and recommendations for future work.

2.0 Environmental impacts of shipping

2.1 Introduction

Shipping is widely considered as one of the most efficient modes of freight transport, and until recently the environmental impacts of shipping have been less of a priority when compared with other sectors. Despite being responsible for around 90% of global trade transport (Hoffman & Kumar, 2010; IMO, 2011; UNCTAD, 2014) – including the supply of raw materials, food, consumer goods and energy – shipping is considered a minor contributor to marine pollution compared to land based industries (IMO, 2011).

The Third IMO Study on Greenhouse Gas (GHG) emissions from ships was carried out in 2014. This study suggests that shipping contributes around 3% of total anthropogenic CO_2 emissions globally, with emissions predicted to increase significantly (in the region of 50 - 250%) by 2050 (Smith *et al*, 2014). Shipping as a sector was excluded from the 2015 United Nations Framework Convention on Climate Change Conference of Parties (UNFCCC COP 21) held in Paris and hence a global CO_2 reduction target from shipping activities was not set at the time, however a separate target has recently been agreed by the IMO in an *'Initial Strategy on reduction of GHG emissions from ships'* (IMO, 2018[a]). The strategy sets out a target of 'at least' 50% reductions in CO_2 emissions compared with 2008 levels, by 2050, with the aim of cutting emissions to 100% by 2050 if this can be proven to be feasible. Such targets are considered to be in line with the requirements of the Paris Agreement (United Nations, 2015) of reducing global CO_2 emissions 'well below' the amount needed to achieve a less than 2°C increase in global average atmospheric temperatures above pre industrial levels, by 2050.

Despite the industry's relatively small contribution to CO_2 emissions currently, projections suggest shipping could be responsible for up to 25% of global totals by 2050 if no action is taken to decarbonise (Smith *et al.,* 2014). In addition, ships burn poor quality heavy fuel oil, polluting the atmosphere with emissions of NO_X, SO_X, VOCs, CO and PM amongst other toxic emissions, including ozone depleting substances.

Impacts of shipping on air pollution are a significant concern, however also a concern are the impacts of ship operations on marine ecosystems due to the release of toxic substances into the oceans and other water bodies. Uncontrolled discharges can lead to the spread of diseases and invasive aquatic species, oil spills, and release of toxic chemicals into the water environment. Discharge of pollutants from ships to the sea can have multiple and complex consequences, costing billions of pounds in remediation measures and in some cases cause permanent damage to the marine ecosystem.

Disposal of sewage and waste from shipping is a significant environmental concern, requiring the designation of 'Special Areas' with strict guidelines on disposal at sea. Waste and sewage from ships is often disposed of on land and hence the provision of adequate reception facilities is a challenge, while the process of ship decommissioning and disposal of hazardous materials can damage the environment.

Other environmental issues include the impacts of noise from shipping near population centres, and the effects of noise on the behaviour and communication of certain aquatic species. It has been found that the main source of noise from ships is from the propellers, which dominate the low frequencies – the range that whales use to communicate (Green, 2004). Large marine mammals can also be threatened by the risk of collision with ships in the open ocean. Ship strikes have been known to kill the larger species of whales, with the biggest risk to species inhabiting waters with high shipping volumes (OSPAR, 2009).

This chapter will identify the source of environmental threats and pollutants (including biohazards) associated with shipping, and present the science behind the impacts of the pollutants on the environment. This includes authorised operational releases, and releases resulting from accidental and other unauthorised activities. For the purpose of this research, pollution of the marine environment is defined in accordance with UNCLOS article 1, which refers to the '*direct or indirect introduction of substances or energy by man into the marine environment'*. Pollutants are grouped according to the aspect or sphere of the environment to which they are emitted, known as the *'environmental receptor'*. Biohazards such as invasion of alien species impacting on local ecosystems are considered in the context of ballast water releases, and biohazards caused by hull fouling are also acknowledged. The impacts associated with ship emissions to air, discharges to water, pollutant releases to land, anthropogenic noise, and physical contact with marine animals are detailed in this chapter. The findings are summarised in this chapter, and presented in an environmental impact table for ships, shown in Appendix A.

2.2 Emissions to air

According to the Third IMO GHG study (Smith *et al.*, 2014) ships are estimated to have emitted 1.036 billion tonnes per annum of equivalent CO_2 (CO_2e) into the atmosphere, averaged over the period 2007-2012. The same study estimates average annual emissions from shipping of NO_X and SO_X of 20.9 million and 11.3 million tonnes respectively, over the same time period.

While the emissions of CO_2 compare favourably with those produced by road transport - 3% of total global GHG emissions comes from shipping as opposed to 15% from road vehicles (International transport forum, 2010) - the volumes can be regarded as a significant contribution towards anthropogenic climate change. Oceans play a significant role in the carbon cycle as a natural CO_2 sink, however the accelerated anthropogenic release through burning of fossil fuels can cause the oceans to uptake too much carbon, increasing the pH causing ocean acidification.

The release of NO_X and SO_X through burning poorly refined fuel oils in ships' engines can have a significant impact on both the marine and continental environment due to their high atmospheric persistence, and coastal winds carrying the pollutants inland (OSPAR, 2009). Air pollutants can be carried hundreds of kilometres causing health and environmental problems to populated urban centres inland through atmospheric accumulation. The uptake of nitrogen from plants and vegetation in marine habitats can cause nutrient blooms leading to eutrophication (Jonson *et al.*, 2015).

The persistence of NO_X and SO_X in the atmosphere can lead to the formation of acid rain. NO_X and SO_X are able to rise high into the atmosphere, reacting with water vapour to form nitric and sulphuric acid in the presence of sunlight. The persistence of these pollutants can also lead to the formation of low level ozone which can have considerable health effects in populated port areas (OSPAR, 2009). Ships also emit ozone depleting gases from refrigerants used for cooling, fire safety systems, cargo vapours etc. (OSPAR, 2009).

Ship emissions have been identified as an environmental risk, the scale of which is reflected in the development of specific maritime regulations to control and ultimately reduce harmful emissions from ship exhausts. However, concerns remain over the accuracy and availability of global emissions data and subsequent environmental impact and energy efficiency of ships. With this in mind, the focus of the IMO and the EC (European Commission) in the immediate future is on improving the Monitoring, Reporting and Verification (MRV) of ship emissions. The agreed methodology for calculating emissions in the MRV process is:

$$CO_2 \text{ emissions} = \text{emission factor x fuel consumption} \quad (2.1)$$

The process requires all ships to submit a verified monitoring plan and emissions report to the EU.

Meanwhile, energy efficiency in shipping is measured using the EEDI (Energy Efficiency Design Index) and SEEMP (Ship Energy Efficiency Management Plan), mandatory measures introduced by the IMO through amendments to MARPOL Annex VI (resolution MEPC.203 (62)), which entered into force on 1 January 2013. The EEDI is designed to promote the use of energy efficient technologies in engines in newly built ships, however it does not apply to pre-existing ships. It requires a minimum level of energy efficiency (grams CO_2) per capacity mile (e.g. tonne mile) to be achieved, known as the baseline EEDI. New ship designs must meet this reference level for a given ship type. The SEEMP is designed as an operational approach to improve energy efficiency in both new and existing ships, using EEOI (Energy Efficiency Operational Indicator) as a guide.

Multiple studies have highlighted the impact of NO_X emissions from shipping on the environment. Lawrence and Crutzen (1999) highlighted the effects of NO_X from ships on the formation of tropospheric ozone causing atmospheric cooling due to the reflectivity of aerosols and the impact of lower level ozone on the persistence of greenhouse gases in the atmosphere. This may be seen as a positive influence on the net warming effect of global climate change, however Jonson *et al* (2000) describe how NO_X from shipping can increase eutrophication and acidification, highlighting negative impacts on the environment. Efforts to control emissions of air pollutants have been implemented through proposals to designate emission control areas for NO_X, SO_X and particulates (EPA, 2009[a]; IMO, 2009).

2.2.1 Greenhouse Gases

Since the industrial revolution atmospheric concentrations of greenhouse gases (GHGs) have increased considerably due to the burning of fossil fuels. The third IMO GHG Study (*Smith et al.,* 2014) states that 3% of total global GHG emissions come from shipping activities, and the contribution from shipping is likely to increase in the future unless action is taken to mitigate the source of emissions. According to the IPCC (Intergovernmental Panel on Climate Change), atmospheric concentrations of Carbon dioxide (CO_2), Methane (CH_4) and Nitrous oxide (N_2O) (which, along with water vapour, are considered to be the main GHG contributors) are higher at present than at any time in at least the last 800,000 years (IPCC, 2013).

2.2.1.1 Climate change

The earth's global mean climate is controlled by the extent of incoming solar radiation and the properties of the earth's surface and its atmosphere. The amount of solar energy received is governed by the orbital pattern of the earth around the sun. The elliptical nature of the orbit results in variations in the intensity of solar radiation reaching the earth, while solar cycles and sun spots are also known to affect the intensity of solar irradiance on the planet (Eddy, 1976; Solanki *et al.,* 2013).

Climatic conditions are influenced by the extent of solar radiation reaching the earth's surface and atmosphere. To maintain a stable temperature energy that enters and leaves the atmosphere must be in equilibrium. Radiation from the sun enters the atmosphere and some of it is reflected straight back into space by clouds, atmospheric particles and reflective surfaces, but the majority (approximately 70%) is absorbed by the atmosphere and earth's surface (Stocker *et al.,* 2013). Radiation is emitted from the sun across the full range of the electromagnetic spectrum, with a significant proportion (approximately 43%) at visible wavelengths. Some atmospheric gases such as water vapour and Ozone (O_3) are effective absorbers of direct solar radiation at shorter wavelengths, which occurs in the upper atmosphere. Visible radiation is not absorbed by gases in the atmosphere, and is instead absorbed by the earth's surface. Energy absorbed by the earth's surface is then re-emitted back into the atmosphere at longer wavelengths. Atmospheric gases such as water vapour (clouds), CH_4 and CO_2 are effective absorbers of long wave radiation, thus the atmosphere is heated up by radiation from the ground. Some of the energy absorbed in the atmosphere is reemitted back to the surface, resulting in further warming. This process is known as the greenhouse effect, and is important in maintaining stable temperatures on earth to enable life to thrive (Lindgren *et al.,* 2016[a]).

Global temperatures remain relatively stable when there is a balance between the amount of radiation entering and leaving the atmosphere. Anything that causes an imbalance can alter temperatures down or up. Historically, the earth has gone through natural cycles of warming and cooling. The planet entered a warming trend approximately 11,700 years ago known geologically as the Holocene Epoch, and records from deep sea cores suggest that the global climate fluctuates from an ice age to a period of warming approximately every 100,000 years, in relation to the shape of the earth's orbit around the sun, which varies from near circular to elliptical over long time periods (Shackleton, 2000). There have been other periods of climate variability within the Holocene, most notably during the Little Ice Age – a period of cooling in the northern hemisphere from 1450 to 1850 AD - and the Medieval Climate Anomaly (or Medieval Warm Period) - a time of warm climate from about 950 to 1250 AD – however these times are widely considered as periods of regional climate variability rather than global climate phenomena (Mann, 2002; Jones *et al.,* 1998; IPCC, 2013). Furthermore, the IPCC states with *high confidence* that it is *very likely* (90-100% probability) that the mean temperature in the northern hemisphere over the last 50 years exceeds the mean for any 50 year period at any point in the last 800 years, including during the Medieval Climate Anomaly (Masson-Delmotte *et al.,* 2013).

According to the IPCC (2013), human influence on the climate system is clear due to the increase in greenhouse gases in the atmosphere since 1750, and the effects of this are continuing (WHO, 2018). Significant research has taken place in order to develop an understanding of the effects of human induced GHG emissions on the planet, however the system is complex. Anthropogenic emissions are responsible for significant increases in the atmospheric concentrations of CO_2, CH_4 and N_2O since the pre industrial era. Since 1750, 2040 (±310) $GtCO_2$ have been emitted into the atmosphere, approximately half of which have occurred in the last 40 years (IPCC, 2013). About 40% of the total emissions in this period have remained in the atmosphere, the rest have been stored on land and in the ocean.

GHGs influence the warming of the planet differently depending on the lifespan in the atmosphere and the radiative efficiency of the gas. The impacts of different gases are compared using the Global Warming Potential (GWP), which is the measure of how much energy the emissions of 1 tonne of a gas will absorb over a period of time (typically 100 years) compared with 1 tonne of CO_2, thus CO_2 has a GWP of 1 (Mhyre *et al.,* 2013). CO_2 is the main contributor to GHGs from shipping, formed during the combustion process from carbon based fuels used to propel vessels, and from production of energy and heat on board vessels.

Methane is a considerably more potent greenhouse gas than CO_2, with a GWP over 100 years of 28 and an atmospheric lifetime of 12.4 years (Mhyre *et al.,* 2013). Methane is released to the atmosphere from natural sources such as wetlands, freshwater reservoirs, and organic waste deposits, however the precise contributions from the various sources and sinks of the methane cycle are not yet fully understood (Kirschke *et al.*, 2013). Shipping's contribution to atmospheric CH_4 is through potential slippage (unburned emissions) and spillage of LNG fuel (Liquefied Natural Gas) during handling and combustion (Salo *et al.,* 2016). LNG contains no sulphur and has a lower carbon content compared with the more common marine fuels such as HFO (Heavy Fuel Oil) and MGO (Marine Gas Oil), and its use is becoming increasingly widespread due to the need to meet strict sulphur regulations within the marine industry (IMO, 2016[a]).

Nitrous oxide is a powerful GHG with a GWP over 100 years of 298 and a relatively long lifetime in the atmosphere of 121 years (Mhyre *et al.,* 2013). N_2O enters the atmosphere through the earth's natural nitrogen cycle, mainly through the breakdown of nitrogen in soils and the oceans by bacteria through nitrification (Khalil & Rasmussen, 1992). About a third of global N_2O emissions are from anthropogenic sources with the majority coming from agricultural processes, and around 15% of the anthropogenic emissions are from energy and transport (Davidson and Kanter, 2014). Shipping's contribution is through fuel combustion, where N_2O is formed through oxidation of nitrogen in the air at low temperatures and under lean fuel conditions where there is more air in the combustion chamber (Hayhurst & Lawrence, 1990).

Climate change is considered a global environmental issue as localised emissions have global impacts on the natural environment and human health. According to the IPCC, increased GHGs in the atmosphere have already caused a number of observed changes in the earth's climate system. Mean global surface temperatures have increased by 0.85°C from 1880 to 2012, while the upper 75m of the world's oceans have warmed by 0.11°C per decade since 1971. Glacial cover has reduced significantly over the last 20 years, while sea ice conditions in the Arctic have decreased in every season due to substantial Arctic warming. Global average sea levels have risen over the last century, likely down to loss of glaciers and ocean thermal expansion caused by rising temperatures (IPCC, 2013). Changes in the natural environment can lead to habitat changes and loss of species, while increased temperatures can lead to spread of infectious diseases impacting human health. The occurrence of more extreme weather can affect farming practices resulting in loss of crops causing malnutrition, while humans are directly affected by heat waves (Lindgren *et al.,* 2016[a]).

2.2.1.2 Ocean acidification

Another impact of anthropogenic CO_2 emissions is increased acidification of the world's oceans. The uptake of CO_2 by oceans occurs as part of the planets natural carbon cycle, however increased levels of CO_2 in the atmosphere are resulting in greater absorption by the sea. Once dissolved in seawater, CO_2 forms carbonic acid affecting the pH levels of the water. The mean surface ocean pH has become more acidic since pre industrial times, decreasing from 8.2 to 8.1 on the pH scale (Gattuso and Hansson, 2011), and could decrease by a further 0.3 pH units by 2100 (Gattuso and Lavigne, 2009). The pH scale is logarithmic therefore the acidity of the oceans has increased by a factor of 10, resulting in a near 30% increase in ocean acidity since 1750 (Raven *et al.*, 2005; Doney *et al.*, 2009).

Acidification of the oceans can affect marine species in a variety of ways. Calcification of shell forming organisms can be inhibited due to a decrease in the saturation state of calcium carbonate ($CaCO_3$), stunting the growth rate of such organisms resulting in reduced fertilisation success and development of larvae (Doney *et al.*, 2009). Ocean acidification can accelerate photosynthesis in organisms without carbon concentrating mechanisms (Gattuso and Hansson, 2011), although it is also thought that the effects on photosynthetic response may be minor as there is a high level of variability throughout taxa (Mackey *et al.*, 2015). Photosynthesis can also be indirectly affected through changes to biological processes as lower pH levels can affect the thermodynamics and kinetics of nutrients such as phosphorus, nitrogen and iron affecting the bioavailability of such species in the ocean (Millero *et al.*, 2009). The effects of acidification on photosynthetic organisms such as phytoplankton and benthic organisms is important due to their trophic level and the subsequent impacts on marine organisms higher up the food chain.

It is thought that ocean acidification can affect the behavioural response of some marine species. Munday *et al.* (2009) indicate that clownfish larvae are unable to detect predators due to sensory disruption in acidic conditions, while Vargas *et al.* (2013) suggest a reduction in the intensity of larval feeding of the Chilean abalone sea snail (*Concholepas concholepas*) at lower pH levels. This could suggest a decline in populations of certain sea species, however the correlation between increased acidification and species populations is uncertain due to on-going physical and chemical processes in the ocean that may be of influence (Lindgren *et al.,* 2016[a]).

2.2.2 Ozone Depleting Substances (ODPs)

Historically, gases used in refrigeration and air conditioning units exhibited ozone-depleting properties. In 1987 the Montreal Protocol was introduced to gradually phase out the use of substances that deplete the ozone layer. The IMO also introduced a phase out plan for the use of ozone depleting substances on ships through MARPOL Annex VI, however a complete ban on all ODPs has yet to enter force, and due to the long lifespan of vessels there is some risk that ODP containing substances may continue to leak from older vessels in the future.

2.2.2.1 Ozone depletion

Ozone depletion refers to the reduction in concentrations of ozone (O_3) in the stratosphere due to human activity. O_3 is a reactive gas that forms freely in the atmosphere due to the splitting of oxygen (O_2) molecules by intense UV radiation (Rowland, 2009). Single oxygen atoms are very reactive and immediately bond with O_2 molecules to form ozone. Such reactions occur continually where there is a presence of UV radiation and hence a thick layer of ozone is formed in the tropical stratosphere which thins out towards the poles where solar radiation is less intense. O_3 production is balanced by its subsequent destruction through reactions with natural and anthropogenic chemicals in the atmosphere. One of the main ozone depleting chemicals is Chlorine (Cl), which resides in the atmosphere naturally due to emissions from oceans (Graedel and Keene, 1995) and terrestrial plants (Yakouchi *et al.*, 2000). Human induced emissions of chlorine occurs primarily through use of halocarbons for cooling in e.g. refrigeration and air conditioning units.

The impacts of anthropogenic halocarbon emissions on the ozone layer are well documented (Farman *et al.,* 1985; Solomon *et al.*, 1986). Atmospheric O_3 acts as a protective barrier to flora and fauna from UV-B radiation. Depletion of O_3 results in more UV-B reaching the earth's surface, which can be harmful to human health causing skin cancer, it can also effect the physiological development of plants and marine organisms. UV-B radiation has a wavelength of 290-320 nm and can damage cells at a molecular level causing DNA mutations (Marrot and Meunier, 2008). In 1987, a global agreement known as the Montreal Protocol '*on substances that deplete the ozone layer'* was reached (UNEP, 2018), initially to reduce halocarbon emissions by 50% by 2000, and later to completely phase out the use of halocarbon containing gases (CFC's and HCFC's) by 2030.

Other ozone depleting chemicals include Bromine (Br), which occurs naturally through marine aerosols (Sturges and Harrison, 1986) and is also contained in halocarbons, and N_2O, which occurs naturally and anthropogenically, but is not controlled by the Montreal Protocol (Ravishankara *et al.*, 2009).

Emissions of ODPs from ships originate from refrigeration plants on reefer ships and fishing vessels, and refrigerated containers and air conditioning provisions on board all types of vessels. N_2O emissions are generated due to incomplete combustion of fuel. Refrigerant gas losses can occur during refrigerant handling, disposal of equipment and leakage through loose seals (Salo *et al.,* 2016). CFC's and HCFC's are regulated in the marine industry through Regulation 12 of Annex VI of MARPOL 73/78, banning the use of all CFC's in refrigeration systems on board vessels constructed on or after 19th May 2005, and use of HCFC's in new installations by 1st January 2020.

2.2.3 Sulphur Oxides (SO_X)

According to the Third IMO GHG study (Smith *et al.*, 2014) 13% of global anthropogenic emissions of sulphur oxides (SO_X) can be attributed to shipping, estimated at an average of 11.3 tonnes per year for the period 2007 to 2012. SO_X is the abbreviation used for both sulphur dioxide (SO_2) and sulphur trioxide (SO_3), although most anthropogenic sulphur emissions are SO_2 (Salo *et al.,* 2016). Sulphur occurs naturally in the atmosphere in multiple forms. Volcanic emissions contribute significant volumes of hydrogen sulphide (H_2S), SO_2, and SO_3, while sea spray deposits sulphate ions (SO_4^{2-}) into the atmosphere above the world's oceans. A significant natural source of atmospheric sulphur comes from the biological reduction of sulphur compounds such as marine algae, decaying vegetation, and bacteria as di-methyl sulphide (DMS) (Cullis and Hirschler, 1980).

Anthropogenic sulphur emissions increased significantly from 1850, peaking around 1970, and have subsequently reduced in the years up to the turn of the 21st century (Smith *et al.*, 2011). Additional studies by Klimont *et al.* (2013) show further global increases up to 2006, followed by steady decline. The peaks in sulphur concentrations can be attributed to industrialisation of developed and developing nations, with the decline from the 1970's onwards in line with considerable emissions reductions from developed nations due to the introduction of air pollution policies such as the LRTAP (Long-Range Transboundary Air Pollution) regulations in 1979 (Vestreng *et al.*, 2007), and a further peak representing activity in newly industrialised countries such as China, along with international shipping (Klimont *et al.*, 2013).

The main source of anthropogenic sulphur is from the burning of fossil fuels. The amount of sulphur emitted varies based on the refinement of the fuel. Historically, ships have used heavy fuel oils (HFO's) and residual fuels which have a greater sulphur content than refined distillate fuels, however the sulphur content of the fuels will likely reduce in future with the introduction of a strict global sulphur cap by the IMO. The current IMO fuel oil sulphur limit is 3.5% m/m, which reduces to 0.5% in 2020. Residual fuels used in shipping contain an average of 2.54% sulphur (IMO, 2018[b]), significantly above the target for 2020. SO_X emissions are a concern due to effects on the environment and human health (EPA, 2008[a]).

2.2.3.1 Acid rain

Anthropogenic sulphur from shipping is emitted into the atmosphere mainly as SO_2 in the gas phase. SO_2 is oxidised by hydroxyl radicals (OH) to produce $HOSO_2$ (hydroxylsulfonyl radical), which reacts with O_2 in the atmosphere to form hydroperoxyl (HO_2) and SO_3. In the presence of water vapour, SO_3 reacts rapidly to form sulphuric acid (H_2SO_4). Acid rain occurs via wet deposition of H_2SO_4 through precipitation. Sulphuric acid is dissolved into rain or snow droplets forming sulphate ions, which can then be carried long distances in clouds and deposited on land or water. Studies by Corbett and Fischbeck (1997) suggest that sulphur from ship emissions can travel up to 1200km before deposition, hence SO_X is considered a long range transboundary air pollutant (United Nations, 1979) and can affect the environment in areas hundreds of kilometres from the point of emission.

Sulphuric acid rain can affect ecosystems, infrastructure, and human health. Acidification of aquatic environments can result in increased mortality rates and skeletal deformities of organisms (Watt *et al.*, 1983), while amphibians such as frogs and toads are sensitive to changes in pH (Whelpdale, 1983). Some species of flora and fauna are tolerant to high acidity and flourish in such conditions (Singh and Agrawal, 2008), however it is evident that changes in pH can alter the natural biodiversity of habitats. Acid depositions on forested land can impact certain species of trees, resulting in receding canopy cover and in some cases whole tree death (Tomlinson, 1983), while reductions in the yields of certain crop types such as soybean have also been observed, as a result of reduced carbon assimilation due to low soil pH (Norby and Luxmoore, 1983; Evans and Lewin, 1981).

Acid rain can speed up the chemical weathering of exposed building materials such as ferrous metals, limestone and marble. Buildings exposed to wet deposition have suffered from erosion and corrosion, as calcium carbonate (limestone and marble) reacts with sulphur forming calcium sulphate, which is subsequently washed off causing accelerated erosion. SO_2 also causes metals such as iron to rust more quickly, with a study by Tolba (1983) suggesting corrosion rates up to 10 times faster in urban polluted areas than observed in less polluted countryside.

Acid rain can indirectly affect human health by impacting on food and water supplies that are later ingested. Acidification causes mobilisation of heavy metals in soil which can contaminate food grown in the soil, and infiltrate into fresh water supplies. Accumulation of heavy metals in the body can lead to health problems such as asthma, headaches, and dry coughs (Singh and Agrawal, 2008).

2.2.3.2 Dry deposition

Sulphur particles emitted from ships can be adsorbed and absorbed onto and into land and water surfaces through dry deposition. The impacts of dry deposition on ecosystems and infrastructure are much the same as those caused by acid rain, while the suspension of SO_2 particles in the lower atmosphere in aerosol form can directly impact human health. Breathing can be affected by concentrations of airborne particles, which can also cause eye and skin irritations (Lynn, 1976; Okita, 1983). Suspended particles are known to impact on visibility due to the development of haze.

2.2.3.3 Radiative forcing

The net effect of air emissions from shipping results in an overall cooling effect on the climate (Eyring *et al.*, 2010; Fuglevstedt and Bernsten, 2009). This is largely down to the emissions of SO_2 forming sulphate aerosols in the atmosphere, which reflect incoming solar radiation and hence reduce the extent of warming of the planet. Sulphur emissions can also impact on radiative forcing indirectly through perturbation of cloud microphysics on a localised scale. Sulphur particles can act as cloud condensation nuclei (CCN) upon which cloud droplets form, enhancing cloud albedo causing larger amounts of solar radiation to be reflected (Devasthale *et al.*, 2006). While the current effect of ship emissions on radiative forcing is negative, future projections of GHG emissions coupled with stricter sulphur regulations will likely result in ships contributing to a net warming (Fuglevstedt and Bernsten, 2009).

2.2.4 Nitrogen Oxides (NO_X)

The abbreviation NO_X refers to oxides of nitrogen which generally include nitrogen monoxide (NO) and nitrogen dioxide (NO_2). Shipping contributes approximately 15% of global anthropogenic NO_X emissions (Smith *et al.*, 2014), predominantly due to reactions of nitrogen and oxygen during the fuel combustion process. NO_X is formed as a by-product of combustion when nitrogen (N_2) and O_2 in the air react under certain conditions, while nitrogen contained in the fuel can also be oxidised to form NO_X. Formation of NOx in a diesel engine requires a long residence time at elevated temperatures, therefore formation rates increase when the temperature is higher, the conditions in the combustion chamber are oxygen rich and the engine rpm is lower, allowing the time for NO_X formation to be prolonged (Stone, 1999). NO_X emissions are a concern due to the effects on the environment and human health (EPA, 2008[b]).

NO_X occurs naturally in the atmosphere through lightning strikes and biogenic soil emissions. Natural sources account for approximately 30% of atmospheric NO_X, the rest comes from anthropogenic sources including fossil fuel combustion (50%) and biomass burning (20%) (Delmas *et al.*, 1997). Anthropogenic NO_X emissions contribute to an increase in atmospheric nitrate (NO_3^-) concentrations which can cause acidification and eutrophication. NO is oxidised on the atmosphere to form NO_2, which can increase the rate of low level ozone formation while also impacting on human health, causing e.g. breathing difficulties due to airway inflammation (Salo *et al.,* 2016). Atmospheric NO_X also impacts on climate due to increased O_3 generation and destruction of CH_4, and hence the contribution of NO_X emissions from shipping results in a net cooling of the climate (Eyring *et al.,* 2010).

2.2.4.1 Acidification

Acidification by NO_X occurs due to the formation of Nitric acid (HNO_3) in the atmosphere and subsequent deposition to the earth's surface through precipitation and particulate. Dry and wet deposition of nitrate can alter the pH of water bodies and cause erosion and corrosion to infrastructure and buildings.

2.2.4.2 Eutrophication

Eutrophication refers to excess nutrients in water bodies causing dense growth of plant life. High levels of nutrients in the oceans occur due to disruptions in the earth's natural nitrogen and phosphorus cycles. Elevated nitrogen levels lead to increased biological productivity of phytoplankton in water bodies (Smith *et al.,* 1999). The rapid growth and subsequent death of primary consumers can result in dissolved oxygen deficiency in the water body, leading to hypoxia and anoxia.

2.2.4.3 Surface ozone formation

Ozone is present at ground level due to reactions of NOx in the presence of sunlight. NO_2 is broken down by radiation into NO and a free oxygen atom, which reacts with O_2 to form O_3. An additional rapid reaction takes place between the newly formed O_3 and the residual NO which converts the NO and O_3 back to NO_2 and O_2 respectively. Ground level ozone concentrations increase in the presence of volatile organic carbons (VOCs), Cl and Br, as the free radicals released in the reaction of VOCs with OH in the atmosphere react with the NO, reducing the amount of O_3 converted back to O_2 (Pleijel, 2000).

Due to its oxidising properties, ground level ozone is hazardous to human health causing damage to lungs and inflammation of airways, and can also damage infrastructure and buildings by shortening the lifespan of textiles and paints and weakening the bonds of polymers (Pleijel, 1999). It has also been known to effect ecosystems and vegetation such as forests and crops (Pleijel, 2009).

2.2.4.4 Radiative forcing

The chemical processes involving NO_X in the atmosphere can lead to both an enhancement and dampening of the greenhouse effect. The processes which lead to increased ozone formation at ground level can also occur in the upper atmosphere resulting in an overall warming effect, while the destruction of CH_4 results in negative radiative forcing (Bernsten *et al.,* 1997). The warming effect caused by increased O_3 formation in the troposphere occurs on a regional scale as the atmospheric lifetime of O_3 is limited to 100-200 days, and hence occurs relatively close to the point of emission and in a short time after the emission. However the impact of NOx emissions causing destruction of CH_4 can result in radiative cooling on a global scale, as methane has an atmospheric lifetime of 12 years (IPCC, 2013), and hence the degradation of CH_4 impacts global atmospheric concentrations.

CH_4 is broken down in the atmosphere by OH radicals. Reactions involving NO and O_3 with hydroperoxyl (HO_2), an abundant free radical in the atmosphere, result in the formation of additional OH radicals. Therefore, NO_X emissions can directly and indirectly lead to the destruction of CH_4 through primary reactions and secondary reactions due to increased ozone formation (Isaksen *et al.*, 2014).

2.2.5 Particulate

Particulate matter (PM) is the term given to atmospheric aerosol particles of microscopic solid or liquid matter. PM refers to particles from both anthropogenic and natural sources, and includes organic and inorganic materials such as dust, smoke, soot, pollen, sea spray and liquid droplets. Particulate from industrial sources tends to be finer than natural particles, with diameters from 0.002 – 2.5 μm (Salo *et al.*, 2016). Particle growth occurs due to aggregation, coagulation and surface growth. Aggregation involves clustering of primary particles of the same species to form bigger particles, while coagulation happens when particles collide and merge resulting in a reduced number of particles (PN), and surface growth occurs when species attach to existing particles and the PN remains unchanged. Particles from shipping originate from multiple sources including fuel combustion, wear of materials and emissions from lubricating oils and greases (Salo *et al.*, 2016). Ships emit around 1.7 Tg (Teragrams) of particulate annually (Eyring, 2005). Particulate is considered a concern to the environment and human health (EPA, 2009[b]; WHO, 2013; WHO, 2016).

Particles form in the ships engine due to incomplete combustion of fuel. Microscopic particles of soot are emitted immediately after the fuel is injected, particularly under high temperatures and fuel rich conditions. The soot nuclei begin to grow to form larger particles, some of which undergo oxidation to form CO and CO_2 and some are released though the ships exhaust into the atmosphere (Stone, 2012). The combustion conditions of the engine (e.g. type, design and load) influence the number, size and concentration of particles while the fuel type determines the chemical content (Eyring *et al.*, 2010). Slow speed marine diesel engines operate at higher temperatures and pressures than medium speed diesel engines therefore are likely to emit more particulate (Lack, 2009), while particulate formation also increases with engine load (Stone, 2012).

Particulates from material wear occur due to erosion during processes that cause friction, such as the piston ring rubbing against the engine cylinder during fuel combustion. Wear of materials from ship engine processes result in emissions of inorganic particles including metals such as iron (Fe), nickel (Ni), and vanadium (V), which are associated with burning of heavy fuel oils (Stone, 2012). Other inorganic particles such as calcium (Ca), zinc (Zn) and phosphorus (P) are associated with emissions from lubrication oils (Moldovana *et al.*, 2009). Other emitted particles from a ship include black carbon (BC) elemental carbon (EC), organic carbon (OC), and sulphate (SO_4).

Ships emit various species of particles into the atmosphere with multiple potential impacts on the environment and human health. Particulate is considered an environmental concern, particularly where ships interface with human populations in coastal cities and ports. The European Port Industry Sustainability report has repeatedly identified particulate dust as one of the top 10 environmental priorities for European ports (ESPO, 2018).

2.2.5.1 Human health

Modelling of particulate emissions suggests that releases from maritime transport have significant impacts on human health, with approximately 60,000 mortalities annually due to lung and heart related diseases directly from ship emissions (Corbett *et al.*, 2007). Emissions of ultrafine particulate (diameter less than 10nm) are also related to cases of asthma and bronchitis, as the particles are small enough to reach and penetrate the lungs and enter the bloodstream, and hence can be transported to other parts of the body (Pope and Dockery, 2006). Ultrafine particles can act as carriers for toxic compounds such as vanadium and iron, which cause respiratory diseases (Donaldson *et al.*, 2005).

2.2.5.2 Radiative forcing and albedo effect

Different species of particles affect radiative forcing in different ways. BC and soot particles absorb solar radiation and contribute to positive radiative forcing, while OC and sulphate particles reflect and scatter UV rays contributing a cooling effect (Isaksen *et al.*, 2009; Forster *et al.*, 2007). Particles also affect climate indirectly through cloud formation. Sulphate particulates act as CCN in the atmosphere leading to the formation of clouds, which reflect incoming solar radiation. BC emissions that are deposited on surfaces covered by snow and ice can affect the earth's albedo by reducing the reflectivity of the surface, causing increased melting of snow and ice. The particulate deposits darken the surface and reduce reflectivity, and absorb solar radiation, which warms the surface resulting in ice and snow melting (Isaksen *et al.*, 2009).

2.2.5.3 Acid rain

Nitrogen and sulphur based aerosols that form clouds in the atmosphere can be precipitated out through dry deposition and acid rain. SO_X and NO_X particulates are oxidised to form H_2SO_4 and HNO_3 respectively, which are then deposited to the earth's surface. Suspended aerosols can create haze, reducing visibility and impacting upon human health in populated areas.

2.2.6 Volatile Organic Compounds (VOC's)

VOC's are carbon based compounds that exist in the gas phase under atmospheric conditions. VOC's have a high vapour pressure and low boiling point, causing large numbers of molecules to evaporate from a liquid or solid and enter the surrounding atmosphere. Organic compounds with low numbers of carbon atoms tend to be most volatile, for example methane (CH_4) - which is the smallest hydrocarbon – exists in the gas phase in atmospheric conditions. VOC's are often categorised to exclude methane and the term NMVOC's (non-methane VOC's) is commonly used instead, the reason for this is that methane primarily originates from other sources and has different environmental implications to NMVOC's such as climate change (Salo *et al.,* 2016).

The biggest contribution to atmospheric NMVOC concentrations is from biogenic sources, mainly vegetation, but also including animals and microbes (Guenther *et al.*, 2000). Emissions of NMVOCs occur mainly from the leaves of plants and trees, and the extent of emissions depends largely on temperature and light (Niinemets *et al.*, 2004). Temperature regulates the synthesis of two of the most common biogenic VOCs, Isoprene and Monoterpene, while availability of light affects the production of VOC precursors formed during photosynthesis. Biogenic emissions of NMVOCs on a global scale are significantly greater than from anthropogenic sources (Guenther *et al.*, 2000; Goldstein and Galbally, 2007), however concentrations over urban populations are dominated by emissions from human activities (Freidrich and Obermeier, 1999; Na *et al.*, 2001; Badol *et al.*, 2008). The main anthropogenic sources of NMVOCs are from fuel combustion from motor vehicles and other industrial processes, chemical manufacturing facilities, refineries and solvent containing consumer products such as paints and cleaning chemicals.

From a shipping perspective, NMVOC's originate from the handling of crude oil during production, transport and storage, and from the combustion process. NMVOC's vaporise from the crude oil stored in tanks and are held in the space between the surface of the cargo and the top of the tank. The vapours are often vented to atmosphere during cargo loading and unloading. Tankers that hold 100,000 tonnes of crude oil can emit between 10 and 280 tonnes of NMVOC's (Salo *et al.,* 2016). Technologies and methods exist to treat and control emissions of

NMVOCs from oil tankers during loading and transit (OCIMF, 2019). According to the 3rd GHG study (Smith *et al*., 2014) ships can emit up to 3kg of NMVOC's per tonne of fuel burned. NMVOCs also emanate from solvents used in paints and chemicals for cleaning on board ships, but in much lower volumes.

NMVOC's can have a direct impact on human health. Hydrocarbons emitted during fuel combustion such as benzene are carcinogenic and can affect the respiratory system and cause haematological problems (Kampa and Castanas, 2008), while formaldehyde is also a known carcinogen (Pilidis *et al.,* 2009). NMVOC's have a relatively short atmospheric life span ranging from hours to months, and therefore have only minimal direct impact on radiative forcing. However there are secondary influences due to the effects of NMVOC's on aerosol and O_3 formation, and subsequent impacts on OH radicals and methane production (IPCC, 2013). NMVOC's contribute to the formation of O_3 in the presence of NO_X and sunlight in the troposphere (Atkinson, 2000). Other products such as carbonyls and organic acids are also formed in this reaction contributing to increased acidity of precipitation (Kawamura *et al.*, 2001). The reactions of products of NMVOCs can also lead to the formation and growth of atmospheric aerosol particles, which can affect climate and human health.

2.2.6.1 Photochemical smog

The presence of NMVOCs along with other pollutants such as CO, NO_x and O_3 in the atmosphere can lead to development of a brown haze in the lower troposphere, particularly in heavily urbanised areas with a warm climate, known as photochemical smog. It occurs when NO_x and hydrocarbons in NMVOCs react with sunlight, forming species such as peroxyacetyl nitrates (PANs), aldehydes and ketones. These chemicals, along with other secondary pollutants such as O_3, HNO_3 and NO_X can accumulate at ground level in the troposphere under certain meteorological conditions, forming a chemical haze. Photochemical smog tends to form in dry, warm and still conditions in the presence of a tropospheric temperature inversion, where warm air sits above the smog layer, trapping it near the surface.

Photochemical smog impacts both the environment and human health, causing respiratory problems and eye irritation due to direct contact. Smith (1963) suggests that human exposure to PAN exacerbates respiratory problems, while studies show that photochemical oxidants are causally associated with damage to plants and vegetation (Guderan *et al.,* 1984).

2.3 Discharges to water

In addition to air emissions, ships also pollute the environment through discharges of solid and liquid substances to the immediate surrounding media. Vessels operate in seas, rivers, lakes and inland canals, and there is potential to pollute through accidental losses and spillages of chemicals, controlled and uncontrolled discharges of waste material, and indirectly through dissolution of chemicals from e.g. paint coatings, and transfer of alien species and diseases in ballast water.

Many of the potential pollutants discharged to water from vessels are controlled by regulations. The IMO MARPOL 73/78 convention regulates and restricts the usage of a number of pollutants which could be discharged to sea globally, while other localised regulations are implemented for vessels operating inland. The MARPOL regulations control discharges of oil, chemicals, sewage and garbage through various annexes, while ballast water release is regulated by the IMO BWM (Ballast Water Management) convention, and release of toxic chemicals from antifoul coatings are controlled by the International Convention on the Control of Harmful Anti-fouling Systems on Ships (AFS convention).

2.3.1 Oil

Pollution of the seas by oil coincides with an increased reliance on petroleum based products during the twentieth century. Ships transport almost 2 billion tonnes of petroleum around the world (Rodrigue *et al.*, 2009), most of which is carried in VLCC (very large crude carriers) and ULCC vessels (ultra large crude carriers) with a deadweight capacity of up to half a million tonnes (Rogowska and Namiesnik, 2010). A number of factors can influence the impact of oil discharges on the environment such as the volume of material discharged, the composition of the oil, and the geographical location of the discharge in terms of proximity to habitats, shorelines and ecosystems. Large tankers with a greater carrying capacity have the potential to release bigger volumes of oil into the marine environment therefore the need to reduce the risk of discharges increases as tankers get bigger.

It has been estimated that an average of 1,250,000 tonnes of oil are released into the marine environment annually (GESAMP, 2007). Approximately half of this occurs through natural seepage from the seabed (Mitchell *et al.*, 1999), a further 11% is estimated to enter the oceans due to industrial runoff, and around a third is attributed to shipping (Lindgren *et al.,* 2016[b]). Accidental spillages from large tankers receive a lot of media attention, are well documented (ITOPF, 2018), and cause significant marine pollution, however the biggest anthropogenic contributor to oil discharges is from routine shipping operations (Farrington, 2013).

Operational discharges of oil from ships into the sea have been estimated at around 200,000 tonnes annually (Jernelov, 2010). Such spillages are small relative to tanker accidents however the frequency is much greater, and the impacts on the environment can be significant. Operational discharges can occur through a variety of different pathways. Spillages often occur during fuel bunkering and cargo loading and unloading, and leakages occur from the propeller shaft and stern tube when bearing seals become worn causing small but continuous discharges. Propeller shaft repairs tend to take place during dry-docking therefore it is possible that small continuous leaks from worn seals could occur for years at a time (Lindgren, 2015). Bilge water collected in the ship's hull can also be a source of oil pollution to the sea. IMO regulations state that vessels over 400 GT (gross tonnage) must not discharge bilge water that exceeds 15ppm for hydrocarbons, however it has been estimated that more than 16,000 tonnes of oil enters the sea annually as a result of bilge releases (Lindgren *et al.*, 2016[b]). This is because the regulations do not apply to vessels smaller than 400 GT, and it is likely that unknown and illegal discharges also take place, suggesting the estimate could be conservative. Other sources of oil pollution include shipwrecks - which can slowly release residual pollutants into surrounding water if remediation activities are not carried out - and unregulated small craft such as pleasure boats where operational spills can be substantial due to the use of two-stroke diesel engines where 20-30% of fuel is not combusted and is washed out to sea in the exhaust (Lindgren *et al.*, 2016[b]).

Once oil enters the ocean it can behave in different ways depending on its characteristics. Oil that is highly viscous is likely to remain relatively confined, while less viscous oils can spread across the surface of the ocean. Weather conditions (wind) and currents can affect the extent of spreading, while higher water temperatures accelerate oil diffusion (Hamam, 1987). The lighter hydrocarbons contained in oil undergo almost immediate evaporation from the surface of the ocean and enter the atmosphere, and the extent to which oil evaporates depends on the volatility of the hydrocarbons e.g. HFO will evaporate less than light crude oil. Evaporated oil particulate can be carried to other locations by weather (Rogowska and Namiesnik, 2010).

Some of the oil that remains on the surface of the ocean undergoes photolysis in the presence of UV light, forming potentially more toxic products such as PAHs (polycyclic aromatic hydrocarbons), which are hazardous to marine species and ecosystems (Hylland, 2007). A proportion of oil undergoes emulsification, where droplets are mixed in with the surrounding water due to wind and currents which expands the volume of contaminated water between two and five times (Lindgren *et al.*, 2016[b]), making it more difficult to remediate in a clean-up. Less than 1% of the oil is dissolved in seawater, while a larger fraction becomes dispersed into the water column as small droplets, which is eventually degraded (Kingston, 2002). The process of degradation increases the bioavailability of toxins to marine species, which refers to the amount of substance available to enter living organisms by crossing the cellular membrane from surrounding media. The heavier fraction of oil can sink to the sea bed, or adsorb to organic particles in water increasing the particle weight and sink in a process called sedimentation (Gong *et al.*, 2014).

2.3.1.1 Impacts of large discharges

The effects of oil discharges on marine species and habitats can vary depending on the characteristics of the discharge and the sensitivity of the biota. Exposure of oil contaminants to biota can occur through a number of different pathways including direct contact, ingestion of contaminated prey, and uptake of bioavailable components through water (Boehm and Page, 2007). Large discharges can have lethal effects on biota due to direct toxification and suffocation due to a lack of oxygen. Hypoxia (depletion of oxygen) occurs due to nutrient enrichment of the water, which is exacerbated by oil discharges due to the organic content of the oil (Craig *et al.,* 2013). Hypoxia can also impact marine organisms indirectly through habitat loss. Other sub-lethal impacts of oil discharges can occur such as hypothermia in sea birds and marine mammals, as even small amounts of oil can affect insulation capabilities (Piatt and Ford, 1996). Large discharges can also cause physical damage to marine species due to clogging, and to beaches and shorelines requiring extensive clean-up operations.

2.3.1.2 Impacts of small continuous discharges

Small continuous discharges of oil can also impact on marine species and habitats, causing sub-lethal but long terms effects such as cancer, reduced fertility and stunted growth. Such effects arise due to the presence of PAHs, which can be passed down through generations of species due to bioaccumulation resulting in a manifestation of health issues in future generations (OECD, 2006).

2.3.2 Sewage and Grey Water

Ships generate wastewater from passengers and crew on-board, and hence large cruise ships carrying significant numbers of people tend to generate the most. Wastewater can be separated into two main strands, black water (sewage) and grey water. Sewage can be defined as faecal contaminated wastewater emanating from toilets, medical facilities and premises containing animals, while grey water includes other less contaminated wastewater streams from washing facilities such as sinks, showers and kitchens, along with storm water and surface run off. Black and grey water are collected and treated together in municipal treatment plants on land, however due to space limitations and the structure of the wastewater regulations in shipping, sewage and grey water tend to be collected separately.

Annex IV of the IMO MARPOL 73/78 regulations requires sewage emanating from vessels over 400 GT to be treated to certain standards prior to discharge within 12nm of land, while grey water is not currently regulated by the IMO. There are no restrictions on discharges of raw sewage on the ‘high seas’, and while grey water discharge is not regulated by the IMO, countries and regions impose their own restrictions for territorial waters e.g. through Directive 2012/49/EU in Europe (Butt, 2007).

The amount of sewage and grey water generated on a vessel depends on the number of people on board. It has been estimated that on cruise ships, between 25-70 litres per person per day of sewage are generated and between 120-130 litres per person per day of grey water (HELCOM, 1990; Butt, 2007). Raw sewage contains high concentrations of pathogens, organic matter and nutrients and hence requires treatment before discharge. Annex IV of MARPOL requires treated sewage discharge to meet standards for faecal coliform content (FCS), total suspended solids (TSS), Biochemical oxygen demand (BOD) and Chemical oxygen demand (COD) amongst other criteria which are in line with the requirements of EU Directive 91/271/EEC on urban wastewater treatment. The requirements state that treated sewage effluent must not contain more than 250 faecal coliform per 100ml, while BOD and COD must not exceed 25 mg/l and 125 mg/l respectively. Despite not being regulated, grey water can often contain a variety of pollutants including bacteria, chemicals, metals, micro-plastics and suspended solids. It is assumed that grey water pollutants are less concentrated than raw sewage, however the concentrations of faecal matter, suspended solids, BOD and COD can in some cases far exceed the discharge requirements outlined in MARPOL Annex IV (EPA, 2011).

Sewage discharge is directly related to the number of people on board a vessel, and hence passenger ships are considered the most significant threat in this regard and are therefore regulated more stringently. As of 1st January 2016, passenger ships must use approved treatment plants before effluent can be discharged to sea within special areas, while vessels operating outside of special areas must ensure sewage is *'comminuted and disinfected'* before discharge, but only at a minimum distance of 3nm from shore. A significant source of wastewater pollution is from leisure craft and passenger vessels less than 400 GT, which carry significant numbers of people on board but are not covered by MARPOL requirements. Such vessels tend to operate near the shoreline and in tourist zones where discharges can affect bathers and cause aesthetic damage.

2.3.2.1 Impacts on marine species and habitats

Wastewater discharge into the sea can impact on marine life and habitats directly through toxification and indirectly though nutrient enrichment causing eutrophication. Raw sewage contains significant concentrations of nitrogen and phosphorus, estimated to be up to 15 grams and 5 grams per person per day respectively (Lindgren *et al.,* 2016[b]). Eutrophication increases the risk of algal blooms which can affect the balance of marine ecosystems. Elevated populations of phytoplankton at the surface can reduce light penetration, affecting the growth and nutrition of certain marine flora and fauna (Pastorok and Bilyard, 1985). The subsequent decomposition of organic matter can lead to hypoxia (low oxygen between 1-30% saturation) and anoxia (0% oxygen saturation) at the sea floor, creating *'dead zones'* in the ocean due to low oxygen levels being unable to support marine life (Hagy *et al.,* 2004). Decomposition of organic matter in anoxic waters can result in the formation of hydrogen sulphide (H_2S), as oxygen used by bacteria as a source of energy is unavailable and sulphate is used instead (Bernes, 2005).

Fish and shellfish are directly impacted by wastewater discharges as they retain toxic particles when filtering seawater, while calcification of shellfish can be inhibited by nutrient enrichment. High concentrations of suspended solids can affect growth rates of coral reefs and the diversity of populations living within coral ecosystems (Pastorok and Bilyard, 1985). The accumulation of toxic substances in fish and shellfish can also lead to disease and ill health further up the food chain (Koboevic *et al.,* 2011).

2.3.2.2 Human health

Pathogenic organisms, viruses and bacteria are contained in sewage which may cause damage to human health including diseases such as hepatitis A and E, salmonella, gastrointestinal diseases and infections. Sewage is a particular threat to human health if it is discharged within public coastal areas used for recreation (Koboevic *et al.,* 2011). Various studies highlight the adverse health outcomes for recreational swimmers and bathers coming in to contact with wastewater polluted waters, with faecal bacteria emphasised as the principal cause of symptoms such as skin irritation, infections and respiratory diseases (Soller *et al.*, 2010).

2.3.3 Antifoul systems

A significant proportion of a ship's hull is situated below the waterline and therefore is in direct contact with the ocean. The process of biofouling begins almost immediately when a surface such as a vessel hull enters the sea. Within a short period of time (minutes), organic particles such as proteins, proteoglycans and polysaccharides accumulate on the surface forming an organic conditioning layer (Callow and Fletcher, 1994; Abarzua and Jakubowsky, 1995). Within hours, bacteria and single cell diatoms attach to the conditioning layer - initially through adsorption, then through adhesion - along with other single celled organisms to form a microbial biofilm. The organisms making up the biofilm release adhesive substances known as EPS (extracellular polymeric substances) which, along with the friction caused by rough surfaced microbial colonies in the biofilm, help to attract more organisms to the surface. Within a week, additional organisms such as spores of macro-algae and protozoa accumulate creating a more complex community, and within two to three weeks larger marine invertebrates such as larvae of barnacles and molluscs begin to settle and grow on the surface, forming a layer of macro-fouling (Yebra *et al.*, 2004).

The characteristic of biofouling varies according to a number of conditions, including the operating pattern of the vessel, the geographical location, and water quality parameters such as temperature, salinity and pH. Fouling can be broadly divided into soft and hard organisms. Soft organisms are those which lack solid structures such as sea weeds and sponges, while hard organisms have tough shells or skeletons such as barnacles, mussels and corals (Lewis, 1994). Both types of fouling create problems for the shipping industry due to increased friction of vessel hulls and the surrounding ocean, and increased weight through accumulation. These impacts result in decreased vessel speed and manoeuvrability, and therefore increased fuel consumption and associated atmospheric emissions. Another environmental effect of ship biofouling is the potential for introduction of alien marine species to non-native marine environments as organisms detach from the hull naturally or during cleaning. (Yebra *et al.*, 2004).

The process of prevention of marine biofouling from ships has been attempted for more than 2000 years (Yebra *et al.,* 2004). Various compounds have been applied to vessel hulls over the years in order to reduce the extent of fouling, from resins of tar and wax to lead and copper sheathings. In the mid 1800's, antifoul paints were developed using toxic materials such as arsenic and mercury, with the aim of releasing toxicants from polymer based coatings to prevent build-up of organisms. Many of the coatings were ineffective up until the Second World War when synthetic petroleum based resins were introduced, and later compounds containing organotin (Yebra *et al.*, 2004).

Organotin based compounds such as TBT (Tributyltin) are extremely effective biocides due to being highly toxic, particularly to shell based organisms, while also being colourless and having no corrosive properties (Omae, 2003). In 2001, the IMO introduced regulations in relation to the International Convention on the Control of Harmful Anti-fouling Systems in Ships (AFS Convention), which banned the use of TBT coatings due to the effects of the chemicals released on marine organisms, such as imposex in sea snails and defective shell growth in oysters (Gibbs *et al.,* 1991; Dyrynda, 1992). The AFS Convention prohibits ships from using organotin based coatings as antifoul agents, and organotin compounds of any kind should not be present in coatings at concentrations greater than 2,500 mg tin (Sn) per Kg of dry paint.

Since the enactment of the AFS Convention, alternative coating types have been utilised, typically copper based (Srinivasan and Swain, 2007). Copper is a naturally occurring metal in the environment, which enters the oceans through weathering. Up to 250,000 tonnes of copper enter the marine environment naturally annually, compared to about 15,000 tonnes through use of antifoul coatings (Lindgren *et al.,* 2016[b]). In certain ionic forms such as Cu^{2+}, copper can be toxic to living organisms as it can easily pass through cell membranes causing significant bioaccumulation leading to growth inhibition (Debelius *et al.,* 2009). Copper used in antifoul coatings is in ionic form, and is an effective repellent to hard organisms including barnacles, tube worms and certain algal species, however some species (typically soft organisms) display high tolerance and hence additional biocides are added to the copper coatings (Yebra *et al.*, 2004).

Numerous so called 'booster biocides' are available on the market, and are intended to be used in addition to copper based antifoul paints to improve the removal rate of species with a high tolerance to copper. The most common of these compounds are

Irgarol 1051 and Diuron, which have been found to persist in surface waters and accumulate in marine sediments (Manzo *et al.,* 2008). Irgarol has a lifetime in water of about 350 days, and considerably longer in sediment as particulate (Gatidou *et al.,* 2007), while Diuron can persist in seawater for more than 42 days (Thomas and Brooks, 2010). Irgarol has been found to be toxic to various species of seaweed and sea grass, while Diuron can be detrimental to corals, sea urchin, and marine invertebrates (Konstantinou and Albanis, 2004). Due to the persistence of these compounds in the marine environment, these substances can be toxic to organisms in the sea and not just those that have accumulated on vessel hulls (Lindgren *et al.,* 2016[b]). Both Irgarol and Diuron have since been banned in several European countries including the UK (Price and Readman, 2013).

More recently, alternative biocide free coatings have been utilised which rely on physico-chemical properties to deter organisms from attaching to a surface, and reduce the strength of adhesion of the organisms that do attach (Callow and Callow, 2011). Such products are known as Fouling Release Coatings (FRC's) and are typically silicone or fluorine based (Lejars *et al.*, 2012). Coatings developed from silicone-based polymers undergo a process called curing, which hardens the silicone and removes the adhesive properties. Curing is carried out through hydrosilylation and condensation reactions in the presence of platinum or tin based catalysts (Mincheva, 2016). There are concerns that the tin compounds contained in the biocide free coatings may be released into the marine environment due to abrasion (Watermann *et al.,* 2005), while (Lagerstrom *et al.,* 2016) suggest that organotin compounds are still being released in the oceans due to ineffective removal of historic paint layers.

2.3.4 Ballast water

Ballast is the term used for the material used to stabilise or balance a vessel when at sea. Historically, ships have used dry ballast materials such as sand and stones placed in the ships' keel in order to counter balance the weight of unloaded cargo. Modern ships with steel hulls use seawater as ballast, stored in the ship's hull or more commonly in ballast tanks. Large tankers and cargo ships tend to carry the most ballast water, in excess of 200,000 m^3 in some cases (US National Research

Council, 1996). Ballast water is taken on board when loaded ships dock at port and discharge cargo. The ballast water stabilises the vessel during voyage, and when the ship docks at the destination port the ballast water is discharged into the surrounding water to make room for new cargo loads. This process results in the transfer of seawater from one geographical location to another. The seawater collected in the ballast tanks also contains indigenous aquatic organisms, which are transported to different ports and coastal waters around the world.

It has been estimated that between 3,000 and 4,000 different species of organisms are carried around the world in ballast tanks daily (Carlton and Geller, 1993), with some estimates as high as 10,000 (Bax *et al.,* 2003). Many of the species transported are unable to survive in the ballast tanks under low oxygen conditions and with no access to sunlight, however survival rates can increase when journey times are cut shorter due to new improved shipping logistics and rapid transportation (Lindgren *et al.,* 2016[b]). The fate of many organisms is also dependent on the environmental conditions at the destination port, as variations in water temperature and salinity at different locations can eliminate species with low tolerance to such changes.

The IMO introduced the Ballast Water Management Convention in 2004, which entered force in 2017. The convention requires vessels to remove or render harmless aquatic organisms contained in ballast water before its release into a new location. The regulation applies to ships registered under contracting parties to the convention and to ships that dock at ports which are party to the convention, and outlines standards for treatment of ballast water. Ships are required to maintain a ballast water management plan and record book, and ships over 400 GT will carry an International Ballast Water Management Certificate. The risks, and techniques for mitigating risks associated with organisms carried in ships' ballast water are well researched, as outlined in the report led by the IMO and World Maritime University (GEF-UNDP-IMO GloBallast Partnerships Programme and WMU, 2013).

2.3.4.1 Invasive species

The IMO defines non-indigenous species as *"any species outside its native range, whether transported intentionally or accidentally by humans or transported through natural processes"* (IMO, 2007). Non-indigenous species can become invasive if they have a high tolerance to changes in water quality parameters and become established in an alien location. Studies suggest that the rate of establishment of foreign species is increasing and the impact of the introduction of new organisms is considered a major threat to marine biodiversity and contributor to environmental change (Bax *et al.,* 2003). There are many examples of species invasions with varying impacts. Zebra mussels (*Dreisenna polymorpha*), which were native to the Caspian Sea can now be found in many locations across Europe including the UK, and in the Great lakes in America due to their introduction from shipping through ballast water and hull fouling. Zebra mussel's impact on local marine ecosystems by competing with indigenous species for food, they have also been found to cause damage to infrastructure, blocking the inlet pipes to water treatment systems and damaging ship engines (Lindgren *et al.*, 2016[b]). Introductions of other invasive species such as the comb jellyfish to the Black Sea have impacted significantly on populations of aquatic life by feeding on many of the primary consumers in large quantities, and therefore impacting e.g. fish species further up the food chain, greatly affecting the fishing industry (Lindgren *et al.*, 2016[b]).

2.3.4.2 Spread of disease

Ballast water can also carry viruses and pathogens that can lead to ill health in humans (David and Gollasch, 2015). Ships are known to have spread pathogenic diseases such as cholera, leading to an outbreak in Peru in 1991 that was directly related to ballast water discharges in Latin American waters. Other studies provide evidence of bacteria such as E. Coli and Faecal Streptococci present in significant concentrations in ballast water samples (Whitby *et al.,* 1998), which can lead to disease in humans though ingestion, particularly in areas used for recreation and bathing.

Toxins can also be passed on to humans through ingestion of contaminated shellfish that have filtered water containing toxic micro algae and fed on toxic phytoplankton. Such algae are present in resting forms in marine sediment, which can be transferred to different locations in ballast water tanks. Human ingestion of contaminated shellfish can result in poisoning and potential fatalities (Lindgren *et al.,* 2016[b]).

2.3.5 Marine litter

Marine litter or debris consists of incorrectly disposed solid waste products from human activities that end up in the marine environment. It can enter the marine environment from two main pathways, land based sources and ocean or waterway based sources. Around 80% of the world's marine litter comes from land based sources (GESAMP, 1991). Discarded litter in the streets enters drains and sewers and accumulates in rivers and streams before being carried out to sea, while unwanted waste from commercialised areas by the coast, including beaches and seaside towns can be blown through wind or washed into the sea through precipitation (Sheavly and Register, 2007). This study focuses on marine litter from ocean based sources.

Ocean or waterway based sources such as ships, drilling rigs and other offshore platforms are responsible for the other 20% of marine litter (Lindgren *et al.,* 2016[b]). Packaging waste and unwanted consumer goods are the main types of litter to enter the marine environment from ocean sources, such as food packaging, beverage containers, cigarette butts and cosmetics. Litter typically enters the ocean environment due to accidental loss, illegal dumping or poor waste management practices (Sheavly and Register, 2007).

In the past, much of the waste to enter the ocean was made up of organic and degradable materials, however in the last 100 years synthetic elements such as plastics have become far more abundant. Plastics are durable and buoyant, and hence are a significant threat to the marine environment as they can float over long distances and are difficult to break down (Derraik, 2002). Plastics that settle in sediment may remain for centuries (Hansen, 1990; Goldberg, 1997).

The IMO introduced regulations prohibiting the discharge of garbage into the sea from ships through Annex V of MARPOL 73/78, which includes all waste products with the exception of food waste, animal carcasses, non-toxic cargo residues, and non-harmful cleaning agents and additives contained in ship deck wash water. Food waste can only be disposed of at a distance of 12 nm or greater from the nearest land, and must be comminuted if the ship is operating inside a designated special area. Outside special areas, comminuted food waste can be disposed of at a distance of 3nm from land. The disposal of non-harmful cleaning agents from deck wash water are not restricted at any distance, however cargo residues and cleaning agents contained in cargo hold wash water must be disposed of at a minimum distance of 12 nm from land.

2.3.5.1 Human health and safety

The presence of litter in the marine environment can impact upon human health and safety. Litter on beaches and shorelines such as broken glass or discarded syringes can cause physical harm to recreational visitors walking on the shore line, while swimmers can become entangled in disposed fishing ropes and floating debris. Hazardous wastes such as from used medical products containing various types of bacteria can greatly impact on water quality, causing subsequent effects to bathers such as skin infections, diarrhoea, and in some cases more serious diseases such as typhoid and cholera (Sheavly and Register, 2007).

2.3.5.2 Aesthetics and economics

The economic costs associated with marine litter can be significant, as debris on beaches can discourage visitors affecting local income from tourism, while costs are also incurred to clear up. Significant amounts of money are spent annually by local communities in the North Sea region on cleaning up beaches to maintain aesthetic and safety aspects, while damage to ships and other infrastructure from marine litter can also incur considerable economic costs (Lindgren *et al.,* 2016[b]).

2.3.5.3 Wildlife

Marine litter can also impact upon marine wildlife by causing entanglement from fishing nets and other debris leading to strangling or drowning of larger animals such as sea birds, seals and sea turtles. Many fragmented particles of waste, particularly micro plastics, can be mistaken for food and ingested by fish and marine mammals causing blockages of the digestive tract and other internal injuries (Lindgren *et al.,* 2016[b]). Debris can inhibit mobility and block feeding vectors by preventing wildlife from opening mouths and blocking access to food sources, while large debris can cause physical smothering leading to suffocation and drowning.

2.3.5.4 Habitat destruction and introduction of invasive species

Debris can cause physical damage to shorelines, coral reefs and living habitats. Litter can be carried in currents and tides and accumulate in different locations e.g. Great Pacific Garbage Patch, affecting habitats at considerable distances from the source of the waste. The transport of litter in ocean currents can also carry invasive species to different locations, indirectly affecting habitats, while large patches of garbage can block sunlight, inhibiting important processes for marine flora such as photosynthesis (Sheavly and Register, 2007).

2.3.5.5 Vessel and infrastructure damage

Nets, ropes and discarded fishing gear can become entangled with ship propellers and rudders causing significant damage. Plastic bags and other large items and can block inlet pipes of coastal utilities and power stations.

2.3.5.6 Source and fate of micro plastics

Micro plastics can originate from secondary sources as fragmented plastic waste, or as primary sources from cosmetics and fibres. The National Oceanographic and Atmospheric Administration (NOAA) define micro plastics as small pieces of plastic less than 5mm in size. They can be persistent in sea water at concentrations of up to 100,000 particles per m^3 of ocean (Wright *et al.,* 2013), and are easily ingested by primary consumers and can therefore be passed on to marine organisms at higher trophic levels, although the long term impacts of this are not well established (Wright *et al.,* 2013).

2.3.6 Hazardous and Noxious Substances (HNS)

Chemicals from shipping can enter the marine environment through a number of different pathways. Discharges can occur from cargo related activities, ship operation, and operational wastes. According to the IMO HNS Convention, hazardous and noxious substances are defined as oils, other liquid substances defined as noxious or dangerous, liquefied gases, liquid substances with a flash point not exceeding 60°C, hazardous and harmful materials and substances carried in packaged form or in containers, and solid bulk materials considered as chemical hazards. HNS are a concern if they come into contact with the marine environment, most likely through spillage due to an accident or during handling. The IMO have estimated that more than 200 million tonnes of chemicals are transported annually by shipping tankers, with more than 2,000 different types of chemicals transported on a regular basis (IMO, 2016[b]). The most common chemicals to be transported by ships are sulphuric acid (H_2SO_4), hydrochloric acid (HCl), sodium hydroxide (NaOH), phosphoric acid (H_3PO_4), nitric acid (HNO_3), LPG/LNG, ammonia (NH_3), benzene (C_6H_6), xylene (C_8H_{10}), and phenol (C_6H_5OH) (IMO, 2016[b]).

The impact of chemical spillages on the environment depends on the quantity and properties of the substance spilled. Chemical spillages can cause potential harmful consequences to human health, result in economic losses, and cause environmental damage through toxification of marine species and habitats. Table 2.1 classifies the chemicals mentioned above in terms of acute toxicity to humans and aquatic species, categorised according to the Global Harmonised System (GHS) of classification and labelling of chemicals (see Chapter 4, Sections 4.8.3 and 4.8.4 for further information on this classification system). Using the GHS, substances classified as Category 1 are considered to be the most toxic, with decreasing toxicity as the category number increases (see Table 4.4. for definitions of each).

Table 2.1 Acute toxicity of chemicals according to GHS

Chemical	Toxicity category (aquatic)	Toxicity category (Humans)
HNO_3	3	2
C_6H_5OH	2	3
NH_3	2	4
NaOH	3	4
C_6H_6	3	4
C_8H_{10}	2	5
HCl	4	4
H_2SO_4	3	5
H_3PO_4	4	5

The fate and behaviour of noxious chemical pollutants in the marine environment can vary considerably depending on the characteristics of the chemical. A comprehensive study was conducted by Cunha *et al.* (2015) to examine the extent of chemicals released into the environment through spillages, and the fate, behaviour and impact of such chemicals on marine habitats. The study found that many historic chemical spills are poorly documented and hence the fate and behaviour of such pollutants in the marine environment are not well known. Neuparth *et al.* (2011) also state that the ecological hazards associated with chemical spills are not as well understood as those related to oil pollution. Nevertheless, some inferences can be drawn from the limited data that is available. Cunha *et al.* (2015) developed a publically accessible database highlighting the toxicity and persistence of 24 chemicals which are known to have been released into the aquatic environment through spillage. Biodegradation half-life is in the order of weeks, with only a small number of the chemicals listed persisting for longer than a month. Cunha *et al.* (2015) also state that while there is limited data regarding the behaviour of chemicals at sea, the incidents that were analysed as part of the study suggest the effects on the marine environment are localised. However it is acknowledged that improved monitoring and modelling is required to provide a more accurate assessment.

MARPOL Annex II on the '*carriage of noxious liquid substances in bulk'* sets out a categorisation system for noxious and liquid substances which are potentially harmful to the environment. Substances are grouped into 4 categories: X; Y; Z; and other. Substances grouped into Category X are those which are considered to be severely harmful to the environment or human health, and are prohibited from being discharged to sea. Category Y substances are those which are deemed to present a hazard to the environment or human health, and therefore discharge to sea is limited based on the quality and quantity of the substance. Category Z substances are considered to present a minor hazard, and therefore less stringent discharge restrictions are incurred. Substances classed as other present no harm to the environment or human health and there are no discharge restrictions on such substances. Appendix 1 to Regulation 6 of MARPOL Annex II lays out the guidelines for categorisation of noxious liquid substances.

The IMO also introduced the HNS Convention on '*Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea'* in 1996, however it is yet to be ratified. The convention introduces a system of compensation in the event of an accident involving the transport of chemicals at sea, whereby ship owners are liable to pay all associated costs up to a compulsory limit (typically covered by insurance), and the rest is covered by an HNS fund. If the convention becomes ratified, it is expected that the HNS fund will be generated by the states party to the convention. Other regulations governing the carriage of chemicals by ship include the SOLAS 1974 Convention (Safety of Life at Sea), which requires chemical tankers to comply with the International Bulk Chemical (IBC) Code, which sets out standards for minimising the risk of harm to the environment, the ship and crew from hazardous substances.

2.4 Impacts on land

By definition, ships operate on water and therefore rarely make direct contact with land, with the exception of dry-docking which takes place infrequently, for a relatively short period of time and typically for a specific purpose. Even when in port the structure of the vessel remains sea bound, however there are activities that take place during ship operation that can impact on the land environment. The scope of this study focuses on environmental impacts of the operational phase of vessels, however there are additional impacts associated with construction and decommissioning of vessels that are indirectly related to the operational phase, as ship operation could not occur without the construction phase. This section highlights both direct operational impacts and indirect impacts associated with construction and decommissioning, on the land environment.

2.4.1 Waste disposal

Disposal of waste from ships is governed by Annex V of the MARPOL 73/78 regulations. All waste streams with the exception of food, animal carcasses, non-harmful cargo residues and cleaning agents and additives must be disposed of onshore, and the MEPC (Marine Environment Protection Committee) have developed guidelines for waste disposal (Resolution MEPC.295(71)). The guidelines state the need for garbage management practices, training and education on board ships, along with adequate waste reception facilities at ports. Operational wastes from ships include ash from on-board incinerators and boilers, harmful chemical cleaning agents and additives, and municipal solid wastes. Waste collected at port reception facilities is handled in accordance with the waste regulations of the country in which the port resides e.g. Directive 2008/98/EC in the EU.

Ship waste disposal onshore can have various environmental impacts depending on the type of waste. Garbage sent to landfill can result in methane emissions due to the organic content of the waste, while leaching of chemicals and pathogens into the watercourse is an associated problem, particularly where there is flood risk (Laner *et al.,* 2009). In addition, waste disposal sites can be aesthetically unpleasing and produce unpleasant odours, affecting port workers and local communities.

2.4.2 Resource depletion

During the design and construction phase of a vessel raw materials are extracted and undergo manufacturing and production processes which impact on the environment. Extraction of raw materials from land can impact upon land quality, causing degradation through deforestation and quarrying. Ship construction is an energy intensive process resulting in direct emissions of CO_2 from the burning of fossil fuels, while metal extraction also releases greenhouse gases and other air pollutants (Lindgren *et al.,* 2016[c]). Steel production also produces significant volumes of wastewater containing chemicals such as phenol, cyanide and ammonia requiring treatment (Jorgensen, 1979). Metal construction processes result in emissions of particulate matter into the atmosphere which can be washed into the environment, along with other contaminants from cleaning and maintenance operations. Studies show that elevated concentrations of metal contaminants along with TBT, PCBs (Polychlorinated Biphenyls) and PAHs have been found in sediment and water bodies near ship construction yards (Lindgren *et al.,* 2016[c]).

2.4.3 Ship decommissioning

The environmental impacts associated with ship decommissioning arise from the disposal of materials. The process of decommissioning involves the separation of different materials, however ships are primarily made up of steel which is a valuable commodity, and most of which can be recycled (Lindgren *et al.,* 2016[c]). Ships also tend to contain hazardous materials including asbestos, heavy metals, hydrocarbons and refrigerants, which can be harmful to the environment if not disposed of correctly. Separation of materials can be costly, especially in the shipping industry where *'design for recycling'* has not historically been considered in shipping when compared with other industries (Lundqvist, 2004), and therefore the possibility of hazardous materials interacting with the environment is higher. Scrapping often takes place in developing countries where the conditions for dismantling are not sophisticated hence the environmental and safety risks are heightened (Lindgren *et al.,* 2016[c]). A review of ship breaking and recycling in developing countries is provided by the World Bank Report (2010), which highlights the issues in Pakistan and Bangladesh.

Ship dismantling involves cutting of the vessel structure into steel plates which can result in discharges of toxic pollutants including heavy metals and TBT. Furthermore, the process involves the removal of oils, greases and cargo residues which are at risk of discharge to the environment. Currently no international regulation exists to control the process of ship decommissioning, however there are local regulations in some areas for disposal of hazardous materials that cover dismantled vessels e.g. the 1989 UN Basel Convention (UNEP, 1989). The IMO established the Hong Kong convention in 2009, with the aim of reducing the risks associated with ship dismantling by requiring all ships to carry an inventory of hazardous materials, however the convention has not yet been ratified.

2.5 Noise

The marine environment is the source of and is subjected to a variety of natural physical and biological sounds, such as from breaking of waves at the ocean surface, underwater earthquakes and volcanoes, communication between and movement of marine organisms, and *‘thermal noise’* associated with the pressure fluctuations caused by thermal agitation of the ocean (US National Research Council, 2003). Intentional and unintentional anthropogenic sounds are a significant contribution to background noise in the marine environment, and can differ from natural sounds in terms of direction, frequency and duration (Weilgart, 2007).

Noise from ships and shipping activities can impact upon humans and marine life above and below the surface of the ocean. Above the surface, noise from operational processes such as handling of cargo, horns, and warning sirens create noise along with the running of engines and generators. Surface noise becomes a nuisance to humans whilst ships are berthed in ports and harbours near to population centres, and ship crew are subjected to noise whilst at sea. Ships also produce underwater noise from propellers (exacerbated during cavitation), vibrations from the ship’s hull and from the main and auxiliary engines (Badino *et al.*, 2012), potentially affecting aquatic life.

2.5.1 Underwater noise interference with aquatic life

Sound is an important sensory mechanism for aquatic life in an environment where the other senses are dampened, and many animals depend on it for navigation, communication and to search for mates and food (Jasny *et al.,* 2005). Marine mammals produce sounds in a broad range of frequencies from less than 10 Hz to more than 200 kHz (US National Research Council, 2003), while sound waves can travel hundreds of kilometres in water, and at speeds almost five times faster than in air (Lindgren and Wilewska-Bien, 2016). Propagation of sound in water is mainly affected by the frequency of the noise and the properties of the water such as temperature, salinity, turbidity and density (Urick, 1983).

Anthropogenic noise has increased in amount and variety in recent decades due to human activity at sea. High intensity impulsive noise tends to emanate from industrial activities such as pile driving for installation of large structures, seismic exploration, sonar, and underwater blasting, while low intensity stationary noise tends to originate from ships (Peng *et al.,* 2015). Marine species vary in their sensitivity and range of hearing, and hence sound can affect species in different ways at varying frequencies. Some species such as the Lusitanian toadfish have a low auditory threshold and can detect sounds at frequencies between 50 and 200 Hz, by contrast, the hearing range of a sea lion is between 1 and 10 kHz (Slabbekoorn *et al.,* 2010). Therefore, the range of intensity and frequency of anthropogenic noise has been shown to have adverse impacts on a wide variety of marine species.

2.5.1.1 Acoustic masking

Anthropogenic noise can cause auditory masking of communication signals between species of marine organisms. Many species use acoustic interpretation as a means of survival, and external noise from ships can interfere causing the standard sound signals of some species to be inaudible. A study into the Lusitanian toadfish suggests that communication signals need to be 36db louder in the presence of ship noise in order to be detectable to the species (Vasconcelos *et al.,* 2007).

2.5.1.2 Behaviour

The behaviour of marine organisms at an individual level has been known to alter due to external anthropogenic noise. Responses to seismic airgun shots and naval sonar of certain marine mammals and fish species show behavioural changes such as altered swimming patterns, disruption of foraging and avoidance responses such as diving deeper into the ocean (Peng *et al.*, 2015). Noise from large vessels at high speed and smaller vessels at accelerating speed is shown to cause avoidance responses in Pacific herring (Schwarz and Greer, 1984), while Bruintjes and Radford

(2013) suggest that vessel noise can result in reduced nest digging and decreased response to predators in cichlid fish. Increased vulnerability to predators due to ship noise has also been shown in other marine species (Chan *et al.,* 2010; Wale *et al.,* 2013).

2.5.1.3 Populations

Underwater anthropogenic noise has been shown to have an impact upon population distribution and abundance of certain marine species. Population densities of free swimming organisms can reduce in noisy environments as species leave to seek more favourable conditions (Peng *et al.,* 2015). Populations of aquatic mammals are known to have reduced in areas where marine industrial activity has taken place (Morton, 2002; Carstensen *et al.,* 2006; Thompson *et al.,* 2010), and reductions in fish catches are a signal of lower population abundance in areas affected by anthropogenic noise (Lokkeborg and Soldal, 1993; Engas *et al.,* 1996). Emigration of marine species can also affect the balance between predators and prey in specific habitats.

Evidence of relationships between anthropogenic noise and mass strandings of marine species on beaches has been identified, caused by damage to ears and brain from mid frequency sonar exposure (Cox *et al.,* 2006; Fernandez *et al.,* 2005; Jepson *et al.,* 2003). In addition, anthropogenic noise can affect reproduction rates of certain species and development in juvenile organisms causing body malformations, impacting upon populations (Peng *et al.,* 2015).

2.5.1.4 Physiological impacts

Noise pollution from ships can result in a number of physiological impacts on marine organisms. Elevated noise levels typically lead to increased stress responses, stimulating nervous activity of aquatic species. Studies suggest that anthropogenic noise from ships and other marine based industrial activities can cause increased heart rate and hormone levels in marine mammals (Romano *et al.,* 2004; Lyamin *et al.,* 2011), along with increased metabolism and reduced immunity (Peng *et al.,* 2015). The combination of high metabolism and reduced food intake due to stress can result in reduction in growth of marine organisms (Anderson *et al.,* 2011).

2.5.2 Surface noise

Noise from ships and shipping can impact on people working on board vessels and in ports, and in communities close to ports, harbours and the shoreline. Sounds generated from shipping can propagate in air, and unlike in water, the extent of propagation depends on the characteristics of the surrounding area rather than the frequency and amplitude of the sound wave. Sound emissions in air are influenced by weather conditions and population and distribution of obstacles such as buildings and orography, therefore the impact of noise from ships is controlled by external factors (Badino *et al.*, 2012).

Sound is generated from the various operational processes on board ships and in ports. Engines, ventilation fans and warning sirens are common sources of noise, along with auxiliary engines when a vessel is berthed at port. Studies indicate that ship generators and electric motors typically produce noise levels between 100 and 115 decibels (Khoo and Nguyen, 2011), which can be harmful to humans if exposure is prolonged.

The human ear is sensitive to sound frequencies between 20 Hz and 20 kHz (Turan *et al.,* 2011). There are several negative health effects associated with noise pollution, including hearing issues, increased blood pressure, heart disease, sleep disturbance and annoyance (van Kempen *et al.,* 2002). It has also been suggested that noise can affect human performance leading to errors from vessel crew, which can increase the risk of accidents at sea (Turan *et al.,* 2011).

2.6 Physical collisions

Ships are large, heavy, solid structures that travel at relatively high speeds through the water. Over the last century, the number of ships travelling in the ocean has increased, with an observed 4 fold increase globally from 1992 to 2012 (Tournadre, 2014). Owing to a ships physical structure, collisions with aspects of the marine environment can occur, causing damage to ecosystems such as coral reefs and physical harm to aquatic species. Such collisions can also cause damage to the structure of the ship, and in extreme cases result in shipwrecks which have environmental consequences (Lindgren *et al.,* 2016). There has been an increase in the number of known collisions between ships and marine mammals recorded worldwide since the 1950's, which coincides with increased traffic and ship speeds (Laist *et al.,* 2001).

The oceans are home to more than 115 species of marine mammals including cetaceans such as whales and dolphins, and pinnipeds which include seals, sea lions and walruses (Kaschner *et al.,* 2011). Large mammals are most vulnerable to ship strikes due to their physical size, but collisions between vessels and many marine species can occur anywhere that their paths cross, however are most common in areas of heavy traffic near ports and harbours and near shipping lanes. Information regarding the fate of marine life following a ship strike is limited and often anecdotal, however evidence suggests that it often results in serious injury or fatality, particularly when the vessels involved are traveling at higher speeds (Laist *et al.,* 2001).

Marine animals can be difficult to avoid for ship operators as they are not always visible on the surface of the ocean, and there is often no time to manoeuvre the vessel out of its path. Species with migration routes close to major ports and shipping lanes are most at risk, while animals which surface during feeding and breeding season are also at risk as they are more likely to come into contact with moving vessels than animals located deeper in the ocean. Animals that make contact with vessels often suffer serious injury due to the force of the impact with a ship's hull, they can also become entangled with the propellers suffering from deep cuts and slashes.

Collisions of ships with large marine animals can also pose a threat to human safety with considerable damage to ships reported, while the impact can injure passengers and crew and cause fatality in extreme cases (Carrillo and Ritter, 2006).

2.7 Summary

Ships impact on the environment through a number of sources and a variety of different pathways. Combustion processes on board pump significant volumes of exhaust gases into the atmosphere including CO_2, N_2O, NO_X, SO_X, particulate matter, and volatile organic compounds, which have detrimental effects on the surrounding environment. Methane is also released through potential slippage and handling of LNG fuel, while gases used in air conditioning units and refrigeration systems with potential ozone depleting properties are leaked into the atmosphere. The potential impacts of air emissions from ships are a significant threat to the environment. Greenhouse gases from shipping account for approximately 3% of worldwide annual emissions, and that figure is expected to increase in the future based on current projections. GHGs are the most significant contributor to climate change, while CO_2 also causes ocean acidification, raising the pH levels of the ocean and impacting on aquatic species. Emissions of NO_X, SO_X, and PM can have far-reaching environmental implications, damaging buildings and infrastructure through acid rain, affecting the health of human populations in port and coastal cities, and upsetting the radiative balance of the planet through net cooling. VOCs can also affect human health and radiative cooling through secondary reactions in the atmosphere leading to the development of photochemical smog.

Ships also pollute the marine environment through direct discharge of pollutants into the surrounding water body. Release of oil through spillages and continuous operational discharges can cause considerable damage to marine wild life and habitats, and affect the chemical quality of seawater. Other discharges include sewage and grey water release, which can affect marine species by altering the chemical and biochemical oxygen demand of the water, and affect human health in bathing waters through release of bacterial pathogens causing disease and infection. Shipping is also a common cause of invasive species transfer through ballast water release and use of antifouling agents on vessel hulls. Disposal of waste at sea causing marine littering is a significant environmental concern, affecting the health of numerous marine species and destroying ecosystems and habitats. Due to ocean currents, waste can accumulate in hotspots in the open sea and at shorelines potentially causing damage to infrastructure, while the aesthetic degradation of beaches can impact on the tourist economy of many coastal towns and cities.

Shipping is a sea-based activity, however certain operations can impact upon the terrestrial environment due to the interface of vessels with ports and the practice of construction and decommissioning of vessels on land. Due to changes in regulations, many ships now dispose of solid waste on land at port reception facilities rather than dumping it all out at sea. Waste collected in port is handled in the same way as municipal waste, and hence can be sent to land fill contributing to toxic gas emissions such as methane, and potential chemical leaching into soil and the watercourse. Ship construction involves the extraction of large volumes of raw materials and is an energy intensive process. Meanwhile, ship decommissioning typically takes place on land in less regulated conditions, which can result in various discharges of hazardous materials to the environment.

Another side effect of the sea-land interface is the effect of ship noise in ports and harbours on nearby populations. Sounds from ships can cause disturbance and annoyance, affecting cardiovascular activity of humans and increasing safety risks. Noise generated by vibrations of the ship's hull and operation of the propellers can affect the physiology and behaviour of aquatic species due to the properties of underwater sound waves. Ships can also make physical contact with larger aquatic species causing injury and fatality.

The impacts of shipping on the environment are extensive and well recognised. The IMO have introduced pollution regulations in the form of the MARPOL 73/78 convention and supplementary annexes to legislate pollutant emissions and discharges from ships. More recently the IMO introduced the Ballast Water Management Convention to prevent the discharge of poor quality ballast water, the AFS convention to regulate the use of antifoul coatings, and the Hong Kong convention for the recycling of hazardous materials from ships, which is yet to be ratified.

Despite the introduction of pollution regulation in shipping, there is often a significant time gap between when the regulations are adopted and when they legally enter force. In addition to regulation, various voluntary environmental initiatives exist in attempt to bridge this gap, reduce environmental impacts and raise the environmental profile of ships. The next chapter will critically assess the methods currently adopted for assessing, managing and controlling environmental impacts and ship environmental performance, and identify improvements in the systems in order to achieve greater sustainability in shipping.

3.0 Environmental management, assessment and control in the maritime sector

3.1 Introduction

Humans and the actions of humans have had a considerable effect on the natural environment throughout history. Whilst legislative responses to environmental problems can be traced back to medieval times, it was not until the industrial revolution that pollution related issues were evident at a larger scale, and hence environmental law at a civic level began to take shape (Pontin, 2007). From a shipping perspective, the impacts of maritime activities on the marine environment were largely ignored up until mid-way through the 20th century, with the introduction of the OILPOL convention in 1954 on the prevention of pollution of the sea by oil, the first piece of maritime environmental regulation to be introduced. Since then, various regulations have been adopted in response to an improved understanding of the impacts of emissions and discharges of pollutants on the environment, along with a general acceptance that controls must be put in place to minimise the detrimental effect of human actions on the natural world.

In addition to regulations, other responses for protection of the natural environment include the use of proactive environmental management strategies to identify, evaluate, and control environmental risks through prevention and mitigation of emissions and discharges. Environmental management strategies help to provide a framework for environmental protection, which can be incorporated into an organisation, operation or system. Strategies for environmental management encourage a holistic approach to dealing with pollution, by identifying sources of pollutants, exploring the potential pathways into the environment and determining possible impacts, while also devising strategies to monitor and control pollutant releases and develop techniques for mitigation and prevention.

There are various tools available for managing impacts of human activity on the environment. Good management is possible through better understanding of the processes that lead to pollution incidents, and of the potential risks associated with such incidents. Life Cycle Assessment (LCA) is a common tool used to determine the impacts of a product, process or activity through each stage of the life cycle from extraction of raw materials, to construction and operation, through to disposal. Other methods include scenario modelling and analysis, where the inputs and outputs of a potential process are modelled to determine the risk of associated environmental threats. The impact of an activity or action on the environment can be quantified using indicators and indices, which provide a mechanism for comparisons between products, processes and activities. In the shipping sector, many environmental initiatives exist that are designed to measure and communicate environmental performance, which use indicators and indices as a means of quantifying and ranking the performance of vessels (Andersson *et al.,* 2016). Where proactive environmental management is not possible, emissions and discharges of pollutants can be abated reactively through technological advancements, or cleaned up after the event through remediation activities. However, impact avoidance is generally considered to be the most efficient approach to environmental management (Andersson *et al.,* 2016).

This chapter reviews the most effective strategies for environmental management and assessment in the shipping sector, and highlights the barriers to environmentally sustainable shipping associated with current regulation, practices and initiatives by critically assessing the methods adopted. A suitable best practice approach for holistic assessment of ship environmental performance is subsequently proposed in Chapter 4.

3.2 Environmental regulations in shipping

The need for regulation in shipping arises from the increase in human activity on the seas. Maritime regulations have developed throughout history, and environmental regulation has been influenced by the technological improvements in the shipping sector. The development of laws relating to human activity on the seas can be traced back to the birth of international law (Tanaka, 2015), and was based on the principles of freedom of the seas and sovereignty (Linne and Svensson, 2016). The concept of freedom of the seas proposes the safeguarding of freedom of navigation to ensure that no state can prevent another state from accessing the oceans, a necessity for expanding trade around the world. Meanwhile, the principle of sovereignty acts as a counterbalance and protects the interest of states whose coastline is subject to shipping operations from other states. These two basic principles have shaped the UN Convention on the Law of the Sea (UNCLOS, 1982) which provides the basic legislative framework for shipping activities at sea. It contains rules that protect the regulatory requirements of coastal and port states, but also maintains the notion of free navigation of the seas and considers the maritime interests of flag states i.e. the state in which a ship has been granted to sail under its flag.

Regulatory focus on marine pollution to the environment is a relatively new concept, with the OILPOL convention on the prevention of pollution of the sea by oil introduced in 1954. Despite being regarded as the first multilateral agreement for shipping pollution to be accepted by the international community (Linne and Svensson, 2016), the OILPOL convention was not deemed successful due to problems with enforcement from flag states who were either not party to the convention or lacked enthusiasm for enforcement outside of their own jurisdiction, and from a belief that the convention restricted the principle of freedom of the seas (Linne and Svensson, 2016).

The maritime sector became more environmentally conscious following a major oil spill from a shipping tanker in March 1967 off the south west coast of the UK. Incidents such as this became catalysts for the development of maritime environmental regulation (Linne and Svensson, 2016), and in 1973 the MARPOL 73 convention was adopted. MARPOL was supported by the IMO, and has become a flagship piece of environmental legislation in the shipping industry regulating the emission and discharge of many pollutants including oil spills, chemicals, sewage, garbage and toxic gases. The IMO now play a central role in the development of regulations, guidance and recommendations regarding the international marine environment.

3.2.1 The role of the IMO

The IMO was founded in 1948, initially as the Inter-Governmental, Maritime Consultative Organization (IMCO). In 1982 its name changed from IMCO to IMO, as it was no longer thought that ‘consultative’ was the correct word to describe its function, with an ability to take decisions and act rather than just talk (Linne and Svensson, 2016). It is a specialised, autonomous agency of the UN connected through agreements with the UN ECOSOC (Economic and Social Council). It is the international body responsible for safety, security and pollution prevention in international shipping (Boisson, 1999). 174 member states are party to the IMO, with an additional 3 associate members (IMO, 2018[c]). One of the key roles of the IMO is to develop new, and amend existing, environmental conventions to be recommended for adoption by member states, whilst also developing other instruments such as guidelines and codes that are not legally binding. The IMO has a hierarchical structure as follows:

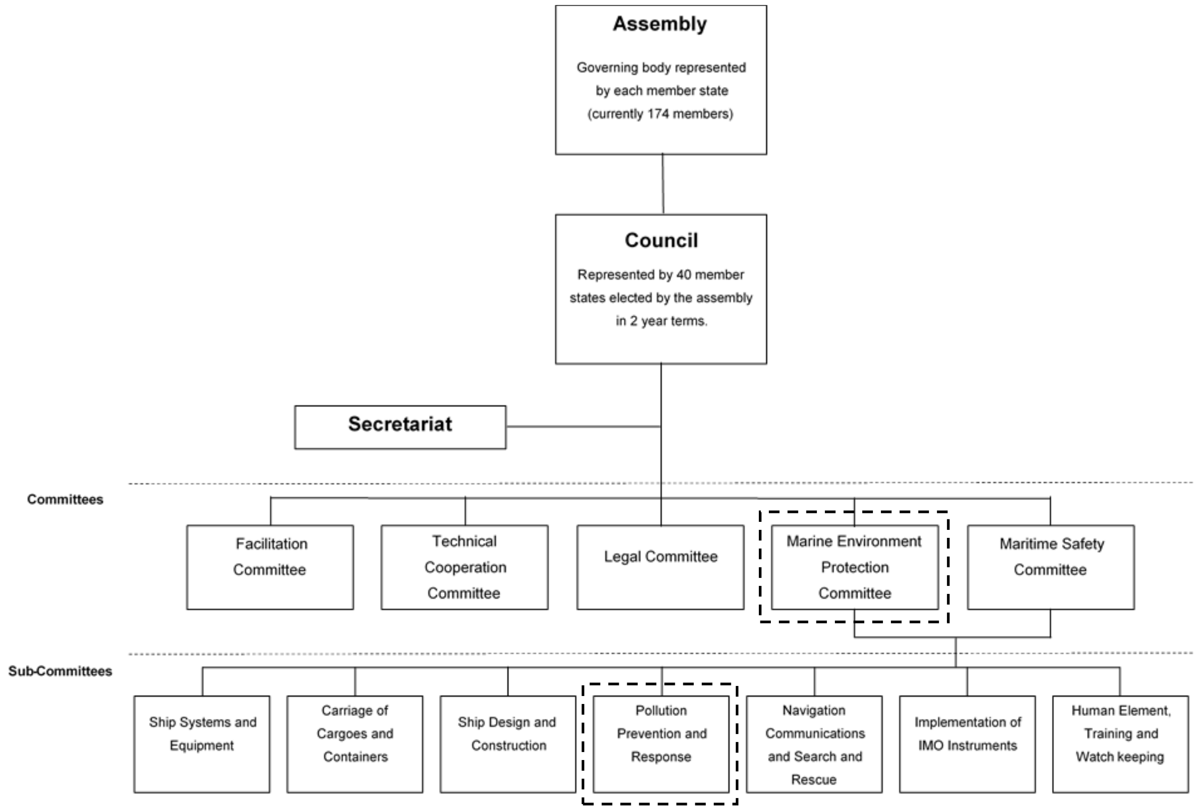

Figure 3.1 Hierarchical structure of the IMO (adapted from Linne and Svensson, 2016)

The Assembly is responsible for recommending the adoption and amendment of policy and regulations to member states, however such recommendations are not legally binding. The Council assumes a supervisory role over the workings of the organisation, and is responsible for appointing a secretariat. The role of the secretariat is to liaise with each member state and act as a negotiator. The committees are for decision-making and political negotiations, while the subcommittees are given instructions to conduct technical work and report back with proposed actions. Most technical work on environmental issues is assigned by the Marine Environment Protection Committee (MEPC) to the sub-committee on Pollution Prevention and Response (PPR).

3.2.1.1 IMO Actors

The positions of member states of the IMO are influenced by other actors such as inter-governmental (IGO's) and non-governmental organisations (NGO's). The IMO convention allows all states to become members, however it sets out provisions which favour states party to the UN (Linne and Svensson, 2016). Territories within member states (e.g. Hong Kong, Macao, Faroe Islands) can also become associate members of IMO, but have no formal decision making powers and are excluded from membership of the council (Karim, 2015).

The derivation and drafting of IMO policy can be described as a political contest between maritime interests and coastal interests (Linne and Svensson, 2016). Interests vary between coastal states, flag states and states of maritime interests, and also between developed and developing states. For example, coastal states assert the right to environmental protection of their shores and waters and seek strict regulations for pollution from ships. Traditional coastal states such as Canada and Australia, along with developed western states (Europe and US) are generally in favour of environmental protection in the marine sector, while flag states traditionally emphasise the choice to use vessels with freedom whilst at sea (Tan, 2006).

Many ships are registered to flag states but have owners from different countries. This is often known as *'Flags of Convenience'*, where ship owners use the availability of open registry to register ships to different states where regulations are more relaxed. In 2014, 57% of the world's shipping fleet (by dead weight tonnage) was registered to 5 flag state countries, namely Panama, Liberia, the Marshall Islands, Hong Kong and Singapore (UNCTAD, 2014).

The IMO is funded proportionally by member states based on the size of their merchant fleets, therefore Panama, Liberia and the Marshall Islands have been the top economic contributors despite a large proportion of the fleet being foreign owned

(IMO, 2017). Developing states form the majority of IMO membership as more than 75% of the world's shipping fleet was constructed in developing nations (UNCTAD, 2014), however the developed states assert far more influence. One reason for this is the ability of developed states to supply large delegations of representatives with a high level of expertise to participate in meetings (Linne and Svensson, 2016).

The IMO convention allows for co-operation of members with IGO's if their interests and activities are related to the purpose of IMO e.g. the EU. Currently 64 IGOs have entered agreements with the IMO (IMO, 2018[c]) and they are normally represented at IMO meetings as observers, meaning they can contribute to discussions but have no formal decision making powers. They can however have powerful influence over member states.

NGO's can involve themselves in IMO forums in an attempt to shape environmental policy, however like IGO's they are not afforded any decision-making powers. The member states can determine which NGO's can participate and the terms in which they can participate. However the IMO convention is not specific with regards to conditions for membership and participation of NGO's, and they are often granted *'consultative status'* to the IMO council, which gives them rights to submit and receive documents, be represented at sessions and to speak on agenda items of interest. Currently 81 NGOs hold consultative status within the IMO (IMO, 2018), which includes professional bodies such as the IMarEST (Institute of Marine Engineering, Science and Technology).

3.2.2 IMO environmental regulations

The IMO have introduced a number of regulations to help safeguard the marine environment from shipping practices. In 1973, the IMO introduced the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), which is the primary piece of environmental legislation for the control of pollution from ships.

MARPOL 73/78 includes six annexes containing marine pollution requirements (Figure 3.2). Annexes I and II are mandatory to all parties to the convention, and III to VI are optional, therefore it is left to the discretion of the member states whether to adhere to the regulations or not. Other international agreements for regulation of pollution from ships have also been introduced by the IMO, listed in Figure 3.2.

Table 3.1 List of IMO conventions relating to the environment

Convention	Date of entry into force (year)	Description
MARPOL 73/78	1983	Prevention of pollution from ships.
Annex I	1983	Prevention of pollution by oil.
Annex II	1983	Control of pollution by noxious liquid substances in bulk.
Annex III	1992	Prevention of pollution by harmful substances carried by sea in packaged form.
Annex IV	2003	Prevention of pollution by sewage from ships.
Annex V	1988	Prevention of pollution by garbage from ships.
Annex VI	2005	Prevention of air pollution from ships.
AFS Convention	2008	Control of harmful anti-fouling systems on ships.
BWM Convention	2017	Control and management of ships' ballast water and sediments.
HNS Convention	Yet to enter force	Control of hazardous and noxious substances transported by sea.
Hong Kong Convention	Yet to enter force	Safe and environmentally sound recycling of ships.
Nairobi Convention	2015	Removal of shipwrecks.

3.2.3 Enforcement of international law and the division of maritime zones

The need for international law regarding the environment is clear as many environmental issues transcend national boundaries (Linne and Svensson, 2016). A level of co-operation between states is required to solve many environmental issues. States are the main entities of international law and not individual citizens, while other entities include international organisations such as the IMO (Shaw, 2008).

International law differs from national law in that no global government exists to enforce international law within the global community, whereas national laws are enforced through a hierarchy of a legislature (supreme rule maker), a judiciary (court system) and an executive authority (government) within a specific nation (Cassese, 2005). The United Nations was set up with the intention of having a governing role in the international community, however it does not hold the same powers as national governments (Shaw, 2008).

The decentralised, non-hierarchical system of international law lacks executive authority to enforce the rules (Linne and Svensson, 2016), and ruling often only takes place if or when the parties have accepted the courts right to resolve a conflict. This is seen as a significant weakness in international law, and particularly international environmental law (Bodansky, 2010).

The Law of the Sea (UNCLOS, 1982) is classed as international law in a maritime context, and covers marine activities such as navigation on the sea, over flight, laying undersea cables and pipelines, fishing, and marine research. The international law of the sea designates marine spaces as jurisdictional zones and forms the bases of international co-operation among states for protecting the marine environment (Tanaka, 2015).

Jurisdiction (or power to make legal decisions) in the context of maritime international law can be described as either legislative jurisdiction, or enforcement jurisdiction. Legislative jurisdiction refers to the adoption of laws by a state that enable the protection of its coastal environment either through international law or through its own initiative. Enforcement jurisdiction refers to situations requiring enforcement of compliance with laws, for example investigation of offences, detainment, arrest and prosecution of offenders (Bodansky, 1991; De la Rue and Anderson, 2009).

A state can act as a flag state, a coastal state and a port state in the context of maritime law. Flag states are states which have granted a ship the right to sail under its flag (Tanaka, 2015), coastal states are states in whose zone a maritime ship is situated at a given time (Churchill and Lowe, 1999), and port states are those in whose ports and internal waters a ship is situated at a given time (Tan, 2006). States can act in more than one role at a time, and the roles determine the conditions for either legislative or enforcement jurisdiction of ships (Linne and Svensson, 2016).

On the high seas, a flag state has exclusive jurisdiction over vessels flying its flag (Tanaka, 2015). Considering the roles of states, the primary responsibility to create and enforce rules for ships belongs to the flag state (De la Rue and Anderson, 2009). However due to the increasing interests of coastal states regarding marine pollution and their discontent towards flag state jurisdiction, coastal states are assuming increased power to legislate and enforce (Linne and Svensson, 2016). A greater potential also exists for port states to legislate and enforce. Within its legislative jurisdiction, a port state is generally unrestricted from adopting rules and standards for ships voluntarily entering its ports and internal waters (De la Rue, 2009).

The conflict between the basic principles of freedom and sovereignty has led to the division of maritime zones, balancing the freedom of the seas with protection of coastal areas (Tanaka, 2015). UNCLOS (1982) divides the seas into 5 zones as follows:

(1) Internal waters (landward from the shoreline).

(2) Territorial seas (shoreline to 12nm) also includes airspace, seabed and subsoil areas – beginning of states maritime territory.

(3) Contiguous zone (shoreline to 24nm).

(4) Exclusive economic zone (shoreline to 200nm).

(5) High seas (>200nm) – open to all states.

The legal obligations of flag states remain consistent regardless of which sea zone a vessel is located, while the rights of coastal states to legislate ships depends on the maritime zone it is in, but in general the power to enforce reduces with distance from the coast. Within internal waters, a coastal state has full sovereignty to legislate foreign ships. Ships entering internal waters (including ports within these waters) must abide by the regulations set by the coastal state, including discharge standards and requirements (UNCLOS, 1982). Within the territorial seas zone, coastal states maintain sovereignty to make laws and legislate, however foreign vessels have the *'right of innocent passage'* in accordance with UNCLOS. Coastal states cannot create anti-pollution laws for foreign ships if they apply to generally accepted CDEM (construction, design, equipment and manning) standards, however for cases not involving such standards, a coastal state can create anti-pollution laws for foreign ships provided they are made public (De la Rue, 2009).

Within the contiguous zone, coastal states are restricted from being able to legislate foreign ships (Tan, 2006), with the exception of preventing breaches of its customs, fiscal, immigration or sanitary laws within its territorial seas (De la Rue, 2009). Within the exclusive economic zone, coastal states have legislative rights over matters concerning economic exploration and the exploitation of marine natural resources, and also for protection of the marine environment including effects from ship based marine pollution (UNCLOS, 1982). However pollution control within this zone cannot go beyond regulations outlined in international law (i.e. the IMO). In the high seas zone, a coastal state has no right to regulate marine pollution and all states are granted freedom of the seas under flag state rules (Linne and Svensson, 2016).

3.2.4 Regulatory barriers to sustainable shipping

According to Lister *et al*. (2015), shipping as an industry is under regulated regarding environmental impacts, and lags behind other industries in terms of environmental protection as a result. Lister *et al.* (2015) believe that *'regulatory fragmentation'* is growing in the industry as a result of the divergence of international, regional, national and local regulations and a multitude and diversity of private standards, along with delays in ratification and weak enforcement. Similarly, a report by Transparency International (2018) outlines the challenges of international governance and decision-making in the IMO, and provides recommendations for overcoming these barriers.

The IMO have suffered numerous delays in regulation ratification. Once new laws are adopted they must be ratified by a specific number of member countries representing a proportion of the world's gross tonnage in order to become legally binding, hence it can take many years before they come into force. The MARPOL Convention for the prevention of pollution from ships was originally adopted in 1973, however it did not fully enter force until 1983. Similarly, the Ballast Water Management convention was adopted in 2004 but did not enter force until late 2017, and the Hong Kong convention was adopted in 2009 but has yet to enter force.

The attitude of ship owner associations towards environmental legislation is also seen as a barrier, who are often critical of new regulation and have lobbied against the introduction of certain environmental measures such as the introduction of NECA's, SECAs, the BWMC and market based measures (MBMs) regarding CO_2 emissions (Lister *et al.,* 2015). Having conducted interviews with several shipping companies, Lister *et al*. (2015) claim that ship owners prefer global regulation agreed by the IMO to local or regional initiatives from other bodies, however there is concern regarding the incoherence and fragmentary nature of IMO regulation. The perceived barriers associated with maritime regulation leaves space for other measures for controlling ship environmental impacts.

3.3 Environmental assessment tools used in shipping

Numerous environmental assessment tools exist which have been adopted for use in the shipping sector. A number of studies in the field of environmental systems analysis have developed frameworks for comparative analyses between the different types of tools available (Baumann and Cowell, 1999; Finnveden and Moberg, 2005; and Ness *et al.,* 2007). Andersson *et al.* (2016) classify a selection of tools to have been adapted for use in shipping as either procedural; analytical; or aggregated. In conducting an environmental assessment it is important to select the right tools or combinations of tools for it to be a success. This section discusses the methods utilised for conducting environmental assessments in shipping.

3.3.1 Environmental Impact Assessment (EIA)

EIA is described by Andersson *et al.* (2016) as a procedural tool. It is typically used for decision support in development projects, with the aim of identifying all potential impacts of a project on the environment at the implementation stage, but prior to commencement. An EIA should include the direct and indirect impacts on humans, animals, plants, soil, water, the atmosphere, the climate, the landscape, the cultural environment, and the management of land and water resources.

EIA's are carried out in the EU by following Directive 2011/92/EU, and are mandatory for all projects covered by the directive across all industries. The directive includes development of inland waterways, and ports for inland traffic which permit the passage of vessels over 1,350 tonnes. EIA's are implemented in multiple locations across the globe, using similar principles to those outlined in the EU directive.

As a precursor to EIA, Strategic Environmental Assessment (SEA) is also implemented under Directive 42/2001/EC in the EU. It involves strategic assessment of the wider social, economic and environmental impacts of alternative proposals at the beginning of a project i.e. at the decision stage rather than implementation stage. It is designed to assist the decision making process in policy making, planning and programme development. According to Andersson *et al.* (2016), the use of EIA and SEA for evaluating impacts from shipping is uncommon. Such tools are not suitable for assessment of environmental impacts of vessels during operation.

3.3.2 Scenario Analysis

Scenario analysis is a technique used to develop understanding of possible future impacts based on changes to e.g. current policies, practices and technologies. It can be defined as "*a description of how the future may unfold based on if-then propositions*" (Alcamo and Henrichs, 2008). It is typically used to analyse several alternative options and determine possible futures by following certain decision making processes. Duinker and Greig (2007) discuss the use of scenario analysis in EIA, and investigate its application in assessment of cumulative future impacts, and forecasting the influence of future changes e.g. in climate on specific projects, however it is not common practice to conduct scenario analyses in EIA procedures.

From a shipping perspective, Corbett *et al.* (2010) use scenario analysis to quantify ship emissions in the Arctic under different shipping scenarios, assuming varying levels of growth in shipping operations, and different vessel types, up to 2050. This type of analysis can assist decision making in policy and logistics, and provide a picture of the potential impacts of such decisions.

Similarly, the IMO 3rd GHG study (Smith *et al*., 2014) uses scenario analysis to develop future emissions projections from global shipping, using historic data as the baseline to model potential emissions up to 2050 based on several scenarios. The study uses estimated fleet activity, transport demand, and proposed advances in energy efficiency and regulations to predict a number of possible futures. The study's is intended to inform policymakers, scientists and other stakeholders about the development of potential drivers of environmental impacts of shipping, and the relevance of policy instruments to address emissions.

Scenario analysis is adopted to develop estimations and predictions of future states based on decision pathways. It can be used to guide decisions on policy, technology, logistics and operation, however it is not typically used as a measure of operational performance.

3.3.3 Multi Criteria Decision Analysis (MCDA)

Linkov and Moberg (2017) provide an overview of how MCDA can be effectively utilised as an environmental management tool. The method enables comparisons of alternatives using criterion, allowing preferential options to be prioritised through rigorous mathematical assessment. The process of MCDA involves 5 key steps according to Linkov and Moberg (2017); and Belton and Stewart (2003):

(1) Problem identification – define the overall problem.

(2) Problem structuring – outline possible *alternative*s or options, and a set of properties (*criteria*) to describe the performance of the options.

(3) Model assessment and building – assign numerical values to the criteria, and score the alternatives against the criteria.

(4) Model application – use the scores to provide a decision on the best alternative option, based on the data.

(5) Planning and extension – use the outputs to make decisions or inform further planning.

There are many variations of MCDA models as described by Linkov and Moberg (2017), all of which adopt the basic methodological steps described above. For shipping applications, MCDA has been utilised to evaluate potential locations of inland ports in Spain (Awad-Nunez *et al.,* 2016); to compare alternative methods for ballast water exchange (Gomes, 2005); and to assess fuel options to reduce ship emissions (Brynolf *et al.,* 2016).

3.3.4 Environmental Management Systems (EMS)

An EMS is used to systematically manage an organisations environmental activity through development of environmental policy, procedures and processes specific to the needs of the organisation. The overall aim of an EMS is to maintain environmental protection and achieve continuous improvement in environmental performance through implementation of the *'plan, do, check, act'* principle. The EMS methodology is outlined in the international standard, ISO 14001, which provides a comprehensive summary of the system.

The ISO 14001 EMS framework is made up of 10 clauses, which includes the scope of the standard, normative references outlining the application of the standard, and terms and definitions. The remaining clauses outline the requirements of an EMS, including: the context of the organisation; the role of leadership in delivering the system; planning of the system; resource requirement and support within the organisation; operation of the system; evaluating the performance of the system; and delivering improvements to the system.

In the context of shipping, ISO 14001 is implemented at an organisational level and therefore is usually set up to manage the environmental activity of shipping companies rather than individual vessels, however some companies have certification which covers multiple sites, including chartered vessels (NYK, 2018). ISO 14001 certification is awarded following external audit from a qualified certification body, and provides a statement of a company's environmental management practices and commitment to continuous improvement, however it does not provide an indication of environmental performance (Andersson *et al.,* 2016). The principles of environmental management systems are also common in change management processes such as the SEEMP, which adopts a '*plan, do, check, act*' approach to managing energy efficiency (Andersson *et al.*, 2016).

3.3.5 Life Cycle Assessment (LCA)

LCA is an analytical tool used to quantify environmental impacts from '*cradle to grave'*. The method is used to assess environmental impacts throughout the life cycle of a product, process or service from raw material extraction and construction, operation and maintenance, through to decommissioning, disposal and end of life. There are 4 main stages to an LCA (Murali Krishna and Manickam, 2017):

(1) Goal and Scope – definition of the assessment boundaries and purpose of the study.

(2) Inventory Analysis – description of environmental inputs and outputs, including material and energy flows, and waste streams.

(3) Impact Assessment – classification of environmental impacts of inputs and outputs described in the inventory analysis. This involves use of environmental indicators to quantify impacts.

(4) Interpretation – evaluation of results of LCA, and development of conclusions based on the impact assessment.

The LCA methodology is outlined in the international standard, ISO14044, which provides a comprehensive framework of the assessment. Partial LCA's can be undertaken to identify interactions of a product, process, or service with the environment without investigating the impacts. This is known as a Life Cycle Inventory Analysis (LCIA) (Andersson *et al.,* 2016). Software packages exist to enable LCA's to be conducted using pre-defined inventory data, however one of the challenges of adopting LCA for shipping purposes is the availability of life cycle inventory data used to characterise material and energy flows (Kameyama *et al.,* 2005), although some inventories do exist (Tincelin *et al.,* 2010).

In shipping, LCA has been implemented to assess the environmental impacts of alternative shipping fuels (Gilbert *et al.*, 2018; Hua *et al.,* 2017; Bengtsson *et al.,* 2012), and is useful for drawing comparisons between different options based on environmental effects. LCA is utilised to estimate environmental impacts over the whole life cycle of a vessel, therefore is not the most appropriate tool to use as an indicator of operational performance.

3.3.6 Risk Assessment

Environmental risk assessment is a tool used to evaluate the impact of pollutants on the environment, taking into account the likelihood of the pollutant entering the environment, and the consequences of the subsequent impacts. It is utilised as a decision making tool to establish the risks associated with proposed actions. According to Ostrom and Wilhelmsen (2012), *“Risk assessments provide a basis for comparing, ranking, and prioritising risks”*.

A set of generic guidelines for environmental risk assessment have been developed by Gormley *et al.* (2011), outlining a structured approach to managing environmental risk in 4 key steps:

(1) Problem formulation

(2) Risk assessment

(3) Appraisal of options

(4) Addressing the risk

The first step is carried out in order to set the boundaries of the assessment to prevent ambiguous outputs (Gormley *et al.,* 2011), and clearly define the scope of the problem, typically through development of a conceptual model. Conceptual models represent the relationships between the sources of pollutants, the pathways by which exposure to the environment might occur, and the features (or receptors) of the environment which may be caused harm due to the exposure.

3.3.6.1 Risk assessment methods

Impacts and the risk of impacts can be determined in step 2 through an evaluation of the consequences of a pollution incident, and estimation of the probability of the incident occurring. Risk can be quantified using quantitative, semi-quantitative or qualitative methods.

<u>Quantitative methods</u>

Assessment of risk based on numerical data inputs, using numerical scales to derive likelihood and consequence criteria. This method relies heavily on the availability of quantitative data derived from probability analysis, impact assessments and expert judgement. Quantitative methods can provide a more realistic assessment of risk providing accurate data is available and is used correctly, however it can be ambiguous depending on the use and availability of data (Altenbach, 1995).

Semi-quantitative methods

Use of a combination of subjective opinion and numerical data to define risk. Subjective definitions are quantified using an index, score, rank, or logic based system (Gormley *et al.,* 2011). Semi-quantitative methods are systematic and offer consistency in approach, however are based largely on subjective assessment of risk likelihood and consequence assessment. Therefore, justification of the assumptions and data applied must be clearly defined in the assessment, and judgements regarding risk must be backed up by sound scientific evidence (Gormley *et al.*, 2011).

Qualitative methods

Assessment of risk is based on subjectivity and the relative judgement of the assessor (Altenbach, 1995). Qualitative assessments tend to be carried out using simple scales for estimating likelihood and consequence, and hence are useful when definitive numerical data is not applicable or available to quantify risk. Such methods are less common in risk assessment due to the level of subjectivity (Altenbach, 1995), but have value in establishing a logical basis for more detailed quantitative or semi quantitative assessments (Gormley *et al.,* 2011).

3.3.6.2 Techniques for determining risk

Risk can be quantified by adopting one or more of a series of techniques to determine probabilities of occurrence or exposure, potential causes of the risk, and possible mitigation options to reduce or prevent the risk. The following list outlines some common alternative methods:

Failure Mode and Effects Analysis (FMEA)

Provides analysis of defined failures and the effects of a failure on a system. A detailed analysis outlining the potential ways in which a process or product can fail to meet critical requirements is carried out. A list of all possible failures and effects is created, from which mitigation options and procedures can be devised to reduce or eliminate the risk of the failure occurring.

Fault Tree Analysis (FTA)

FTA is an integral part of Probabilistic Risk Assessment (PRA), and is used to identify and analyse hazard prevention and mitigation options, using a systematic approach. A top down approach is utilised to identify faults or accidents, then consider the possible direct causes, and the origins of the causes.

Expert Opinion

Gathering data from a group of subject experts is often used in the development of risk criteria and assessment of risk significance, particularly in the absence of quantitative data. However, expert opinion is used in both qualitative and quantitative risk assessment to assign risk ratings for probability and severity indicators (Yildiz *et al.,* 2014).

Fuzzy Logic

The principles of fuzzy logic were first defined by Zadeh (1965). It is used as a method of defining imprecise and uncertain information or data in a precise way. This technique can be used in environmental risk and impact assessment to numerically define subjective or linguistic descriptions of a state. It is often used in qualitative risk assessment where there is an absence of quantitative data and/or there is a degree of uncertainty in the data and information available.

Historic data

Use of historic data sets to determine probabilities of occurrence and magnitude of future impacts. Use of historic data sets is adopted where significant, meaningful data is available to provide an inference of future probabilities and impact magnitudes.

HAZOP Analysis

The purpose of Hazard and Operability Analysis is to investigate the extent of deviation of operational conditions from the intended design conditions. HAZOP considers that a deviation from the intended conditions could result in a potential hazard, therefore the risk and consequence of any deviation must be assessed. HAZOP is used as standard in the Oil and Gas industry in the North Sea, and is commonly used in the chemical processing and manufacturing industries involving operation of industrial plants.

Preliminary Hazard Analysis (PHA)

Developed by the US Army, PHA is designed to identify hazards at the conceptual design phase of a product or process. It is carried out early in order to gain maximum benefit, and is often the first step in a more complicated hazard analysis, however in more simple cases it can be used on its own.

Failure Mode, Effects and Criticality Analysis (FMECA)

FMECA is similar to a standard failure mode and effects analysis but with an added dimension analysing the probability and criticality of a failure. Criticality is often assessed qualitatively based on experts' opinion, or quantitatively using historical data, or data forecasting. It is used to rank risk of failures in a system, allowing risks to be prioritised.

Event Tree Analysis (ETA)

ETA is a graphical representation of possible events in an accident sequence. When using ETA, it is assumed that there are only two possible outcomes to each event as it occurs, failure or success. If the outcome of the event in the sequence is success, the accident is averted, if the outcome is failure, the accident outcome moves on to the next possible event in the sequence. Event trees are used to analyse the probability of an impact by analysing the probability of a sequence of events occurring which lead to the impact. Each event is analysed in terms of probability of failure and success.

Probabilistic Risk Assessment (PRA)

PRA is a systematic approach to evaluating the risks associated with a process, product or service. Risk is assessed by considering the consequences of a process, product or service and an evaluation of the significance of the consequences is conducted by assessing the probability of occurrence and the magnitude (severity) of the impact. It is commonly used in engineering projects and to assess the effects of stressors on the environment. PRA often encompasses other tools such as FTA and ETA to assess the significance of consequences/impacts of a process, product or service.

Source Pathway Receptor Analysis (S-P-R)

S-P-R analysis uses the principle of a conceptual model to identify the source of a pollutant, the pathway into the environment and the environmental receptor of the pollutant. Pollutant sources may have multiple pathways and receptors. It is used to identify potential environmental hazards due to pollutant emissions. This method can help to reduce pollutant risks and mitigate impact of emissions.

3.3.6.3 Risk assessment in shipping

Following a risk assessment, an appraisal of options is carried out in accordance with Gormley's model (step 3). Options appraisal is the process of selecting the most appropriate risk management strategy to deal with the identified risks. The risk management strategy adopted will likely depend on the significance of the risk and the constraints of the assessor, but will most likely result in termination of the source of the risk; mitigation of the effects of the risk; transfer of risk; exploitation of opportunities presented by the risk; or acceptance of the risk. The final step in Gormley's model involves addressing the risk by taking the appropriate actions to fulfil the objectives of the risk management strategy.

In a shipping context, Landquist *et al.* (2013) evaluate the use of environmental risk methodologies used to assess oil leakage from shipwrecks, and suggest a comprehensive framework for assessing such risks based on ISO 31000 standards. Magnusson *et al.* (2018) use risk assessment to model the potential ecological risk posed by continuous bilge water discharge in the Baltic Sea using toxicity indicators, and Blasco *et al.* (2014) assess the environmental risk of emissions from ocean going ships by modelling the distribution and fate of air pollutants. A risk assessment approach has also been adopted under the BWM Convention to enable a selective approach to ballast water management. Quantitative risk assessment studies such as these often have a limited scope as large volumes of data are analysed to provide accurate risk based models. A quantitative model representing environmental impacts from multiple emission and discharge sources would be extremely data intensive, and hence a semi quantitative approach would be more appropriate.

Another approach to modelling the environmental impact of pollutants from ships is to use performance indicators and indices. Indicators are considered as simple measures that represent the state of an environmental system in a defined region (Ness *et al.,* 2007). Indicators provide a useful alternative to raw data measurements where a data requirement for modelling is either too vast, or the data is unavailable. Indicators have also been used as tools for measuring performance in green shipping initiatives.

3.4 Green shipping initiatives

The use of voluntary initiatives as self-governance mechanisms has become apparent in many industries, including shipping. The chemical industry introduced an initiative called 'Responsible Care' to improve health, safety and environmental awareness following the Bhopal disaster in 1984 (Dominelli, 2013). Other such reactive responses to events have been reported by the ILO (1999), suggesting that development of voluntary schemes can be considered a reactionary response to overcome the threat of tight regulations and limit loss of confidence from within industry sectors. Voluntary schemes, including established standards such as ISO 14001, provide a framework for meeting standards and can therefore operate effectively alongside international regulations.

The perceived barriers associated with environmental regulation in shipping has led to the proliferation of '*independent initiatives'* to improve environmental credentials, and meet the demands of customers and other stakeholders in the shipping industry (Lister *et al.*, 2015). The development of voluntary measures is driven by the concept of 'self governance', as discussed by Supiot (2017). The term '*independent initiative'* in this context refers to action being taken by non-regulatory bodies within the shipping sector to improve environmental performance within the industry. This includes the development of environmental indicators and indices to communicate environmental data related to shipping, the concept of incentive schemes offering rewards for achieving environmental targets, and development of mitigation strategies and awareness campaigns to reduce environmental impacts.

It is apparent that a large number of environmental initiatives have been developed for use in the shipping sector, both from independent bodies and the IMO. Approximately 50 different initiatives are identified in the Clean Baltic Sea Shipping (CBSS) CLEANSHIP project (Fridell *et al.,* 2013), and other reports by Svensson & Andersson (2011) and EMSA (2007) have compiled inventories of 38 and 47 respectively. Pike *et al.*, (2011) review 29 different schemes, while the Sustainable Shipping Initiative (SSI, 2013) have created a search and compare tool containing 11 schemes, and a report by the Danish environmental protection agency (Stuer-Laridsen *et al.*, 2014) discusses 10 different schemes in detail. Based on these studies, 85 different environmental initiatives in the shipping sector have been identified and compiled into a Ship Environmental Initiative Inventory (see Appendix B).

3.4.1 Categorisation of initiatives

According to Lister *et al.* (2015), the number and diversity of initiatives available for use in the shipping sector can cause confusion, add a significant administrative burden, and hinder progress towards improved sustainability due to a lack of cohesion between them and the widely different audiences they are designed to target. Previous studies have attempted to categorise the different initiatives available in the shipping sector into groups. Pike *et al.* (2011) classify initiatives into 4 groups based on intended purpose: Research and Innovation; Corporate Social Responsibility and Marketing; Awareness Raising/Environmental Education; and Voluntary Class Notations and Certification. Svensson and Andersson (2011) have also carried out a classification, categorising initiatives into 5 groups based on the service provider or developer: IMO instruments; National Instruments and Initiatives; Classification Societies; Ports and Port Associations; and Cargo owners, NGO's and Shipping Associations. The Fridell *et al.* (2013) study focuses on environmentally differentiated port fees, and highlights the use of environmental initiatives in the development of port incentive schemes, and Stuer-Laridsen *et al.* (2014) analyse a number of '*environmental ship performance indices',* without providing a classification. The European Maritime Safety Agency (EMSA, 2007) published an inventory of initiatives that contribute towards '*green shipping'*, categorising them into several groups: Awards; Certificates; Incentive Systems; Initiatives; Labels; and "Different systems".

Previous studies in this field have used different criteria to categorise ship environmental initiatives in to groups (EMSA, 2007; Pike et al., 2011; Svensson and Andersson, 2011; Fridell et al., 2013; SSI, 2013; Stuer-Laridsen et al. 2014), however it is evident that no single, unanimously accepted system of classification exists. Therefore, this study compiles the inventories developed in previous research and classifies the initiatives according to Figure 3.2.

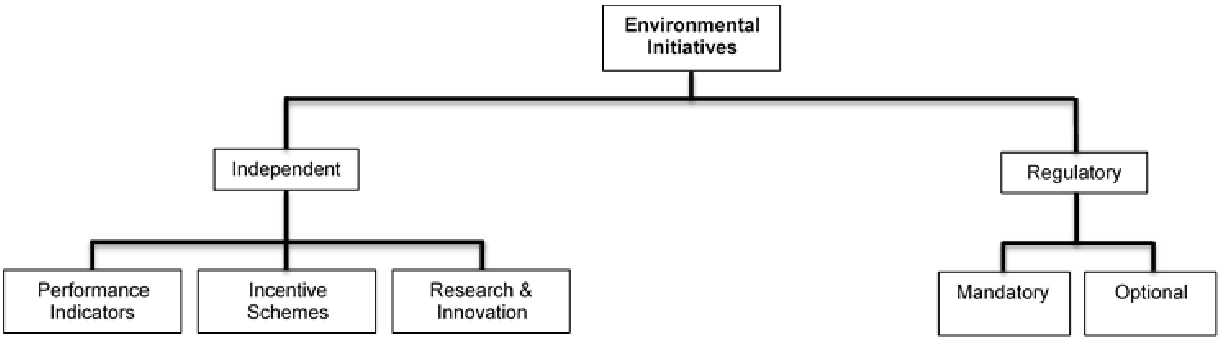

Figure 3.2 Categorisation of environmental initiatives in shipping

Based on the systems of classification developed by Pike *et al.* (2011), EMSA (2007), and Svensson and Andersson (2011), a holistic categorisation model has been developed to classify all of the initiatives identified (Figure 3.2). At a high level, the initiatives can be classified as either '*Regulatory*' or '*Independent*' schemes. Regulatory instruments are defined as environmental initiatives developed by the regulator (IMO), and independent initiatives are those which are not developed by the IMO. The regulatory initiatives can be further classified as '*Mandatory*' or '*Optional*'. The independent initiatives are classified into 3 groups based on intended purpose, as:

(1) *'Performance Indicators'* - to provide an indication of environmental performance;

(2) *'Incentive Schemes'* - to provide an incentive to improve environmental performance; and

(3) *'Research & Innovation'* - innovative research activities, strategies or actions designed to improve the environmental landscape in shipping, and /or raise awareness and promote sustainability in the shipping sector.

The initiatives identified in the literature have been systematically categorised according to Figure 3.2, summarised in Table 3.2. A complete inventory based on the initiatives identified in this study is available in Appendix B.

3.4.1.1 Regulatory instruments

5 of the initiatives identified are mandatory (EEDI, SEEMP, and STCW) and optional (EEOI, Green Passport) instruments developed by the IMO and are classified as '*Regulatory*' in Table 3.2. The IMO Convention on Standards of Training, Certification and Watch-keeping (STCW) outlines the basic training requirements for seafarers, including on marine environment awareness, and the Green Passport is a concept discussed in the Hong Kong Convention for an inventory of hazardous materials on-board vessels, however the convention is yet to enter force, therefore is considered '*optional*'. The EEDI and EEOI are indicators of ship energy efficiency at design stage and during operation respectively. The EEDI is a mandatory requirement for new build ships, while the EEOI is currently optional. The Ship Energy Efficiency Management Plan (SEEMP) is a mandatory tool to assist ship owners in managing energy efficiency on-board.

It is also noted that other non-mandatory regulatory instruments exist which are not mentioned in the literature analysed in this study, such as the IMO guidelines related to ship recycling, bio fouling, and garbage management.

3.4.1.2 Performance Indicators

28 of the initiatives in the inventory are classified as performance indicators. Many of the performance indicators identified use multiple criteria to provide a thorough assessment of environmental performance, while others are focussed on single environmental pollutants. Many of the performance indicators identified are developed by classification societies and shipping companies.

3.4.1.3 Incentive Schemes

30 incentive schemes have been identified. The incentive schemes are designed to reward vessels for meeting environmental requirements, benchmarked against defined thresholds or targets to encourage continuous improvement, often with certification, class notation, or economic gains to provide market advantage. Many of the incentive schemes identified in the literature have been developed by port

authorities or other independent bodies with the intention of using the schemes to reward ship owners for achieving certain environmental targets in ports, typically through financial compensation.

3.4.1.4 Research and Innovation

22 of the initiatives are schemes categorised as research and innovation. These initiatives are designed to improve sustainability in the shipping sector through research, and in many cases focus on the development of new technologies designed to reduce the impact of shipping on the environment. Other schemes in this category include industry and academic partnerships, facilitating and coordinating knowledge growth and environment related research activities in the maritime sector, and education and awareness campaigns related to the impacts of shipping on the environment.

Table 3.2 Classification of initiatives identified in the literature

Classification	No. of initiatives
Independent Initiatives	**80**
Performance Indicators	28
Incentive Schemes	30
Research & Innovation	22
Regulatory Initiatives	**5**
Mandatory	3
Optional	2
Total	***85***

3.4.2 Analysis of existing initiatives used in the shipping sector

Many, but not all, of the existing initiatives mentioned in the literature are well marketed and can be found in the public domain via web searches. Some initiatives can be accessed online, however no further information regarding the methodology of the schemes is provided, and in some cases registered access is required. Not all of the initiatives listed in the inventory have been designed specifically for use in the shipping sector, and some are only applicable in certain companies, countries, regions or ports. Many of the schemes are designed to assess specific pollutants as single indicators, or multiple pollutants using indices. This section highlights the diversity of green shipping initiatives and investigates the transparency and applicability of the schemes. The research identifies where published methodologies are available in the public domain, and an analysis of the scope and ambition of the initiatives is conducted to compare the different methods adopted for ship environmental assessments.

3.4.2.1 Transparency

Following a systematic web-based search it was found that many of the initiatives referenced in the literature are not publically transparent as they do not have their own website or any other published documentation outlining the requirements of the scheme. 47 of the initiatives were found to be publically transparent (listed in Appendix B), however some of these require registration and login to access further information regarding participants of the scheme and award criteria. Some of the initiatives listed, such as the VCS (Verified Carbon Standard) programme and the Good Environmental Choice award, are sustainability eco labels not specifically designed for the shipping sector, and a large number are designed for use in a specific region, country or port.

In some cases, a description of the scheme is available in the public domain, however the detail of vessel assessment outcomes is not. The Clean Cargo Working Group (CCWG) for example publishes a list of participants to its '*environmental performance scorecard*' but does not provide detail of the assessment outcomes, such information is only available to members who are participants of the scheme, and access is conditional upon signing a non-disclosure agreement (Scott *et al*., 2017). The Green Award lists the holders of the Green Award certificate by company name and by individual vessel including the date of certification, however there is no detail of the environmental assessment outcomes (Green Award, 2018). From the information available it is not possible to ascertain vessel environmental performance.

By contrast, the ESI lists the top 50 vessels participating in the scheme in order of decreasing score, the dates in which the assessment is valid, and a breakdown of performance in each of the assessment categories, so it is possible to determine how well a vessel has performed in each category based on publically available information. Only 50 ships are listed, however there are over 8000 vessels with a recorded ESI score which can be found using the search function on the ESI website. While ESI scores are visible, there is no breakdown of actual emissions or detail of how vessel scores are awarded (ESI, 2018). Another initiative provider, RightShip's EVDI (in conjunction with the Carbon War Room), have taken steps to improve transparency by making performance assessment outcomes available for participating vessels, however access requires registration via the website (Scott *et al.*, 2017).

The lack of transparency means it is not possible within the scope of this research to determine how effective all of the schemes are in assessing ship environmental performance, or how well vessels are performing, and to what extent they are impacting on the environment. It is also not possible to compare schemes like for like where information outlining the assessment methodologies is limited.

3.4.2.2 Initiative scope & indicator weightings

A number of initiatives have been analysed to determine their environmental scope i.e. the number and variation of environmental indicators used in the assessment methodology (Figure 3.3). It was not possible to analyse all of the initiatives listed in Appendix B as information regarding scope and methodologies was not available, however the following schemes have been analysed in more detail, where information could be accessed:

(1) ABS Enviro

(2) ABS Enviro+

(3) CCWG Environmental Performance Scorecard

(4) CSI

(5) DNV Clean

(6) DNV Clean Design

(7) EEDI

(8) EEOI

(9) ESI

(10) EVDI

(11) Green Award (Oil tankers; Bulk carriers; LNG carriers; Chemical tankers; Container ships; LPG carriers; Inland vessels)

(12) Green Ship Incentive Programme

(13) RINA Green Plus

(14) RINA Green Star

(15) Norwegian NOx Fund

(16) The Blue Angel (Operation)

Some of the initiatives have a wide environmental scope and are made up of several indicators with different weightings, while others use single indicators to assess specific pollutants. Five of the schemes analysed in this research are single pollutant indicators: the Norwegian NO_X fund, which is a tax incentive scheme set up to reduce NO_X emissions from ships in Norway; Green Ship, which is a financial incentive programme implemented at the Port of Long Beach in the United States which also targets NO_X reductions; the EEDI and EEOI, which are indicators of a vessels CO_2 emissions designed by the IMO; and the EVDI, which is a CO_2 indicator developed by RightShip to calculate EEDI scores for existing vessels.

Many of the schemes that assess multiple pollutants do not assign specific weightings to pollutant indicators, and use audit style checklists to assess vessel performance, requiring ships to meet a list of mandatory criteria in order to qualify for certification. In such cases, all criteria must be met in order to achieve accreditation and therefore the schemes are not suitable for comparing vessels' environmental performance in detail. The only distinction that can be made is between vessels with or without certification. Examples include the Clean and Clean Design eco-labels developed by DNV, the Enviro and Enviro+ eco-notations developed by ABS, and the RINA Green Star notation.

Other initiatives are designed for performance benchmarking, allowing ships to be distinguished from others by a system of ranking. Such schemes use thresholds and scales to assess and grade environmental criteria, and allocate points totals for each criteria which can be totalled to give an overall score. Total scores can then be used to compare against other vessels, or benchmarked against threshold values for which different ratings or levels of certification can be achieved.

For the CSI, environmental criteria are split into five equally weighted groups – CO_2, NO_X, SO_X, Chemicals, Water & Waste Control - with 30 points available for each group, adding up to a total of 150 points. However if the groups are broken down into individual pollutants, the number of points available for each criterion varies (Figure 3.3). Many of the initiatives allocate a different number of points for individual criteria, as shown in Figure 3.3. The difference in criteria weighting suggests that in some initiatives, certain environmental pollutants are prioritised over others.

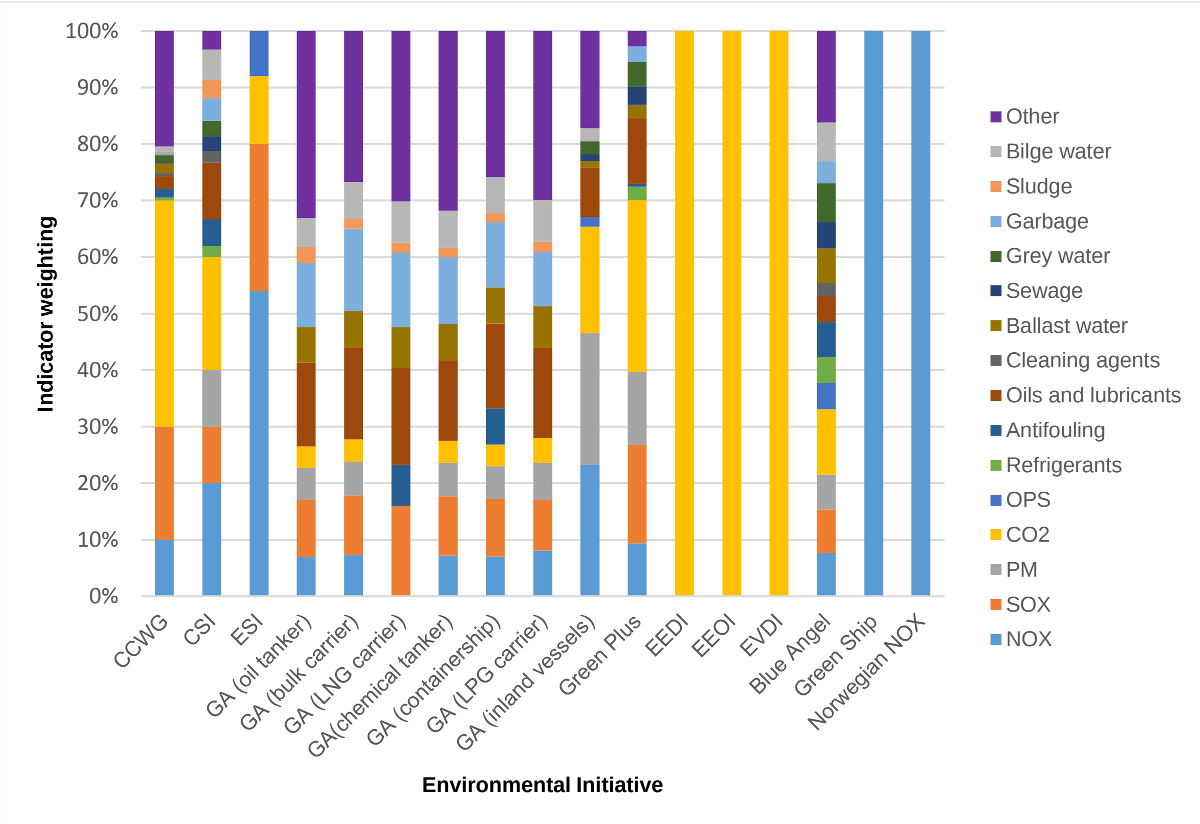

Figure 3.3 Breakdown of environmental criteria weightings

Comparisons between the weighting factors of each pollutant for each initiative can be made by categorising the criteria into groups (Table 3.3). The pollutant criteria listed in Figure 3.3 are categorised based on interaction type with the environment. The pollutant criteria can be categorised as '*emissions to air'*, '*discharges to sea'*, or '*other'*. Using this method of categorisation, NO_X, SO_X, PM, CO_2, OPS and Refrigerants are classed as emissions to air. Antifouling, Oils and lubricants, Cleaning agents, Ballast water, Sewage, Grey water, Garbage, Sludge, and Bilge water are classed as discharges to sea. All other criteria in Table 3.3 are categorised as other.

The method of categorisation shown in Table 3.2 shows a clear difference between initiatives in terms of the weighting factors used per type of environmental interaction. Each of the single criteria initiatives are designed to assess air emissions only, while the weighting factors used in the multi criteria initiatives vary greatly. CCWG, CSI, ESI and the RINA Green Plus eco label clearly prioritise pollutant emissions to air over discharges to sea and other criteria. The weighting factors for emissions to air and discharges to sea in The Blue Angel are equally split (42% each), while the Green Award initiatives are weighted more heavily in favour of discharges to sea.

Table 3.3 Criteria weightings per interaction type with the environment

No. of criteria	Environmental initiative	Weighting		
		Emissions to air	Discharges to sea	Other
Multi-criteria	CCWG	71%	9%	20%
	CSI	62%	35%	3%
	ESI	100%	0%	0%
	GA (oil tanker)	27%	40%	33%
	GA (bulk carrier)	28%	46%	27%
	GA (LNG carrier)	16%	54%	30%
	GA (chemical tanker)	28%	41%	32%
	GA (containership)	27%	47%	26%
	GA (LPG carrier)	28%	42%	30%
	RINA Green Plus	72%	25%	3%
	The Blue Angel (Operation)	42%	42%	16%
Single criteria	EEOI	100%	0%	0%
	RightShip EVDI	100%	0%	0%
	Green Ship Incentive Program	100%	0%	0%
	Norwegian NO_X Fund	100%	0%	0%

Many of the initiatives have a broad environmental scope but the weightings of the criteria vary significantly. For example, 54% of the points available in ESI are allocated to NO_X, significantly more than in any of the other multi criteria initiatives (ESI, 2017). NO_X is allocated 20% in CSI, 10% in CCWG and less than 10% in each of the other schemes with the exception of the Green Ship incentive programme and the Norwegian NO_X fund, which are specifically designed to promote NO_X reductions from shipping. Vessels with low NO_X emissions are likely to receive a high overall score in ESI even if they score low in the other categories. A ship with zero NO_X – assuming it does not score points in any of the other categories - would gain a score of 67 points in ESI (54% of the total).

Many ports around Europe use the ESI as a benchmarking tool, and offer financial incentives if vessels meet a minimum point's threshold (Table 3.4). Point's requirements to obtain discounts vary from 20 to more than 50, depending on the policy of the port. A score of 67 points is enough to comfortably achieve the required score to receive maximum financial benefit from each of the example incentive schemes for ports shown in Table 3.4. A vessel with low NO_X clearly has some significant environmental benefits, however it may not necessarily be considered 'eco-friendly' in other pollutant categories.

There is no evidence provided in the published methodologies to justify the criteria weightings used in each initiative, therefore it is assumed that the weightings have been decided subjectively by the developers. A more transparent approach could be implemented, using objective, quantifiable indicators to assess each pollutant and allocate criteria weightings. By doing this, criteria could be assessed objectively and weightings assigned based on the environmental impact of the pollutant.

Table 3.4 ESI points requirement for reduced duty fees at selected ports (adapted from CNSS, 2014)

Port	Minimum ESI points requirement	Discount
Rotterdam	≥ 31	10%
	≥ 31 total and ≥ 31 NO_X*	20%
Oslo	25-49	20%
	≥ 50	40%
Bremen & Bremerhaven	≥ 20	5%
Kiel	≥ 31	10%
Setubal	≥ 31	3%
Hamburg	> 50	10% (capped at €2,000)
Antwerp	≥ 31	10%
Wilhelmshaven	≥ 31	5%
Zeebrugge	≥ 20	10%
Groningen sea ports	≥ 20	5%

3.4.2.3 Environmental ambition

The main purpose of many of the initiatives analysed is to provide an indication of the environmental performance of a vessel, often by benchmarking against the performance of other vessels. The ESI is a tool for calculating environmental performance scores for individual vessels. Vessel scores can then be compared against each other to rank vessel environmental performance. Additionally, vessel scores can be benchmarked against a threshold value as shown in Table 3.4, and used to determine eligibility for incentives such as port discounts. CSI uses its own benchmarking scheme to classify ships based on environmental performance. CSI-class 1 is awarded to vessels scoring between 0-37 points, with higher classifications awarded to vessels achieving higher scores. Ships are awarded the highest classification (CSI-class 5) if they receive 125 points or more.

While CSI uses a multi-tiered classification system to rank ship environmental performance, other initiatives are less ambitious, with just a single classification. In order to qualify for the RINA Green Plus certification vessels must achieve 100 points or more out of 621 available (16%) (see Table 3.5), and vessels taking part in the Blue Angel scheme must achieve 40 out of 113 points (35%).

In the examples in Table 3.5, the number of points required to achieve accreditation is low. In each case, the minimum point threshold is a requirement to obtain overall certification of the award. There are no minimum thresholds set for individual pollutants. An oil tanker using Green Award (GA – oil tanker) for example is not required to obtain any points for reduction of NO_X, Particulate Matter or CO_2, therefore a vessel can obtain the award by gaining a satisfactory number of points in other criteria.

Incentive based initiatives such as the port discount schemes outlined in Table 3.4 set unambitious environmental targets for vessels. The highest achievable score in ESI is 100 points (Murphy *et al.*, 2013), however the maximum threshold for the incentive schemes in Table 3.4 is capped at 50 points.

Scott *et al.* (2017) suggest that one of the reasons for this is to not discourage participation by setting standards that are deemed unrealistic for many vessels. However, a more ambitious system, such as using multi-tiered benchmarking offering bigger financial incentives for high scoring vessels and smaller incentives for lower scoring vessels could encourage a wide uptake.

It is also noted that the incentives offered are small relative to the total operating costs of a ship, and hence may not encourage shippers to participate in such schemes (Murphy *et al.,* 2013; Scott *et al.,* 2017), and hence lack incentive to enhance environmental performance.

Table 3.5 Thresholds for Accreditation

Environmental	Points threshold (%)
GA (oil tanker)	20%
GA (bulk carrier)	21%
GA (LNG carrier)	40%
GA (chemical tanker)	20%
GA (containership)	26%
GA (LPG carrier)	18%
RINA Green Plus	16%
The Blue Angel	35%

Where possible, initiatives were analysed to determine the level of ambition in regards to individual pollutant criteria. Many of the schemes are considered to go '*beyond regulatory requirements'* (Scott *et al*., 2017) however further analysis suggests that most of the schemes are unlikely to encourage pollutant reductions significantly below the levels set out in MARPOL Annex VI. Many of the schemes do not measure pollutants in absolute terms, and performance is assessed relative to emissions from other vessels, or average emissions from similar vessels.

For example, the CCWG assesses vessel CO_2 emissions relative to a calculated trade lane average. Vessel emissions must be below the trade lane average to obtain a minimum score, and 10% below the trade lane average to achieve the maximum score. CCWG also uses relative thresholds rather than absolute thresholds for SO_X emissions. The minimum requirement is an average fuel S content of 15% above the trade lane average, and the maximum score is achieved if it is 15% below the trade lane average. Therefore if the trade lane average S content rises, the S content required to achieve a score will also rise. Conversely, if the average S content reduces then the threshold for scoring in CCWG also reduces. This could be considered a useful mechanism for lowering Sulphur emissions, given the introduction of increasingly stringent regulations planned for the near future, requiring all ships to use fuel oil with a maximum S content of 0.5% by 1st January 2020.

The NO_X and SO_X criteria for a number of initiatives are compared in terms of absolute values (see Figures 3.5 and 3.6). Each of the initiatives in Figure 3.5 use the requirements set out in MARPOL Annex VI as a scale to assess performance. For all of the initiatives, vessels are required to achieve at least Tier 1 emission levels in order to score points, while some initiatives set more stringent minimum requirements. CCWG is one of the more ambitious schemes in this regard, setting the minimum NO_X threshold at 20% below Tier 1 levels, however the maximum score is capped at Tier 3. Each of the Green Award initiatives offer maximum points for vessels achieving better than Tier 3 emissions, while CCWG, CSI, The Blue Angel and Green Ship Incentive Programme (Green Ship) set the maximum threshold at the regulatory limit (i.e. Tier 3).

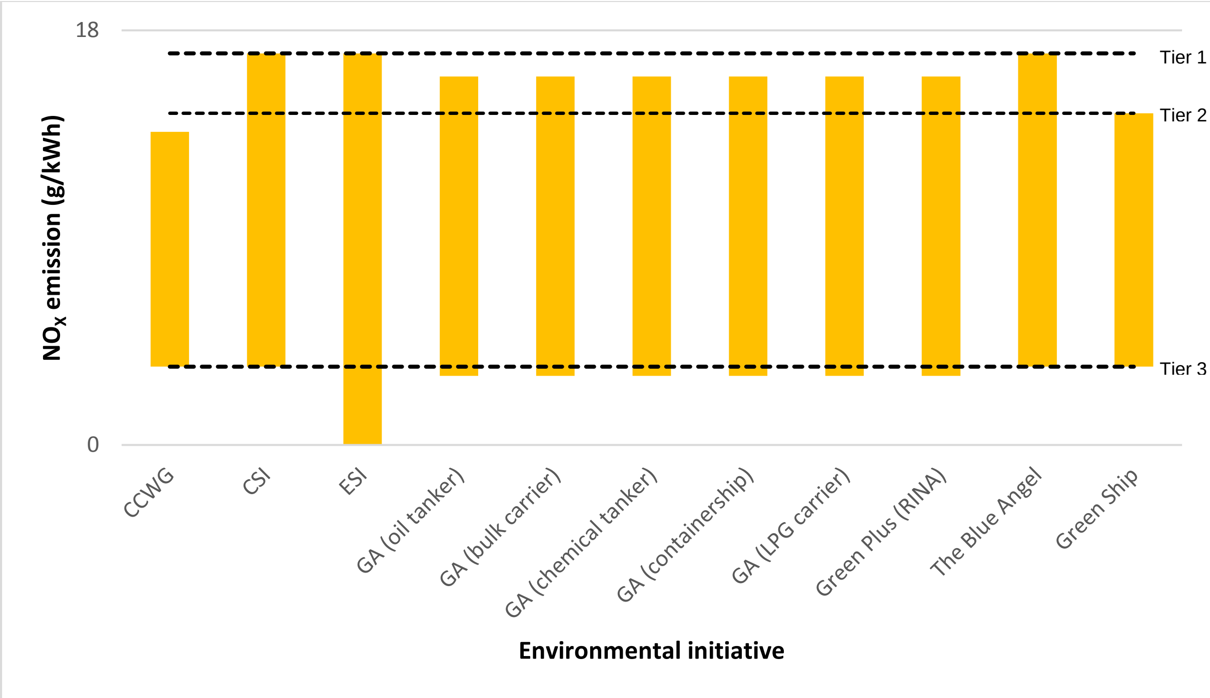

Figure 3.4 NO_X Scoring Range

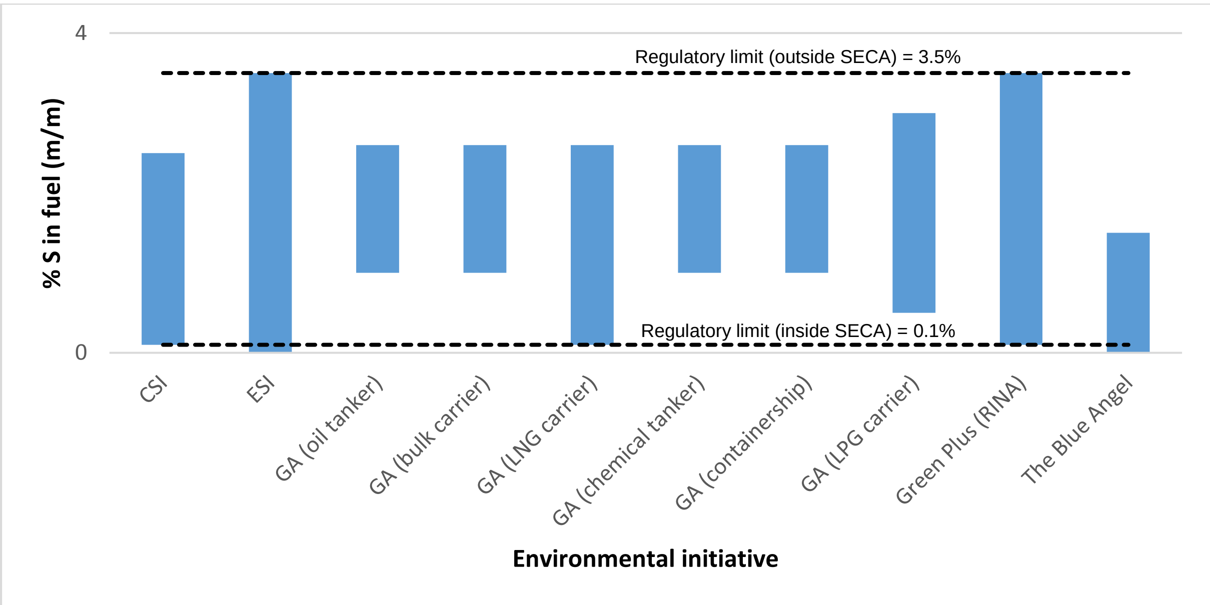

Figure 3.5 SO_X Scoring Range

The ESI is by far the most ambitious scheme with regards to assessment of NO_X and SO_X. It is the only scheme that rewards ships for reducing NO_X and SO_X emissions to zero, using a calculation based methodology to determine points based on emission level rather than using absolute threshold values. However it is limited in assessing CO_2, apportioning only 20% of the total available points in the scheme to

CO_2 related criteria - 4% for reporting of EEOI on fuel consumption and distance sailed, and up to 8% for energy efficiency improvements, and 8% if the vessel has OPS capability on board. Also, NO_X and SO_X scores are calculated based on the installed power of a ships engines and the published % S content of the fuel respectively, rather than the actual emissions of each pollutant.

As shown in Figure 3.5, the initiatives use more ambitious thresholds to assess SO_X emissions with only ESI and RINA Green Plus setting the minimum requirement at the regulatory limit, the other schemes require a fuel S content lower than 3.5% in order to qualify. However only ESI and the Blue Angel use a scoring range which goes beyond the regulatory limit for SECA's of 0.1% S. The low level of ambition shown for parameters such as NO_X, SO_X and CO_2 questions the success of private initiatives in the context of improving sustainability, as in most cases the criteria do no more than reinforce the regulatory standards set out by the IMO.

It is also noted that most of the initiatives analysed use one single, rigid assessment methodology for all ships, and only the Green Award uses different scoring criteria for different vessel types. The other schemes analysed have a standard methodology which is either applied to a range of ship types, or is only suitable for application to a limited range of ship types e.g. the CCWG is for container ships only. In some cases, additional or alternative bonus points are available for different ship types where the criteria is relevant to a specific characteristic of a ship e.g. the Blue Angel offers more points for passenger ships using OPS while in port than other ship types. The extent to which a ship impacts on the environment may vary depending on the characteristics of the vessel, and assuming that different ship types affect the environment in different ways, a '*one size fits all'* performance assessment methodology for all ships is not appropriate.

3.5 Summary

Regulations exist to minimise the damage to the marine environment caused by ship operations, by limiting the amount of harmful pollutants released. Shipping regulations have evolved in recent years to become more stringent as global environmental awareness has increased. However, the jurisdictional structure of international law provides a barrier to enforcement of environmental regulations in shipping. In addition, the process of ratification of IMO conventions leads to delays in when regulations can enter force legally, which along with a divergence of international, national, regional and local regulations, contributes to the fragmentary nature of shipping legislation.

Another method of controlling the release of pollutants to the marine environment is through adoption of environmental management strategies. Many global shipping companies have adopted a corporate social responsibility to promote environmental protection, and implement environmental management strategies and systems, such as ISO 14001, to showcase their credentials. Many cross-industry environmental assessment tools and methods are available for use to manage environmental performance and assess environmental impacts, and have been adopted for use in shipping. So called '*green shipping initiatives'* have become increasingly common in the shipping sector, to meet the environmental demands of customers and other stakeholders in the industry, and 'bridge the gap' caused by the barriers associated with shipping regulations.

This research identifies 85 different environmental initiatives relevant to shipping, and uses a holistic categorisation method to classify the schemes based on intended purpose. Initially the schemes are classified as either regulatory or independent instruments. The regulatory instruments are categorised further into optional or mandatory, and the independent schemes are classified as performance indicators, incentive schemes, and research and innovation activities.

Analysis of the initiatives reveals some limitations with the methods used to assess environmental performance, the applicability of the schemes to different ship types and locations, their environmental scope, and ambition to meet the increasing environmental demands of the industry. Many of the performance indicators identified are designed to assess multiple environmental pollutants, however the rationale behind the allocation of pollutant weightings is unclear, as some pollutants are weighted more heavily than others without justification. It is proposed that weightings should be justified and allocated based on the environmental impacts of the pollutant. None of the initiatives assess ship environmental performance based on actual pollutant emissions and discharges, and instead use proxy indicators such as fuel S content to assess SO_X emissions, and engine tier ratings to assess NO_X. It is proposed that actual measurements of emissions, or emissions estimates based on fuel use, would provide a more accurate assessment method.

Most of the initiatives analysed use a limited scoring range to assess pollutant emissions and discharges, with maximum scores capped at the regulatory limit, or just below. The ESI is an exception to this, as NO_X and SO_X scores are not capped and scores increase as emissions reduce down to zero. It is proposed that a ship performance assessment should include a scoring range starting at zero emissions/discharges, and scores should decrease as the amount of pollutants emitted or discharged, increase. It is also evident that most of the initiatives use a single assessment method, which is applied to all ship types, and therefore lack the flexibility to assess different vessel types where pollutant emissions and discharges may vary significantly. In some cases, the initiatives are only applicable to one type of ship e.g. the CCWG for containerships.

To summarise, a broad set of limitations with existing environmental initiatives have been identified in the research, these are:

- A lack of transparency of results and assessment methods.
- Limited applicability of initiatives to a wide range of ship types.
- Some initiatives have a narrow environmental scope.
- Biases towards certain pollutant indicators and unjustified weighting factors.
- Low thresholds for certification and limited ambition to go beyond regulatory requirements.
- Assessment of vessel performance based on design parameters rather than operational performance.

In the next chapter, a framework for a holistic environmental assessment methodology is proposed which can be applied to multiple different vessel types, whilst adopting a broad, relevant environmental scope based on the environmental impacts of emissions and discharges of pollutants. The method uses justified, calculated, pollutant weightings based on a set of environmental indices, and calculates vessel environmental performance scores based on actual vessel emissions and discharges of pollutants.

4.0 Development of a holistic environmental assessment model

4.1 Introduction

Shipping has a considerable impact on the environment due to the intentional and accidental release of pollutants. Maritime environmental legislation has tightened since the introduction of the MARPOL 73/78 regulations, however there is often a significant time gap between when the regulations are adopted and when they legally enter force.

The emergence of private voluntary environmental initiatives has occurred in an attempt to bridge the gap, reduce environmental impacts and raise the environmental profile of ships. However, there are inconsistencies in the methodologies used to define ship performance, while the number and diversity of initiatives available for use can cause confusion, hindering progress towards greater sustainability.

A critical analysis of existing environmental initiatives in the shipping industry has been conducted in Chapter 3, challenging the applicability, scope, environmental ambition and integrity of the methodologies adopted. Analysis of the initiatives highlights significant differences regarding their applicability to ship types and locations, assessment rationale and environmental scope. The existing initiatives lack the flexibility to be ship specific and many show bias towards certain environmental indicators, while others lack ambition and assess a limited number of environmental pollutants.

An alternative approach to environmental assessment of ships is proposed in this chapter, offering a holistic method of assessment which can be applied to multiple vessel types. The method adopts a broad, relevant environmental scope based on assessment of ship environmental impacts and determines environmental performance based on actual vessel emissions and discharges. The approach adopts a risk assessment based methodology using source pathway receptor (S-P-R) analyses to characterise and prioritise environmental impacts from pollutant discharges and emissions from ships. A comprehensive scoring system is adopted to indicate vessel environmental performance. A method and set of criteria for prioritising environmental pollutants is proposed.

4.2 Overview of methodology

The holistic environmental assessment framework is comprised of several steps as outlined in Figure 4.1. First, the scope of the assessment must be set, to determine what is and is not included. The framework is divided into two parts, part A (steps 1 to 6) is designed to characterise the pollutant emissions and discharges released from the vessel through environmental impact determination and assessment using environmental indicators, and part B (steps 7 to 11) provides the vessel assessment based on calculations, estimations and measurements of actual discharges and emissions.

A risk assessment method has been adopted as it is considered to be the most appropriate tool for evaluating the impacts of pollutants on the environment based on the severity of impact, and probability of occurrence. Section 3.3.6 reviews a number of different risk assessment methods. For this purpose, a semi quantitative method has been adopted so that ship related pollutants can be assessed subjectively but can be backed up by sound scientific evidence, and can be applied consistently by following the steps of the method.

The first step involves the identification of ship interactions with the environment in order to understand which aspects of the environment the vessel may impact upon. The second step identifies a broad list of environmental pollutants, or hazards, associated with ship operation. The next step consists of an S-P-R analysis to determine the possible impacts of the identified ship hazards on the environment. S-P-R analysis was selected from the various techniques outlined in Section 3.3.6.2 as it enables a systematic, consistent approach to identifying impacts of pollutant emissions and discharges. Next, the hazards are assessed using numerical severity indicators (spatial extent, residence time, toxicity, and global warming potential) and a total severity score is calculated in order to determine a weighting factor score for each hazard.

The second part of the method (part B) requires vessel specific data to be collected via checklist, in order to calculate a Vessel Environmental Performance (VEP) indicator score for each hazard. The hazard weighting factors (from part A) and VEP indicator scores are multiplied together to calculate overall severity scores for each hazard, which are then multiplied by the likelihood of occurrence to give scores for hazard significance. This allows ship environmental hazards (i.e. pollutants) to be assessed based on the effects of the pollutant on the environment and the amount discharged or emitted to the environment from a specific vessel.

Hazard significance scores for each pollutant are combined to provide a total VEP (Vessel Environmental Performance) Index score for the vessel.

Figure 4.1 outlines the framework of the methodology, including the inputs and outputs.

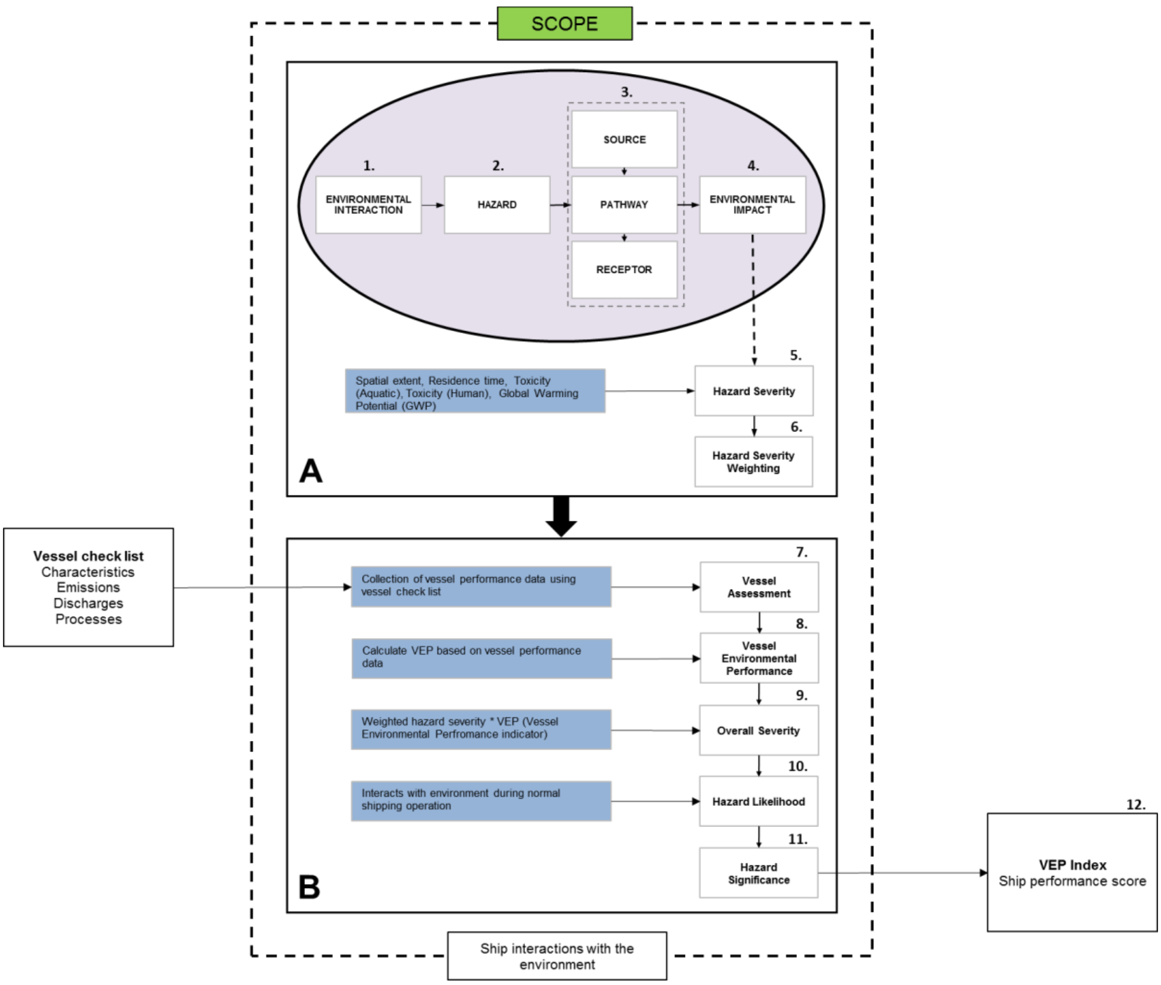

Figure 4.1 Holistic environmental assessment framework

The method is implemented as follows:

Part A:

Step 1: Identify key interactions of ships with the environment.
Step 2: Identify environmental hazards.
Step 3: Conduct Source-Pathway-Receptor analysis.
Step 4: Identify environmental impacts.
Step 5: Assess severity of hazards.
Step 6: Calculate hazard severity weighting.

Part B:

Step 7: Conduct vessel assessment using inputs from vessel checklist.
Step 8: Determine Vessel Environmental Performance (VEP).
Step 9: Calculate overall severity.
Step 10: Determine likelihood of hazards.
Step 11: Calculate hazard significance.
Step 12: VEP Index score

This approach enables identification of the major environmental threats associated with specific ships by assessing and prioritising pollutant emissions based on impact severity and actual vessel emissions and discharges. The outputs of assessments of different vessels can be compared, providing an indication of vessel environmental performance.

4.3 Assessment scope

An important first step in the development of impact assessments is to quantify the scope of the problem or investigation (Gormley, 2011). In order to assess the impacts of shipping, or more specifically ships, on the environment, definitions for 'ships' and 'the environment' must be determined. The purpose of this assessment methodology is to provide an indication of ship environmental performance based on the impacts of vessel operations on the surrounding natural environment, therefore the definition of 'ship' in this instance refers to individual vessels during the operational phase, it does not include fleets or 'shipping' in the wider industry context, and does not include impacts associated with construction and maintenance of the vessel during dry docking, or breaking at end of life.

Ships are man-made entities and are not part of the natural environment of the earth, therefore the definitions of 'ship' and 'environment' are clearly distinguished. 'Environment' refers to the surrounding conditions in which a vessel operates, which includes the maritime environment, atmosphere and ports. Environmental impacts of ships are considered to be primary or secondary effects resulting from direct emissions or discharges from a vessel to land, sea, and air, and the impacts associated with such emissions on earth systems and living organisms (biota). For the purpose of this research, the environmental impacts assessed are limited to those which have been identified in Chapter 2 and summarised in Appendix A.

In summary, the scope of this assessment methodology includes direct emissions and discharges of pollutants from vessels during the operational phase, whilst in operation at sea and/or other water bodies, and in port.

4.4 Step 1: Ship interactions with the environment

The earth's environmental system is made up of five interacting spheres (Manahan, 2017). The hydrosphere consists of all water on the earth's surface, the atmosphere is made up of air and other gases which envelope the earth's surface, the geosphere consists of soil, rocks and mineral matter on or below the earth's surface, the biosphere consists of all living organisms, and the anthrosphere represents the parts of the earth that are made, modified or operated by humans.

The scope of the assessment methodology has been constructed based on the interaction of ships with the environment during operation. Ships are designed for transportation of goods and people by sea or other water bodies, therefore there is a direct interaction of ships with the hydrosphere. Ships also interact with the atmosphere through emissions of various exhaust and other gases. Direct interactions of ship pollutants with the hydrosphere and atmosphere also lead to interactions with the biosphere and have impacts on the earth's geochemical activities (the transfer of substances to different environmental spheres). Ships interact with the geosphere due to the release of pollutants (e.g. in municipal solid waste) which come into contact with the earth's natural landscape when berthing at ports and harbours. Harbours and ports are manmade landscapes, hence vessels also interact with the anthrosphere. Ships also produce sounds that can cause annoyance or disturbance to living organisms in the biosphere, and can make physical contact with marine organisms.

During the operational phase, ships interact with aspects of each of the five spheres of the environment. Therefore, this assessment method categorises ship interactions with the environment into five groups, considering each of the environmental spheres. Interactions with the biosphere have been separated into two categories: noise; and physical contact with marine animals, to represent different types of interaction. Interactions with the geosphere and anthrosphere are combined into a single category, 'Land'. The interactions are categorised as follows:

(1) Emissions to Air (atmosphere)

(2) Discharges to Water (hydrosphere)

(3) Land (geosphere and anthrosphere)

(4) Anthropogenic Noise (biosphere)

(5) Physical Contact (biosphere)

4.5 Step 2: Determination of Environmental Hazards

A hazard in environmental risk assessment is defined by Gormley *et al.* (2011) as *"a situation or biological, chemical or physical agent which may lead to harm or cause adverse effects"* to an aspect of the environment. Therefore in the context of this assessment method, ship hazards are considered to be emissions or discharges of pollutants from a vessel which interact with the environment. Vessels produce various pollutant releases to the environment due to the operation of different processes and equipment on board. The most common discharges include oil and chemical spills, wastewater releases, chemical releases from paint coatings, ballast water release, dumping of waste material, and emissions of exhaust gases and other air pollutants. Chapter 2 provides a detailed assessment of environmental impacts associated with pollutants from ships. Based on the impacts identified, a summarised list of ship hazards is presented, categorised per interaction type, shown in Table 4.1. The list does not include hazards associated with the construction or end of life phases of a vessels life cycle as such phases are not included in the scope of this research (and therefore resource depletion and ship decommissioning are omitted as hazard categories).

The method distinguishes between operational releases and those that are considered accidental and/or violations of current regulations (Figure 4.2). For example, air emissions occur during routine operation of the ship. Similarly, discharge of treated ballast water may also be considered a controlled release, whilst untreated may be considered a violation. Pollutants can also be distinguished from biohazards such as invasive species, which can impact on the environment due to biological effects on local ecosystems. The method acknowledges operational and non-operational releases in Section 4.13 by coarsely assessing hazard likelihood. The method distinguishes pollutants (including biohazards) based on discharge pathway, as shown in Table 4.1.

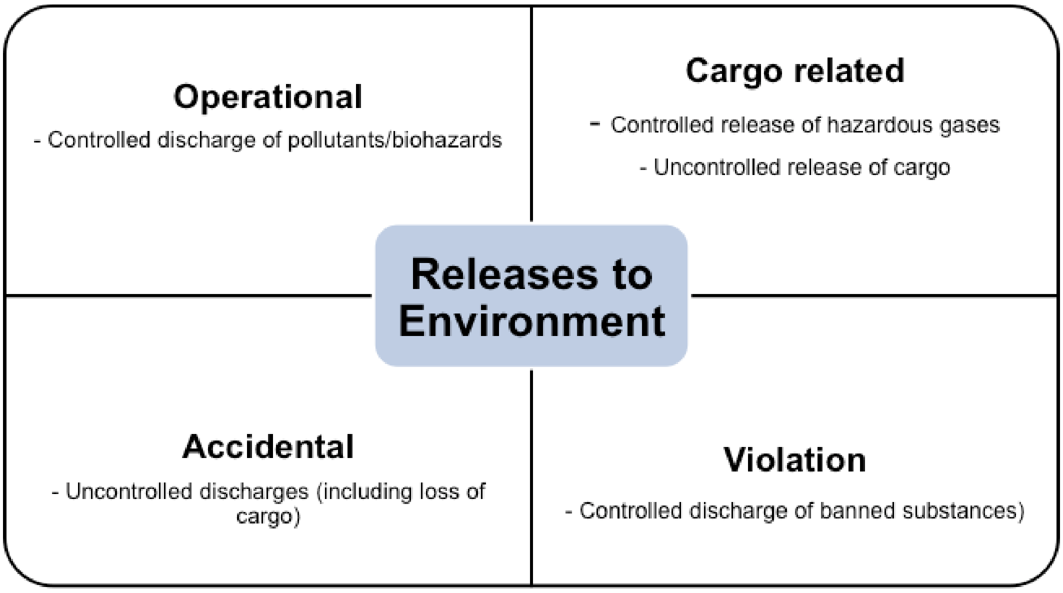

Figure 4.2 Types of environmental release from ships

The list of hazards is intended to be generic and is based on the environmental interactions determined from the literature in Chapter 2. However, the list can be tailored by an environmental assessor to a specific group of vessels depending on the scope of the assessment. In order to compare vessels like for like, the hazard list must remain constant. For the purpose of this research, the hazard list in Table 4.1 is adopted.

Table 4.1 List of ship environmental hazards

Interaction with the Environment	Environmental Hazard
Emissions to Air	GHGs (CO_2, CH_4, N_2O)
	ODPs (Refrigerants)
	SO_X
	NO_X
	PM
	VOCs
Discharges to Water	Oil
	Sewage
	Grey water
	Antifoul systems
	Ballast water
	Marine litter
	Chemicals
Land	Garbage
Anthropogenic Noise	Underwater noise
	Surface noise
Physical Contact	Collisions with marine animals

4.6 Step 3: Source Pathway Receptor Analysis

As discussed in Section 3.3.6 (Chapter 3), a common tool in risk assessment for quantifying impacts and risks of pollution is S-P-R (source pathway receptor) analysis. This technique has been utilised in this research to categorise the impacts of ships on the environment into the interaction groups outlined in Table 4.1, and to determine the pathways into the environment of the pollutants (hazards) discharged from ships. An S-P-R analysis has been conducted for each environmental hazard outlined in Chapter 2, summarised in Table 4.2.

Table 4.2 S-P-R analysis of ship hazards

Interaction	Hazard	Source	Pathway	Receptor
Emissions to Air	CO_2 (GHG)	Engine	Combustion of fuel	Atmosphere
	CH_4 (GHG)	Slippage due to incomplete combustion of natural gas in engine / loss during handling	Handling and combustion of LNG	Atmosphere
	N_2O (GHG)	Engine	Fuel combustion at low temperatures	Atmosphere
	Refrigerants	Leakage	Refrigeration units Air conditioning units	Atmosphere
	SO_X	Engine	Fuel combustion	Atmosphere
	NO_X	Engine	Fuel combustion	Atmosphere
	PM	Engine	Fuel combustion Material wear Lubrication oil	Atmosphere Humans
	VOCs	Solvent containing materials (paints, thinners) Crude oil (tankers) Engine	Solvent evaporation during paint application and cleaning Solvent evaporation in oil tanks (vented to atmosphere) Fuel combustion	Atmosphere Humans
Discharges to Water	Oil	Fuel tanks Storage containers	Spillage Leakage	Sea Aquatic species Marine ecosystems Humans
	Sewage	Toilets Medical facilities Live animal premises	Disposal Spillage	Sea Humans Marine ecosystems
	Grey water	Washing facilities Oily water separators	Disposal Spillage	Sea Marine ecosystems
Discharges to Water (continued)	Antifoul coating	Hull coatings	Leakage Dissolution	Sea Aquatic species
	Invasive species transfer (Ballast water)	Ballast water Hull fouling	Ballast water release Detachment from hull	Sea Marine ecosystems Aquatic species
	Marine litter	Discarded from ship Lost from ship	Disposal Accidental loss	Sea Humans (bathing) Marine ecosystems
	Chemicals	Cargo Cleaning products	Spillage Leakage	Sea Aquatic species Marine ecosystems Humans

Continued overleaf…

Interaction	Hazard	Source	Pathway	Receptor
Land	Garbage	On-board solid waste	Disposal at port/harbours Fly tipping Accidental loss	Land Soil
Anthropogenic Noise	Underwater noise	Propellers Engines	Soundwaves (exacerbated by cavitation)	Sea Aquatic species
	Surface noise	Shipping activities Warning sirens	Soundwaves	Humans
Physical Contact	Collisions with marine animals	Ship's hull	Ship movement Movement of aquatic species	Aquatic species (Cetaceans) and other sea life

4.7 Step 4: Identification of Impacts

The environmental impacts reviewed in Chapter 2 have been collated for each ship related emission and discharge (hazard) in Table 4.3. The purpose of this step is to understand how ship emissions and discharges impact on the environment, and develop a summary of impacts to inform the severity assessment in the next step.

Table 4.3 Environmental impacts of ship operations

Interaction	Hazard	Environmental impacts
Emissions to Air	CO_2 (GHG)	Climate change
		Ocean acidification
	CH_4 (GHG)	Climate change
	N_2O (GHG)	Climate change
	Refrigerants	Ozone depletion Climate change
	SO_X	Acid rain
		Dry deposition
		Radiative forcing
		Secondary particulate formation
	NO_X	Acidification
		Eutrophication
		Surface ozone formation
		Radiative forcing
		Secondary particulate formation

Continued overleaf…

Interaction	Hazard	Environmental impacts
Emissions to Air	PM	Human health
		Radiative forcing
		Decrease in snow/ice albedo
		Acid rain
	VOCs	Human health
		Secondary radiative forcing
		Secondary acid rain
		Photochemical smog formation
Discharges to Sea	Oil	Toxification of biota
		Suffocation of biota
		Ocean hypoxia
		Hypothermia in sea birds
		Physical damage to shore line
		Disease in marine species
		Bioaccumulation in marine species
	Sewage and Grey water	Direct toxification of biota
		Eutrophication
		Ocean hypoxia and anoxia
		Hydrogen Sulphide formation
		Stunted growth rate of marine species
		Human health
	Antifoul coating	Imposex and stunted growth of marine species due to TBT release
		Bioaccumulation of Copper in marine organisms
		Toxification of marine organisms (Irgarol and Diuron)
	Invasive species transfer (Ballast water)	Relocation and establishment of alien species
		Competition for resources with native species
		Damage to infrastructure
		Spread of disease
		Increase in fuel consumption due to hull fouling
	Marine litter	Human health
		Shoreline aesthetics
		Infrastructure damage
		Entanglement of marine species
		Bioaccumulation of micro plastics in marine species
		Habitat destruction
	Chemicals	Human health
		Toxification of biota
		Bioaccumulation in marine species
		Habitat destruction

Continued overleaf…

Interaction	Hazard	Environmental impacts
Land	Garbage	Chemical leaching into soil and watercourse
		Odour
		Aesthetics of waste disposal sites in ports/harbours
Anthropogenic Noise	Underwater noise	Acoustic masking of communication signals in marine species
		Behavioural disruption of marine species
		Reduced population density of marine species
		Physiological impacts on marine species
	Surface noise	Human health
		Annoyance
		Distraction leading to increased safety risks
Physical Contact	Collisions with marine animals	Serious injury to aquatic species
		Death of aquatic species

4.8 Step 5: Hazard Severity Assessment

In order to quantify the potential severity of impact of vessel emissions and discharges on the environment, each hazard is assessed using a set of severity indicators. In risk assessment, characterisation of impact can be subjective especially where quantitative data is not readily available. The use of severity indicators in this case attempts to minimise the subjectivity of the assessment by providing clear definitions for characterising the impact of pollutants on the environment.

In some cases there may not be data available in order to accurately determine e.g. the spatial extent of an impact, however it may be possible to '*best fit'* the effects within a broader definition. For example, a global environmental phenomenon such as climate change could generally be considered to have both global and localised effects on the environment, however a detailed climate model would be required in order to predict the effects in detail. This level of resolution is outside of the scope of the methodology, which is designed to provide a broad assessment of environmental impacts related to shipping emissions and discharges. Therefore in this case the effects of climate change are considered to be global.

A set of severity indicators used to assess each hazard is outlined in Table 4.4. The indicators are defined with definitive boundaries to provide a framework for objective assessment, but also require minimal scientific interpretation or data input. The process of qualitative risk assessment is inherently ambiguous as it relies on personal interpretation, therefore the use of well-defined severity indicators is important, especially where availability of data is limited. In this case, the indicators are clearly defined as described in Table 4.4.

The hazards are assessed based on spatial distribution of the pollutant in the environment (estimated from the literature), the residence time of the hazard in the environment, the toxicity of the hazard to aquatic species, toxicity to humans, and Global Warming Potential (GWP).

The indicators are assigned a numerical score based on the definitions for each indicator outlined in Table 4.4. A linear numerical scale was chosen to score the indicators from 1 to 5 to enable vessels to be scored on a simple scale. The indicator scores do not represent the magnitude of impact of a pollutant incident.

Using spatial extent as an example, pollutants which have a global effect on the environment are given a score of 5, while pollutants considered to have a local effect on the environment at a port or city level are given a score of 3.

Residence time is established where possible from the literature, for example the lifetime of greenhouse gases in the atmosphere has been extensively researched by the IPCC (Intergovernmental Panel on Climate Change), with the latest findings published in the 5th Assessment Report (5AR) in 2013. The GWP of gases is also readily available using the same source, while data on pollutant toxicity can be obtained through the EU established ECHA (European Chemicals Agency) database and through GESAMP, (2018) (Group of Experts on the Scientific Aspects of Marine Environmental Protection), a report listing hazardous substances commonly transported via shipping.

Table 4.4 Environmental indicators and definitions

Indicator		Score	Definition
Spatial extent	Global	5	Spatial distribution at a global level, resulting in effects on the global environment e.g. a change in global atmospheric conditions
	Regional	4	Spatial distribution at a continental and/or national level
	Local	3	Spatial distribution at a port or city level
	Individual	2	Spatial distribution which affects individual structures or organisms
	Negligible	1	No spatial distribution of pollutants
Residence time	Very long term	5	Residence time greater than 1000 years
	Long term	4	Residence time < 1000 years > 100 years
	Medium term	3	Residence time < 100 years > 1 year
	Short term	2	Residence time < 1 year > 1 day
	Negligible	1	Residence time < 1 day
Toxicity (Aquatic)	Category 1	5	Globally Harmonised System (GHS) classification for acute aquatic toxicity (LC_{50} ≤ 1 mg/L)
	Category 2	4	Globally Harmonised System (GHS) classification for acute aquatic toxicity (LC_{50} > 1 ≤ 10 mg/L)
	Category 3	3	Globally Harmonised System (GHS) classification for acute aquatic toxicity (LC_{50} > 10 ≤ 100 mg/L)
	Category 4	2	Globally Harmonised System (GHS) “safety net” classification for poorly soluble substances for which no acute toxicity is recorded at levels up to the water solubility, and are not rapidly degradable, indicating a potential to bio accumulate.
	Not classified	1	Classification under GHS undefined
Toxicity (Human) **Air emissions**	Category 1	5	GHS classification for toxicity - acute inhalation (LC_{50} ≤ 0.05 mg/L)
	Category 2	4	GHS classification for toxicity - acute inhalation (LC_{50} > 0.05 mg/L ≤ 0.5 mg/L)
	Category 3	3	GHS classification for toxicity - acute inhalation (LC_{50} > 0.5 mg/L ≤ 1 mg/L)
	Category 4	2	GHS classification for toxicity - acute inhalation (LC_{50} > 1 mg/L ≤ 5 mg/L)
	Not classified	1	Classification under GHS undefined
Toxicity (Human) **Other pollutants**	Category 1	5	GHS classification for toxicity – acute oral (LD_{50} ≤ 5 mg/L)
	Category 2	4	GHS classification for toxicity – acute oral (LD_{50} > 5 mg/L ≤ 50 mg/L)
	Category 3	3	GHS classification for toxicity – acute oral (LD_{50} > 50 mg/L ≤ 300 mg/L)
	Category 4	2	GHS classification for toxicity – acute oral (LD_{50} > 300 mg/L ≤ 2000 mg/L)
	Category 5/Not classified	1	GHS classification for toxicity – acute oral (LD_{50} > 2000) or GHS classification undefined
GWP (Global Warming Potential)	Very High	5	> 3,000
	High	4	1,000 - 3,000
	Moderate	3	300 - 1,000
	Low	2	1 - 300
	Negligible	1	< 1

4.8.1 Spatial extent

A qualitative index of spatial extent is used to broadly define the spread of a pollutant in the environment from a point source discharge or emission. For the purpose of this methodology, spatial extent is defined as outlined in Table 4.4. A numerical scale (1 to 5) rather than a qualitative scale has been selected to represent the spatial extent indicator. The lower end of the scale (score = 1) signifies little or no spatial distribution or diffusion of pollutants, and the top end of the scale (score = 5) signifies a global distribution of pollutants. A scale using quantified distances was considered for this indicator, however modelling the distribution of a pollutant from a point source is detailed, complex and dependent on many factors, and data at that level of detail is not considered to be required for this methodology.

The pollutants outlined in Table 4.3 have been subjectively assessed using the qualitative spatial extent indicator described in Table 4.4. The impacts associated with each pollutant were also taken into account when determining spatial extent e.g. the consequence of emissions of ozone depleting substances (e.g. halocarbons in certain refrigerants) is depletion of the ozone layer, which is considered to be a global issue – emission is local however impact is global. CO_2, CH_4 and N_2O are GHGs with a long residence time in the atmosphere, and therefore are considered to have global environmental impacts regardless of whether the source of the emissions is localised, and are therefore categorised as '*globa*l' using the spatial extent indicator. NO_X, SO_X and PM have shorter atmospheric residence times than GHGs, but can travel relatively long distances and are considered to be transboundary pollutants, therefore are classed as having '*regional*' spatial extent using the indicator in Table 4.4. Emission of VOCs containing methane have global environmental effects (climate change), however NMVOCs have short atmospheric residence times and contribute to localised environmental impacts such as photochemical smog production, therefore are considered to be '*local*' using the spatial extent indicator in Table 4.4.

The issue of ozone depletion is covered by the Montreal Protocol which is a global treaty, and emissions of ozone depleting substances through refrigerants affect the ozone layer on a global scale. In many cases however, modern refrigerants have very low or zero ozone depleting potential, however some gases used in e.g. air conditioning systems have significant global warming potential (e.g. R410a has a GWP of 2088 (Linde, 2019)). Therefore, the spatial extent of refrigerants in this research is considered to be '*globa*l'.

The spatial distribution of oil can depend on many factors including the volume of oil discharged due to a spillage, and its viscosity. Vessels carrying large quantities of oil as cargo pose a greater risk to the environment from a spillage than non-cargo vessels, due to having a greater quantity of oil on board. Once the oil enters the marine environment, it can spread across relatively large areas as an oil slick, while diffusion can result in oil molecules being transported further from the point source of the discharge. Modelling can be conducted to predict the trajectory and fate of oil spills in the ocean (Abascal, *et al.,* 2018; Maslo *et al.,* 2014; Kileso *et al.,* 2014) which can be taken into account for detailed vessel assessments, however for the purpose of this research, a generalised, subjective assessment of oil spatial extent has been made. Major historic oil spills from shipping have resulted in hundreds of thousands of tonnes of oil being released into the ocean from individual accidents (Lindgren *et al.,* 2016[b]). In such cases, the discharge can spread hundreds of kilometres (Marchand, 1980; Gonzalez *et al.*, 2006), potentially impacting on the marine environment in regions spanning multiple countries and/or continents. Therefore, the spatial extent of oil is considered to be '*regional*' for this research. This indicator is flexible depending on the oil carrying capacity of the vessel.

Data regarding the spatial distribution in the environment of sewage and grey water, and chemicals from antifoul paints discharged from ships is limited, however each are released at a low rate and in small quantities compared with a major oil spill. The fate of sewage sludge in the marine environment has been studied by Oviatt *et al.* (1987), who suggest that sewage is rapidly re-mineralised in sea water due to its organic content, and therefore has a short residence time, however other studies (Boesch, 1982; Steimle *et al*., 1982) suggest that sludge traces can be found 10-15km from the point of disposal. Oviatt *et al.* (1987) suggest that sludge settles to the sea bed in a matter of days to months depending on the depth of the water, where it is consumed by benthic organisms. It is therefore plausible that sewage sludge could impact the marine environment at a local level due to the proposed residence time and evidence of sludge traces found at relatively short distances from the point of discharge in previous studies.

Antifoul paints can persist in water from days to years depending on the chemicals used, and have been found in relatively high concentrations in localised areas of high boating activity such as harbours and ports, with limited concentrations in offshore waters (Thomas, 2001). Therefore for the purpose of this research, the spatial extent of sewage and grey water, along with antifoul paint is considered to be '*local*'. Regarding the transfer of invasive species, it becomes an environmental concern when ballast water discharge takes place in coastal waters and in port areas allowing non-native species to become established in local marine ecosystems, therefore for this research the spatial extent of invasive species is considered to be '*local*'.

The distribution of disposed litter from ships into the marine environment can vary depending on the characteristics of the litter. Biodegradable waste streams are likely to have a limited residence time in the marine environment and are therefore unlikely to spread long distances from the point source, however other waste streams can remain in the environment for long periods, and hence can be transported to other locations through ocean currents. Micro-plastics for example are small enough to be transported thousands of kilometres in ocean currents, however research in this field is emerging, and their fate and impact in the marine environment is uncertain (Avio *et al.,* 2017). The IMO consider micro plastics to be 'a global problem' (GESAMP, 2015), therefore the spatial extent of marine litter in this research is considered to be '*global*'. Scientific understanding regarding the distribution of chemicals in the marine environment following a pollution incident is limited, however Cunha *et al.* (2015) suggest that data from historical spillages indicates localised impacts on the environment, therefore the spatial extent of chemicals is considered to be *'local'*.

Noise can propagate hundreds of Km in water (Lindgren and Wilewska-Bien, 2016), and hence the spatial extent of underwater noise is classified as '*regional*' in this research, however in air it is limited by external factors and tends to be a nuisance at a port or harbour level (Badino *et al.*, 2012), and hence is classified as '*local*' in this research. Physical contact tends to occur between a vessel and individual marine animals which are large enough to incur ship strikes, so is classified as '*individual*'. Waste disposed of at port reception facilities is contained within a confined area, however odours and toxic gases released into the atmosphere can spread depending on the meteorological conditions. Nevertheless, the spatial extent of waste disposal on land is considered to be '*local*' for this research.

Based on the rationale as explained in this section, a summary of the spatial extent scores for ship related pollutants is outlined in Table 4.5.

Table 4.5 Spatial extent indicator scores per hazard

Interaction	Hazard	Spatial extent	Score
Emissions to Air	CO_2	Global	5
	CH_4	Global	5
	N_2O	Global	5
	Refrigerants	Global	5
	SO_X	Regional	4
	NO_X	Regional	4
	PM	Regional	4
	VOC's	Local	3
Discharges to Water	Oil	Regional	4
	Antifoul coating	Local	3
	Ballast water	Local	3
	Sewage	Local	3
	Grey water	Local	3
	Marine litter	Global	5
	Chemicals	Local	3
Land	Garbage	Local	3
Anthropogenic noise	Underwater noise	Regional	4
	Surface noise	Local	3
Physical	Collisions with marine animals	Individual	2

4.8.2 Residence time

The residence time indicator uses quantitative thresholds to assess each pollutant based on the period of time in which the primary pollutant remains in the environment, according to relevant literature. As outlined in Table 4.4, pollutants are assessed on a numerical scale of 1 to 5 to provide a broad indication of time spent in the environment, from less than 1 day to greater than 1,000 years. The consistency of application of residence time scales has been questioned by Monsen *et al.* (2002), suggesting the definitions of such metrics are not applied with rigour. There are numerous definitions which describe the period of time spent by a compound in the environment before they are removed through reactive or exchange processes. The

IPCC (2013) describes GHGs in terms of *atmospheric lifetime*, which is the time taken for a concentration pulse to decrease by a factor of *e* (2.71). The same definition cannot be applied to pollutants emitted to other aspects of the environment. For example, the residence time of oil in this instance is defined as the half-life of oil in sea water, which is the time taken for its quantity to reduce by half through biodegradation (Hazen *et al.,* 2016; Prince *et al.,* 2016). Residence times for each pollutant are defined in Table 4.6.

In this research, the scale for measuring residence time is broad and therefore the accuracy of time data required is low. Residence times of each pollutant in the environment have been adapted from the literature where available, summarised in Table 4.6.

Table 4.6 Assumed residence times of pollutants in the environment

Interaction	Hazard	Residence time	Contextual definition of Residence time	Source
Emissions to Air	CO_2	> 1000 years	IPCC definition of atmospheric lifetime: time taken for a concentration pulse to decrease by a factor of e (2.71).	IPCC (2013)
	CH_4	9.1 years	IPCC definition of atmospheric lifetime: time taken for a concentration pulse to decrease by a factor of e (2.71).	IPCC (2013)
	N_2O	131 years	IPCC definition of atmospheric lifetime: time taken for a concentration pulse to decrease by a factor of e (2.71).	IPCC (2013)
	Refrigerants	10's to 100's of years	Average of estimated steady state lifetimes of a gas from the time of peak burden (i.e. the rate of change in mass of a gas) onwards. Gases are in steady state in the atmosphere when the sources balance the sinks. Lifetimes represent the sum of all losses from the atmosphere.	Rigby *et al.* (2013)
	SO_X	Days (troposphere)	*e*-folding lifetime of SO_X	Miyakawa et al. (2007);

Continued overleaf…

Interaction	Hazard	Residence time	Contextual definition of Residence time	Source
Emissions to Air	NO_X	Hours (surface) to days (upper troposphere)	*e*-folding lifetime of NO_X	Kenagy *et al.* (2018); Zhang *et al.* (2002)
	PM	Days to weeks	Not specified.	Giere and Querol (2010)
	VOCs	Hours to months	IPCC definition of atmospheric lifetime: time taken for a concentration pulse to decrease by a factor of *e* (2.71).	IPCC (2013)
Discharges to Water	Oil	Days to months	Half-life of oil in sea water: time taken for quantity of oil to reduce by half through biodegradation.	Hazen *et al.* (2016)
	Sewage	Days to months	Settling rate of sludge in sea water. (e.g. In water depth of 5m, 85% settlement in 24h; at 2700m depth, 50% settlement within 2 months).	Oviatt *et al.* (1987)
	Grey water	Days to months	Assumed to be the same as sewage.	Oviatt *et al.* (1987)
	Antifoul coating	< 24 hours to hundreds of days	Degradation half-life (varies depending on coating).	Thomas (2001; 2010)
	Ballast water	Permanent	Establishment of alien species in new location (considered to be permanent).	Bax *et al.* (2003)
	Marine litter	100's to 1000's of years	Degradation lifetime of micro plastics in the marine environment.	Wang *et al.* (2016)
	Chemicals	Weeks to months	Biodegradation half-life of selected chemicals known to have entered the marine environment through spill events	Cunha *et al.* (2015)
Land	Garbage	Days to tens of years	Persistence of plastic waste in landfill (more than 20 years). Webb *et al.* (2012). Biodegradation rate of municipal solid waste in landfill (around 10,000 days). McDougall (2011).	Webb *et al.* (2012); McDougall (2011)
Anthropogenic Noise	Underwater noise	Negligible	Attenuation from point source at rate of speed of sound in sea water.	Wilson (1960)
	Surface noise	Negligible	Attenuation from point source at rate of speed of sound in standard air.	Wong (1986)
Physical Contact	Collisions with marine animals	Negligible	Not applicable. Physical contact is considered to be instantaneous.	n/a

In many cases, data regarding the lifetime of pollutants in the environment is readily available in the literature, however assumptions have been made for some of the pollutant categories outlined in Table 4.6. For each pollutant, residence times are defined in the context of previous studies conducted, hence the definition is not consistent for all pollutants. The residence times of sewage and grey water have been broadly assumed based on the estimated settlement rate of sludge in sea water (Oviatt *et al.,* 1987), while the residence time of antifoul coatings is broadly defined based on studies by Thomas (2001; 2010) where the half-lives of different antifoul paint biocides have been investigated. For invasive species transfer due to ballast water release, it is assumed that for an invasion to take place a species must be established permanently in a new location, while the residence time of marine litter is assumed based on the degradation rate of micro plastics in the ocean. Marine litter can be composed of many different waste streams, with micro plastics one of the more persistent constituents (Wang *et al.,* 2016).

The residence times of NO_X and SO_X in the atmosphere are assumed based on studies by Kenagy *et al.* (2018) and Zhang *et al.* (2010), and Miyakawa *et al.* (2007) respectively. Residence times of each are defined by the *e*-folding lifetime in the atmosphere, which is the time taken for the concentration to decrease to 1/*e* of the original concentration. Particulates are assumed to reside in the atmosphere for days to weeks according to studies by Giere and Querol (2010), and the residence time of ozone depleting substances is assumed based on the steady state lifetimes of a number of prominent ozone depleting gases taken from a study by Rigby *et al.* (2013). The residence time of NMVOCs in the atmosphere varies from hours to months depending on the characteristics of the gas (IPCC 2013).

For underwater and above surface noise emissions, the residence time is considered to be negligible as sound propagates from a point source at a considerable rate in sea water and in air. The spatial distribution of sound can be significant, particularly in water, however the persistence of the sound wave at a specific point is considered to be negligible in this research. Likewise, the residence time of physical contact with marine animals is considered to be negligible. For waste disposal to land, residence time has been assumed based on the degradation of organic and inorganic waste streams in landfill, ranging from days (organic wastes) to tens of years (plastic polymers).

A summary of the residence time scores for ship related pollutants is outlined in Table 4.7.

Table 4.7 Residence time indicator scores per hazard

Interaction	Hazard	Residence time	Score
Emissions to Air	CO_2	Very long term	5
	CH_4	Medium term	3
	N_2O	Long term	4
	Refrigerants	Medium term	3
	SO_X	Short term	2
	NO_X	Short term	2
	PM	Short term	2
	VOCs	Short term	2
Discharges to Water	Oil	Short term	2
	Antifoul coating	Short term	2
	Ballast water	Very long term	5
	Sewage	Short term	2
	Grey water	Short term	2
	Marine litter	Long term	4
	Chemicals	Short term	2
Land	Garbage	Medium term	3
Anthropogenic Noise	Underwater noise	Negligible	1
	Surface noise	Negligible	1
Physical Contact	Collisions with marine animals	Negligible	1

4.8.3 Toxicity (Aquatic)

The indicator for toxicity to aquatic organisms uses the Globally Harmonised System (GHS) of Classification and Labelling of Chemicals, developed by the United Nations (2017). The GHS guidelines define acute aquatic toxicity as *“the intrinsic property of a substance to be injurious to an organism in a short term aquatic exposure to that substance”*, and chronic aquatic toxicity as *“the intrinsic property of a substance to cause adverse effects to aquatic organisms during aquatic exposures which are determined in relation to the life cycle of the organism”*. Substances are classified using data from OECD (Organisation for Economic Co-operation and Development) internationally harmonised test methods where possible, or from equivalent national test methods.

Acute aquatic toxicity is measured using a 96 hour LC_{50} test for fish (OECD test guideline 203), a 48 hour EC_{50} test for Crustacea (OECD test guideline 202), or a 72 or 96 hour EC_{50} test for algal species. These species are considered surrogate for all aquatic organisms. LC_{50} is the concentration of a substance in air or water which causes the death of 50% of a group of test animals, and EC_{50} is the effective concentration of a substance required to cause 50% of the maximum response to exposure after a specified time.

Chronic toxicity measurements are less standardised than acute, and are therefore less widely available. Data generated using OECD test guidelines 201 (freshwater alga and cyanobacteria, growth inhibition test), 210 (fish, early life stage toxicity test) and 211 (Daphnia magna reproduction test) are normally acceptable for measuring chronic aquatic toxicity, along with other validated and internationally accepted methods (United Nations, 2017). The availability of data for chronic toxicity is limited, therefore the GHS categories for acute toxicity have predominantly been adopted for this indicator as shown in Table 4.4, with the exception of Category 4 which is a '*safety net*' classification for where no acute toxicity data is available. The severity of aquatic toxicity of pollutants is scored from 1 to 5, 5 being the most toxic and 1 being unclassified. Pollutant categorisation data can be obtained using the European Chemicals Agency database (ECHA, 2018), any published material safety data sheet (MSDS) for a given substance, and the GESAMP (2018) report on chemicals substances at sea. A summary of the aquatic toxicity scores for ship related pollutants is outlined in Table 4.8. It is noted that ocean acidification due to CO2 absorbance causes toxicity to aquatic organisms, however this is not quantified on the GHS scale and hence is not considered in the scope of this analysis.

Table 4.8 Aquatic toxicity indicator scores per hazard

Interaction	Hazard	Toxicity (aquatic)	Score
Emissions to Air	CO_2	Not classified	1
	CH_4	Not classified	1
	N_2O	Not classified	1
	Refrigerants	Not classified	1

Continued overleaf…

Interaction	Hazard	Toxicity (aquatic)	Score
Emissions to Air (continued)	SO_X	Not classified	1
	NO_X	Not classified	1
	PM	Not classified	1
	VOCs	Not classified	1
Discharges to Water	Oil	Category 2	4
	Antifoul coating	Category 4	2
	Ballast water	Not classified	1
Discharges to Water (continued)	Sewage	Category 3	3
	Grey water	Not classified	1
	Marine litter	Not classified	1
	Chemicals*	Category 2	4
Land	Garbage	Not classified	1
Anthropogenic Noise	Underwater noise	Not classified	1
	Surface noise	Not classified	1
Physical Contact	Collisions with marine animals	Not classified	1

*the aquatic toxicity of chemicals is assumed to be the most toxic classification according to Table 2.1 in Chapter 2.

4.8.4 Toxicity (Human)

Toxicity to humans is also measured using the GHS method of classification. The guidelines define acute toxicity as *"serious adverse health effects (i.e. lethality) occurring after a short-term oral, dermal, or inhalation exposure to a substance or mixture"*. The toxicity thresholds vary depending on the type of exposure to a substance as the concentration or dose required to cause harm depends on whether it is inhaled, ingested or exposed to skin. The most likely interactions of ship related pollutants with humans are through inhalation and oral ingestion. Therefore in this instance, toxicity categories for exposure to inhalation of dust and mist have been adopted for pollutant emissions to air, while the oral exposure categories have been used for all other pollutants where applicable (see Table 4.4).

Acute toxicity to humans is expressed as LD_{50} (amount of chemical given at once which causes 50% mortality rate in group of test animals) values for oral exposure, and as LC_{50} values for inhalation. Where this information is not available, acute toxicity estimates (ATE) - which are a derivation of LD_{50} and LC_{50} using conversion values - are used (United Nations, 2017). As is the case with all of the indicators adopted, the severity of toxicity to humans is assessed on a numerical scale of 1 to

5, 1 being lowest and 5 being highest. A summary of the human toxicity scores for ship related pollutants is outlined in Table 4.9.

Table 4.9 Human toxicity indicator scores per hazard

Interaction	Hazard	Toxicity (humans)	Score
Emissions to Air	CO_2	Category 4	2
	CH_4	Not classified	1
	N_2O	Category 2	4
	Refrigerants	Not classified	1
	SO_X	Category 2	4
	NO_X	Category 1	5
	PM	Not classified	1
	VOCs	Not classified	1
Discharges to Water	Oil	Category 4	2
	Antifoul coating	Category 4	2
	Ballast water	Not classified	1
	Sewage	Not classified	1
	Grey water	Not classified	1
	Marine litter	Not classified	1
	Chemicals*	Category 2	4
Land	Garbage	Not classified	1
Anthropogenic Noise	Underwater noise	Not classified	1
	Surface noise	Not classified	1
Physical Contact	Collisions with marine animals	Not classified	1

*the human toxicity of chemicals is assumed to be the most toxic classification according to Table 2.1 in Chapter 2.

4.8.5 Global Warming Potential (GWP)

Global Warming Potential (GWP) is used to assess the relative contribution to climate change of each pollutant. CO_2 acts as a reference and has a GWP of 1 over a reference time period of 100 years. Substances with a GWP of greater than 1 which are emitted to the atmosphere result in greater warming of the earth than is caused by CO_2. At present there is no generally accepted classification of GWP, however a UNEP Technology and Economic Assessment Panel task force report (UNEP, 2010) outlines proposed groupings for greenhouse gases according to GWP (Table 4.10).

Table 4.10 GWP classification adopted from UNEP (2010), adapted for VEP Index in Table 4.4

GWP value	Classification
< ~30	Ultra-low
< ~100	Very low
< ~300	Low
< ~1,000	Moderate
< ~3,000	High
< ~10,000	Very high
> ~10,000	Ultra-high

The classification groupings outlined in Table 4.10 have been adapted for this research into 5 groups (very high; high; moderate; low; negligible) as shown in Table 4.4. Pollutants are scored on a numerical scale of 1 to 5, 1 represents pollutants with a '*negligible*' GWP (less than 1) and a score of 5 is given to pollutants with a '*very high'* GWP value (more than 3,000). GWP scores are applicable to gaseous pollutants (per molecule), while all other pollutants are considered to have negligible GWP and receive a score of 1. A summary of the GWP scores for ship related pollutants is outlined in Table 4.11.

Table 4.11 GWP indicator scores per hazard

Interaction	Hazard	GWP (100 years)	GWP indicator	Score
Emissions to Air	CO_2	1	Low	2
	CH_4	21	Low	2
	N_2O	298	Moderate	3
	Refrigerants (*varies depending on substance – assumed based on value of R600a refrigerant gas)	3	Low	2
	SO_X	n/a	Negligible	1
	NO_X	n/a	Negligible	1
	PM	n/a	Negligible	1
	VOCs	n/a	Negligible	1
Discharges to Water	Oil	n/a	Negligible	1
	Antifoul coating	n/a	Negligible	1
	Ballast water	n/a	Negligible	1
	Sewage	n/a	Negligible	1
Discharges to Water (continued)	Grey water	n/a	Negligible	1
	Marine litter	n/a	Negligible	1
	Chemicals	n/a	Negligible	1
Land	Garbage	n/a	Negligible	1
Anthropogenic Noise	Underwater noise	n/a	Negligible	1
	Surface noise	n/a	Negligible	1
Physical	Collisions with marine animals	n/a	Negligible	1

For refrigerants, the GWP value assumed in this research is for R600a refrigerant gas as this substance is used in the case studies in Chapter 5. However, in cases where other refrigerants are utilised, the GWP value can be adjusted (for example the Max Pruss - Chapter 5 - uses air conditioning units containing refrigerants with a GWP of 2088, which impacts on the overall hazard significance score for refrigerants). GWP values for CO_2, Methane and N_2O are taken from the IPPC (2013) report, and the GWP of R600a is taken from the MSDS for Isobutane (Linde, 2018).

4.9 Step 6: Hazard Severity Weighting

The hazards are assessed using the severity indicators outlined in Table 4.4. Scores for each indicator are added together to calculate a total score for each hazard (see Table 4.12). The hazard severity scores for each pollutant are divided by the total for all pollutants to give a hazard weighting score (%) for each pollutant, as shown in Table 4.13. The % weighting scores are used in step 9 of the methodology to calculate an overall severity score for each hazard.

CO_2, CH_4 and N_2O have been combined into one category (GHGs) as they are all greenhouse gases and have largely the same effects on the environment. The highest indicator scores from each of the pollutants are used to calculate the total severity weighting for GHGs. An additional hazard is presented in Table 4.13. Oil is included in the assessment through two separate sources, as on board stored oil, and as oily water (bilge). The severity scores for each are assumed to be equal, as shown in Table 4.13. Both hazards present an environmental risk through discharge to water.

Table 4.12 Total severity score per hazard

Hazard	Spatial	Residence time	Toxicity (aquatic)	Toxicity (human)	GWP	Total
GHGs	5	5	1	4	3	**18**
Refrigerants	5	3	1	1	2	**12**
SO_X	4	2	1	4	1	**12**
NO_X	4	2	1	5	1	**13**
PM	4	2	1	1	1	**9**
VOCs	3	2	1	1	1	**8**
Oil	4	2	4	2	1	**13**
Antifoul coating	3	2	2	2	1	**10**
Ballast water	3	5	1	1	1	**11**
Sewage	3	2	3	1	1	**10**
Grey water	3	2	1	1	1	**8**
Marine litter	5	4	1	1	1	**12**
Chemicals	3	2	4	4	1	**14**
Garbage	3	3	1	1	1	**9**
Underwater noise	4	1	1	1	1	**8**
Surface noise	3	1	1	1	1	**7**
Collisions with marine animals	2	1	1	1	1	**6**

Table 4.13 Weighting factor (%) per hazard

Interaction	Hazard	Hazard Severity	Hazard
Emissions to Air	GHGs	18	9.33%
	Refrigerants	12	6.22%
	SO_X	12	6.22%
	NO_X	13	6.74%
	PM	9	4.66%
	VOCs	8	4.15%
Discharges to Water	Oily water (bilge)	13	6.74%
	Antifoul coating	10	5.18%
	Ballast water	11	5.70%
	Sewage	10	5.18%
	Grey water	8	4.15%
	Marine litter	12	6.22%
	Chemicals	14	7.25%
	On board stored oil	13	6.74%
Land	Garbage	8	4.15%
Anthropogenic Noise	Underwater noise	7	3.63%
	Surface noise	9	4.66%
Physical	Collisions with marine animals	6	3.11%
Total		**193**	**100%**

4.10 Step 7: Vessel Assessment

To conduct the vessel assessment, a vessel check list method has been developed which is used to characterise the environmental features of individual vessels and determine the pollutant emissions and discharges entering the environment. The data derived from the vessel check list is used to assess the environmental performance of specific vessels over individual voyages. This allows for comparisons of environmental performance between different vessels, but also between different voyages of the same vessel. Data from multiple vessel checklists can be combined to assess the vessels environmental performance over a longer time period.

4.10.1 Vessel check methods

The vessel checklist methodology consists of categories related to the environmental hazards defined in Step 2. Data is collected for each hazard as outlined in Table 4.14. There are different methods for collecting the data with varying levels of accuracy. The most accurate method of data collection is through direct measurement, providing actual discharge volumes of pollutants. Where direct measurement is not possible due to e.g. a lack of technology or resource, estimated discharges based on operational data can be calculated. For instances where operational data is not available, estimates based on design criteria can be made, however this is the least accurate method of measurement. Therefore, the hierarchy of data quality is as follows:

(1) Direct measurement of emission/discharge.

(2) Estimation of emission/discharge based on operational data.

(3) Estimation based on design specification.

(4) No data.

Table 4.14 Check methods per hazard

Hazard	Check method		
	Direct measurement	**Estimate based on operation**	**Estimate based on design**
GHGs (CO_2, CH_4 and N_2O)	Direct measurement of GHG emissions (monitoring equipment).	Fuel use * EF for CO_2, CH_4, and N_2O.	Estimated fuel use based on distance travelled.
Refrigerants	Refrigerant leak test in accordance with EU Regulation no. 517/2017 (automatic or manual).	n/a	Refrigerant capacity on board in tonnes CO_2 eq.
SO_X	Direct measurement of SO_X emissions (monitoring equipment) - depends on accuracy and calibration of equipment.	Fuel use * EF for SO_X.	Sulphur content of fuel estimated fuel use.
NO_X	Direct measurement of NO_X emissions (monitoring equipment).	Fuel use * EF for NO_X.	Rated power of engine (EIAPP certificate).
PM	Direct measurement of PM emissions (monitoring equipment).	Fuel use * EF for PM.	n/a
VOCs	Direct measurement of VOC emissions (monitoring equipment).	Usage * VOC content = emissions.	n/a
Oily water (bilge)	Automated monitoring of oil levels on storage tanks, bilge water, oily water separators.	Bilge water storage volume and estimated release rate.	Bilge water storage capacity and estimated release rate.
Sewage	Automated/manual measurement of sewage flows.	Volume collected in sewage tanks.	Litres of sewage per flush * average number of flushes.
Grey water	Automated/manual measurement of grey water flows.	Volume collected in grey water tanks.	Litres of grey water per activity * frequency of activity.
Antifoul coating	Continuous monitoring of water quality around hull to detect chemical traces contained in antifoul coating.	Measured volume of coating applied * release rate of chemicals.	Chemical content of coating (data sheet).
Ballast water	Automated monitoring of ballast water collection and release.	Manual monitoring of ballast water tanks.	Ballast water tank size * estimated rate of release.
Marine litter	Record of volume and type of waste going overboard.	Estimate based on average garbage generation.	n/a
Chemicals	Record of chemicals stored on board, record of spillage incidents.	Estimated usage/spillage of chemicals.	Manual audit of stored chemicals.
On board stored oil	Record of oil stored on board, record of spillage incidents.	Oil record book (MARPOL Annex 1: Regulation 17).	Manual audit of stored oil.
Garbage	Measure weight of garbage produced.	Estimate garbage production based on consumption habits.	n/a

Continued overleaf...

Hazard	Check method		
	Direct measurement	**Estimate based on operation**	**Estimate based on design**
Underwater Noise	Direct measurement of noise at specified distance using noise monitoring equipment.	n/a	Engine noise level taken from engine spec.
Surface noise	Direct measurement of noise at specified distance using noise monitoring equipment.	n/a	Engine noise level taken from engine spec.
Collisions with marine animals	Record of strikes with marine animals.	n/a	n/a

4.10.2 Vessel check list

The extent of the vessel assessment is dependent on the availability of data and the operational characteristics of the ship being assessed. For example, vessels of a certain type or profile may not require ballast water release and therefore data regarding invasive species transfer would not be collected. In cases where vessels implement a Ballast Water Management (BWM) system, controlled releases that meet regulatory standards regarding ballast water treatment are not considered an environmental hazard. In certain cases actual recorded data may not be available and estimates will be used instead, as per the methods outlined in Table 4.14. Vessel check lists can be customised for specific vessels based on the characteristics of the vessel.

A standard vessel check list template is shown in Table 4.15. Some general information on the vessel is collected so that certain calculations can be carried out e.g. the number of persons on board is used to calculate garbage production per person. An inventory of chemicals, oils and other hazardous materials on board should also be collected so that the total volume of hazardous materials can be calculated.

Where continuous monitoring of actual emissions to air is not available, emissions are estimated using emissions factors, and hence operational data (fuel type, use, distance, speed etc.) must be collected.

It is advised that a vessel specific voyage check list is custom designed for individual vessels, so that the correct data is collected. It is possible that much of the data required for this methodology may be collected already as part of routine data collection e.g. for a Ships Energy Efficiency Management Plan (SEEMP). If so, it is possible that the check sheet could be designed to incorporate the data already being collected, to avoid increasing administrative work load.

Table 15 Vessel checklist (blank template)

Pollutant category		Checklist
General	General vessel information	Vessel length (m)
		Vessel breadth (m)
		Vessel draft (m)
		Vessel weight (t)
		Engine size (kW)
		Number of engines
		Number of persons on board
		Inventory of materials
Emissions to Air	GHGs (CO_2, CH_4, N_2O), SO_X, NO_X, PM, VOCs	Fuel type
		Distance travelled (nm)
		Average speed (knots)
		Top speed (knots)
		Fuel use (l)
	Refrigerants	GWP of refrigerants
		Refrigerant type
		Refrigerant quantity (Kg)
	SO_X	Sulphur content of fuel (%)
Discharges to Water	Oily water (bilge)	Volume of bilge water (l)
	Sewage	Volume of sewage produced per voyage (l)
	Grey water	Volume of grey water produced per voyage (l)
	Antifoul coating	Type of antifoul coating applied to vessel
	Ballast water	Volume of ballast water collected (l)
		Volume of ballast water released (l)
	Marine litter	Method of waste disposal
		Waste separation on board (y/n)
	Chemicals	Volume of chemical liquids on board (l)
		Volume of chemicals used (l)
		Record of chemicals spilled (l)
	On board stored oil	Volume of fuel on board (l)
		Volume of oil stored on board (l)
		Oil use per voyage (l)
		Record of oil spilled (l)
Land	Garbage	Volume of waste produced per voyage (Kg)
Anthropogenic noise	Noise	Noise level of engine (dB)
		Noise measurements recorded using noise measuring equipment? (y/n)
		If y, recorded noise levels for surface and underwater noise (dB)
Physical Contact	Collisions with marine animals	Number of vessel strikes with aquatic species

4.11 Step 8: Vessel Environmental Performance (VEP)

The raw data collected in the vessel check list is processed and compiled, and can then be used to calculate a VEP score for each hazard. The VEP represents the actual emissions performance of the ship.

The VEP score for each hazard is calculated (units are shown in Table 4.16), the scores must then be normalised so that each hazard can be assessed using a consistent numerical scale, as the VEP units of each pollutant can vary depending on the characteristics of the emission or discharge and the way the emission or discharge is measured. For example, VEP scores relating to emissions to air are measured in Kg/tonne-mile, which is an appropriate unit for measuring the amount of emissions relative to the distance the vessel has travelled per tonne of displacement. However, garbage production is measured in Kg/person-day, an appropriate measurement of the amount of waste produced per day divided by the number of persons on board. In order to combine and compare data sets, the VEP scores must be normalised on a standardised scale. A detailed example of VEP score calculations is shown in the case studies in Chapter 5.

4.11.1 Normalisation of VEP severity scale

VEP scores are normalised (VEP_n) on a scale of 0 to 5 according to a maximum and minimum level of emission or discharge. The minimum level is set at 0 (zero emissions or discharges of a pollutant), and the maximum is set at a pre-defined maximum permissible emission or discharge level based on regulatory requirements or some other measure determined from the literature. The rationale for this is where regulatory limits for emissions or discharges are applicable, vessels must not exceed the limits. Where absolute limits are not set in the regulation, other maximum permissible limits have been set based on maximum usage estimates taken from the literature.

For example, there are currently no absolute limits set in the regulation for GHG emissions (CO_2, N_2O and CH_4), so a maximum permissible limit is used based on a calculated value for GHGs in grams per tonne-mile, based on the Energy Efficiency Design Index (EEDI). Similarly, there are no regulatory limits set for volumes of garbage production per person or per vessel, therefore the maximum permissible limit has been set based on upper boundary municipal solid waste production data for a high income country, taken from the World Bank Study on waste generation (Hoorweng & Bhada-Tata, 2012).

A list of maximum and minimum permissible limits of pollutant emissions and discharges for each hazard are outlined in Table 4.16. The maximum limits for some of the pollutants will vary from vessel to vessel depending on the characteristics of the vessel. For example, the maximum permissible level of GHGs emitted in grams per tonne-mile will vary depending on the calculated EEDI value of the vessel. The EEDI formula calculates CO_2 emissions per transport work in g per tonne-mile based on the design characteristics of the vessel. The same principle is applied to other pollutants to calculate a reference emission value based on vessel design for each hazard. The reference value is set as the maximum permissible emission limit, to which the operational emissions can be compared. The formula for calculating the reference emission value is as follows:

$$E_{ref} = P * EF * SFC / (V * D) \quad (4.1)$$

Where:

E_{ref} = Maximum permissible emission limit

P = Maximum power of engine(s)

EF = Emission factor of pollutant

SFC = Specific fuel consumption of engine

V = Maximum speed of vessel

D = Vessel displacement

The operational emissions and discharges (VEP) of each vessel are normalised against the maximum and minimum permissible limits outlined in Table 4.16, to calculate VEP_n values. The emissions of CO_2, CH_4 and N_2O are combined and calculated in grams CO_2 equivalents of GHGs, and a maximum permissible limit for GHGs is also calculated.

Table 4.16 Maximum and minimum permissible emission/discharge levels for each pollutant

Hazard	Maximum	Minimum	Unit	Rationale	Calculation of max. limit
CO_2, CH_4, N_2O, SO_X, NO_X, PM, VOCs	Calculated reference value	0	g/tonne-mile	Calculated reference value based on vessel design characteristics.	E_{ref} = P * EF * SFC / (V * D).
Refrigerants	500	0	Tonnes CO_2 eq.	Maximum CO_2 eq. threshold for leak check requirements in refrigeration systems according to EU F gas regulations. Systems containing 500 t CO_2 eq. or more must install mandatory leak check equipment. (Note: this is not mandatory legislation for ships). (Gluckman Consulting, 2016).	Refrigerant mass (tonnes) * GWP = CO_2 eq.
Oily water (bilge)	26	0	m^3/day	Maximum discharge based on upper level estimate for discharge from large cruise ships (BTS, 2002).	No calculation required.
Sewage & grey water	Calculated maximum discharge rate.	0	m^3/hr	Maximum discharge rate calculated based on IMO Annex IV requirement (IMO MARPOL Annex IV, 2003).	DR_{max} = 0.00926 * V * B * D (velocity * breadth * draft).
Antifoul coating	2500	0	mg/kg	2500 mg/kg of Tin is the regulatory limit set by the IMO Convention on the Control of Harmful Anti-Fouling Systems on Ships (IMO AFS Convention, 2001).	No calculation required.
Ballast water	20,000	0	m^3/hr	Upper limit pumping rate for large tankers (National Research Council, 1996).	No calculation required.
Marine litter	14	0	Kg/person-day	Upper boundary for municipal solid waste production (high income) (Hoorweng & Bhada-Tata, 2012).	No calculation required.
Chemicals	50,000	0	Tonnes	Maximum capacity of a reference chemical tanker (dwt) (https://opensea.pro/blog/ships-types-and-sizes).	Total quantity of chemicals on board.

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Hazard	Maximum	Minimum	Unit	Rationale	Calculation of max. limit
On board stored oil	550,000	0	Tonnes	Maximum capacity of a reference oil tanker (dwt) (https://opensea.pro/blog/ships-types-and-sizes).	Total quantity of stored oil on board.
Garbage	14	0	Kg/person-day	Upper boundary for municipal solid waste production (high income) (Hoorweng & Bhada-Tata, 2012).	No calculation required.
Underwater noise	230	0	dB	Recommended harmful (i.e. probable onset of injury) sound pressure exposure threshold for cetaceans based on proposed injury criteria (hearing and behavioural response) (Southall *et al*., 2008).	No calculation required.
Surface noise	110	0	dB	Maximum acceptable noise level (work spaces including hearing protection) according to IMO code on noise levels on board ships (IMO, 2012).	No calculation required.
Collisions with marine animals	1	0	Collisions per voyage	Collisions are rare, therefore any number of injuries or fatalities per voyage is considered significant.	No calculation required.

4.12 Step 9: Overall Severity

Overall severity is a calculation of the severity of each hazard taking into account the calculated weighting factor and the extent of emissions and discharges of pollutants. It is calculated using the following equation:

$$\textit{Overall severity} = \textit{weighted hazard severity (step 6)} * \textit{VEP}_n \textit{ (step 8)} \quad (4.2)$$

The severity assessment must also take into account the type of release to the environment, as discussed in section 4.5 (Figure 4.2). The assessor must consider whether the release is intentional during normal operation, and/or if the release is accidental or in violation of regulatory standards. For example, a vessel may discharge significant quantities of treated ballast water into the environment with limited impact, however if untreated the environmental risk would increase significantly. Controlled, permissible releases that have negligible impact on the environment shall be scored zero in the severity assessment.

4.13 Step 10: Hazard Likelihood

In addition to severity, the likelihood of occurrence of the hazard must be taken into account in order to determine significance. Likelihood, or probability, is an estimate of how often an emission or discharge of the hazard is likely to occur. Estimates can often be determined through review of historic events, or through an epistemic understanding of processes which result in pollutant releases. Likelihood of occurrence in impact assessment is often a qualitative measure where data is not available to accurately represent the frequency of occurrence of an unplanned event. However there are shipping activities which occur during routine operation, therefore the likelihood of occurrence can be broadly assessed on this basis.

In the absence of extensive historical failure data for the shipping activities that cause pollutant discharges to the environment, likelihood is assessed in absolute terms. If the action or event that causes an impact occurs during routine shipping operation and the occurrence of the event causes an emission or discharge (hazard) to the environment, the hazard is given a score of 2 for likelihood. Alternatively, if the event does not occur during routine operation or the event does not cause a routine emission or discharge into the environment, a score of 1 is given (see Figure 4.2).

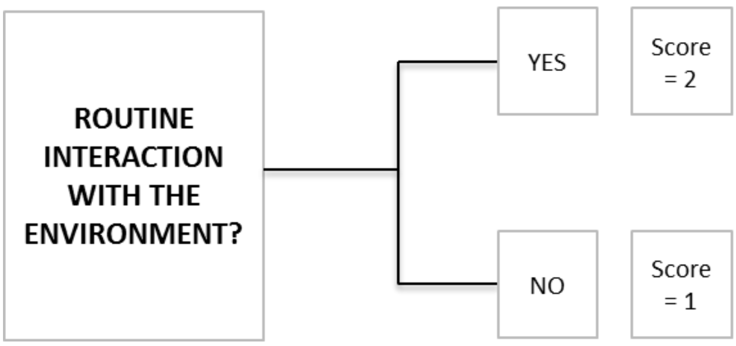

Figure 4.2 Likelihood assessment

4.14 Step 11: Calculation of Hazard Significance

The data from the previous steps is used to calculate a numerical score representing hazard significance. A score is calculated for each hazard in Table 4.1.

Hazard significance (H_{SIG}) is calculated using the following formula:

$$H_{SIG} = O_{SEV} * Li \qquad (4.3)$$

Where:

O_{SEV} = overall severity

Li = hazard likelihood

Overall severity (O_{SEV}) is calculated using the following formula:

$O_{SEV} = WH_{SEV} * VEP$

Where:

WH_{SEV} = Weighted hazard severity

VEP = Vessel Environmental Performance indicator

Weighted hazard severity is calculated using the following formula:

$$WH_{SEV} = \Sigma I_{SEV} / TH_{SEV} \qquad (4.4)$$

Where:

I_{SEV} = Severity Indicators:

S: spatial extent indicator

R: Residence time indicator

$T_{(aq)}$: Aquatic toxicity indicator

$T_{(h)}$: Human toxicity indicator

GWP: Global Warming Potential indicator

TH_{SEV} = Total hazard severity, calculated using:

$$TH_{SEV} = \Sigma I_{SEV} * n \qquad (4.5)$$

Where:

$$\Sigma I_{SEV} = S + R + T_{(aq)} + T_{(h)} + GWP \quad (4.6)$$

n = number of hazards

4.15 Step 12: VEP Index score

Hazard significance scores for each pollutant are added together to give a total environmental score for the vessel. Total ship scores range from 0 to 10. A score of zero represents an emission free ship, with no pollutant discharges to the environment. Scores closer to 10 represent increasingly polluting vessels.

4.16 Uncertainties and limitations

In risk assessment there are a number of inherent uncertainties which can affect the reliability of the study. Uncertainty is associated with numerous components of risk assessment (Gormley *et al.,* 2011), including several steps of this methodology. Uncertainties are borne from a lack of knowledge or data, or from the intrinsic variability of natural systems. According to Gormley *et al.,* (2011), uncertainty can be classified into different groups as:

(1) Data – level of confidence in accuracy, availability and reliability of data.

(2) Language – clarity of language used, terms may be not specific enough or may be ambiguous.

(3) System – level of knowledge regarding processes, causes and effects within systems.

(4) Variability – inherent unpredictability in any human or natural system.

(5) Analytical – variability within analytical processes employed, such as interpretation of data.

(6) Model – confidence in modelling of real world processes.

(7) Decision – doubts regarding the preferred course of action, which may vary depending on the scope and objective of the assessment.

Table 4.17 categorises the uncertainties associated with this methodology, and provides an explanation of measures implemented to mitigate uncertainties where possible.

Table 4.17 Uncertainties associated with assessment methodology

Uncertainty	Step(s) in method	Classification	Mitigating measure
Hazard likelihood assessment	10	Variability	Simplified likelihood assessment. Hazard likelihood determined as either 'yes' or 'no' depending on if emissions or discharges take place during routine operation.
Hazard severity assessment	5	Data System	Use of indicators with clearly defined severity thresholds. Referenced data sources.
Use of maximum and minimum permissible emission and discharge limits	8	Data Decision	Data is backed up using referenced sources. Decision to set limits is clearly defined in the methodology.
Confidence in emission and discharge data	7	Data	Data collection methods clearly defined. Hierarchy of data quality also clearly outlined.
Clarity of assessment outcomes	All	Language	Clearly defined scope. Method broken down into individual steps, with each step clearly defined.
Quantification of environmental hazards	2,3,4,5,6	System	Environmental impacts of hazards identified through S-P-R analysis and review of literature (Chapter 2). Hazards quantified using environmental indicators to reduce ambiguity.

4.17 Summary

This chapter outlines a comprehensive alternative methodology for assessing the environmental performance of ships based on the potential impact and extent of pollutant emissions and discharges during operation. The methodology is comprised of two parts, A and B, each consisting of several steps. Part A of the method defines the scope of the assessment by identifying the interactions of ships with the surrounding environment, the potential pollutant (hazard) emissions and discharges associated with such interactions and the subsequent impacts. The method adopts an S-P-R approach to identify potential impacts, which alongside a selection of environmental indicators are used to quantify the environmental severity of hazards (pollutants) from ships. Hazard severity is determined based on the spatial extent of the pollutant in the environment, its environmental residence time, the toxicity of the pollutant to aquatic organisms and humans, and GWP. The indicators are assigned a numerical scale from 1 to 5 and each hazard is assessed based on the severity definitions outlined in Table 4.4. A score out of 25 is assigned to each hazard, which is then used to calculate % weighting factors for each. The outcome of part A is the development of a set of weighted environmental pollutant indicators for vessels.

Part B of the method outlines the procedure for the collection of vessel and voyage data, and describes how the data is used to calculate vessel environmental performance scores for each hazard. Voyage data is used to calculate actual and potential emissions and discharges of pollutants. Actual and potential emissions are defined through implementation of a likelihood step, which is used to determine whether the hazards are released during routine operation of the vessel. The voyage data is combined with the pollutant weighting factors to calculate hazard significance scores. The hazard significance scores are added together to give an overall environmental score for the vessel. Adopting a risk assessment based methodology incurs some uncertainties, which are also highlighted in this chapter.

5.0 Testing the Methodology – the VEP Index

5.1 Introduction

The method developed in this research has been designed to assess vessels based on operational performance. The method is tested on two case study vessels, a sea going catamaran used for academic research and offshore supply in coastal regions, and an inland research vessel used on European inland waterways. The vessels have similar design specifications and operational characteristics, are of comparable size, and therefore pose similar environmental threats,. This chapter emphasises the sensitivity and flexibility of the environmental assessment method developed in this research by pointing out the differences between the two vessels in terms of environmental performance. The case study results are also compared with scores from existing indices currently used in the shipping sector, highlighting the benefits of assessing environmental performance based on operational data rather than assumed test conditions.

5.2 Coastal research vessel: The Princess Royal

The environmental assessment method developed in this research has been tested using actual pollution data from some case study vessels. An assessment of the Newcastle University owned Princess Royal research vessel was undertaken.

Figure 5.1 Newcastle University research vessel, the Princess Royal

5.2.1 Scope of study

Data for the Princess Royal was collected over 2 weeks from 18th February to 5th March 2018. During this period, 4 short voyages took place covering a total distance of 136 nautical miles. Voyages took place at various times throughout the day, the earliest starting at 07:30 and the latest finishing at 16:00. The voyage details are as follows:

Voyage 1

Took place on 18/02/2018, starting at 07:30 and finishing at 12:00. The vessel started at the harbour in Blyth, UK, travelled north to Newbiggin-by-the-Sea then back to Blyth harbour. Observed weather and sea conditions were described as calm, with a wind speed of around 6 knots and WMO sea state code of 1.

Voyage 2

The vessel departed Blyth harbour at 09:00 on 22/02/2018, travelling south to the village of Seaton Sluice before travelling back north to Cresswell in Northumberland, and back to Blyth harbour. Weather and sea conditions were observed as light south westerly winds at approximately 10 knots, and WMO sea state of 3.

Voyage 3

The vessel departed Blyth harbour on 26/02/2018 at 09:00, travelled to the mouth of the River Tyne to carry out some research activities and returned to Blyth harbour at 16:00. Some strong south easterly winds were observed at roughly 12 knots, along with some sea swell, WMO sea state of 4.

Voyage 4

Took place on 05/03/2018, starting at Blyth harbour at 09:00, travelling to the mouth of the River Tyne to carry out research, and returning to Blyth harbour at 15:00.

Observed weather and sea conditions were described as south east winds at approximately 10 knots and sea swell (WMO sea state of 4).

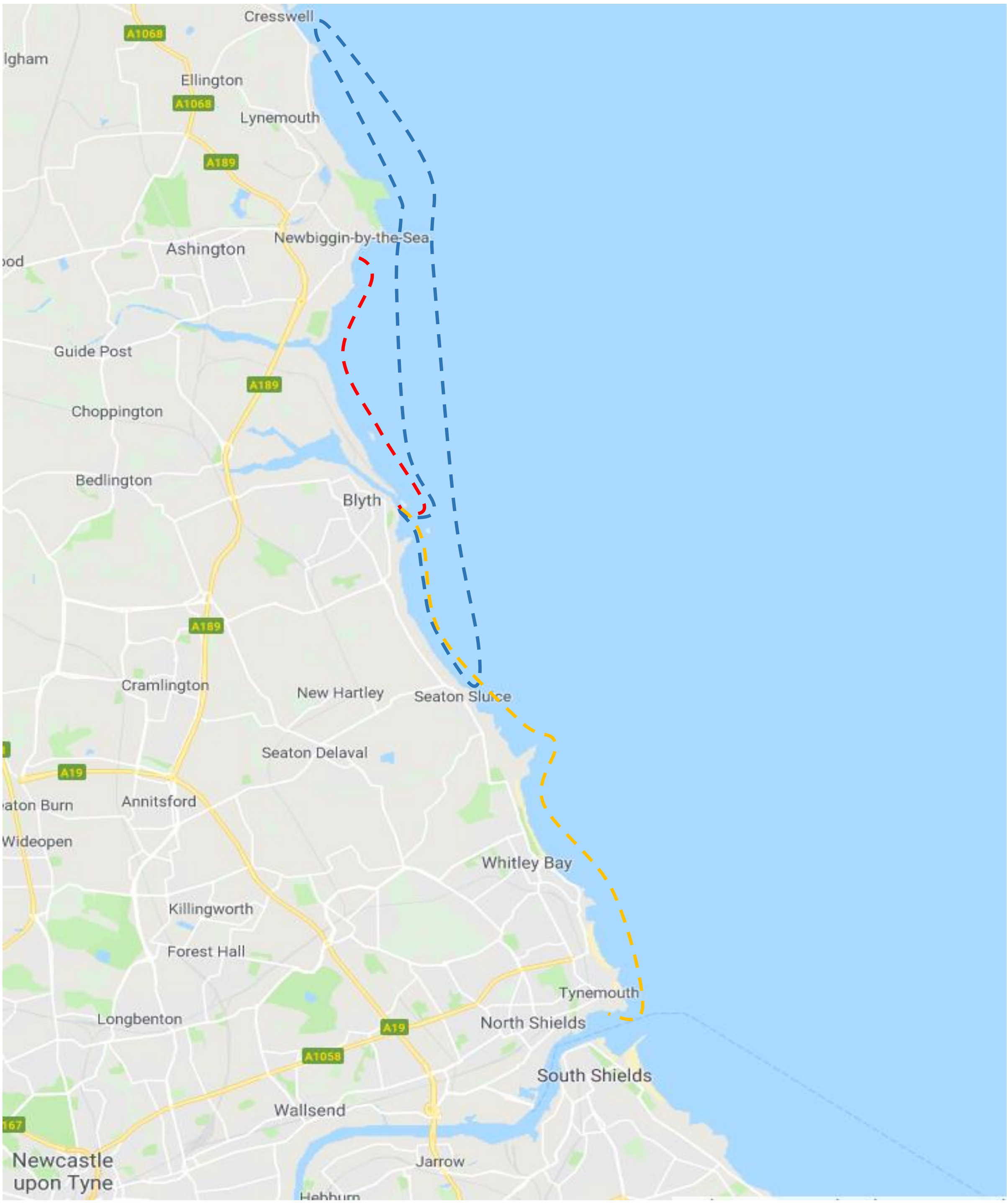

Figure 5.2 Illustration of voyage routes of the Princess Royal

- - - - = Voyage route 1

- - - - = Voyage route 2

- - - - = Voyage routes 3 and 4

The ship is a 19m (length) catamaran designed as a small scale research vessel, most of the work conducted on-board the vessel takes place within 60 miles of Blyth harbour in the UK, although some longer voyages take place on occasions. The vessels breadth is 7.3 m, with a draft of 1.64 m, and has a total displacement of 41 tonnes (light displacement plus payload). The vessel is fitted with two 447 kW MAN D2676 marine diesel engines, and operates using MGO (Marine Gas Oil) fuel.

Data for each voyage was collected by the vessel skipper. The vessel was fitted with continuous monitoring apparatus to measure real time emissions of air pollutants, however it was not in operation at the time of the study therefore estimates have been calculated using IMO emissions factors for a Tier I medium speed diesel engine. The vessel was launched in 2011, however the exact build date is not clear therefore for the purpose of this research it is assumed that it was built pre-2011 and must meet Tier I requirements in MARPOL Annex VI. Fuel use data along with vessel speed and distance travelled was recorded manually by the skipper.

An inventory of materials was collected prior to the first voyage on 18th February. No further inventories were collated so the data collected before the 18th was assumed to be correct throughout the entire data collection period. Refrigerant gases were present on the vessel in small volumes throughout each voyage, however no leakage detection equipment was installed and a leakage rate could not be determined. Refrigerants have therefore been assessed based on the capacity of refrigerants on board in CO_2 eq.

Sewage and grey water are collected together in a single tank on board the vessel, there were no measurement devices fitted to the tank so sewage production per voyage was estimated by the crew. The vessel hull is painted with an antifoul coating (Intersleek 1100), no tests were carried out on the coating to establish % tin content therefore this information was established using the MSDS for the coating and online sources (ECO, 2016). The vessel is not fitted with ballast tanks and ballast water is not collected or released on board. Bilge water is collected on board, however no method of measurement was available at the time of the study. Engine noise data was not available, and no information regarding engine noise level was available in the engine specification.

5.2.2 Data Collection and Processing

In order to carry out the environmental assessment of the Princess Royal, vessel *and* voyage data is required. Environmental data was collected by the crew using the vessel checklist procedure outlined in Table 4.15. The data for each voyage is summarised in Table 5.1. General vessel information was collected in order to calculate certain emissions and discharges of pollutants (as per the required units for each hazard outlined in Table 4.16). For example, emissions to air (with the exception of refrigerants) are measured in g/tonne-mile, therefore the weight (tonnes) of the vessel is required, along with distance travelled (nautical miles). Continuous fuel monitoring equipment was installed on the vessel, however it was not operating correctly at the time of the study, therefore fuel use was recorded manually by the crew.

Table 5.1 Voyage data for Princess Royal

Pollutant category		**Checklist**	**18/02/2018**	**22/02/2018**	**26/02/2018**	**05/03/2018**
General	General information	Vessel length (m)	19	19	19	19
		Vessel breadth (m)	7.3	7.3	7.3	7.3
		Vessel draft (m)	1.64	1.64	1.64	1.64
		Vessel weight (t)	41	41	41	41
		Engine size (kW)	447	447	447	447
		Engine rated speed (rpm)	2100	2100	2100	2100
		Number of engines	2	2	2	2
		Number of persons on board	4	5	14	13
		Inventory of materials	Appendix C	Appendix C	Appendix C	Appendix C
Emissions to Air	CO_2, CH_4, N_2O, SO_X, NO_X, PM, VOCs	Fuel type	Diesel (MGO)	Diesel (MGO)	Diesel (MGO)	Diesel (MGO)
		Distance travelled (nm)	6	50	40	40
		Average speed (knots)	5	15	10	10
		Top speed (knots)	18	19	20	20
		Fuel use (l)	120	660	300	310
	Refrigerants	GWP of refrigerants	3	3	3	3
		Refrigerant type	R600a	R600a	R600a	R600a
		Refrigerant quantity (Kg)	0.037	0.037	0.037	0.037
	SO_X	Sulphur content of fuel (%)	0.1	0.1	0.1	0.1
Discharges to Water	Oily water	Volume of bilge water (l)	0	0	0	0
	Sewage	Volume of sewage produced per voyage (l)	10	30	50	50

Continued overleaf…

Pollutant category		Checklist	18/02/2018	22/02/2018	26/02/2018	05/03/2018
Discharges to Water	Grey water	Volume of grey water produced per voyage (l)	0	0	0	0
	Antifoul coating	Type of antifoul coating applied to vessel	Intersleek 1100	Intersleek 1100	Intersleek 1100	Intersleek 1100
	Ballast water	Volume of ballast water collected (l)	0	0	0	0
		Volume of ballast water released (l)	0	0	0	0
	Marine litter	Method of waste disposal	On shore	On shore	On shore	On shore
		Waste separation on board (y/n)	No	No	No	No
	Chemicals	Volume of chemical liquids on board (l)	14.28	14.28	14.28	14.28
		Volume of chemicals used (l)	0	0	0	0
		Record of chemicals spilled (l)	0	0	0	0
	On board stored oil	Volume of fuel on board (l)	2700	2700	2700	2700
		Volume of oil stored on board (l)	242.3	242.3	242.3	242.3
		Oil use per voyage (l)	0	0	0	0
		Record of oil spilled (l)	0	0	0	0
Land	Garbage	Volume of waste produced per voyage (Kg)	0	15	15	15
Anthropogenic noise	Noise	Noise level of engine (dB)	Not available	Not available	Not available	Not available
		Noise measurements recorded using noise measuring equipment? (y/n)	No	No	No	No
		If y, recorded noise levels for surface and underwater noise (dB)	n/a	n/a	n/a	n/a
Physical	Contact with marine animals	Number of vessel strikes with aquatic species	0	0	0	0

The voyage data in Table 5.1 was then used to calculate the emissions and discharges (VEP) of each pollutant using the methods outlined in Table 4.16. VEP scores have been calculated for each voyage, along with a Total VEP score, which is the calculated weighted average for the complete data set (all four voyages). The VEP scores are outlined in Table 5.2.

Table 5.2 VEP scores for each pollutant

Hazard	**Calculated emissions/discharges of pollutants**					
	Units	**18/02/2018**	**22/02/2018**	**26/02/2018**	**05/03/2018**	**Total**
GHGs	g CO_2 eq./tonne-mile	1348.37	889.93	505.64	522.49	689.06
Refrigerants	Tonnes CO_2 eq.	0.00011	0.00011	0.00011	0.00011	0.00011
SO_X	g/tonne-mile	4.15	2.74	1.55	1.61	2.12
NO_X	g/tonne-mile	23.57	15.55	8.84	9.13	12.04
PM	g/tonne-mile	0.40	0.27	0.15	0.16	0.21
VOCs	g/tonne-mile	1.28	0.84	0.48	0.49	0.65
Oily water (Bilge)	m^3/day	0.00	0.00	0.00	0.00	0.00
Antifoul coating	mg/Kg tin	1000	1000	1000	1000	1000
Ballast water	m^3/hr	0	0	0	0	0
Sewage	m^3/hr	0.0022	0.0043	0.0071	0.0083	0.0057
Grey water	m3/hr	0	0	0	0	0
Marine litter	Kg/person-day	0	0	0	0	0
Chemicals	Tonnes	0.26	0.26	0.26	0.26	0.26
On board stored oil	Tonnes	0.21	0.21	0.21	0.21	0.21
Garbage	Kg/person-day	0.00	3.00	1.07	1.15	1.25
Underwater noise	dB	n/a	n/a	n/a	n/a	n/a
Surface noise	dB	n/a	n/a	n/a	n/a	n/a
Collisions with marine animals	No. of known collisions	0	0	0	0	0

Normalisation of the VEP is carried out by assessing the actual emissions and discharges of pollutants against the pre-determined maximum and minimum permissible levels (shown in Table 4.16). The normalised scores for each hazard per voyage of the Princess Royal are outlined in Table 5.3. Full calculations of VEP scores and VEP_n scores are shown in Appendix C.

Table 5.3 Normalised VEP scores per voyage for each hazard

Hazard	Normalised VEP scores				
	18/02/2018	22/02/2018	26/02/2018	05/03/2018	Total
GHGs	5.00	4.79	2.72	2.81	3.71
Refrigerants	0.0000011	0.0000011	0.0000011	0.0000011	0.0000011
SO_X	1.82	1.20	0.68	0.71	0.93
NO_X	5.00	3.77	2.14	2.21	2.92
PM	1.29	0.85	0.48	0.50	0.66
VOCs	5.00	5.00	3.62	3.74	4.93
Oily water (Bilge)	0.00	0.00	0	0.00	0.00
Antifoul coating	2.00	2.00	2.00	2.00	2.00
Ballast water	0	0	0	0	0
Sewage	0.018	0.012	0.032	0.036	0.027
Grey water	0	0	0	0	0
Marine litter	0	0	0	0	0
Chemicals	0.000026	0.000026	0.000026	0.000026	0.000026
On board stored oil	0.0000021	0.0000021	0.0000021	0.0000021	0.0000021
Garbage	0.00	1.07	0.38	0.41	0.45
Underwater noise	5.00	5.00	5.00	5.00	5.00
Surface noise	5.00	5.00	5.00	5.00	5.00
Collisions with marine animals	0	0	0	0	0

Likelihood of occurrence of each hazard was also assessed in accordance with step 10 of the methodology (Section 4.13). The results for the Princess Royal are shown in Table 5.4.

Table 5.4 Likelihood of occurrence

Hazard	Routine interaction with environment? (y/n)	Score
GHGs	Yes	2
Refrigerants	No	1
SO_X	Yes	2
NO_X	Yes	2
PM	Yes	2
VOCs	Yes	2
Oily water (bilge)	Yes	2
Antifoul coating	Yes	2
Ballast water	No	1
Sewage	No	1
Grey water	No	1
Marine litter	No	1

Continued overleaf…

Hazard	Routine interaction with environment? (y/n)	Score
Chemicals	No	1
On board stored oil	No	1
Garbage	Yes	2
Underwater noise	Yes	2
Surface noise	Yes	2
Collisions with marine animals	No	1

5.2.3 Environmental Assessment

For part A of the assessment of the Princess Royal, the procedures described in steps 1 to 6 in chapter 4 were utilised. The severity weightings calculated for each hazard are presented in Table 5.5.

Table 5.5 Hazard severity weighting (Princess Royal)

Hazard	Hazard Severity Score	Hazard Weighting
GHGs	18	9.33%
Refrigerants	12	6.22%
SO_X	12	6.22%
NO_X	13	6.74%
PM	9	4.66%
VOCs	8	4.15%
Oily water (bilge)	13	6.74%
Antifoul coating	10	5.18%
Ballast water	11	5.70%
Sewage	10	5.18%
Grey water	8	4.15%
Marine litter	12	6.22%
Chemicals	14	7.25%
On board stored oil	13	6.74%
Garbage	9	4.15%
Underwater noise	8	3.63%
Surface noise	7	4.66%
Collisions with marine animals	6	3.11%
Total	**193**	**100.00%**

For part B of the assessment (steps 7 to 11), data from the vessel checklist was utilised to conduct the vessel assessment and determine normalised VEP scores for each hazard on a per voyage basis (Table 5.3), and likelihood scores were assigned to each hazard (Table 5.4).

Overall severity scores for each hazard were calculated per voyage by multiplying the VEP_n score by the weighting factor for each hazard, in accordance with step 9 in the methodology. Hazard significance scores were then calculated by multiplying the overall severity score for each hazard by the likelihood of occurrence (step 10). Hazard significance scores for each voyage are shown in Table 5.6.

Table 5.6 Hazard significance scores per voyage for the Princess Royal

Hazard	Hazard Significance per voyage				
	18/02/2018	**22/02/2018**	**26/02/2018**	**05/03/2018**	**Total**
GHGs	0.93	0.89	0.51	0.52	0.69
Refrigerants	0.00000006	0.00000006	0.00000006	0.00000006	0.00000006
SO_X	0.23	0.15	0.08	0.09	0.12
NO_X	0.67	0.51	0.29	0.30	0.39
PM	0.12	0.08	0.04	0.05	0.06
VOCs	0.41	0.41	0.30	0.31	0.41
Oily water (bilge)	0	0	0	0	0
Antifoul coating	0.21	0.21	0.21	0.21	0.21
Ballast water	0	0	0	0	0
Sewage	0.00093	0.00062	0.0016	0.0019	0.0014
Grey water	0	0	0	0	0
Marine litter	0	0	0	0	0
Chemicals	0.0000019	0.0000019	0.0000019	0.0000019	0.0000019
On board stored	0.00000014	0.00000014	0.00000014	0.00000014	0.00000014
Garbage	0.41	0.41	0.41	0.41	0.41
Underwater noise	0.36	0.36	0.36	0.36	0.36
Surface noise	0.00	0.10	0.04	0.04	0.04
Collisions with marine animals	0	0	0	0	0
Total	**3.35**	**3.13**	**2.25**	**2.29**	**2.70**

Hazard significance scores are added together to give a total score for the vessel, per voyage. A percentage score per voyage is calculated by dividing the total score by the maximum possible score. The percentage ship score for each voyage, and the total percentage ship score (calculated weighted average for all four voyages) are shown in Table 5.7.

Table 5.7 Vessel environmental score per voyage for the Princess Royal

Voyage	Score	Score (%)
18/02/2018	3.35	33.5%
22/02/2018	3.13	31.3%
26/02/2018	2.25	22.5%
05/03/2018	2.29	22.9%
Total	**2.70**	**27.0%**

5.3 Inland vessel: The Max Pruss

The method was utilised to conduct an environmental assessment of the Max Pruss, an inland research vessel operating in western Germany along the River Rhine.

Figure 5.3 Inland research vessel, the Max Pruss

5.3.1 Scope of study

Data for the Max Pruss was collected for a single voyage on 25th January 2019. The voyage started at 09:58 and ended at 14:55, a total of around 4.5 hours was spent in transit. Data collection started when the vessel left port in Duisburg-Homburg, and ended when the vessel returned to the same port. The vessel route is illustrated in Figure 5.12. The Max Pruss is a research vessel, owned and operated by the State Agency for Nature, Environment, and Consumer Protection in North Rhine Westphalia (LANUV). The ship measures 33 m (length) by 7.57 m (breadth), with a draft of 1.1 m, and weighs 141 tonnes. The vessel is predominantly utilised for water sampling on the river Rhine, and has also been used for emissions testing as part of the CLINSH project.

An inventory of potentially hazardous materials on board the vessel was collected (see Appendix D). At the time of data collection, the vessel emissions monitoring equipment was not operating continuously, however it was used to collect a small sample of NO_X data in order to verify the calculated NO_X values presented in Table 5.14 (Appendix D.4). Individual air pollutant species for the entire voyage have therefore been estimated using emission factors. The vessel is fitted with two 254 kW medium speed marine diesel engines (model number MAN D 2866 LXE 43), built circa. 1999. Emissions of CO_2, N_2O, NO_X, SO_X, PM, CH_4 and VOCs have been calculated using emission factors for a medium speed diesel engine built pre 2000, taken from a report by the IVL Swedish Environmental Institute (IVL, 2002). The emissions factors used for NO_X, CO_2, PM, and SO_X were published by Lloyds Register (1995) and are relevant to medium speed diesel engines under steady state conditions. The emissions factors for N_2O, VOCs and CH_4 are taken from the IPCC default emissions factors for ocean going ships (IVL, 2002), as no emissions factors for these pollutants are cited by Lloyds Register (1995).

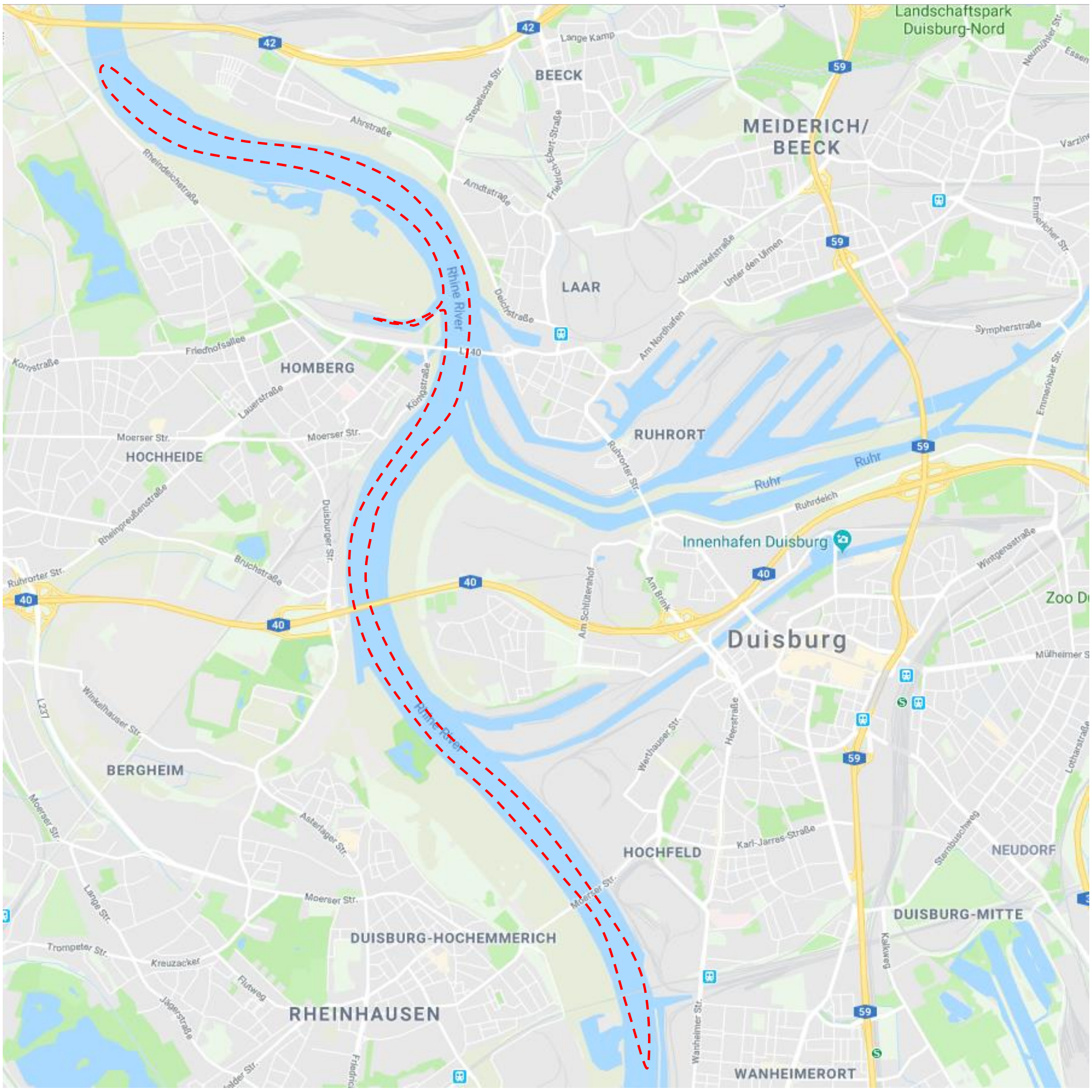

Figure 5.4 Illustration of voyage route of the Max Pruss

The vessel has three on board lavatories, including washing facilities. Sewage and grey water are collected together and stored in an on board sewage tank, with a capacity of 5,000 litres. No measurement devices are fitted to the tank, so estimated sewage data was obtained from the vessel crew. The vessel is fitted with a bilge water alarm system, set at 350 litres. There are no additional measurement devices fitted to the bilge water system, therefore bilge water production data is estimated based on the outcome of the vessel assessment survey using operational knowledge of the crew. The bilge water tank is emptied once every 6 months from full (approx.), therefore bilge water collection per day was estimated. The vessel does not collect ballast water, and no ballast tanks are on board. During the survey it was confirmed by the crew that the vessel hull has not been painted with an antifoul coating. Refrigeration and air conditioning units containing refrigerant gases were present on board the vessel. No automatic leak check equipment was installed and scheduled checks were not permitted to take place on such vessels under the EU F-gas regulations (EC 517/2014), therefore it is not possible to ascertain the leakage rate of refrigerants. Refrigerants are therefore assessed based on the capacity of refrigerants on board, measured in tonnes CO_2 equivalents (see Table 5.9).

The vessel generates engine noise when in operation. Noise propagation testing did not take place during the period of data collection, therefore actual noise propagation data could not be obtained. Underwater and on board noise are therefore assessed based on the noise level of the engines in decibels, taken from the engine specification.

Only one complete data set for a single voyage was collected for this case study due to time and cost limitations, owing to the vessels' geographical location.

5.3.2 Data Collection and Processing

Environmental data for the Max Pruss was collected using the vessel check list method via survey, in person during a visit to the vessel. The data is summarised in Table 5.8. General information for the vessel was collected, some of which has been used to calculate emissions and discharges of pollutants (e.g. the number of persons on board to calculate garbage production in Kg/person-day). Vessel weight was recorded from the vessel specification, it is unclear whether this weight includes payload, and it does not include the weight of persons on board the ship.

The fuel data was collected using continuous fuel monitoring. Temporary continuous monitoring equipment was installed on the vessel by Multronic Emissions Systems (mutronic.be), the raw data received by Multronic was processed to calculate distance travelled, speed and total fuel use (summary of raw data available in Appendix D).

Table 5.8 Voyage data for Max Pruss

Pollutant category		Checklist	Data
General	General information	Vessel length (m)	33
		Vessel breadth (m)	7.57
		Vessel draft (m)	1.1
		Vessel weight (t)	141
		Engine size (kW)	254
		Engine rated speed (rpm)	1800
		Number of engines	2
		Number of persons on board	16
		Inventory of materials	See Appendix D
Emissions to Air	CO_2, CH_4, N_2O, SO_X, NO_X, PM, VOCs	Fuel type	Diesel (MGO)
		Distance travelled (nm)	33.3
		Average speed (knots)	7.45
		Top speed (knots)	13.91
		Fuel use (l)	175.26
	Refrigerants	GWP of refrigerants	R410a = 2088 R600a = 3
		Refrigerant type	R410a (air conditioning units) R600a (refrigeration units)
		Refrigerant quantity (Kg)	R410a = 4.65 R600a = 0.25
	SO_X	Sulphur content of fuel (%)	0.1
Discharges to Water	Oily water (bilge)	Volume of bilge water (l)	2
	Sewage	Volume of sewage produced per voyage (l)	300
	Grey water	Volume of grey water produced per voyage - if separate from sewage (l)	n/a
	Antifoul	Type of antifoul coating applied to	n/a
	Ballast water	Volume of ballast water collected (l)	0
		Volume of ballast water released (l)	0
	Marine litter	Method of waste disposal	Onshore (municipal
		Waste separation on board (y/n)	No
	Chemicals	Volume of chemical liquids on board (l)	1102.5
		Volume of chemicals used (l)	0
		Record of chemicals spilled (l)	0
	On board stored oil	Volume of fuel on board (l)	5000
		Volume of oil stored on board (l)	470
		Oil use per voyage (l)	0
		Record of oil spilled (l)	0

Continued overleaf…

Pollutant category		Checklist	Data
Land	Garbage	Volume of waste produced per voyage (Kg)	8.5
Anthropogenic noise	Noise	Noise level of engine (dB)	104
		Noise measurements recorded using noise measuring equipment? (y/n)	No
		If y, recorded noise levels for surface and underwater noise (dB)	n/a
Physical	Contact with marine animals	Number of vessel strikes with aquatic species	0

The data collected in Table 5.8 has been used to calculate emissions and discharges of the pollutants identified in the assessment methodology in Chapter 4. VEP scores have been calculated for each pollutant, along with the VEP_n scores (Table 5.9). The full calculations for VEP scores and VEP_n scores are shown in Appendix D.

Table 5.9 VEP and VEPn scores for each pollutant

Hazard	Units	VEP	VEP_n
GHGs	g CO_2 eq./tonne-mile	101.53	2.13
Refrigerants	Tonnes CO_2 eq.	9.71	0.097
SO_X	Tonnes	0.06	0.11
NO_X	g/tonne-mile	1.81	1.71
PM	g/tonne-mile	0.04	0.47
VOCs	g/tonne-mile	0.07	1.96
Oily water (Bilge)	m^3/day	0.002	0.00038
Antifoul coating	mg/Kg tin	0	0
Ballast water	m^3/hr	0	0
Sewage	m^3/hr	0.067	0.583
Grey water	m3/hr	0	0
Marine litter	Kg/person-day	0	0
Chemicals	Tonnes	1.1	0.00011
On board stored oil	Tonnes	4.65	0.000047
Garbage	Kg/person-day	0.53	0.19
Underwater noise	dB	104	2.260
Surface noise	dB	104	4.73
Collisions with marine animals	No. of known collisions	0	0

Likelihood of occurrence of each hazard was assessed, as shown in Table 5.10.

Table 5.10 Likelihood of occurrence

Hazard	Routine interaction with environment? (y/n)	Score
GHGs	Yes	2
Refrigerants	No	1
SO_X	Yes	2
NO_X	Yes	2
PM	Yes	2
VOCs	Yes	2
Oily water (bilge)	Yes	2
Antifoul coating	Yes	2
Ballast water	No	1
Sewage	No	1
Grey water	No	1
Marine litter	No	1
Chemicals	No	1
On board stored oil	No	1
Garbage	Yes	2
Underwater noise	Yes	2
Surface noise	Yes	2
Collisions with marine animals	No	1

5.3.3 Environmental Assessment

Part A of the environmental assessment for the Max Pruss was completed using the procedure outlined in Chapter 4, steps 1 to 6. The calculated hazard severity weightings are shown in Table 5.11. The severity scores are the same as those utilised for assessment of the Princess Royal with the exception of Refrigerants, which has a higher severity score in this case due to the GWP of R404a being significantly higher than that of R600a. The higher refrigerant score has altered the % weighting factor of each hazard when compared with the Princess Royal case study. Refrigerants have increased from 5.48% to 6.33%, and hence the percentage weight of each of the other hazards have slightly reduced.

Table 5.11 Hazard severity weighting (Max Pruss)

Hazard	Hazard Severity Score	Hazard Weighting
GHGs	18	9.23%
Refrigerants	14	7.18%
SO_X	12	6.15%
NO_X	13	6.67%
PM	9	4.62%
VOCs	8	4.10%
Oily water (bilge)	13	6.67%
Antifoul coating	10	5.13%
Ballast water	11	5.64%
Sewage	10	5.13%
Grey water	8	4.10%
Marine litter	12	6.15%
Chemicals	14	7.18%
On board stored oil	13	6.67%
Garbage	8	4.10%
Underwater noise	7	3.59%
Surface noise	9	4.62%
Collisions with marine animals	6	3.08%
Total	**195**	**100%**

The vessel assessment was carried out using data from the vessel checklist, and VEP and likelihood scores were calculated (Tables 5.9 and 5.10). Overall severity scores for each hazard were calculated, and multiplied by the likelihood scores to calculate significance scores for each hazard (Table 5.12).

Table 5.12 Hazard significance scores for the Max Pruss

Hazard	Hazard Significance
GHGs	0.39
Refrigerants	0.0070
SO_X	0.0134
NO_X	0.23
PM	0.044
VOCs	0.16
Oily water (bilge)	0.000051
Antifoul coating	0
Ballast water	0
Sewage	0.030
Grey water	0
Marine litter	0
Chemicals	0.0000079
Garbage	0.0000031
On board stored oil	0.19
Underwater noise	0.34
Surface noise	0.017
Collisions with marine animals	0
Total	**1.42**

Hazard significance scores are added together to give a total score for the vessel. The % score for the Max Pruss was calculated (Table 5.13).

Table 5.13 Vessel environmental score for the Max Pruss

Voyage	Score	Score (%)
25/01/2019	1.42	14.2%

5.4 Comparing the new method with other initiatives

In this section, the environmental assessment scores generated for the Princess Royal and the Max Pruss are compared with the scores from existing environmental index schemes, where possible. The existing initiatives listed in Section 3.4.2.2 of Chapter 3 were found to publicise the scope and/or methodology of the scheme. Following further investigation, it was found that only a limited number of the schemes provide enough information to complete environmental assessments for the case study vessels, listed as follows:

(1) CCWG Environmental Performance Scorecard (CCWG)

(2) CSI

(3) ESI

(4) EVDI

(5) Green Award

(6) The Blue Angel (Operation)

Assessments using the existing initiatives were conducted using the data collected for each case study, no additional data collection was carried out.

5.4.1 CCWG

The CCWG Environmental Performance Scorecard is an initiative designed to assess the environmental performance of marine containerships, and therefore neither the Princess Royal nor the Max Pruss are eligible to be assessed using this method. Nevertheless, the method has been applied to each vessel and scores generated based on the data available. The CCWG methodology assesses vessels based on several environmental parameters: CO_2 emissions; SO_X emissions, NO_X emissions, operation of an Environmental Management System (EMS); Waste, Water and Chemicals; and Transparency.

5.4.1.1 CO_2 emissions

CO_2 emissions are assessed by using the CCWG CO_2 emissions methodology (BSR, 2015) to calculate emissions from a vessel, and comparing the result against the average emissions recorded in the CCWG database for a specified trade lane. Emissions are calculated in g CO_2/TEU-Km for containerships, and compared with trade lane averages to determine the number of points awarded. For vessels with emissions higher than the CCWG average for a given trade lane, 50 points are awarded; for emissions within 10% of the CCWG average, 75 points are awarded; and for emissions less than 10% below the CCWG average, 100 points are awarded.

The points awarded in the CO_2 emissions category account for 40% of the total points available.

Emissions from the Princess Royal and Max Pruss cannot be calculated in g CO_2/TEU-Km as they are not containerships, and therefore cannot be compared against the CCWG average. The lowest score available in this category is 50 points (for ships with emissions greater than CCWG average), therefore the Princess Royal and Max Pruss are awarded 50 points each in this category, which accounts for 20% of the total available score for the index.

5.4.1.2 SO_X emissions

SO_X emissions are also measured in g/TEU-Km, and are compared with CCWG average emissions for a given trade lane. Vessels with SO_X emissions greater than 15% above the CCWG average are awarded zero points; between the average and 15% above average are given 50 points; between the average and 15% below average are awarded 75 points; and for emissions less than 15% below the average, 100 points. Points awarded in the SO_X emissions category account for 20% of the total.

Emissions from the Princess Royal and Max Pruss cannot be calculated in g/TEU-Km or compared with the CCWG trade lane average, therefore both vessels are awarded the minimum number of points in this category, which is zero.

5.4.1.3 NO_X emissions

NO_X is assessed by comparing vessel emissions in g/kWh against the IMO standards outlined in Regulation 13 of MARPOL Annex VI. Emission levels from the main and auxiliary engines are assumed based on the design conditions of the engine, and are taken from the engines EIAPP certificate. Vessels with emissions that are less than 20% below the regulatory limit are awarded a score of 50 points; less than 40% below the limit are awarded 75 points; and less than 80% below are awarded 100 points. Main and auxiliary engines are assessed separately based on emission performance, the scores are then combined and an average calculated to determine the overall number of points awarded for the category. Points awarded in this category account for 20% of the total.

Valid EIAPP certificates were not accessible for either the Princess Royal or the Max Pruss during this research, therefore NO_X emissions in g/kWh have been calculated based on the voyage data available. In each case, NO_X emissions (g/kWh) have been calculated as follows:

$$NO_X \text{ (g/kWh)} = E / (T / P) \quad (5.1)$$

Where:

E = Total emission of NO_X during voyage (grams)

T = Total time of complete voyage (hours)

P = Average engine power during voyage (kW)

Average engine power data during each voyage was obtained from the vessel skippers for each case study, which is noted as the operational power shown in Table 5.14. For the Princess Royal, NO_X emissions in g/kWh have been calculated for the total period of data collection (all 4 voyages). The data used to calculate NO_X emissions for each vessel is shown in Table 5.14.

Table 5.14 Calculation of NO_X emissions in g/kWh based on voyage data

Vessel	NO_X (g)	T (hrs)	Average operational power (kW)	NO_X (g/kWh)	% above/below regulations
Princess Royal	67,156	24.50	373.3	7.34	-25.1%
Max Pruss	8,491	4.47	163.1	11.65	+13.7%

Calculated NO_X emissions were verified by comparing the calculated value for the Max Pruss with actual NO_X emission data from a sample period during the voyage. Continuous monitoring equipment was used to collect real time NO_X emissions data whilst the engines were running at 1600rpm, at a vessel speed of 7.3 knots. Actual emissions were found to be within 15% of the calculated emissions (see data in Appendix D.4).

The calculated NO_X emissions in g/kWh are compared with the MARPOL Annex VI requirements for Tier I, to determine the required number of points for each vessel. According to the regulations, Tier I engines with a maximum operating speed of between 130 and 2000 rpm (n) must not exceed a calculated NO_X limit using the following formula:

$$\text{Tier I } NO_X \text{ limit} = 45 * n^{-0.2} \quad (5.2)$$

For Tier I engines above 2000 rpm, the NO_X limit is fixed at 9.8 g/kWh. The maximum rpm of the engines used in the Princess Royal is 2100 rpm, and the Max Pruss is 1800 rpm, therefore they must not exceed 9.8 and 10.05 g/kWh respectively. To gain a score in CCWG, NO_X emissions must be at least 20% below the regulatory requirements set out in MARPOL Annex VI, in which case 50 points (5% of the total for CCWG) are awarded. If NO_X emissions are at least 40% below the regulatory requirement, 75 points (7.5%) are awarded. Calculated emissions from the Princess Royal are 25.1% below Tier I requirements, therefore the vessel receives 5% in this category. NO_X emissions from the Max Pruss are 13.7% above the regulatory threshold for Tier I engines. As the engine was built before 2000 and the engine power is less than 5000 kW, the vessel is not obliged to meet Tier I requirements. Nevertheless, for the purpose of this case study the Max Pruss receives zero points in this category.

5.4.1.4 EMS

Neither vessel operates a certified environmental management system therefore zero points are awarded in this category.

5.4.1.5 Waste, Water and Chemicals

Several criterion make up this category as shown in Table 5.15. The Princess Royal and Max Pruss were assessed against each of the criteria based on previously collected data, the number of points allocated to each are shown in Table 5.15. The total number of points makes up 100% of the points available in the category, and the category accounts for 10% of the total for the CCWG index. The Princess Royal scores 56% and the Max Pruss 41% in this category, which accounts for 5.6% and 4.1% of the total index, respectively. The difference in scores owes to the use of a biocide free antifoul coating on the Princess Royal, whereas the Max Pruss has no coating and therefore scores zero.

Table 5.15 Criteria and scores for Waste, Water & Chemicals

Criteria	Max points	Princess Royal	Max Pruss
Anti-fouling paints: Self-Polishing Coating (SPC)	15%	15	0
OR Anti-fouling paints: Use of non-toxic anti-fouling paints			
Stern Tube Oil: Based on biodegradable oil or air seal	13%	0	0
OR Stern Tube Oil: Use of water lubrication or not applicable			
External hydraulic fluids: Based on biodegradable oil or ext. hydraulic system capped	5%	0	0
OR External hydraulic fluids: Ext. hydraulics exchanged to electrical power			
Thrusters (gear oil): Based on biodegradable oil or not applicable	5%	5	5
Cleaning agents: Use of cleaning agents not classified as CMR, dangerous to the environment, or toxic	5%	5	5
Refrigerants: Use of refrigerants that are natural (NH3, CO2) OR HFC complying with GWP<3500 and ODI=0	5%	5	5
Boiling/cooling water treatment: Not classified as CMR, toxic, sensitizing, dangerous to the environment	12%	0	0
Ballast water: Mid-ocean ballast water exchange	18%	18	18
OR Ballast water: Treatment to IMO final approval - non-toxic level or not applicable			
Bilge water treatment: Active treatment installed and <5ppm oil in outgoing water and emissions control box in place	10%	0	0
Sewage/Black water: No discharge of sewage in sensitive areas (PSSA) or sewage treatment plant on board	4%	4	4
Sludge handling: No incinerator on board or documentation of no incineration of sludge and disposal of sludge to treatment on shore			
Garbage handling: No incinerator, no waste overboard, and reuse, recycling and disposal	2%	2	2
Garbage handling: Documented no incinerator, no waste overboard, and reuse, recycling and disposal	2%	2	2
Crew awareness: Documented education of personnel on environmental awareness, health risks, and adequate protective equipment	4%	0	0
Subtotal for Waste, Water & Chemicals	**10%**	**5.6%**	**4.1%**

5.4.1.6 Transparency

The CCWG measures transparency according to a set of ‘core’ and ‘additional’ indicators. 50 points are awarded when five core indicators are met, 75 points are awarded for meeting five core indicators and two additional indicators, and 100 points for five core and five additional indicators. The indicators are as follows:

Core:

(1) Public reporting on annual CO_2 emissions from operations.

(2) Public reporting on environmental goals and targets.

(3) Public description of policies/programs on the management of environmental impacts.

(4) Public description of initiatives to use renewable energy sources and increase energy efficiency.

(5) Participation in CCWG data sharing with BSR.

Additional:

(1) Public disclosure of breakdown of fleet composition.

(2) Public reporting on charter partners’ environmental impacts.

(3) Public reporting on initiatives to influence charter partners’ environmental impacts.

(4) Public description of initiatives to control urban air emissions.

(5) Public description of initiatives to control traffic congestion, and noise in relation to road transport.

(6) Public description of environmental impact of major infrastructure assets.

Neither the Princess Royal nor the Max Pruss meet any of the transparency criteria, and therefore score zero in this category.

5.4.1.7 Total score for CCWG Index

The total scores for the Princess Royal and Max Pruss are shown in Table 5.16.

Table 5.16 CCWG scores for Princess Royal and Max Pruss

Category	Princess Royal	Max Pruss
CO_2 emissions	20	20
SO_X emissions	0	0
NO_X emissions	5	0
EMS	0	0
Waste, Water & Chemicals	5.6	4.1
Transparency	0	0
Total	**30.6**	**24.1**

Both vessels score 20 percentage points each for CO_2 despite not being able to calculate CO_2 emissions in g/TEU-km. This is because there is no limit on CO_2 emissions, and the minimum possible score is 50 points, which accounts for 20% of the total score for the index. Therefore a vessel which is assessed by the CCWG automatically gains 20% of the total score in the CO_2 category. Similarly SO_X emissions in g/TEU-Km cannot be calculated, however the minimum points available in the SO_X category is zero therefore neither ship scores any points.

NOx emissions from the Princess Royal meet the requirements outlined in the CCWG to qualify for points (minimum 20% below IMO regulations) based on Tier I engines, and therefore receives 5%, however the Max Pruss does not meet the minimum criteria and scores zero. Both vessels score moderately in Waste, Water & Chemicals, with 56% and 41% of the total available in this category. These scores are largely attributable to not having a ballast water system on board, and the difference in scores being due to the use of an antifoul coating which is considered to be non-toxic (Princess Royal). The coating used on the Princess Royal (Intersleek 1100) is approved as biocide free, however research suggests that tin compounds contained in the catalyst could be released into the environment (Watermann *et al.,* 2005). The environmental assessment method developed in this research (Chapter 4) uses tin content as the reference environmental indicator for antifoul coatings rather than AFS convention approval, which is an appropriate measure for antifoul coating toxicity.

Neither vessel scores any points in the transparency or EMS categories as there are no requirements for either vessel to report on emissions, or operate an EMS. Many of the transparency indicators are not applicable to either vessel.

5.4.2 CSI

There is no information on the CSI website outlining the eligibility requirements of vessels for the index, only that the index covers *"existing ships of different types"* (CSI, 2018). The methodology refers to several ship types derived from the IMO (MEPC, 2011), and uses referenced EEDI values from the MEPC to calculate CO_2 scores in the index. Neither the Princess Royal nor the Max Pruss fit any of the defined ship types outlined in MEPC (2011), and hence CO_2 scores in CSI cannot be calculated. It can therefore be assumed that the CSI is not a suitable methodology for assessing the environmental performance of either vessel. Nevertheless, the method has been applied to both ships and scores generated where possible.

The CSI assesses environmental performance in five categories: SO_X and PM; NO_X; CO_2; Water and Waste; and Chemicals. Scores are calculated in each category and added together to give a total CSI score. A CSI rating is assigned to the vessel based on the number of points awarded, according to Table 5.17. Higher CSI scores indicate better vessel environmental performance.

Table 5.17 CSI rating scheme

Rating	Points achieved
CSI 5	125-150
CSI 4	100-124
CSI 3	75-99
CSI 2	38-74
CSI 1	0-37

5.4.2.1 SO_X and PM

SO_X and PM are assessed based on the sulphur content of the fuel used by the vessel. The total average S content in all fuel on board as a percentage by weight over a 12 month period is considered, and points are awarded for operation of main and auxiliary engines inside and outside of ECA's. A total score of 30 points can be achieved in this category, 15 for SO_X and 15 for PM. A maximum of five points each are available for the main engine fuel S content within ECAs, and the same for operation outside of ECAs. A maximum of three points are available for auxiliary engines, and an additional two points are available as a harbour bonus. Both the Princess Royal and the Max Pruss operate using 0.1% S MGO, therefore points have been awarded accordingly (see Table 5.18). The points awarded are based on the data collected during this research, as annual data was not available.

Table 5.18 NO_X and SO_X scores

Category	Criteria	Princess Royal	Max Pruss
		Score	Score
SO_X	Main Engine (non-ECA)	4	4
	Main Engine (ECA)	0	0
	Harbour Bonus	1	1
	Aux Engine	0	0
PM	Main Engine (non-ECA)	4	4
	Main Engine (ECA)	4	4
	Harbour Bonus	0	0
	Aux Engine	0	0
Total points		**13**	**13**

5.4.2.2 NO_X

For NO_X, a maximum of 30 points are awarded for a vessels main (21 points) and auxiliary (9 points) engines. Points are awarded based on the emission rating of the engine in g/kWh, as identified in the engines EIAPP certificate. In cases where no auxiliary engines are on board, the main engine emission ratings are used. Points are awarded by comparing the emissions rating of the engines with the IMO requirements for Tier I engines, outlined in MARPOL Annex VI regulation 13. The calculated emissions rating for the Princess Royal and Max Pruss can be compared with the Tier I requirements as shown in Table 5.19.

Table 5.19 Comparison of actual emissions with IMO requirements

NO_X (g/kWh)	Princess Royal	Max Pruss
Actual	7.34	11.65
Tier I limit	9.8	10.05
Tier II limit	7.7	7.57
Tier III limit	1.96	2.01
Actual % difference from Tier 1 limit	-25.1%	+13.7%

In CSI, nine points are awarded if the emissions rating of the main engine meets Tier II requirements, 12 points are awarded if the emissions rating is 30% below Tier I requirements, 15 are awarded if the emissions rating is 40% below Tier I, and 21 points are awarded for meeting Tier III. Emissions from the Princess Royal are lower than Tier II requirements therefore nine points are awarded, however the Max Pruss receives zero points as it does not meet Tier I requirements, based on the calculated NO_X data. Neither vessel has auxiliary engines, therefore points are awarded based on the emissions rating of the main engines. For auxiliary engines, three points are awarded to the Princess Royal for meeting Tier II levels, but zero points are awarded to the Max Pruss. The total number of points for NO_X are outlined in Table 5.20.

Table 5.20 NO_X CSI points

Category	Criteria	Princess Royal	Max Pruss
NO_X	Main Engine	9	0
	Auxiliary Engine	3	0
	Total points	**12**	**0**

5.4.2.3 CO_2

A maximum of 30 points are available in this category, three points are awarded for recording CO_2 emissions in g/tonne-nm (in line with EEOI) or g/TEU-km (in line with CCWG for containerships), and 27 are rewarded based on emission performance compared with a calculated EEDI reference for a particular ship type. EEDI reference values cannot be calculated for the Princess Royal or Max Pruss, therefore a score of zero is allocated for CO_2 emission performance. In both case studies, data has been recorded in g/tonne-nm, therefore three points can be awarded to each for CO_2 reporting.

5.4.2.4 Water and Waste

CSI assesses water and waste using six pollutant categories: grey water; sewage/black water; garbage handling; sludge handling; bilge water treatment; and crew awareness. The criteria for scoring and points awarded for the Princess Royal and Max Pruss are shown in Table 5.21.

Table 5.21 Criteria and points awarded for Water and Waste

Criteria	Requirement	Points	Princess Royal	Max Pruss
Grey water	No data/no treatment	0	4	4
	No discharge in PSSAs or treatment on board	4		
Sewage	No data/no treatment	0	4	4
	No discharge in PSSAs or treatment on board	4		
Garbage handling	No data/incineration	0	6	6
	No incineration and sorted and disposed onshore	6		
Sludge handling	No data/incineration	0	5	5
	No incineration and disposal onshore	5		
Bilge water	No data/gravimetric separation	0	0	0
	treatment to <15 ppm oil	4		
	treatment <5ppm oil	6		
	Treatment to <5ppm oil and emission control box in place, or discharge to onshore facility	8		
Crew awareness	No data	0	0	0
	Education of environmental awareness, health risk and personal protective equipment (ppe)	3		
Total		**30**	**19**	**19**

The vessels score 19 points each in this category. In both cases grey water and sewage are collected together. Neither vessel discharges the effluent into PSSAs (Particularly Sensitive Sea Areas), it is collected in holding tanks and disposed of onshore, therefore the maximum number of points is awarded for each. Both vessels collect and dispose of garbage onshore and neither has an incinerator on board, nor do they operate processes which result in sludge formation, therefore the maximum number of points is awarded to each for garbage and sludge handling. On inspection of each vessel, treatment of bilge water was not evident and no evidence of environmental awareness training schemes were present, hence no points are awarded in either category.

5.4.2.5 Chemicals

Chemicals are assessed using seven different pollutant categories: antifouling; stern tube oil; external hydraulic fluids; gear oils for thrusters and controllable pitch propellers; boiling/cooling water treatment; cleaning agents; and refrigerants. The criteria for scoring and points awarded for the Princess Royal and Max Pruss are shown in Table 5.22.

Table 5.22 Criteria and points awarded for Chemicals

Criteria	Requirement	Points	Princess Royal	Max Pruss
Antifouling	No data/other/CPD	0	7	0
	SPC/accepted biocides	5		
	Non-toxic (biocide free)	7		
Stern tube oil	No data/mineral oil based	0	0	0
	Air seal	3		
	Based on biodegradable oil	5		
	Water lubrication/not applicable	7		
Hydraulic fluids	No data/mineral oil based	0	0	0
	External hydraulics exchanged to electrical power/based on biodegradable oil/external hydraulic system capped	3		
Gear oils	No data/mineral oil based	0	0	0
	Based on biodegradable oil/not applicable	5		
Boiling/cooling water	Toxic (according to DSD)/no data	0	0	0
	Not classified as toxic	2		
Cleaning agents	Toxic CMR substances (according to EU DSD)/no data	0	3	3
	Not classified as toxic	3		
Refrigerants	Non-natural HFCs with GWP > 3500; ODP > 0/no data	0	3	1
	HFCs with GWP < 3500 and ODP = 0	1		
	GWP < 1850 and ODI = 0	3		
Total		**30**	**13**	**4**

The Princess Royal scores a total of 13 points in this category compared to four for the Max Pruss. For antifouling, the Princess Royal scores the maximum number of points for using a coating that is considered ‘biocide free’, however the Max Pruss scores zero due to not having a coating applied. Both vessels score zero for stern tube oil, hydraulic fluids, gear oils and boiling/cooling water as no data was collected for any of the categories. Both vessels score three points for cleaning agents, as the chemicals stored on board are not classed as carcinogenic, mutagenic, or reprotoxic (CMR) substances (see Appendices C and D) under the EU Dangerous Substances Directive (67/548/EEC), superseded by the EU CLP Regulations (1272/2008). For refrigerants, the Princess Royal scores three points as the GWP of R600a is less than 1850, however only one point is given to the Max Pruss due to the use of R410a (GWP = 2088) in the air conditioning systems.

5.4.2.6 Total score for CSI

The total scores in CSI for the Princess Royal and Max Pruss are shown in Table 5.23.

Table 5.23 CSI scores for Princess Royal and Max Pruss

Category	Princess Royal	Max Pruss
SO_X and PM	13	13
NO_X	12	0
CO_2	3	3
Water and Waste	19	19
Chemicals	13	4
Total	**60**	**39**
CSI rating	**CSI 2**	**CSI 2**

Both vessels achieve a CSI rating of two, although the Princess Royal scores more points than the Max Pruss overall. This is due to lower NO_X emissions and the use of a biocide free antifoul coating, and refrigerants with a lower GWP. It is not possible to compare the results with the environmental ratings of other vessels without contacting CSI to access the database, which must be done by signing a confidentiality agreement. Both vessels score low for CO_2 due to the calculation method only being applicable to a limited range of ship types. Both vessels score higher for SO_X and PM than in the CCWG index. For SO_X and PM the methodology used in the CCWG index is not compatible with either vessel and is only suitable for containerships, the CSI method is more universal in that respect.

The categories for water and waste, and chemicals are separate in CSI and combined in CCWG. If the scores for both categories in CSI are combined and a percentage calculated, the score outputs from each scheme are similar. The Princess Royal scores 53% in CSI and 56% in CCWG, and the Max Pruss scores 38% and 41% respectively. According to the CCWG guidance, "*the waste, water and chemicals questions are based on the Clean Shipping Index (CSI) "Chemicals" and "Water and waste control" questions, but designed to integrate with the CCWG data collection system"* (CCWG, 2015), therefore this outcome is to be expected.

5.4.3 ESI

The ESI is an air emission index designed for seagoing ships, therefore is suitable for assessing the Princess Royal but not the Max Pruss. However for the purpose of this research, ESI scores will be calculated for both vessels. The ESI uses four categories to assess a ships emission performance: NO_X; SO_X, CO_2 and OPS. ESI scores are calculated by combining the scores in each category, as follows:

$$\text{ESI score} = \text{ESI } NO_X + \text{ESI } SO_X + \text{ESI } CO_2 + \text{ESI OPS} \qquad (5.3)$$

5.4.3.1 NO_X

ESI NO_X is calculated using the following formula:

$$\text{ESI } NO_X = \frac{100}{\text{Rated Power } \Sigma \text{ of all Engines}} \times \frac{(NO_X \text{ limit value} - NO_X \text{ rating}) \times \text{Rated Power}}{NO_X \text{ limit value}} \Sigma \text{ of all Engines} \qquad (5.4)$$

The NO_X limit value in this formula is set at Tier I (see Table 5.19), and the NO_X rating is that which appears on a vessels EIAPP (Engine International Air Pollution Prevention) certificate. The ESI guidelines state that "s*hips that do not have an EIAPP certificate cannot obtain points for ESI NO_X, unless such ships have been issued with an approved statement to the effect that engines meet Tier I requirements*" (ESI, 2017).

EIAPP certificates for the Princess Royal and the Max Pruss were not evident during the period of study, therefore both ships would score zero for ESI NO_X. For the purpose of this research however, the calculated actual NO_X emission ratings for each vessel shown in Table 5.19 have been used. The calculated ESI NO_X scores for the vessels are as follows:

Princess Royal = 22 points

Max Pruss = 0 points

The maximum points total for this category is 67, given to vessels with zero NO_X emissions. The Princess Royal and Max Pruss are awarded 33% and 0% of the maximum respectively.

5.4.3.2 SO_X

ESI SO_X scores are calculated based on the S content of bunkered fuel, using the following formula:

$$\text{ESI } SO_X = x * 30 + y * 35 + z * 35 / 3 \qquad (5.5)$$

Where:

x = relative reduction of average S content of high sulphur fuels (0.5 < S % < 3.5)

y = relative reduction of average S content of mid sulphur fuels (0.1 < S % < 0.5)

z = relative reduction of average S content of low sulphur fuels (0.0 < S % < 0.1)

Both the Princess Royal and Max Pruss use low sulphur MGO (0.1%), therefore the maximum number of points are awarded for *x* and *y* as no mid or high S content fuels were on board. The relative reduction in low S fuel content is the maximum threshold % S content value (0.1) minus the actual fuel % S content value (0.1), which equals zero. Therefore, ESI SO_X scores for both vessels were calculated as follows:

$$30 + 35 + 0 / 3 = 21.6 \text{ (rounded up to 22 points each)}$$

5.4.3.3 CO_2

The ESI CO_2 points are awarded based on the fuel efficiency of the vessel. Efficiency is calculated over a three year baseline period as fuel consumption over distance sailed. The vessels performance is compared to the calculated baseline fuel efficiency and points are awarded for every % increase in efficiency, up to a maximum of 10 points (10% increase in efficiency). In addition, if the vessel reports on a minimum of two EEOI data sets (such as fuel consumption and distance sailed), as outlined in the Guidelines for Voluntary use of the Ship Energy Efficiency Operational Indicator (MEPC.1/Circ.684), a further five bonus points are added, up to a maximum score of 15 for this category.

Data was not available to calculate the baseline fuel efficiency for the Princess Royal or the Max Pruss, therefore no points in this category could be awarded to either vessel.

5.4.3.4 OPS

An additional 10 points are added to the ESI score if the vessel is fitted with an Onshore Power Supply (OPS) installation. If there is no OPS installation then the vessel scores zero for this category. Neither the Princess Royal nor the Max Pruss are fitted with OPS technology, therefore score zero. The vessel skippers confirmed that the engines are switched off whilst berthing, however the ESI method does not account for this.

5.4.3.5 Total score for ESI

The total scores for the Princess Royal and Max Pruss are shown in Table 5.24. Both vessels score 22 points in the SO_X category as they bunkered fuel with the same % S content. Princess Royal achieves a higher overall ESI score due to having lower calculated NO_X emissions. However it should also be noted that under the rules of the ESI, neither vessel would achieve any scores in the NO_X category due to the absence of EIAPP certificates, so the overall ESI scores would be 22 points each. Neither vessel scores points for OPS, due to a lack of OPS technology, however neither vessel emits pollutants whilst at berth.

Table 5.24 ESI scores for Princess Royal and Max Pruss

ESI criteria	**Princess Royal**	**Max Pruss**
NO_X	22	0
SO_X	22	22
CO_2	0	0
OPS	0	0
Total	**44**	**22**

5.4.4 EVDI

The Existing Vessel Design Index (EVDI) is a tool for measuring the CO_2 emissions of existing vessels. The method adopts the same formula as is used to calculate a ships EEDI, however it is applicable to existing vessels. The EVDI provides a means of comparing the theoretical efficiency of the existing fleet by measuring a vessels theoretical CO_2 emissions (g) per nautical mile travelled. A ships' generated EVDI score can then be compared with other vessels of a similar type and size using the GHG Emissions rating scale (RightShip, 2019). The ship types applicable to this method are those which are compatible with the EEDI, and include tankers, bulk carriers, gas carriers, general cargo ships, container ships, refrigerated cargo carriers, combination carriers, LNG carriers, ro-ro cargo ships, ro-ro passenger ships and cruise passenger ships (IMO, 2019).

Neither the Princess Royal nor the Max Pruss fit any of the defined ship types outlined by the IMO, therefore neither can be assessed using the EVDI and the GHG emissions rating system. Nevertheless, EVDI scores for both ships have been calculated by making a number of assumptions based on the collected data. A vessels EVDI is calculated using the following formula:

EVDI = Engine Power (P) * CO_2 EF * Specific Fuel Consumption (SFC) / Design speed (V) * vessel weight (M)

(5.6)

Where:

P = Total power of all engines, taken from vessel specification.

EF = Emission factors for CO_2 used in vessel case studies (Appendices C and D).

SFC = Specific fuel consumption for engine type, taken from engine manual.

V = vessel top speed, taken from vessel specification (Princess Royal), and top speed during case study (Max Pruss).

M = Total vessel weight, taken from vessel specification.

The calculated EVDI scores for the Princess Royal and Max Pruss are shown in Table 5.25.

Table 5.25 Calculated EVDI scores for the Princess Royal and Max Pruss

Vessel data	Princess Royal	Max Pruss
P	894	508
EF	3.206	3.17
SFC	197	213
V	20	13.91
M	41	141
EVDI score (g CO_2/tonne-mile)	**688.58**	**174.89**

5.4.5 Green Award

There are several methodologies implemented by Green Award to assess the environmental performance of ships based on vessel type. Different criteria are used to assess oil tankers; dry bulk carriers/general cargo carriers; LNG carriers; chemical tankers; container carriers; and inland vessels. The Max Pruss is an inland vessel and therefore can be assessed using Green Award. The Princess Royal does not fit any of the criteria for Green Award, however in this research the inland vessel methodology has been applied to both ships.

The Green Award for inland vessels is separated into two parts, A and B. Part A assesses the vessels engines and part B assesses other environmental requirements including fuel type, propulsion measures, energy saving activities, waste and maintenance, pollution prevention and safety. In order to receive certification, vessels must meet certain criteria pertaining to parts A and B of the assessment. Certification is awarded as either bronze, silver, gold or platinum depending on the outcome of the assessment (a platinum label is awarded for emission free ship operations). For all vessels participating in the Green Award for inland vessels, main engines must meet CCNR 2 emission requirements as a minimum. Vessels' main engines must be CCNR 2 certified or show compliance with the emission requirements of CCNR 2 through post treatment or other measures, proven by means of accredited emissions test reports. In order to achieve gold certification, a vessel's main engine(s) must comply with EU Stage V emission requirements as a minimum. The regulatory standards for emission from inland vessels are shown in Table 5.26.

Table 5.26 Engine emission limits for inland vessels

Pollutant	Regulation	limit (g/kWh)
NO_X	Unclassified	>9.2
	CCNR 1	*45 x $n^{(-0.2)}$
	CCNR 2	6
	Euro V	2.1
PM	Unclassified	0.55
	CCNR 1	0.54
	CCNR 2	0.2
	Euro V	0.1
CO	Unclassified	5.1
	CCNR 1	5
	CCNR 2	3.5
	Euro V	3.5

*For engines with rated power > 130 kW and rpm between 500 and 2,800

Neither vessel is CCNR 2 certified, however for the purpose of this research calculated emissions values will be used. The calculated emissions of NO_X, PM and CO for the Princess Royal and Max Pruss are shown in Table 5.27.

Table 5.27 Calculated emissions and emission ratings for the Princess Royal and Max Pruss

Pollutant	Princess Royal				Max Pruss			
	Fuel use (g)	EF (g/g fuel)	Emissions (g/kWh)	Emission rating	Fuel use (g)	EF (g/g fuel)	Emissions (g/kWh)	Emission rating
NO_X	1,181,500	0.05684	7.34	**CCNR 1**	74,485	0.057	11.65	**Unclassified**
PM		0.00097	0.13	**Euro V**		0.0012	0.23	**CCNR 1**
CO		0.00277	0.36	**Euro V**		0.0074	0.1.51	**Euro V**

Based on the calculated emissions, both vessels meet the Green Award requirements for CO emissions. The Princess Royal meets the criteria for PM emissions, but the Max Pruss does not. Neither vessel meets the requirements for NO_X, therefore based on this data neither the Princess Royal nor Max Pruss are eligible for the Green Award.

5.4.6 The Blue Angel

The Blue Angel is an eco-label developed by the federal government of Germany, *"designed to promote environmentally friendly product design".* The label can be applied to many different products and industries, including shipping. A specific methodology has been developed for ship operation (RAL, 2015), which consists of various criteria that can be applied to three ship types: cargo vessels, passenger ships, and tankers. Some mandatory criteria must be met in order for a vessel to be awarded the eco label, along with some additional optional criteria.

Neither the Princess Royal nor the Max Pruss are considered to meet the defined ship types outlined by the Blue Angel and therefore cannot be assessed using this method. In addition, neither vessel meets a number of the mandatory criteria outlined in the methodology, including implementation of an ISO 14001 environmental management system.

5.5 Results

The scores for the Princess Royal and the Max Pruss using the existing assessment methods and the VEP method developed in this research are summarised in Table 5.28.

Table 5.28 Summarised initiative scores for the Princess Royal and Max Pruss

Index	Score	
	Princess Royal	**Max Pruss**
CCWG	30.6%	29.1%
CSI	40%	26%
ESI	44%	22%
EVDI	688.58	174.89
Green Award	Not eligible	Does not meet minimum standards
Blue Angel	Not eligible	Not eligible
VEP Index	**73%**	**85.8%**

The scores generated using the methodology developed in this research are notified in the table as VEP index, and have been inverted on a scale from 0–100% for ease of comparison with the other initiatives, where 100% represents zero emissions of pollutants. Therefore in the VEP index, Max Pruss receives a better environmental score than the Princess Royal.

5.5.1 Eligibility

Most of the existing initiatives are not eligible to be used to assess the Princess Royal or the Max Pruss according to the respective guidelines. CCWG is designed specifically for containerships, the CSI covers multiple ship types but only those which are outlined in IMO Resolution MEPC.203 (62), the Blue Angel is suitable for assessment of cargo vessels, passenger ships and tankers only, and the EVDI is only eligible for ship types to which the EEDI methodology can be applied. The ESI scoring method is not applicable to inland vessels, therefore can be applied to the Princess Royal but not the Max Pruss, however it can only be implemented where vessels hold a valid EIAPP certificate on board, which was not the case during this study. The Green Award can be applied to the Max Pruss but not the Princess Royal, however in either case the ships engines do not meet the minimum criteria for assessment. It is clear from this analysis that the existing methods are not flexible enough to assess all types of ship.

5.5.2 Scoring

Despite being ineligible, scores have been generated for the Princess Royal and Max Pruss using the CCWG, CSI, ESI and EVDI, however neither vessel could be assessed using the Green Award or the Blue Angel. Scoring is consistent across most of the initiatives with the Princess Royal receiving the most favourable scores in the CCWG, CSI and ESI, the exception to this trend is the EVDI, which scores the Max Pruss more favourably. It is noted that assessment of the vessels using the VEP index also scores the Max Pruss more favourably overall.

In order to confirm the validity of the results with reference to pollutant emissions and discharges, the scores from each initiative are compared with the actual emissions of pollutants from the vessels, in Table 5.29. In the table, the notations PR (Princess Royal) and MP (Max Pruss) are used to signify which vessel generates the highest emissions and discharges per pollutant category based on the case study data, and which vessel scores better in each category of the initiatives. A ‘better’ score in this case is one which is considered to indicate a more environmentally friendly ship, and hence has lower emissions.

The table indicates that the Princess Royal is the bigger polluter in terms of air emissions in all pollutant categories except refrigerants. The Max Pruss has the potential to release more pollutants to water in all categories except antifoul coating, and the Princess Royal produces more garbage per person per day based on the data collected. Noise pollution from the two vessels cannot be compared as no noise data was collected for the Princess Royal, and in each of the other categories the emissions from the vessels are considered to be equal.

Table 5.29 Comparison of emissions vs. index scores

Pollutant		Highest emission/discharge	Better score				
			VEP Index	CCWG	CSI	ESI	EVDI
Emissions to Air	GHGs	PR	MP	Equal	Equal	Equal	MP
	Refrigerants	MP	PR	Equal	PR	n/a	n/a
	SO_X	PR	MP	Equal	Equal	Equal	n/a
	NO_X	PR	MP	PR	PR	PR	n/a
	PM	PR	MP	n/a	Equal	n/a	n/a
	VOCs	PR	MP	n/a	n/a	n/a	n/a
Discharges to Water	Oily water (bilge)	MP	PR	Equal	Equal	n/a	n/a
	Antifoul coating	PR	MP	PR	PR	n/a	n/a
	Ballast water	Equal	Equal	Equal	n/a	n/a	n/a
	Sewage	MP	PR	Equal	Equal	n/a	n/a
	Grey water	Equal	Equal	n/a	Equal	n/a	n/a
	Marine litter	Equal	Equal	Equal	Equal	n/a	n/a
	Chemicals	MP	PR	Equal	Equal	n/a	n/a
	On board stored oil	MP	PR	Equal	Equal	n/a	n/a
Noise	Underwater noise	n/a	MP	n/a	n/a	n/a	n/a
	Surface noise	n/a	MP	n/a	n/a	n/a	n/a
Land	Garbage	PR	MP	Equal	Equal	n/a	n/a
Physical contact	Collisions with marine animals	Equal	Equal	n/a	n/a	n/a	n/a
Total		**PR**	**MP**	**PR**	**PR**	**PR**	**MP**

In most pollutant categories, the existing indices score both vessels equally despite the data showing that emissions for each vessel are not equal. For emissions to air it is clear that the Princess Royal is more polluting than the Max Pruss, however with the exception of the EVDI this is not reflected in the scoring of the existing schemes. This is due to the use of thresholds to compare emissions data rather than absolute values. For example, in CSI the NOx emission rating of the vessels relative to Tier I standards differs considerably as Max Pruss does not meet Tier I standards. While this is reflected in the number of points awarded for the category, both ships are classified as CSI 2 despite contrasting points totals. This is the case with many of the pollutant criteria and hence they do not provide an accurate reflection of emission performance.

The summarised results of the index scores in Table 5.28 suggest that the Princess Royal is a more environmentally friendly vessel than the Max Pruss, despite the data from the case studies suggesting the opposite. In most cases, with the exception of the EVDI and some of the pollutant categories in CCWG and CSI (CO_2), it has been found that the existing indices assess emissions based on the design criteria of the vessel rather than actual or calculated emissions. Table 5.30 compares the air emissions from the Princess Royal and Max Pruss based on the design criteria of the engines, in g/kWh. The table indicates that based on engine design the Max Pruss is more polluting than the Princess Royal in terms of GHGs, NO_X, PM and VOCs, contrary to the voyage data. This analysis suggests that using design criteria to assess vessel environmental performance does not provide an accurate indication of the actual emissions during voyages. The VEP index offers an alternative methodology that measures environmental performance based on actual emissions.

Table 5.30 Comparison of air emissions based on engine design and fuel S content

Pollutant	Emissions (g/kWh)		
	MP	PR	Higher emissions
GHGs	647.8	414.2	MP
NO_X	11.65	7.34	MP
SO_X	0.41	1.29	PR
PM	0.25	0.13	MP
VOCs	0.43	0.40	MP

5.6 Summary

Two case studies have been carried out in order to test and verify the VEP Index developed in this research. Data was collected manually for each case study following vessel surveys, and inventories of on board materials were compiled. The Princess Royal, a coastal research catamaran was assessed based on data from 4 voyages which took place over 2 weeks in March 2018. For the Max Pruss, an inland research vessel, data was collected for a single voyage in January 2019. No further data collection took place due to financial and time constraints.

Air emissions data for both case studies was derived from fuel use using relevant emissions factors, as no pollutant emissions monitoring equipment was continuously active on either vessel. The emissions factors for each vessel were selected based on the age and type of the engine. Both vessels have medium speed diesel engines installed and use low Sulphur MGO, however the Max Pruss is an older vessel and hence different emissions factors were used. For the Princess Royal, IMO emission factors (Smith *et al*., 2014) have been utilised, and for the Max Pruss LR emission factors (IVL, 2002) for engines built pre 2000 are preferred.

Vessel data was collected and processed to calculate pollutant VEP and VEP_n scores per voyage. The steps outlined in Chapter 4 were carried out to calculate significance scores for each voyage, and a total VEP index score was calculated for each vessel.

The VEP index scores have been compared with vessel scores generated using some existing ship environmental index schemes, where possible. It was found that in many cases, the vessels were not eligible to be assessed using the existing schemes as they did not fit the entry criteria. All of the existing schemes analysed, with the exception of the ESI, are applicable to a limited range of ship types only, and are generally more suited to larger vessel types. Nevertheless, scores for the Princess Royal and Max Pruss were generated where possible.

The results show that all of the existing index schemes, with the exception of the EVDI, score the Princess Royal more favourably than the Max Pruss, despite the voyage data suggesting that the Princess Royal generated more emissions in most pollutant categories. For many pollutants, the existing schemes score both vessels equally despite the data showing the Princess Royal to be more polluting. This is because the existing schemes use score thresholds to assess pollutants rather than absolute values, and hence lack the flexibility to differentiate between the emissions from each ship. In addition, many of the existing schemes were found to measure ship performance based on data derived from ship design rather than operation, in most cases the Princess Royal received a better environmental rating than the Max Pruss, despite the voyage data suggesting the opposite.

6.0 Conclusions and Recommendations for Future Work

6.1 Conclusions

This chapter presents the outcomes of the research project, including the contributions to wider research in the fields of sustainable shipping and environmental assessment in shipping. The conclusions of the thesis are presented, highlighting the novelty and achievements of the research. Recommendations for future work are identified which can build on the method developed in this research and potentially improve the accuracy of ship environmental assessments.

The overall aim of the research was to develop a holistic method for assessing the environmental performance of ships, taking into account the interactions and impacts of pollutant emissions and discharges on the environment, and considering actual rather than theoretical ship performance.

Chapter 2 provides a summary of the interactions of ships with the environment, the types of pollutant emissions and discharges originating from ships, and associated impacts on the environment. The purpose of this chapter is to identify a set of pollutant indicators for use in a ship environmental assessment index. The main conclusions from the chapter are as follows:

- Pollutants from ships can be broadly categorised into five groups based on ships' interactions with the environment: emissions to air, discharges to water, pollutant releases to land, anthropogenic noise, and physical interactions with aquatic species.
- The pollutants identified in this chapter form the scope of the VEP index, and a review of subsequent environmental impact has been used to inform the calculation of pollutant weighting factors for part A of the assessment methodology, outlined in Chapter 4.

Chapter 3 highlights the pathways and barriers to sustainable shipping through regulation, environmental management and environmental assessment. The aim of the chapter is to analyse the effectiveness of existing strategies for environmental management and assessment in the shipping sector, and highlight the limitations with current measures. This includes the role of national and international legislation in reducing the impacts of shipping on the environment, the barriers to implementation of regulations, and the use of voluntary environmental schemes and initiatives to fill the void where regulation is deemed to be ineffective. The main conclusions from Chapter 3 are as follows:

- Regulations exist to minimise damage to the environment from ship based pollutants, In addition to existing regulations, shippers and shipping companies have adopted voluntary strategies to meet the environmental demands of the industry including the use of environmental management systems and green shipping initiatives.
- The research highlights a large number of voluntary green shipping initiatives currently available for use. An inventory of initiatives has been compiled as part of this study, shown in Appendix B. The research classifies the schemes and concludes that they fit broadly into three categories based on their intended purpose: incentive schemes, research and innovation initiatives, and performance indicators.

A sample of voluntary initiatives covering the three categories were analysed to determine the transparency, scope, applicability, and ambition of the methodologies implemented. A broad set of limitations with the existing initiatives are identified in the research, summarised as follows:

- A lack of transparency of results and assessment methods.
- Limited applicability of initiatives to a wide range of ship types.
- Some initiatives have a narrow environmental scope.
- Biases towards certain pollutant indicators and use of unjustified weighting factors.
- Low thresholds for certification and limited ambition to go beyond regulatory requirements.
- Assessment of vessel performance based on design parameters rather than operational performance is effective.

The limitations identified were used to set the scope of the alternative environmental assessment methodology (VEP index) discussed in Chapter 4.

The aim of Chapter 4 is to outline the proposal of a framework for assessment of the environmental performance of ships which considers and corrects the limitations of existing initiatives identified in the previous chapter. The proposed methodology, the VEP index, offers the following:

- Applicability to all vessel types.
- A broad, relevant environmental scope made up of the environmental pollutants identified in this research.
- Pollutant weighting factors that are determined using objective environmental indicators to prioritise pollutants based on impact severity.
- Assessment of environmental performance based on operational data rather than the design characteristics of a vessel.
- An ambitious scoring framework which rewards ships for reducing pollutant emissions to zero.

In Chapter 5, the flexibility and sensitivity of the VEP index is tested, to determine its suitability for use across a range of vessels. This was done using two case study vessels with similar design specifications and operational characteristics. The main conclusions from the case studies are as follows:

- The method can clearly distinguish which of the two vessels performs better environmentally, based on voyage data. The use of voyage data for comparing the environmental performance of vessels is therefore an effective approach.
- Based on the data collected, the Max Pruss scores better than the Princess Royal in a majority of pollutant categories. The scores are consistent with the data, in that higher pollutant emissions receive lower environmental scores in the VEP index. This is in contrast to the results from most of the existing environmental initiatives analysed, which for most pollutants score both vessels equally, and overall score the Princess Royal more favourably than the Max Pruss.
- The Princess Royal and Max Pruss are scored equally in numerous pollutant categories using the existing indices. This highlights a lack of flexibility within the scoring systems to differentiate between the environmental performance of each vessel.

- The sensitivity of the VEP index to differentiate between vessels based on operational emissions is highlighted, and unlike many of the existing initiatives, it is capable of assessing all types of ship.

6.2 Contributions to research

The research conducted presents various contributions to the wider research field:

- A comprehensive categorisation of ship related pollutants into groups based on ships' interactions with the environment, detailing the impacts of ship operations on the environment. The review is summarised and presented in the form of a ship environmental impact table in Appendix A.
- Provision of in depth analysis of existing environmental regulation, management and assessment schemes used in the shipping sector, highlighting significant limitations with the current methods. The work conducted in this thesis has led to the publication of Gibson *et al.,* (2019) which presents an evaluation of environmental performance indices for ships.
- Development of a set of pollutant weighting factors for ship related emissions and discharges using quantifiable environmental indicators. The weighting factors developed in this research have been utilised as part of the CLINSH project.
- Development of an alternative methodology for assessing and ranking the environmental performance of ships based on operational performance. The VEP Index has been tested using case studies, and utilised by the CLINSH project. The method consists of the following unique features:

    - Objective assessment of pollutant releases from ships using calculated weighting factors and actual emission data.
    - Can be readily updated as regulations, technologies and operational practices evolve.
    - Flexibility to enable pollutant assessment using real time on board emission measurements.
    - Applicability is not limited to a single type of ship, as demonstrated through case studies.

- Can be used to compare the environmental performance of different ships, along with different voyages of the same ship.

6.3 Limitations of research

The methodology developed has some distinct advantages over the existing schemes, as the analysis in this research indicates. However limitations were encountered which could not be avoided during the research period. There are inherent uncertainties associated with risk assessment regarding data confidence, knowledge of environmental system processes, unpredictability of hazard occurrences and the clarity of language used to develop the method, which have been addressed in section 4.16 of chapter 4.

Access to data was a key limitation in this research, as the type of data required to carry out vessel assessments was not readily available. The methodology was therefore tested based on the data collected during two case studies, however the time frames for which data could be collected was limited. The vessel assessments conducted during each case study were carried out with confidence using the hierarchy of data quality outlined in chapter 4 (section 4.10.1), however data was often estimated due to a lack of monitoring equipment on board the vessels.

In addition, the quantity of data collected was limited due to time restrictions and constraints with the vessel operating schedules, therefore data representing only a snapshot of the ships' operation was used. This did not affect the reliability and integrity of the assessment methodology, however the assessment outcomes reflect vessel environmental performance over a short time period.

6.4 Recommendations for future work

It is recommended that the assessment methodology be conducted using data from direct measurements of emissions and discharges, rather than calculated emissions. This would require vessels to be fitted with species specific continuous monitoring equipment on board so that more accurate measurements of actual emissions can be recorded. This would allow vessels to be assessed based on the pollutants generated during operation, without the need for proxy indicators. Further analysis of the case study vessels could be conducted using different combinations of data based on the data hierarchy, comparing skipper collected data with continuously monitored and estimated data. This would highlight any significant differences environmental scores based on data type.

The method developed in this research has contributed towards the European funded CLINSH project (Clean Inland Shipping). CLINSH is a European consortium promoting clean waterway transport, with the objective of improving air quality in urban areas through emissions reductions from inland waterway transport. As part of the project, 30 ships have been selected and fitted with continuous emissions monitoring equipment for NO_X and PM. The VEP index developed in this research has been used as an environmental performance indicator to assess the emissions performance of the demonstration vessels in preliminary studies, and it is intended that the index will be utilised to assess the entire vessel fleet. Data from the continuous emissions monitoring will be utilised to score each of the vessels using the VEP Index. The method will also be used to assist the development of species specific emissions factors for the test vessels, based on percentage of engine load, and the VEP index will be used to compare vessel emission performance under different engine loads.

The assessment methodology was designed using a risk assessment based approach, using impact severity indicators to calculate quantitative weighting factors for the pollutants used in the index, and combining severity with likelihood of occurrence to determine hazard significance. To improve the accuracy of the calculated weighting factors, it is recommended that more in depth, quantitative risk assessments be conducted to determine more precise probability data for pollutant discharges.

Within the VEP index, pollutant scores are defined by comparing the actual vessel emissions with maximum permissible limits, either calculated based on the EEDI formula for air emissions, or set based on maximum usage estimates taken from the literature. Current regulations tend to set limits based on vessel design rather than actual emissions. It is recommended that further research be conducted to develop absolute emissions and discharge targets for pollutants, so that maximum permissible limits can be more rigorously defined.

This research has resulted in the development of an environmental assessment method for ships, which generates a numerical score for a given ship which can be compared with the scores of other ships. Using this method, the environmental performance of different vessels can be compared. It is suggested that future work in this field focus on the development of a performance scale for ships, so that the numbers generated using this method can provide meaning as independent indicators of environmental performance. This could be done by developing score thresholds based on the operating profiles of some model ships, broken down in to ship type and size, thus providing valuable context to the ship scores generated.

6.5 Concluding remarks

This thesis successfully demonstrates the development and use of an ambitious, relevant, rigorous method, the VEP index, for the assessment of environmental performance of vessels. The method corrects the limitations of existing methods by assessing ships based on operational performance using actual emissions data. The method is flexible and can therefore be applied to all types of ship, and the environmental criteria and pollutant emission parameters can be adjusted in order to adapt to future changes in regulations, technologies, and shipping practices. The VEP index can be used to compare the environmental performance of different vessels, along with different voyages of the same vessel. The research demonstrates that the method in its current form can be used to assess the environmental performance of vessels, however opportunities exist to develop it further into a commercial tool for ship environmental assessment.

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Appendices

Appendix A: Ship environmental impacts, regulations and voluntary control measures

Appendix B: Ship environmental initiative inventory

Appendix C: Princess Royal voyage data

Appendix D: Max Pruss voyage data

Appendix A

Ship environmental impacts, regulations and voluntary control measures

Interaction	Hazard	Source	Pathway	Receptor	Environmental impacts	IMO regulations	Environmental initiatives
Emissions to Air	CO_2 (GHG)	Engine	Combustion of fuel	Atmosphere	- Climate change - Ocean acidification	- MARPOL Annex VI (Regulations 19 to 21 for EEDI and Regulation 22 for SEEMP) - GHG Strategy 2018	Blue Angel; CCWG; CSI; ESI; EEDI; EEOI; EVDI; Green Award; RINA Green Plus
	CH_4 (GHG)	Slippage due to incomplete combustion of natural gas in engine	Handling and combustion of LNG	Atmosphere	- Climate change		n/a
	N_2O (GHG)	Engine	Fuel combustion at low temperatures	Atmosphere	- Climate change		n/a
	Refrigerants (ODP)	Leakage	- Refrigeration units - Air conditioning units	Atmosphere	- Ozone depletion - Climate change	MARPOL Annex VI Regulation 12	ABS Enviro/ Enviro+; Blue Angel; CCWG; CSI; DNV Clean/ Clean Design; RINA Green Plus/ Green Star
	SO_X	Engine	Fuel combustion	Atmosphere	- Acid rain - Dry deposition - Radiative forcing - Secondary particulate formation	MARPOL Annex VI Regulation 14	ABS Enviro/ Enviro+; Blue Angel; CCWG; CSI; DNV Clean; ESI; Green Award; RINA Green Plus/ Green Star

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Interaction	Hazard	Source	Pathway	Receptor	Environmental impacts	IMO regulations	Environmental initiatives
Emissions to Air (continued)	NO_X	Engine	Fuel combustion	Atmosphere	- Acidification - Eutrophication - Surface ozone formation - Radiative forcing - Secondary particulate formation	MARPOL Annex VI Regulation 13	ABS Enviro/ Enviro+; Blue Angel; CCWG; CSI; DNV Clean; ESI; Green Award; Green Ship Incentive Program; Norwegian NO_X fund; RINA Green Plus/ Green Star
	PM	Engine	- Fuel combustion - Material wear - Lubrication oil	- Atmosphere - Humans	- Human health - Radiative forcing - Decrease in snow/ice albedo - Acid rain	Covered by MARPOL Annex VI Regulation 14	Blue Angel; CSI; Green Award; RINA Green Plus
	VOCs	- Solvent containing materials - Crude oil - Engine	- Solvent evaporation cleaning/oil tank ventilation - Fuel combustion	- Atmosphere - Humans	- Human health - Secondary radiative forcing - Secondary acid rain - Photochemical smog formation	MARPOL Annex VI Regulation 15	n/a
Discharges to Water	Oil	- Fuel tanks - Storage containers	- Spillage - Leakage	- Sea/water body - Aquatic species - Marine ecosystems - Humans	- Toxification of biota - Suffocation of biota - Ocean hypoxia - Hypothermia in sea birds - Physical damage to shore line - Disease in marine species - Bioaccumulation in marine species	MARPOL Annex I	ABS Enviro/ Enviro+; Blue Angel; CCWG; CSI; DNV Clean/ Clean Design; Green Award; RINA Green Plus/ Green Star

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Interaction	Hazard	Source	Pathway	Receptor	Environmental impacts	IMO regulations	Environmental initiatives
Discharges to Water (continued)	Sewage	- Toilets - Medical facilities - Live animal premises	- Disposal - Spillage	- Sea/water body - Humans - Marine ecosystems	- Direct toxification of biota - Eutrophication - Ocean hypoxia and anoxia - Hydrogen Sulphide formation - Stunted growth rate of marine species - Human health	MARPOL Annex IV	ABS Enviro/ Enviro+; Blue Angel; CCWG; CSI; DNV Clean/ Clean Design; Green Award (Inland vessels); RINA Green Plus/ Green Star
	Grey water	- Washing facilities - Oily water separators	- Disposal - Spillage	- Sea/water body - Marine ecosystems		Not regulated by the IMO	ABS Enviro+; Blue Angel; CCWG; CSI; DNV Clean Design; Green Award (Inland vessels); RINA Green Plus/ Green Star
	Antifoul coating	Hull coatings	- Leakage - Dissolution	- Sea/water body - Aquatic species	- Imposex and stunted growth of marine species due to TBT release - Bioaccumulation of Cu in marine organisms - Toxification of marine organisms (Irgarol and Diuron)	- AFS Convention	ABS Enviro/ Enviro+; Blue Angel; CCWG; CSI; DNV Clean Design; Green Award; RINA Green Plus/ Green Star
	Invasive species transfer	- Ballast water - Hull fouling	- Ballast water release - Detachment from hull	- Sea/water body - Marine ecosystems - Aquatic species	- Relocation and establishment of alien species - Competition for resources with native species - Damage to infrastructure - Spread of disease - Increase in fuel consumption due to hull fouling	- BWM Convention - Biofouling Guidelines (MEPC.207(62)) - only guidance, not regulation	ABS Enviro/ Enviro+; Blue Angel; CCWG; DNV Clean/ Clean Design; Green Award; RINA Green Plus/ Green Star

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Interaction	Hazard	Source	Pathway	Receptor	Environmental impacts	IMO regulations	Environmental initiatives
Discharges to Water (continued)	Marine litter	- Discarded from ship - Lost from ship	- Disposal - Accidental loss	- Sea/water body - Humans (bathing) - Marine ecosystems	- Human health - Shoreline aesthetics - Infrastructure damage - Entanglement of marine species - Bioaccumulation of micro plastics in marine species - Habitat destruction	MARPOL Annex V	n/a (classified as garbage)
	Chemicals	- Cargo - Cleaning products	- Spillage - Leakage	- Sea/water body - Aquatic species - Marine ecosystems - Humans	- Human health - Toxification of biota - Bioaccumulation in marine species - Habitat destruction	- MARPOL Annex II - HNS Convention - SOLAS Convention 1974	ABS Enviro/ Enviro+; Blue Angel; CCWG; CSI; DNV Clean
Land	Garbage	On-board solid waste	- Disposal at port/harbours - Fly tipping - Accidental loss	- Land - Soil	- Chemical leaching into soil and watercourse - Odour - Aesthetics of waste disposal sites in ports/harbours	MARPOL Annex V	ABS Enviro/ Enviro+; Blue Angel; CCWG; CSI; DNV Clean/ Clean Design; Green Award; RINA Green Plus/ Green Star

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Interaction	Hazard	Source	Pathway	Receptor	Environmental impacts	IMO regulations	Environmental initiatives
Anthropogenic Noise	Underwater noise	- Propellers - Engines	Soundwaves (exacerbated by cavitation)	- Sea/water body - Aquatic species	- Acoustic masking of communication signals in marine species - Behavioural disruption of marine species - Reduced population density of marine species - Physiological impacts on marine species	Guidance on Noise from Commercial Shipping and its Adverse Impacts on Marine Life (MEPC 66/17 2013) – only guidance, not regulation.	Blue Angel
	Surface noise	- Shipping activities - Warning sirens	Soundwaves	Humans	- Human health - Annoyance - Distraction leading to increased safety risks	SOLAS Convention - Code on noise levels on board ships (MSC.337(91))	n/a
Physical Contact	Collisions with marine animals	Ship's hull/ propellers	- Ship movement - Movement of aquatic species	Aquatic species (Cetaceans)	- Serious injury to aquatic species - Death of aquatic species	Guidance for Minimising the Risk of Ship Strikes with Cetaceans (MEPC.1/Circ.674) – guidance only, not regulation	n/a

Appendix B

Ship environmental initiative inventory

Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
ABS Enviro	ABS	Not region specific	Multiple	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011
ABS Enviro+	ABS	Not region specific	Multiple	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; EMSA, 2007
Air Cavity System (ACS)	DK Group	n/a	n/a	Yes	Research & Innovation	Not available	Fridell, *et al.*, 2013
AUSMEPA Membership	Australian Marine Environment Protection Association	Australia	Multiple	Yes	Research & Innovation	Available	Svensson and Andersson, 2011
BREE(D)I - Baltic Region Environmental Efficiency (Design) Index	Deltamarin and Baltic Sea Action Group (BSAG)	Baltic Region	n/a	Yes	Research & Innovation	Not Available	EMSA, 2007
CCWG Environmental performance scorecard	Clean Cargo Working Group (CCWG)	Not region specific	Multiple	Yes	Performance Indicator	Available	EMSA, 2007

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
Class notations for green ships	China Classification Society (CCS)	China	Single	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; EMSA, 2007
Clean Marine Award	EU	Europe	n/a	No	Incentive Scheme	n/a	Fridell, *et al.*, 2013; Svensson and Andersson, 2011
Clean Shipping Index (CSI)	Clean Shipping Project	Not region specific	Multiple	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013
Clean Shipping Project (Sweden)	Clean Shipping Project	n/a	n/a	Yes	Research & Innovation	Available	EMSA, 2007
Cleanship	Bureau Veritas (BV)	Not region specific	Multiple	Yes	Performance Indicator	Available	SSI, 2013
Cleanship Super	Bureau Veritas (BV)	Not region specific	Multiple	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013
CMAQ Improvement Programme(Congestion Mitigation and Air Quality)	New York State Department for Transportation	USA	Single	Yes	Incentive Scheme	Available	Fridell, *et al.*, 2013; EMSA, 2007
Cruise Ship Environmental Award	Port of San Francisco Cruise Terminal Environmental Advisory Committee (CTEAC)	USA	Multiple	Yes	Incentive Scheme	Not available	Fridell, *et al.*, 2013; EMSA, 2007
$CSNO_X$ technology	Ecospec Global Technology	n/a	n/a	Yes	Research & Innovation	Available	Fridell, *et al.*, 2013; EMSA, 2007

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
DNV Clean	DNVGL	Not region specific	Multiple	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; EMSA, 2007
DNV Clean Design	DNVGL	Not region specific	Multiple	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; EMSA, 2007
Earth Environmental Price	Not available	Not available	Not available	Not available	Research & Innovation	n/a	Fridell, *et al.*, 2013; EMSA, 2007
ECO Notation (Lloyds Register)	LR	Not region specific	Multiple	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; Pike *et al.*, 2011
Eco Ship project	NYK Line	n/a	n/a	Yes	Research & Innovation	Available	Fridell, *et al.*, 2013; EMSA, 2007
ECOPRO - voluntary protection programme and exception compliance programme	Washington State Department of Ecology	USA	Single	Yes	Incentive Scheme	Not available	Pike *et al.*, 2011
EcoShip (Sweden)	Volvo - Penta	n/a	n/a	Yes	Research & Innovation	Not available	EMSA, 2007

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
ECOSHIP-UP	Norden Energy and Transport Programme	n/a	n/a	Yes	Research & Innovation	Not available	EMSA, 2007
Energy Efficiency Design Index (EEDI)	IMO	Not region specific	Single	Yes	Regulatory	Available	Fridell *et al.*, 2013; EMSA, 2007
Energy Efficiency Operational Index (EEOI)	IMO	Not region specific	Single	Yes	Regulatory	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; EMSA, 2007
Environmental Awareness	ClassNK	Not region specific	Multiple	Yes	Performance Indicator	Not available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011
Environmental Passport for Design	DNVGL	Not region specific	Multiple	Yes	Performance Indicator	Available	SSI, 2013
Environmental Safety Class Notation (ABS)	ABS	Not region specific	Multiple	No	Performance Indicator	n/a	EMSA, 2007
Environmental Ship Index (ESI)	World Ports Sustainability Programme (WPSP)	Not region specific	Multiple	Yes	Performance Indicator	Available	EMSA, 2007
European Clean Ship Awarding System	Hamburg Port Training Institute	Europe	Multiple	No	Performance Indicator	n/a	EMSA, 2007

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
EVDI	RightShip	Not region specific	Single	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; Stuer-Laridsen *et al.*, 2014
Fair Winds Charter	Civic Exchange (Hong Kong)	Hong Kong	Single	No	Incentive Scheme	n/a	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; Stuer-Laridsen *et al.*, 2014
FellowSHIP programme	DNVGL	n/a	n/a	Yes	Research & Innovation	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; Pike *et al.*, 2011; SSI, 2013; Stuer-Laridsen *et al.*, 2014
Finland I	Port of Helsinki	Finland	Single	Yes	Incentive Scheme	Not available	Stuer-Laridsen *et al.*, 2014

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
Finland II	Finland	Finland	Single	Yes	Incentive Scheme	Not available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; SSI, 2013; Stuer-Laridsen *et al.*, 2014
Finland III (The Aaland System)	Port of Mariehamn	Finland	Single	Yes	Incentive Scheme	Not available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011
Formal Safety Assessment: Criteria for environmental differentiating of ships	Norwegian Green Ship Research Programme	Norway	Multiple	No	Research & Innovation	n/a	Fridell, *et al.*, 2013; Svensson and Andersson, 2012
Good Environmental Choice	Swedish Society for Nature Conservation (SNCC)	Scandinavia	Single	Yes	Incentive Scheme	Available (not specific to shipping)	Fridell, et al., 2013; Svensson and Andersson, 2011; Pike et al., 2011; EMSA, 2007; Stuer-Laridsen *et al.*, 2014

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
Green Award	Green Award	Not region specific	Multiple	Yes	Performance Indicator	Available	Fridell, et al., 2013; Svensson and Andersson, 2011; Pike et al., 2011; EMSA, 2007; Stuer-Laridsen *et al.*, 2014
Green Award - Blue label	Green Award	Not region specific	Multiple	No	Performance Indicator	n/a	Pike *et al.*, 2011; EMSA, 2007; Stuer-Laridsen *et al.*, 2014
Green Flag Incentive Programme	Port of Long Beach	USA	Single	Yes	Incentive Scheme	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011
Green Marine Environmental Programme	Green Marine	USA and Canada	Multiple	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; Pike *et al.*, 2011
Green Passport	IMO	Not region specific	Multiple	Yes	Regulatory	Available	EMSA, 2007

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
Green Plus	RINA	Not region specific	Multiple	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; SSI, 2013; Stuer-Laridsen *et al.*, 2014
Green Port programme (policy)	Port of Long Beach	USA	Single	Yes	Research & Innovation	Available	Svensson and Andersson, 2011
Green Ship Incentive Programme	Port of Long Beach	USA	Single	Yes	Incentive Scheme	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; SSI, 2013
Green Ship programme and certificate	Korean Coast Guard and Korean Finance Corporation (KoFC)	Korea	Multiple	Yes	Incentive Scheme	Not available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; EMSA, 2007; SSI, 2013
Green Star	RINA	Not region specific	Multiple	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; Pike *et al.*, 2011

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
Hamworthy Krystallon sea water scrubbing system	Wartsila	n/a	n/a	Yes	Research & Innovation	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; SSI, 2013
Keep it Blue	French Ports	France	Single	No	Research & Innovation	n/a	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; Stuer-Laridsen *et al.*, 2014
Korean Green Ship System	Korean Ports	Korea	n/a	Yes	Incentive Scheme	Not available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; Pike *et al.*, 2011; EMSA, 2007; Stuer-Laridsen *et al.*, 2014
Life Buoy Award	Port of Stockholm	Sweden	n/a	No	Incentive Scheme	n/a	Svensson and Andersson, 2011

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
Logistics and Transport sector supplement	Global Reporting Initiative (GRI)	Not region specific	Not available	No	Performance Indicator	n/a	SSI, 2013
Low Carbon Consortium	Consortia of UK Universities	n/a	n/a	No	Research & Innovation	n/a	Fridell, *et al.*, 2013; Svensson and Andersson, 2011
Low Sulphur Subsidy Programme (Port of SF - USA)	Port of San Francisco	USA	Single	Yes	Incentive Scheme	Not available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; Pike *et al.*, 2011; EMSA, 2007
Maritime Singapore Green Initiative	Maritime and Port Authority of Singapore	Singapore	Single	Yes	Incentive Scheme	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; Pike *et al.*, 2011; EMSA, 2007
MVEP (Marine Vessel Environmental Performance assessment)	The Society of Naval Architects and Marine Engineers (SNAME)	Not region specific	Multiple	No	Performance Indicator	n/a	Fridell, et al., 2013; Svensson and Andersson, 2011; SSI, 2013

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
Norwegian NO_X Fund	Norwegian Maritime Administration	Norway	Single	Yes	Incentive Scheme	Available	EMSA, 2007
OMS Screener	Washington State Office for Marine Safety	USA	Not available	No	Incentive Scheme	n/a	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; Stuer-Laridsen *et al.*, 2014
Operational CO_2 index certification (EEOI certification)	DNVGL	Not region specific	Single	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011
OVG Hong Kong	Hong Kong Environmental Protection Department	Hong Kong	Single	No	Incentive Scheme	n/a	Fridell, *et al.*, 2013; Svensson and Andersson, 2011
Port of Antwerp incentive for differentiated harbour dues	Port of Antwerp	Belgium	Single	Yes	Incentive Scheme	Not available	Fridell, *et al.*, 2013; Svensson and Andersson, 2011; Stuer-Laridsen *et al.*, 2014

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
Port of Kaliningrad incentive for differentiated harbour dues	Port of Kaliningrad	Russia	Single	Yes	Incentive Scheme	Not available	Pike *et al.*, 2011
Port of New York and New Jersey incentive for differentiated harbour dues	Port of New York and New Jersey	USA	Single	Yes	Incentive Scheme	Not available	Pike *et al.*, 2011
Port of Szczecin-Swinoujscie reduction of pollution	Port of Szczecin-Swinoujscie	Poland	Multiple	Yes	Incentive Scheme	Not available	Fridell *et al.*, 2013; EMSA, 2007
Poseidon Challenge	Interntanko	Company specific	Multiple	Yes	Incentive Scheme	Available	Svensson and Andersson, 2011
Qualship 21	United States Coast Guard	USA	Multiple	Yes	Incentive Scheme	Available	Pike *et al.*, 2011
Rotor Sails	Greenwave Wind Engines	n/a	n/a	Yes	Research & Innovation	Not available	Pike *et al.*, 2011
Save the waves	Royal Caribbean International	Company specific	Multiple	Yes	Research & Innovation	Available	EMSA, 2007
S-Class Ships	Evergreen Marine Corporation	Company specific	n/a	Yes	Research & Innovation	Not available	Pike *et al.*, 2011
Ship Energy Efficiency Management Plan (SEEMP)	IMO	Not region specific	Single	Yes	Regulatory	Available	Pike *et al.*, 2011
STCW (Standards of Training, Certification and Watch-keeping)	IMO	Not region specific	n/a	Yes	Regulatory	Available	Svensson and Andersson, 2011

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
Swedish incentive for differentiated harbour dues	Swedish Shipowners Association, Swedish Port Association and Swedish Maritime Association	Sweden	Single	Yes	Incentive Scheme	Not Available	Pike *et al.*, 2011
The Blue Angel RAL-UZ 110 (operation)	Federal Government of Germany	Germany	Multiple	Yes	Performance Indicator	Available	Svensson and Andersson, 2011
The Blue Angel RAL-UZ 141 (design)	Federal Government of Germany	Germany	Multiple	Yes	Performance Indicator	Available	Fridell, *et al.*, 2013; EMSA, 2007
The Blue Circle Award	Port of Vancouver	Canada	Multiple	Yes	Incentive Scheme	Available	Pike *et al.*, 2011
The Carl Moyer Programme	California Air Resources Board	USA	Single	Yes	Incentive Scheme	Available	Fridell, *et al.*, 2013; Pike *et al.*, 2011; EMSA, 2007
The North Sea Foundation	The North Sea Foundation (Environmental NGO)	North Sea Region	n/a	Yes	Research & Innovation	Available	Fridell, *et al.*, 2013; Pike *et al.*, 2011
The PROSea Foundation	The ProSea Foundation (Environmental NGO)	n/a	n/a	Yes	Research & Innovation	Available	Pike *et al.*, 2011
The Sustainable Shipping Council	The Sustainable Shipping Council (Led by WWF)	Not region specific	Multiple	No	Research & Innovation	n/a	Fridell, *et al.*, 2013; EMSA, 2007

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Name or description	Developer	Country/Region of applicability	No. of environmental criteria	Active	Initiative classification	Availability of Information	Reference
The VCS Program	Verra	Not region specific	Single	Yes	Incentive Scheme	Available (not specific to shipping)	Pike *et al.*, 2011
Thor Heyerdahl Maritime Environmental award	Thor Heyerdahl and the Norwegian Shippers Association	Norway	n/a	Yes	Incentive Scheme	Not available	Pike *et al.*, 2011
TRESHIP	Not available	Not available	n/a	No	Research & Innovation	n/a	Pike *et al.*, 2011
Triple E	DNVGL	Not region specific	Multiple	Yes	Performance Indicator	Available	Svensson and Andersson, 2011; Pike *et al.*, 2011
US Coast Guard Safety Point System	US Coast Guard	USA	not available	Not available	Performance Indicator	n/a	Pike *et al.*, 2011

Appendix C

Princess Royal voyage data

C1. Inventory of materials for 18/02/2018 - 05/03/2018

Material	Description	Quantity	Number of units	Total quantity on board	Liquid containing chemicals (y/n)	CMR classified (y/n)	Volume of chemical containing liquid (litres)	Volume of oil (litres)
Heavy duty degreaser	Contains: Alcohol ethoxylate; 2-aminoethanol; Non-ionic surfactants, Phosphates; Anionic surfactants < 5%	5 litres	2	10 litres	y	n	10	0
hydraulic oil	Mineral oil	20 litres	3	60 litres	y	n/a	60	60
Anti-seize compound	Lubricant blend	0.5 Kg	1	0.5 Kg	n	n	0	0
Household thick bleach	Contains: Sodium hypochlorite; Sodium hydroxide; Sodium laureth sulphate/amides; coco; N-[3-dimethylamino)propyl]; N-oxides	750 ml	1	750 ml	n	n	0	0
WD40 - lubricant	Contains: Hydrocarbons, C9-C11; N-alkanes; isoalkanes; cyclic's; <2% aromatics	450 ml	2	900 ml	y	n	0.9	0.9
Multi surface cleaner	Contains: 5-15% Non-ionic surfactants; <5% Anionic surfactants; Phosphonates Polycarboxylates; Benzisothiazolinone; Perfumes; Citral; Citranellol; Gerianol; Hexyl cinnamal; Limonene; Linalool	885 ml	1	885 ml	y	n	0.885	0
Copper grease	Contains: Hydrocarbons, C6-C7; N-alkanes; Isoalkanes; Cyclics; <5% n-hexane	400 ml	1	400 ml	y	n	0.4	0
Anti-seize copper grease	Lubricant	0.5 Kg	1	0.5 Kg	n	n	0	0
Mechoil - lubricant	Contains: Hydrocarbons, C9-C11; N-alkanes; isoalkanes; cyclics; <2% aromatics	400 ml	1	400 ml	y	n	0.4	0.4
Universal sealant	Mechanical sealant	300 ml	1	300 ml	n	n	0	0

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Material	Description	Quantity	Number of units	Total quantity on board	Liquid containing chemicals (y/n)	CMR classified (y/n)	Volume of chemical containing liquid (litres)	Volume of oil (litres)
Sikaflex - adhesive, sealant, filler	adhesive and sealant	300 ml	1	300 ml	n	n	0	0
Multipurpose grease	Lubricant	0.4 Kg	4	1.6 kg	n	n	0	0
Universal gear oil	Lubricant	1 litre	1	1 litre	y	N	1	1
Air freshner	Aerosol	240 ml	1	240 ml	y	n	0.24	0
White spirit	Contains: Hydrocarbons C9-C12; n-alkanes; isoalkanes; cyclics; aromatics (2-25%) 919-446-0	750 ml	1	750 ml	y	n	0.75	0
Beko refrigerator	Contains: R600a refrigerant gas; Cyclopentane insulation gas (unknown quantity)	0.02 Kg	1	0.02 Kg	n	n/a	0	0
Antibacterial spray	Contains: Benzoalkonium chloride; <5% Nonionic surfactants; Disinfectant; Perfume; Limonene	1 litre	2	2 litres	y	n	2	0
Blue cleaning roll		400 sheets	6	2400 sheets	n	n/a	0	0
Waste bins		20 litre capacity	2	40 litre capacity	n	n/a	0	0
Foam fire extinguishers	Contains: 1.9L water; 60 ml foam additive	2 litres	2	4 litres	n	n/a	0	0
Powder fire extinguishers	ABC70 Dry chemical powder (Mono Ammonium phosphate)	4 litres	2	8 litres	n	n/a	0	0
Washing up liquid	Cleaning product	1 litres	1	1 litre	n	n	0	0
LEC refrigerator	Contains: R600a refrigerant gas	0.017 Kg	1	0.017 Kg	n	n/a	0	0
Ultra-high performance engine oil	Contains: Calcium long chain alkaryl sulphonate	20 litres	4	80 litres	y	n/a	80	80
Diesel	Oil	25 litres	2	50 litres	y	n/a	50	50

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Material	Description	Quantity	Number of units	Total quantity on board	Liquid containing chemicals (y/n)	CMR classified (y/n)	Volume of chemical containing liquid (litres)	Volume of oil (litres)
Engine oil	Contains: Calcium long chain alkaryl sulphonate	25 litres	2	50 litres	y	n/a	50	50
Stat-X G 1000 E integrated fire suppression system for engine room		1 kg	1	1 kg	n	n/a	0	0
On-board lavatory					n	n/a	0	0
Total (l)							**256.58**	**242.30**
Total (m^3)							**0.26**	**0.24**
Total (metric tonnes)*							**0.26**	**0.21**

*For chemicals (assumed): $1m^3$ = 1 metric tonne; for oil (assumed): $1m^3$ = 0.85 metric tonnes

C2. Calculation of VEP scores for each hazard

Emissions to Air

Emissions of each pollutant in grams were calculated based on the fuel use for each voyage. Fuel use in litres was multiplied by the bulk density of the fuel to determine fuel use in Kg, then converted into g. The bulk density of the fuel was assumed to be 0.85 g/ml, the median value for MGO taken from the MGO MSDS (WCF, 2012). Fuel use in g was multiplied by the emission factors for MGO (as published by Smith *et al.*, 2014 – Tables 32, 67, and 68), to determine the amount of each pollutant emitted in grams.

IMO emissions factors for MGO, for each pollutant taken from the Third IMO GHG Study (Smith et al., 2014)

Pollutant	Emission Factor (g/g fuel)
CO_2	3.206
CH_4	0.00006
N_2O	0.00015
SO_X	0.01
NO_X	0.05684
PM	0.00097
VOCs	0.00308

Calculated emissions of air pollutants in g based on IMO emissions factors

Voyage date	Fuel use		Emissions of pollutant in g						
	(Litres)	(g)	CO_2	CH_4	N_2O	NO_X	SO_X	PM	VOCs
18/02/2018	120	102,000	327,012	6	16	5,798	1,020	99	314
22/02/2018	660	561,000	1,798,566	34	90	31,887	5,610	544	1,728
26/02/2018	300	255,000	817,530	15	41	14,494	2,550	247	785
05/03/2018	310	263,500	844,781	16	42	14,977	2,635	256	812
Total	1390	1,181,500	3,787,889	71	189	67,156	11,815	1,146	3,639

VEP scores were calculated by dividing the emissions (g) of each pollutant by the weight of the vessel (tonnes) and the distance travelled (nm) for each voyage. The vessel weight was assumed to be 41 tonnes, taken as the lightweight displacement (36 tonnes) and the payload (five tonnes) from the vessel specification document (Newcastle University, 2018).

The distance travelled in each voyage was as follows:

18/02/2018 = 6 nm

22/02/2018 = 50 nm

26/02/2018 = 40 nm

05/03/2018 = 40 nm

Calculated VEP scores per voyage in g/tonne-mile are as follows:

Voyage date	VEP (g/tonne-mile)						
	CO_2	CH_4	N_2O	NO_X	SO_X	PM	VOCs
18/02/2018	1,329.32	0.025	0.062	23.57	4.15	0.40	1.28
22/02/2018	877.35	0.016	0.041	15.55	2.74	0.27	0.84
26/02/2018	498.49	0.009	0.023	8.84	1.55	0.15	0.48
05/03/2018	515.11	0.010	0.024	9.13	1.61	0.16	0.49
Total	679.32	0.013	0.032	12.04	2.12	0.21	0.65

The VEP scores were normalised according to the maximum and minimum permissible level of pollutants set out in Table 4.16 for air emissions. Maximum limits were calculated based on vessel design using the formula shown in Table 4.16 for air emissions, and the following data for the Princess Royal:

P = 894 kW

SFC = 197 g/kWh

V = 20 knots

D = 41 tonnes

The emission factors (EF) of each pollutants were based on IMO published baseline emission factors (Annex 6 and 7 of Smith *et al.,* 2014). To calculate the reference for maximum emissions, the highest published emissions factors were used for each pollutant, as follows:

Maximum IMO emissions factors for each pollutant taken from Smith et al., 2014

Pollutant	Emission Factor (g/g fuel)
CO_2	3.206
CH_4	0.0512
N_2O	0.00016
SO_X	0.053
NO_X	0.0961
PM	0.00728
VOCs	0.00308

The maximum permissible emissions values (MPL) for CO_2, N_2O and CH_4 were converted into g CO_2 eq. and added together to determine a maximum permissible value for GHGs:

Pollutant	MPL (g/t nm-1)	GWP	MPL (g CO_2 eq./t-nm)
CO_2	688.58	1	688.58
CH_4	10.997	21	230.93
N_2O	0.034	298	10.24
GHGs			**929.75**

The maximum and minimum permissible limits for air emissions from the Princess Royal are tabulated below:

Calculated maximum and minimum permissible limits for air emissions from the Princess Royal based on vessel design

Hazard	Maximum	Minimum	Unit
GHGs	929.75	0	g/tonne-mile
SO_X	11.38	0	g/tonne-mile
NO_X	20.64	0	g/tonne-mile
PM	1.56	0	g/tonne-mile
VOCs	0.66	0	g/tonne-mile

The VEP scores per voyage for each pollutant were normalised on a scale of 0 to 5 using the calculated maximum and minimum permissible limits as a reference. Normalised scores were calculated using the following equation:

$$VEP_n = a + (x - A)\,(b - a)\,/\,(B - A) \quad \text{(C1)}$$

Where: A = minimum permissible emission

B = maximum permissible emission

a = 0 (minimum value of normalised scale)

b = 5 (maximum value of normalised scale)

x = VEP score

VEP_n = normalised VEP score

E.g. for GHG emissions for the total from all voyages,

$A = 0$

$B = 929.75$

$a = 0$

$b = 5$

$x = 689.06$

$VEP_n = 0 + (689.06 - 0)(5 - 0) / (929.75 - 0)$

$= 0 + 689.06 * 5 / 929.75$

$= 3,445.3 / 929.75$

$VEP_n = 3.71$

In certain cases, the actual emissions of pollutants exceeded the maximum permissible limits, in such cases the maximum VEP_n scores are capped at 5. The VEP_n scores for each hazard per voyage are as follows:

Hazard	Normalised VEP scores per voyage				
	18/02/2018	22/02/2018	26/02/2018	05/03/2018	Total
GHGs	5.0	4.79	2.72	2.81	3.71
SO_X	1.82	1.20	0.68	0.71	0.93
NO_X	5.00	3.77	2.14	2.21	2.92
PM	1.29	0.85	0.48	0.50	0.66
VOCs	5.00	5.00	3.62	3.74	4.93

VEP scores for refrigerants were calculated by calculating the total quantity of refrigerants on board in tonnes CO_2 equivalents. The following formula is used to calculate CO_2 eq. in tonnes of refrigerants:

$$Quantity\ of\ refrigerant\ (Kg) * GWP / 1000 = CO_2\ eq.\ (tonnes) \qquad \text{(C2)}$$

$$= 0.037 \text{ kg} * 3 / 1000 = 0.00011$$

Where: $Quantity\ of\ refrigerant\ (Kg) = 0.037$

$GWP = 3$

Normalised VEP scores were calculated using formula C1 for normalisation, and the maximum and minimum permissible limits for refrigerants as outlined in Table 4.16.

The VEP_n score for refrigerants is 0.0000011.

Discharges to Water

The VEP scores and VEP_n scores for antifoul coating, sewage, chemicals, and on-board stored oil were calculated. The vessel did not collect ballast water and the data for oily water (bilge) collection and marine litter was recorded as 0. For antifoul coating, the maximum and minimum permissible limits outlined in Table 4.16 were utilised, and the Tin content of Intersleek 1100 was taken from the literature. Intersleek 1100 is classified as a biocide free coating and does not use Tin as an active ingredient to prevent biofouling. However, it does contain up to

10% diocytyltin dilaurate as a catalysing agent (AzkoNobel, 2017). As is highlighted in Chapter 2, Section 2.3.3 of this thesis, the use of tin based compounds as catalysts in antifoul coatings are an environmental concern (Watermann *et al.,* 2005), therefore are taken into account in this methodology. International Paint, the supplier of Intersleek 1100 SR claim the coatings overall tin content is 1000 mg/kg tin (ECO, 2016), so this figure will be used in this research. The antifoul coating was present throughout each of the voyages, therefore the same VEP_n score was calculated for each voyage.

The VEP_n score for antifoul coating was calculated using equation C1 as follows:

VEP_n = 0 + (1000 - 0) (5 - 0) / (2500 - 0)

= 5000 / 2500

VEP_n = 2

Where,

A = 0

B = 2,500 mg/kg

a = 0

b = 5

x = 1000 mg/kg

To calculate the VEP of sewage for each voyage (X), the discharge rate (m^3/hr) assuming a constant discharge over the duration of the voyage was calculated. This was done by dividing the volume of sewage produced in m^3 by the voyage duration in hours. The maximum permissible discharge rate (B) per voyage was calculated based on the IMO MARPOL Annex IV requirements, using the following equation:

$$DR_{max} = 0.00926 * V * B * D \qquad \text{(C3)}$$

Where,

DR_{max} = maximum allowable discharge date (m^3/hr)

V = vessel average speed (knots)

B = vessel breadth (m)

D = vessel draft (m)

Sewage VEP_n values were calculated per voyage using equation C1 with the following data (grey water was not collected separately and therefore given a score of 0). The maximum permissible discharge rate varies from voyage to voyage as the vessel average speed was different for each voyage (see Table 5.1).

Factor	18/02/2018	22/02/2018	26/02/2018	05/03/2018	Total
A	0	0	0	0	0
B (m^3/hr)	0.55	1.66	1.11	1.11	1.11
a	0	0	0	0	0
b	5	5	5	5	5
X (m^3/hr)	0.002	0.004	0.007	0.008	0.006
VEP_n	0.018	0.012	0.032	0.036	

For chemicals, the VEP score represents the total volume of liquid chemicals (tonnes) on board the vessel during each voyage. The inventory of chemicals was collated prior to the first voyage, and it is assumed that the total volume did not change throughout the total period of data collection. The maximum permissible level was set based on the carrying capacity of a reference large chemical tanker (see Table 4.16). The VEP_n score was calculated using equation C1 based on the following data:

Factor	For all voyages
A	0
B (tonnes)	50,000
a	0
b	5
X (tonnes)	0.26
VEP_n	0.000026

For on board stored oil, the VEP score represents the volume of stored oil on board the vessel in tonnes, as shown in the inventory. Like with chemicals, it is assumed that the volume of stored oil remained constant throughout the period of research. The maximum permissible level was determined based on the carrying capacity of a reference large oil tanker, as outlined in Table 4.16. The VEP_n score for oil was calculated using equation C1 based on the following data:

Factor	For all voyages
A	0
B (tonnes)	500,000
a	0
b	5
X (tonnes)	0.21
VEP_n	0.0000021

Land

The VEP scores for garbage were calculated based on the estimated volume of garbage produced per voyage in Kg, divided by the number of persons on board. The VEP_n scores were calculated using equation C1, the maximum permissible level was set at 14 kg/person day^{-1} in accordance with Table 4.16.

Voyage date	Garbage production (Kg)	No. of persons on board per day	VEP (Kg/person-day)	VEP_n
18/02/2018	0	4	0	0
22/02/2018	15	5	3	1.07
26/02/2018	15	14	1.07	0.38
05/03/2018	15	13	1.15	0.41
Total	45	36	1.25	0.45

Anthropogenic Noise

No data was provided for engine noise levels (dB), therefore the VEP_n score was set at the maximum level of 5. Where data has not been recorded, the VEP is set at the maximum level to encourage more comprehensive data recording and collection.

Physical Contact

The VEP and VEP_n scores for contact with marine animals were set at 0 for each voyage, as no interactions with marine life were recorded. Ship strikes with marine animals are rare, and hence if a strike were to occur during a voyage the vessel would receive the maximum VEP_n score for that voyage.

Appendix D

Max Pruss voyage data

D1. Inventory of materials for 25/01/2019

Material	Description	Quantity	Number of units	Total quantity on board	liquid containing chemicals (y/n)	CMR classified? (y/n)	Volume of chemical containing liquid (litres)	Volume of oil (litres)
Cleaning fluid	Ajax cleaning fluid (contains isopropyl alcohol)	10 litres	3	30 litres	y	n	30	0
Dishwasher fluid	Contains Methylisothiazolinone (MI)	10 litres	1	10 litres	y	n	10	0
Scouring milk (Cif)	Contains Sodium Hypochlorite; Sodium Carbonate; Pareth Sulphate (secondary VOC generation); Methylchloroisothiazolinone (MCI)	750 ml	8	6 litres	y	n	6	0
Floor cleaner	Contains MI and MCI and other VOC's	1 litre	5	5 litres	y	n	5	0
White spirit	Contains hydrocarbons, C9-C12, n-alkanes, isoalkanes, cyclics, aromatics	1 litre	2	2 litres	y	n	2	0
Glass cleaner	Contains anionic surfactants including VOC's	1 litre	1	1 litre	y	n	1	0
Washing up liquid	Cleaning product	750 ml	4	3 litres	y	n	3	0
Antibacterial spray	Contains benzoalkonium chloride; <5% Nonionic surfactants; Disinfectant	750 ml	6	4.5 litres	y	n	4.5	0
Lighter fuel	Contains butane	1 litre	1	1 litre	y	n	1	0
Diesel exhaust fluid	Lubricant	1000 litres	1	1000 litres	y	n	1000	0

Continued overleaf…

Material	Description	Quantity	Number of units	Total quantity on board	liquid containing chemicals (y/n)	CMR classified? (y/n)	Volume of chemical containing liquid (litres)	Volume of oil (litres)
Household paint	Contains multiple VOC's	5 litres	8	40 litres	y	n	40	0
Diesel fuel	In fuel tanks	5000 litres	1	5000 litres	y	n/a	0	5000
Engine oil	Engine room refill tank (300 litre capacity)	90 litres	1	90 litres	y	n/a	0	90
Gasoline	Dinghy fuel tank	60 litres	1	60 litres	y	n/a	0	60
Hydraulic oil	Mineral oil	300 litres	1	300 litres	y	n/a	0	300
Engine oil	additional oil (mobile)	20 litres	1	20 litres	y	n/a	0	20
Refrigerator (1)	Contains R600a refrigerant gas	58 grams	1	58 grams	n	n/a	0	0
Refrigerator (2)	Contains R600a refrigerant gas	31 grams	1	31 grams	n	n/a	0	0
Freezer (1)	Contains R600a refrigerant gas	47 grams	1	47 grams	n	n/a	0	0
Freezer (2)	Contains R600a refrigerant gas	72 grams	1	72 grams	n	n/a	0	0
Freezer (3)	Contains R600a refrigerant gas	47 grams	1	47 grams	n	n/a	0	0
Fire extinguishers	contains 140g CO_2 propellant; 6kg extinguishing powder (ammonium dihydrogen phosphate and ammonium sulphate)	6 Kg	4	24 Kg	n	n/a	0	0
Fire extinguisher	Contains water	3 litres	1	3 litres	n	n/a	0	0
Drinking water	Drinking water tank	5000 litres	1	5000 litres	n	n/a	0	0
Air conditioning unit	Contains R410A refrigerant gas	4.56 Kg	1	4.56 Kg	n	n/a	0	0
Waste bins	Multiple bins, all emptied into 1 large bin	60 kg	1	60 kg	n	n/a	0	0
Sewage tank	500 litre capacity	5000 litres	1	5000 litres	n	n/a	0	0
Total (l)							1102.5	5470
Total (m3)							1.10	5.47
Total (metric tonnes)*							1.10	4.65

*For chemicals (assumed): $1m^3$ = 1 metric tonne; for oil (assumed): $1m^3$ = 0.85 metric tonnes

D2. Summary of raw voyage data for the Max Pruss

The raw data for the complete voyage of the Max Pruss on 25/01/2019 was collected by Multronic Emissions Systems via a Testo 350 portable flue gas analyser. The raw data contains over 15,000 samples taken at approximately 1 second intervals, and includes the time of the sample, the fuel use in litres per hour for each sample, and the vessel speed in kilometres per hour for each sample. This data was used to calculate the total fuel use for the voyage (assuming there were two engines running), the average speed during the voyage, and the total distance travelled, while the top speed and total time of the voyage was inferred from the data. A summary of the raw data is shown in the table below:

Summary of voyage data	
Top speed (km/h) =	25.77
Average speed (km/h) =	13.80
Top speed (mph) =	16.01
Average speed (mph) =	8.57
Top speed (knots) =	13.91
Average speed (knots) =	7.45
Total time (hr:min:sec) =	04:27:56
Total distance (km) =	61.67
Total distance (miles) =	38.32
Total distance (nautical miles) =	33.30
Fuel use (l) =	175.26

D3. Calculation of VEP scores for each hazard

VEP scores for the Max Pruss were calculated using the same process as for the Princess Royal in Appendix C.

Emissions to Air

Fuel use in litres was multiplied by the bulk density of the fuel (0.85 g/ml) to convert to fuel use in g. The following emission factors were used to calculate the emissions of air pollutants in g (excluding refrigerants) for the Max Pruss:

Lloyds Register (1995) emission factors for a medium speed diesel engine (IVL, 2002)

Pollutant	Emission Factor (g/g fuel)
CO_2	3.170
CH_4	0.0003
N_2O	0.00008
SO_X	0.002
NO_X	0.057
PM	0.0012
VOCs	0.0021

The quantity of air pollutants in g for the voyage were calculated as follows:

Fuel use		Emissions of pollutants (g)						
Litres	g	CO_2	CH_4	N_2O	NO_X	SO_X	PM	VOCs
175.259	148,970	472,235.94	44.69	11.92	8,491.29	297.94	178.76	312.84

VEP scores (g/tonne-mile) were then calculated by dividing the total emission of each pollutant by the distance travelled (33.3 nm) and the vessel weight (141 tonnes). The VEP scores for CO_2, CH_4 and N_2O were combined and converted into g CO_2 eq. /tonne mile^{-1}. The VEP scores were normalised on a scale of 0-5 using maximum and minimum permissible emission limits (g/tonne mile^{-1}), calculated using formula 4.1 outlined in Section 4.11. The following vessel data was used to calculate the maximum permissible limits:

P = 508 kW

SFC = 213 g/kWh

V = 13.91 knots

D = 141 tonnes

The EF for each pollutant was taken from Smith *et al.*, 2014, shown below:

Maximum and minimum permissible limits for air emissions from the Max Pruss based on vessel design

Hazard	EF (g/g fuel)	Maximum	Minimum	Unit
CO_2	3206	176.87	0	g/tonne-mile
CH_4	0.0512	0.0088	0	g/tonne-mile
N_2O	0.00016	2.82	0	g/tonne-mile
GHGs	n/a	283.82	0	g CO_2 eq./tonne-mile
SO_X	0.053	2.92	0	g/tonne-mile
NO_X	0.0961	5.30	0	g/tonne-mile
PM	0.00728	0.40	0	g/tonne-mile
VOCs	0.00308	0.17	0	g/tonne-mile

*CO_2, CH_4 and N_2O combined to calculate VEP for GHGs

Normalisation of VEP scores was conducted using equation C1 (Appendix C), the VEPn scores can be found in Table 5.9.

Refrigerants: The VEP for refrigerants (X) was calculated using the following equation:

$$X\,(CO_2 \text{ eq. tonnes}) = \Sigma\,(\text{GWP} * \text{Refrigerant mass (tonnes)}) \quad \text{(D1)}$$

R410a and R600A refrigerants were found on board the Max Pruss in different quantities, therefore the total CO_2 eq. was calculated as follows:

R410a: 2088 * 0.00465 (tonnes) = 9.7092 (CO_2 eq. tonnes)

R600a = 3 * 0.00025 (tonnes) = 0.00075 (CO_2 eq. tonnes)

Total = 9.7092 + 0.00075 = 9.71 CO_2 eq. tonnes

The VEP_n score for refrigerants was calculated using the following data:

Factor	Refrigerants
A	0
B	500 (CO_2 eq. tonnes)
a	0
b	5
X	9.71 (CO_2 eq.
VEP_n	0.097

Discharges to Water

VEP and VEP_n scores were calculated for each pollutant categorised as a discharge to water. The process outlined in Appendix C for calculating scores was repeated for the Max Pruss, using equation C1. The vessel did not collect ballast water or grey water therefore both were given a score of 0. Scores of 0 were also given to antifoul paint (none applied), and marine litter. The other scores were calculated as follows:

Factor	Sewage	Bilge water	Oil	Chemicals
A	0	0	0	0
B	0.57 (m^3/hr)	26 (m^3/day)	500,000 (tonnes)	50,000 (tonnes)
a	0	0	0	0
b	5	5	5	5
X	0.067 (m^3/hr)	0.002 (m^3/day)	4.65 (tonnes)	1.1 (tonnes)
VEP_n	0.58	0.00038	0.000046	0.00011

Sewage: The actual discharge rate (X) and maximum permissible discharge rate (B) were calculated based on the collected voyage data (Table 5.8).

$$X = 300 \text{ litres} / 4.47 \text{ hours} = 67.11 \text{ litres per hour} / 1000 = 0.067 \text{ m}^3/\text{hr}$$

$$B = 0.00926 * 7.45 \text{ knots} * 1.1 \text{ metres} * 7.57 \text{ metres} = 0.57 \text{ m}^3/\text{hr}$$

Bilge water: An estimate of oily bilge water production was recorded during the vessel audit, and converted into m^3 (2 litres = 0.002 m^3). The VEP_n was calculated assuming a maximum permissible discharge of 26 m^3/day, as per Table 4.16.

On board stored oil and chemicals: The quantities of on board stored oil and chemicals were calculated based on the inventory of materials collected during the vessel audit. Maximum permissible limits were set based on Table 4.16.

Land

Garbage generation (Kg/person day^{-1}) was calculated by dividing the total amount of garbage produced during the voyage (8.5 Kg) by the number of persons on board (16). The VEP_n was calculated based on the maximum permissible limit for garbage outlined in Table 4.16.

Anthropogenic Noise

The noise level of the engine in decibels was taken from the engine specification. It was not possible to obtain direct measurements of noise data, therefore an estimate based on design was used, in accordance with the check methods outlined in Table 4.14. The VEP_n score was calculated based on the maximum permissible level outlined in Table 4.16.

Physical Contact

No interactions with marine life were recorded during the voyage, therefore the VEP and VEP_n scores for contact with marine animals were set at zero.

D.4 Verification of calculated NO_X emissions

Continuous emissions monitoring equipment was utilised to determine actual NO_X emissions from the Max Pruss for a subset of the voyage conducted on 29th January 2019. Actual measurements were recorded using a Testo gas analyser. Measurements were taken with the engine running at 1600 rpm, with an operating power of 157 kW, at a vessel speed of 7.3 knots. The following data was recorded:

Engine speed (rpm)	Engine power (kW)	Vessel speed (knots)	Fuel consumption (g/hr)	Actual NO_X (g/hr)	Actual NO_X (g/kWh)
1600	157	7.3	32895	2088.1	13.3

The calculated NO_X emissions based on average engine power of 163.1 kW is 11.65 g/kWh. This is within 15% of the actual emissions recorded at a similar power output. Whilst not conclusive, this provides an indication of the accuracy of the emission calculations.