ISBN 978-82-471-4516-6 (printed version)
ISBN 978-82-471-4517-3 (electronic version)
ISSN 1503-8181

NTNU – Trondheim
Norwegian University of
Science and Technology

Haakon Lindstad

Doctoral Thesis

Doctoral theses at NTNU, 2013:201

NTNU
Norwegian University of Science and Technology
Thesis for the degree of Philosophiae Doctor
Faculty of Engineering Science and Technology
Department of Marine Technology

NTNU

Doctoral theses at NTNU, 2013:201

Haakon Lindstad

Strategies and measures for reducing maritime CO_2 emissions

NTNU – Trondheim
Norwegian University of
Science and Technology

Haakon Lindstad

Strategies and measures for reducing maritime CO_2 emissions

Thesis for the degree of philosophiae doctor

Trondheim, August 2013

Norwegian University of Science and Technology
Faculty of Engineering Science and Technology
Department of Marine Technology

NTNU – Trondheim
Norwegian University of
Science and Technology

NTNU
Norwegian University of Science and Technology

Thesis for the degree of philosophiae doctor

Faculty of Engineering Science and Technology
Department of Marine Technology

ISBN 978-82-471-4516-6 (printed version)
ISBN 978-82-471-4517-3 (electronic version)
ISSN 1503-8181

Doctoral Theses at NTNU, 2013:201

MILJØMERKET 241 TRYKKSAK 731
Printed by Skipnes Kommunikasjon as

Abstract

CO_2 emissions from maritime transport represent 3.3% of global anthropogenic CO_2 emissions. These emissions are forecasted to increase by 150% - 250% up to 2050, due to increased freight volumes (Buhaug et al., 2009). Fulfilling anticipated climate requirements (IPCC, 2007) could require the sector to reduce emissions per freight unit transported by a factor of five or six.

This thesis, focus on strategies and measures for reducing maritime CO_2 emissions within the maritime sector. These emissions can also be reduced outside the sector through market based measures (MBM) by buying emission quotas, which basically means that the shipping sector pays other sectors for reducing their emissions. New and emerging technologies can also contribute to emission reductions. However the objective of this work has been to focus on reducing emission through improving energy efficiency.

One of the objectives for this research, has been to investigate if the available strategies and measures for improving energy efficiency on its own could enable emission reductions by up to 85% per freight unit transported by 2050, which is a substantial challenge. The question is thus how to realize the required greenhouse gas reductions, and at the same time meet sea-transport system mission objectives. A fundamental criterion for enabling this has been to establish the main drivers for making ships more energy efficient and environmentally friendly, and the relationship between the main drivers. The methodological strategy to achieve this has been to include both the micro and macro perspective of shipping.

This thesis consists of three parts. The first part contains: an introduction to maritime transport and emission reductions; the state of the art study; the context for my research and the introduction to my journal papers. The second part contains: the six papers which are the major contribution to this thesis. The third part contains how this research has contributed to state of the art, conclusions and further research.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfillment of the requirements for the degree of philosophiae doctor (PhD).

My thesis is a result of what I have learnt through my PhD research and my working experience since I graduated in 1987 from the Norwegian Institute of Technology (NTH). The title of my M.Sc. thesis (Sivilingeniør) at Department of Industrial Economies and Technology Management was: *Economic optimal production apportionment in an industrial group with many factories* (Lindstad, 1987). After graduation I worked the first 10 years mainly in management positions within manufacturing industry. That was during a time when the emergence of sophisticated logistic thinking and the development of supply chain management systems such as Just in Time (JIT) changed traditional manufacturing principles.

The philosophy of JIT is to optimize the whole value chain from the supplier side to the distribution side, through synchronising all activities in the chain according to the demand pattern of the end-customers. As a result focus was directed towards faster logistic chains with smaller lot-sizes and higher frequencies of delivery, which in several ways are contradictory to the traditional focus of shipping companies on economies of scale through larger vessels, larger lot-sizes and larger inventories both in load and discharge ports.

In 1998 I started working for Norsk Marinteknisk Forskningsinstitutt AS (MARINTEK), on the challenges that JIT and logistics philosophy in general had given maritime transport and shipping. Without going in details, the projects which I worked on included: Development and optimization of the supply logistics for oil companies in the North Sea; Developments of improved port ship interface concept such as in the IPSI project (Pedersen et al., 1999) for Intermodal transport in a "door-to-door" context; Feasibility studies on new vessel and logistics concepts for major aluminium, ferro-alloy, paper, and fertilizer companies. I learnt a lot from these projects, and realized the importance of really understanding the business of the industrial customers served by the shipowners and supply chain providers. Through the SeaChains and SmartLog project, funded by the Norwegian Research Council I was given the opportunity to work in a team to develop a toolbox for analysing and developing shipping solutions as part of a logistics chain. A core part of this methodology was to develop a method for analysing industries. Industry analysis is aimed at creating value by enhancing knowledge about the industrial environment in which one operates, in order to be able to serve the given market in a more effective and innovative manner. The developed toolbox was tested on real business cases for major shipowners.

This was followed by a period where I worked on European funded research projects for developing new short sea shipping concepts. And the Motorways of the Sea concept as outlined by the European Commission. In the beginning I was enthusiastic. However I realized soon that increased frequencies, concentration of cargoes and high speeds could give sea-transport solutions with emission levels similar to road transport and not reductions as foreseen by the European Commission (MOSES, 2009). Anyhow it was a useful experience and it motivated me to apply for a University Scholarship so that I could contribute to make shipping in general more energy effective and hence emit less greenhouse gases (GHG). In March 2009 I started on my 4 year university scholarship at NTNU, where 75% of the time was for the studies and 25% was work for the university.

Acknowledgements

The author wishes to acknowledge the support of the Institute of Marine Technology at the Norwegian University of Science and Technology where the majority of the work was carried out during my four years scholarship. I would also like to acknowledge the support from Norsk Marinteknisk Forskningsinstitutt AS (MARINTEK) with good industrial cases and part time employment during this period.

First of all I would like to thank my supervisor Professor Bjørn Egil Asbjørnslett for guidance, encouragement, discussion capability and support during the four years.

Second, I would like to thank my co-supervisor Professor Anders Hammer Strømman for a useful and pleasant cooperation.

Third, I would like to thank my co-authors on the journal papers, which in addition to my supervisors includes: Dr Jan Tore Pedersen, Egil Jullumstrø, and Inge Sandass. I also wish to thank friends, fellow PhD students, colleagues and professionals within the maritime society for support and discussions.

My special thanks go to my wife Ellen Mette and our children Tor Eivind, Karoline and Jon Anders. And my mother Marit and father Tor.

TABLE OF CONTENTS

List of Tables

List of Figures

1. Introduction

1.1 Motivation

From the first days of our civilization sea transport has dominated trades between nations, regions, and continents. World trade in the form we know today started in the middle of the 19th century as global communication developed with steam engines allowing vessels to move without wind, steel hulls enabling larger ships, screw propellers making ships more seaworthy and deep-sea cables allowing traders and ship owners to communicate across the world (Stopford, 2009). In combination with an incredible industrialisation of the West in the 19th century and its dominance in the rest of the world (Harlaftis and Theotokas, 2002) this enabled a strong growth in trade and transport which continued during the 20th century. Transport is one of the four cornerstones of globalisation. Together with telecommunication, trade liberalisation and international standardisation, the increased efficiency of maritime transport has enabled the Globalization of the world (Kumar and Hoffman, 2002).

Globalization mean that trade is growing faster than the global Gross domestic product (GDP), and that this trade is not only in finished goods and services, but increasingly in components and services that are used within globalized production process (ECLAC 2002). It is therefore of importance to understand why we have trade and what drives trade. Adam Smith (1776) displays trade taking place on the countries exercising absolute cost advantage over one another. David Ricardo (1817) displays that trade are driven by comparative advantage which arises due to differences in technology or natural resources. The Heckscher - Ohlin theory (Ohlin, 1933) of comparative advantages says that countries will produce and export goods that require resources which are relatively abundant and import goods that require resources which are in relative short supply.

Increased trade and transport enables utilization of comparative advantages, including access to raw materials, a skilled work-force, capital and a competitive cost level (Strømman and Duchin, 2006). Table 1 illustrates the strong globalisation of the world from 1950 up to 2010 (BP, 2011; Madison, 2007; OECD, 2011; UNCTAD, 2011; World Bank 2011; WTO, 2011) where all monetary figures are adjusted to 2010 levels.

Table 1: Population, Energy consumption, GDP, transport and trade 1950 – 2010

Year	Population in millions	Energy Consumption in million ton oil equivalents	GDP in billion USD	Maritime transport in million tons	World trade in billion USD	World trade in percentage of GDP
1950	2 500	2 100	8 200	500	400	5%
1960	3 000	3 300	10 900	1 200	800	7%
1970	3 700	4 900	15 000	2 600	1 400	9%
1980	4 500	6 600	27 800	3 700	3 500	13%
1990	5 300	8 100	34 200	4 000	5 400	16%
2000	6 000	9 400	40 400	6 000	8 100	20%
2010	6 900	12 000	63 100	8 000	15 100	24%
Percentage increase from 1950						
1960	20%	60%	30%	140%	100%	
1970	50%	130%	80%	420%	250%	
1980	80%	210%	240%	640%	770%	
1990	110%	290%	320%	700%	1 250%	
2000	140%	350%	390%	1 100%	1 900%	
2010	180%	470%	670%	1 500%	3 700%	

The figures show that the growth has been: Population 180%, Energy consumption 470%, GDP 670%, Maritime transport 1500%, Trade 3700%. This means that maritime transport has increased twice the GDP growth, trade has increased five times as fast as the GDP and trade in percentage of GDP have increased from 5% in 1950 to 24% in 2010. It should be noted that in this thesis all monetary units are in United States dollar (USD), all tons are metric, all other measurements are metric apart from knot and nautical miles.The knot is a unit of speed equal to one nautical mile per hour, and nautical mile (nm) is 1 852 meter of length, which orignialy was defined based on one minute of arc of longitude at the equator.

The environmental consequences of the increased trade have become important as a result of the current climate debate. Anthropogenic emissions of greenhouse gases (GHG) contribute to global warming, and augmentations in temperature to more than 2°C above pre-industrial levels are likely to have catastrophic consequences at a global level (Walker and King, 2008). These implications are well documented by the Intergovernmental Panel on Climate Change (IPCC) which was established in 1988 and acknowledged by our politicians. It is estimated that greenhouse gas emissions need to be reduced by around 50% – 85% in 2050, as compared with current levels, in order to achieve a stabilization of the temperature at 2°C above pre-industrial levels (IPCC, 2007).

Carbon dioxide (CO_2) is the most important greenhouse gas emitted by ships while other greenhouse gas emissions from ships are less important (Buhaug et al., 2009). According to the *Second IMO GHG Study 2009* (Buhaug et al., 2009) for the International Maritime Organisation (IMO), maritime transport emitted 1046 million tons of CO_2, in 2007, representing 3.3% of the world's global anthropogenic CO_2 emissions. These emissions are assumed to increase by 150% – 250% in 2050 if no action is taken, i.e. business as usual scenarios (BAU) with a tripling of world trade. This means that total emissions in 2050 are foreseen to be at 2.5 to 3.5 times today's level. Similar growth prospects have also been reported by OECD (2010) and Eyring et al. (2009). These greenhouse gas emission growth figures stand in sharp contrast to the required total global reductions (IPCC, 2007). Nevertheless, it is a controversial issue how the annual greenhouse gas reductions shall be taken across sectors. Given a scenario where all sectors accept the same percentage reductions, the total shipping emissions in 2050 may be no more than 15% – 50% of current levels based on the required 50% – 85% reduction target set by the IPCC (2007). Moreover, provided that the demand for sea transport follows the predicted tripling of world trade, it can easily be deduced that the amount of CO_2 emitted per ton nautical mile will then as a minimum, have to be reduced from 20 gram to 4 gram of CO_2 per ton nautical mile by 2050. This is a reduction by a factor of 5 to 6 and a seemingly substantial challenge. The question is thus how to realize the required greenhouse gas reductions, and at the same time meeting the mission objectives of sea-transport systems.

1.2 Policy

On the international scene the current international discussion within the United Nations Framework Convention on Climate Change (UNFCCC) which was established in 1992 also covers international shipping. The Kyoto Protocol established in 1997 invites Annex I countries (article 2.2) to the protocol to pursue the limitation or reduction of greenhouse gas emissions from shipping through the International Maritime Organization (IMO). Headquartered in London and established in 1948 by the United Nations (UN), IMO promotes cooperation among governments and the shipping industry to improve maritime safety and to prevent marine pollution.

In the late 1980s, IMO started its work on prevention of air pollution from ships. The first regulatory steps were out-phasing of ozone depleting substances used in refrigerant systems and firefighting systems. In 1997 an air pollution annex, annex VI, was added to the International Convention for the Prevention of Pollution from Ships (MARPOL Convention), which sets amongst others strict rules for nitrogen oxides and sulfur oxides emissions in the exhaust gas. Developments in regulating maritime carbon emissions started in the same year (1997) when the MARPOL conference adopted a resolution requesting IMO to undertake a study on greenhouse gas emissions from ships and to consider feasible emission reduction strategies.

In 2000, the first IMO GHG Study (Skjølsvik et al., 2000) was published, which estimated that ships engaged in international trade in 1996 contributed about 1.8% of the world total anthropogenic CO_2 emissions. In 2003, the IMO Assembly adopted Resolution A.963 (23) related to the reduction of greenhouse gas emissions from ships which urged, IMO's Marine Environmental Protection Committee (MEPC), to identify and develop the mechanisms needed to achieve reduction of GHG emissions from international shipping. In October 2006 the 55th session of the Marine Environmental Protection Committee agreed that IMO should continue to take lead in developing GHG reduction strategies for international shipping. The Committee agreed to a work plan to develop technical, operational and market based methods for dealing with greenhouse gas emissions and to update the IMO 2000 GHG study. The work plan culminated at the

59th session of MEPC in July 2009 with the presentation of the *Second IMO 2009 GHG study* and the approval of the principles for a mandatory Energy Efficiency Design Index (EEDI) and a Ship Energy Efficiency Management Plan (SEEMP). Two years later in July 2011 at the 62nd session of MEPC, the EEDI and SEEMP were adopted as parts of the MARPOL Convention (Resolution MEPC.203 (62)). The EEDI uses a formula to evaluate the CO_2 emitted by a vessel per unit of transport as a function of vessel type and size. The formula has been established by grouping vessels built during the past 10 years into vessel types such as container and dry bulk, and then generating the average values and baselines as a function of size and type by a standard regression model. Common to all vessel types is that as vessel sizes increase, their emissions per transported ton decrease. It should be noted that the EEDI is a technical standard where the measurement is based on the CO_2 emitted when the vessel is fully loaded, and with the speed which it achieves under calm water conditions, when the power outtake from the main engine(s) is 75% of maximum. This in contradiction to the Energy Efficiency Operational Indicator (EEOI), which measures the real operational performance of cargo-carrying vessels, but which so far, is for voluntarily usage. And regarding the EEDI, only marginal reductions will be achieved unless the thresholds are becoming stricter and stricter for each decade in the future. Due to this the discussion in IMO continues regarding how much stricter the requirements per vessel shall be for new-built vessels. The core of this discussion is different views about availability of new technology and what are achievable emission reductions with more energy-efficient hull forms and designs in general.

In addition to the EEDI and the SEEMP, IMO has been discussing market based measures (MBM) in the form of emissions trading, a fuel levy, or a combination of the two. While the EEDI only will reduce emissions from new vessels, which suggests that even after 12 - 15 years, only half of the fleet will be covered, the MBM's will have an immediate full effect. The MBM are based on the assumption that higher fuel prices will incite operators to reduce speeds. There are two major discussions regarding market-based measures: the first concerns whether MBM are needed at all, and the second treats the relationship between the price for emitting CO_2 and potential emission reductions. The main argument against is that EEDI and the SEEMP on its own will deliver the required emission reductions, while the opposite argument is that additional measures are required. Regarding the price of CO_2, price levels of 20 – 50 USD per ton are commonly indicated as being what's required to reduce CO_2 emissions significantly, by the supporter of the MBM concepts. While (Anger et al., 2010) found that higher CO_2 prices is required if MBM's on its own shall significantly reduce emissions. Summarizing the policy section, there are no doubt that IMO has made some progress on emission reductions legislation, however what so far has been agreed is not sufficient to achieve the required reductions as set by IPPC (2007).

This thesis consists of three parts. The first part contains: an introduction to maritime transport and emission reductions which this section is part of; the state of the art study; the context for my research and the introduction to my journal papers. The second part contains the six papers which are the major contribution to this thesis. The third part contains how this research has contributed to state of the art, main conclusions and areas for further research.

2. State of the art

This section contains the main findings from the state of the art study. It starts with an introduction, followed by sections for each of the main identified CO_2 emission reduction option, and a summary in the concluding section.

2.1 Introduction to state of the art

Ships emissions, their impact and solutions to reduce their emissions have been part of major studies such as: the *Second IMO GHG study 2009* (Buhaug et al., 2009); the *Technical support for European action to reducing GHG emissions from International Transport* (Faber et al., 2009); and the Quantify project which assessed the climate impact of global and European transport systems (Eyring et al., 2007). The combustion process in the engine(s) which converts fuel (generally hydrocarbons) into power and exhaust gases is the main source of these emissions. The main gases in the exhaust are carbon dioxide (CO_2), water, nitrogen oxides, sulfur oxides and particles. In addition to the gases emitted from combustion there will be emitted greenhouse gases such as volatile organic compounds (VOC) when loading and discharging crude oil or oil products. VOC are chemicals that have a high vapor pressure at ordinary, room temperature, but compared to the greenhouse gas emissions from the combustion process these emissions are much smaller. The *Second IMO GHG study 2009* (Buhaug et al., 2009) states that ships emission gives significant contribution to the global anthropogenic emissions, since ships emit: 3.3% of the CO_2 and that CO_2 in terms of quantity and global warming potential is the greenhouse gas from shipping which gives the largest impact.

Most studies regarding emission reductions in the transport sector have focussed on reductions which can be achieved within one transport mode, such as aviation (Capoccitti et al., 2010) or sea transport (DNV, 2010), assessing it separately from the rest of the transport market. However, there are some exceptions: Hjelle (2011) compares the environmental performance of short-sea shipping and road haulage; while Psaraftis and Kontovas (2010) compared sea and rail transport for fast-moving consumer goods between Asia and Europe. The *Second IMO GHG study 2009* (Buhaug et al., 2009) compares energy efficiency and CO_2 emissions of freight transport across all transport modes, i.e. rail, road, air and sea. The conclusion is that shipping in general are an energy-efficient means of transportation compared to other modes. However, not all forms of shipping are more efficient than all other forms of transport. The advantage of including more than one transport mode in the analysis is that suboptimal measures, where the reduction achieved by one mode is less than the increase in another mode, can be identified. Ideally, such comparisons should be extended to include total emissions, from sourcing of raw materials and manufacturing in addition to the transport itself (Duchin, 2005; Strømman and Duchin, 2006; Strømman et al., 2008). Going down that path would involve substantial relocation of industries between countries and between regions based on powerful measures rewarding climate change mitigation agreed by UNFCCC and the United Nations.

To enable consistency and transparency in comparisons across transport modes and between competitors the European Standardisation unit (CEN) has developed a standard for calculation and declaration of energy consumption and GHG emissions of transport services (EN 16258:2012). The standard specifies general principles, definitions, system boundaries, calculation methods, and allocation rules and data recommendations. The purpose of the standard is to promote standardized, accurate, credible and verifiable quantitative declarations, regarding energy consumption and GHG emissions related to any transport service quantified. The development of the standard started in 2008 and concluded in 2012 and involved representatives for the different transport modes and transport experts across Europe.

Previous studies have documented that it is possible to improve energy efficiency and reduce fuel cost and emissions in a cost effective manner, i.e. emissions can be cut with net cost savings (Buhaug et al., 2009; Faber et al., 2009; DNV 2010; IMAREST, 2011). However, Russell et al. (2010), claim that these studies in general fall short in identifying, characterizing and assessing the impact of the range of decisions faced by individual shipowners and collectively based on current and future market conditions, and that these studies do not take profit and opportunity cost into consideration. It could be argued that both approaches are needed to understand what drives energy efficiency in shipping and I will revert to this in the Research Context section, in my Paper section and in the Concluding section. While the traditional cost approach will be used in the state of the art section.

Table 2 show the wide range of options for reduction of CO_2 emissions from ships by using known technology and practices which was identified by the *Second IMO GHG study 2009* (Buhaug et al., 2009). The emission reduction options can be divided into two groups. Design measures which generally will be a part of new-building process or through retrofitting and operational measures which will be a function of vessel operations. To give an example, reducing emissions through slow speeding is an operational measure, while reducing emissions through building a slimmer hull is a design measure.

Table 2: Potential CO_2 equivalent emission reductions (source: Buhaug et al. 2009)

Reduction option	CO_2 reduction per ton nautical mile	Combined	Combined
Design – new ships			
Concept, speed & capability	2% to 50%		
Hull and superstructure	2% to 20%		
Power and propulsion systems	5% to 15%	10% to 50%	
Low-carbon fuels	5% to 15%		
Renewable energy	1% to 10%		
Exhaust gas CO_2 reduction	0%		25% to 75%
Operation – all ships			
Fleet management, logistics&incentive	5% to 50%		
Voyage optimization	1% to 10%	10% to 50%	
Energy management	1% to 10%		

Since the primary gateway to these reductions is increased energy efficiency other exhaust gases such as sulphur oxides, nitrogen oxides and particles will generally be reduced proportionally (Buhaug et al., 2009). Nitrogen and sulphur oxide emissions are as described in the introduction section regulated through the MARPOL Convention due to their negative effect on nature and human health. More recently, it has been shown that the emission of particles, nitrogen and sulphur oxides also influences radiative forcing (RF) of climate (Eyring et al., 2009, Lee et al., 2009). Here radiative forcing refers to the change in the earth atmosphere energy balance since the pre-industrial period (before 1750). Apart from soot particles (black carbon) these emissions contributes with a cooling effect (Eyring et al., 2007a; Lauer et al., 2007; Dalsøren et al., 2009) versus the warming effect created by CO_2 emissions.

Issues regarding chemical engineering in the atmosphere is complex, however even if sulphur and nitrogen oxides emissions should be increased due to their cooling effect , the main priority should anyhow be to reduce CO_2. This due to long lasting warming effect of each ton of CO_2 emitted into the atmosphere, versus the cooling gases which trough chemical reactions stay much shorter in the atmosphere. The explanation is that CO_2 does not have a single lifetime, i.e. 50% is removed within 30 years, and 30% is removed over the timescale of a few centuries, and the remaining 20% remains airborne for many thousands of years (IPCC, 2007). A more recent review of carbon-cycle models showed that this long-term airborne fraction may be between 20% - 60% of the original emission (Archer and Brovkin, 2008).

Reverting to Table 2 the main identified CO_2 emission reductions options are. Concept, speed and capability; Hull and superstructure; Power and propulsion systems; Low-carbon fuel; Renewable energy; Fleet management, Logistics and incentives; Voyage optimization; Energy Management. The following sections will describe each of these CO_2 emission reductions options.

2.2 Concept, speed and capability

Speed, size and key parameters such as beam, draught and length have significant influence on the potential energy efficiency of the ship design. With a standard lifetime of 25 - 30 years specifying a ship and subsequently designing to that specification is a highly complex task and their impact on energy efficiency and emissions should not be underestimated (Brett et al., 2006; Winjnholst and Wergeland 2009,). To give an example, large ships tend to be more energy efficient per freight unit than smaller vessels (Cullinane and Khanna, 2000; Sys et al., 2008; Notteboom and Vernimmen, 2009; Stott and Wright, 2011). The key insight is that when the ship's cargo-carrying capacity is doubled, the required power increases with two thirds of the increase in ship size, which implies that when the ship's size is increased, fuel consumption per freight unit is reduced. Another reduction measure is the relationship between speed and emission (Corbett et al., 2009; Seas at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010). The background for the focus on speed reductions is that ships have typically been built to operate at a specific design speed and a key insight is that the power output required for propulsion is a function of the speed to the power of three to four (Kristensen, 2010). This simply implies that when a ship reduces its speed, the fuel consumption per freight work unit is reduced. Emission reductions through speed reductions can be achieved through reducing the design speed by installing a smaller engine, by reducing the operational speed or through a combination of both.

A general weakness with current studies and state of the art design practice regarding concept, speed and capability, is that it is based on marginally improving existing designs and solutions instead of really challenging todays practice. Historically fuel cost has been low compared with the fixed cost of a bulk or tank vessel, its crewing and management. This has rewarded owners for maximizing the cargo carrying capacity at the lowest possible building cost and the outcome has been shoebox shaped vessels with high resistance even at calm sea. The maximum allowable dimensions through the Panama canal has also contributed to rewarding these shoe boxed designs. With today's high cost of fuel and the Panama Canal lock expansion from 2014, it might be more profitable to build vessels slenderer by expanding overall dimensions and by keeping the dead weight constant (dwt) constant. The knowledge about these relationships is not new (Lloyd 1988; Silverleaf and Dawson 1966), however apart from increased beams and additional draughts on some of the new designs, there is a lack of studies regarding the relationship between vessel slenderness and its speed as a function of fuel price. Another example is large container vessels, which traditionally has been built for design speed of 25 knots or more, while after 2008 these designs speeds have been reduced to 21 – 23 knots due to increased fuel costs and lower freight rates. It is easy to see that this reduces both cost and emissions per freight unit transported, however when transport- and total lead times increases more high value goods might be airfreighted and the total emissions might increase. Even with these speed reductions, container vessels continues to transport low value goods and standard commodities at higher speed and emissions compared to if they had been transported with ordinary break bulk, bulk or tank vessels. Despite this, there is a lack of studies which challenge this sub optimization practice and instead put focus on reducing total sea transport emissions or total emissions from transport. Going back in time, focusing on transport technology as such (the container solution) and not the needs of their customers sounds similar to what US railway companies and their analyst did in the 1950-ties when they thought they were in the railway market (Kotler, 1984) and not in the transport market competing with busses, private cars and air planes. A third example is that while larger ships in general is more efficient per freight unit transported than smaller ships when loaded (Buhaug et al., 2009), smaller or better adapted ships may achieve a higher utilization factor and even lower emissions on a roundtrip basis. But there is a lack of studies which have investigated this.

2.3 Hull and superstructure

Traditionally, seagoing vessels have been designed and optimized to operate at standardized maximum economics speeds (Silverleaf and Dawson, 1966) generally called design speed with design loads at still water conditions. This despite that calm sea is the exception in shipping (Faltinsen et al., 1980). These maximum economic speeds is not based on economic calculations, but rather express the highest speed which is wise to drive a vessel of specified fullness and length independently of fuel cost. The hydrodynamic explanation is that the still water drag coefficient which is nearly constant at low speeds for any hull forms increases rapidly when the hull exceeds its boundary speed (Silverleaf and Dawson, 1966). For a short shoe boxed shaped design this boundary speed might be less than 10 knots, while for a long and slender frigate it might be 25 knots or more. This boundary speed is not represented as one specific speed and one specific drag value, but could rather be explained with the curvature of a quarter of a circle which is nearly flat for incremental speed increases in the bottom of the boundary area and nearly completely vertical for incremental speed increases at the top of the boundary area. Which mean that for speeds below the boundary speed, resistance and power required is moderate while for speeds well above it goes against infinity. Since fuel cost historically has been low, the maximum economic speed for a chosen design has been in the upper part of the quarter circle. With increased fuel cost and stricter environmental requirement the economic speed might instead be in the lower part of the quarter circle, but there is a lack of studies which have investigated this.

Hirota et al. (2005) shows how the ship form might be optimized with respect to minimization of fuel consumption in waves, rather than in calm water. MARIN (Van der Boom, 2010) has developed the STAWAVE method to calculate the added resistance in waves. It follows from the STAWAVE method that if two vessels have equal beam measurements and equal length, the one with the longest bow section will experience less added resistance in waves compared to the one with a shorter bow section. Calculation of added resistance in waves has been studied by several other authors (Lloyd, 1988; Steen and Faltinsen, 1998; Arribas, 2007; Guo and Steen, 2010). The results showed that the resistance rises rapidly with increasing wave height and that the peak resistance occurred in head waves when the average length of the waves was close to the length of the vessel.

However, apart from Lloyd (1988), previously published studies have generally chosen to focus on models for moderate sea conditions in combinations with waves only (Orsic and Faltinsen, 2012) or to publish power needed at specific sea conditions based on model tests (Hollenbach and Friesch, 2007). Since seagoing vessels will operate under all sea conditions, there is a need for developing models to calculate added resistance and hence fuel consumption as a function of sea condition and vessel speed, both at the vessel design stage and in the operational phase. Considering the varying operational profile of the ship, optimizing hydrodynamic performance of the hull in a representative range of loading, operational and environmental conditions is an essential step to generate hull forms with low resistance (Turan et al., 2012). This has been acknowledged for some time, but real design innovation to address this issue is limited and knowledge required for this is not currently incorporated in design processes. Some ships even carry significant amount of ballast both in laden and ballast conditions such as LNG carriers, resulting in additional energy demand and higher emissions per freight unit transported.

2.4 Power and Propulsion

Design and optimization of power plants for ships has traditionally been focused around how many engines or generator sets to include based on total power required when operating at design load conditions and design speed. The most economical way to produce this required power has been to install engines with a size where the power outtake to achieve the design speed has been 75% – 90% of maximum power available. The explanation is that combustion engines burning marine diesel oil (MDO) or heavy fuel oil (HFO) have the highest efficiency in this load area, and that the capex cost of the engine increases nearly linearly with the size of the engine. More recently as a consequence of higher fuel prices and lower freight rates, the traditional approach of operating at constant high power no longer gives the lowest cost for all sea and loading conditions (Corbett et al., 2009; Seas at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010). Still the same installed power might be required to ensure sea worthiness in rough weather, however now the power solution also has to perform at low engine loads required for slow steaming in calm and following sea.

Tools and platforms for evaluation and optimization of marine power systems have been suggested by TNO (2004), Pedersen (2009) and Dimopoulos (2010), but few integrated solutions exist. One example are the Streamline project (2010) which is trying to demonstrate radically new propulsion concepts delivering an increase in efficiency of at least 15% over the current state-of-the-art. This is enabled through advanced Computational Fluid Dynamics (CFD) tools and methods to optimise the hydrodynamic performance of the new propulsion concepts, particularly by analysis of integrated hull and propulsion. However much less has been written about how the request for an operational profile varying between very low engine outputs and the traditional high outputs will change the design of marine engines. And how evaluation, testing and demonstration of overall system performance in real operational conditions, both stationary and transients, will require new methods and tools.

2.5 Low Carbon Fuels

Emissions of CO_2 can be cut by switching to fuels with lower total emissions through fuel cycle including production, refining and distribution (Buhaug et al., 2009). Biofuels is one such option which can be considered as an alternative to fossil fuels and there are various studies that examine the feasibility. Bengtsson et al. (2012) derive a conclusion that the biofuels are one possible measure to decrease the global warming impact from shipping, but that it can be to the expense of greater environmental impact for other impact categories. This can be exemplified with that the eutrophication potential and the primary energy use increased with biofuels.

Liquefied natural gas (LNG) have a higher hydrogen to carbon ratio, which results in lower CO_2 emissions compared to more traditional hydro carbon fuels such as marine diesel oil or heavy fuel oil (Buhaug et al., 2009). In addition, LNG is a clean fuel, containing no sulfur; this eliminates the sulfur oxide emissions and nearly all particles. The disadvantage is that when LNG is used on traditional low pressure gas engines or dual fuel engines there will be leakage of un-burnt methane (CH_4) reducing the net greenhouse gas emission reductions from 25% to 15% (Einang, 2007). If the LNG instead is used as a fuel on high pressure two or four stroke engines there will be nearly no methane leakage , but the disadvantage is nitrogen oxide emissions which might not satisfy the emission requirements for new-built vessels in the Baltic from 2016 onwards. However this is solvable with after treatment of the exhaust gas.

Hydrogen is another interesting fuel as its direct combustion has the lowest environmental impact and it is useful when considering energy production through fuel cell technology. A fuel cell convert chemical energy from a fuel into electricity.The operation is similar to a battery and the power will be produced as long as the chemical source such as hydrogen and oxygen are provided.

The basic chemical reaction is that hydrogen reacts with oxygen which gives energy and water; $2H_2 + O_2 \rightarrow \text{Energy} + 2H_2O$. Compared to traditional combustion no nitrogen oxides, sulfur oxides or particles are detectable. The Fuel cell technology in ships, (FCSHIP-project) has investigated the application of fuel cells on board ships for both main propulsion and auxiliary applications. The offshore supply vessel Viking Lady has a fuel cell installed and the objective is that the fuel cell can produce part of the energy that is produced by the auxiliary engines (Biello, 2009). This is the first fuel cell unit to operate on a merchant ship, and proves that fuel cells can be adapted for stable, high efficiency, low-emission on-board operation. But hydrogen production requires a large amount of energy. For these reasons, evaluation of innovative hydrogen production and production based on renewable sources such as wind energy is of high relevance when considering the use of hydrogen as a fuel.

2.6 Renewable energy

Interest has re-emerged in wind assisted ships. These are typically intended to operate in wind-assist or motor sailing mode in which the speed is maintained irrespective of wind speed and direction. Wind propulsion systems can be divided into three groups. The first is modern implementation of conventional soft sail rigs. One example is the Dynarig which offers high aerodynamic efficiency with minimal crew based on concepts proven on mega yachts (Perkins et al., 2004). The second group is kite propulsion such as delivered by Skysails which have been studied by Dadd et al. (2011) and tested on the 140 meter long cargo vessel Beluga Sky-Sails in the Wintecc project (2007). The strength of the kite is for following wind conditions. The third group utilizes the Flettner rotor concept which requires little space on the deck and performs well in side wind condition, but unlike the kite they are inefficient in following wind conditions. Wind conditions differ between regions, so that wind power is more attractive in certain regions and routes than in others. In a study carried out by Clauss et al. (2007), three different types of sails were modelled on two types of ships on three different routes using actual weather data. The study indicates that the potential for sail energy was better in the North Atlantic and North Pacific than in the South Pacific. Fuel savings were typically about 20% for a vessel speed of 10 knots. However the shipowners are not convinced and there is a need for developing models to quantify the benefits of different wind assist options for different ship types, routes, and ship speeds on emission reduction. Models could also explore the opportunities for trades which could be operated on sails alone for very large percentages of time.

Solar cell technology is improving rapidly and might soon be cost competitive with other emission reductions technologies. One example is Nissan’s 1380 capacity car carrier The Nichioh Maru. The ship's deck is covered by 281 solar panels for powering the LED lights through the hold and crew quarters, eliminating the need for a dieselfueled generator. Compared to a conventional car carrier of its size, the Nichioh Maru will save 1,400 tons of fuel and prevent the emission of 4,200 tons of CO_2 each year (Westlake, 2012). The emission reduction potential of installed solar cells on board ships could be addressed, by considering the maximum install deck area, as well as the operational profile and the geographical area where these vessels operate.

2.7 Exhaust gas CO_2 reduction

When fuel goes into the ships main engine 40% – 50% of the fuel energy is transformed to power delivered at the shaft, while the remaining energy is lost as exhaust gas and through heat exchange with air and cooling water. Part of this energy can be recovered from exhaust gas by using steam turbines. The power that is recovered can then be used to drive auxiliary machines or to assist the main engine. This allows for up to 12% savings on primary fuel and hence CO_2 (Emec, 2010). In tests, emissions were reduced up to 14% (Green ship of the future, 2012). For consistency it should be noted that Buhaug et al. (2009) has grouped this measure under power and propulsion.

2.8 Fleet Management, Logistics and Incentives

A ship can also do slow steaming, i.e. operate at a speed slower than its design speed and thus reduce fuel consumption. The background for the focus on speed reductions is as described in the concept section that ships have typically been built to operate at a specific design speed. A key insight is that the power output required for propulsion is a function of the speed to the power of three to four (Kristensen, 2010) which implies that when a ship reduces its speed, the fuel consumption per freight work unit is reduced. Ship scheduling and routing concerns the optimal assignment of available cargoes to a set of ships in the fleet, where "optimal" signifies either lifting (transporting) all cargoes while minimizing costs or maximizing profit by only assigning profitable cargoes. Several authors have in different contexts incorporated speed optimization into the routing decisions (Bausch et al., 1998; Fagerholt, 2001; Alvarez, 2009; Fagerholt et al., 2010; Norstad et al., 2010). These studies show that the fuel savings from including speed optimization can be large. But, berthing policies used at ports often admit vessels on a first-come, first-served basis which is an argument for ensuring that speed optimization is synchronized with port planning (Alvarez et al., 2010). Enabling speed reduction will also affect the size and mix of fleet of vessels operating in coastal or deep sea trades. This is known as fleet size mix and routing problems. Examples of optimization methods applied for Fleet size mix and routing problems are given by Cho and Perakis (1996), Fagerholt (1999), Fagerholt and Lindstad (2000), Christiansen et al. (2007), Fagerholt and Lindstad (2007), Fagerholt et al. (2009).

While the above-mentioned studies have been motivated by the opportunity for cost savings or profit maximization, there has emerged a growing interest in the relationship between speed and emission reductions. Corbett et al. (2009) considered whether the lowering of speed can be a potentially cost-effective CO_2 mitigation option for ships calling at US ports. They found that a fuel tax of about 150 USD per ton would lead to average speed-related CO_2 reductions of approximately 20% – 30%. Moreover, Sea at Risk and CE Delft (2010) investigated how the over-capacity in major shipping markets in 2009 could be utilized for slow steaming and hence emission reductions. It was estimated that emissions of dry bulk, tanker and container vessels can be reduced by about 30%, relative to the situation in 2007, by employing an oversupply to reduce the speed. Psaraftis and Kontovas (2010) studied the implications of various emission reduction policies for maritime logistics, and the slow steaming of container vessels in particular. They concluded that lower speeds have environmental benefits, but if the value of the goods is high, its capital cost in addition to the potential loss of sales would favour higher speeds. The modelling approach used in these studies (Corbett et al., 2009; Sea at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010*)* has involved the assumption of constant total transport volumes. This implies that when speed is reduced, additional vessels will be required to maintain the annual transport capacity. The fuel and emission calculations in these studies have been based on still water conditions, and this despite that a calm sea is quite the exception in shipping (Faltinsen et al., 1980). Since seagoing vessels operate under all sea conditions, there is a need to include real sea conditions when assessing potential emissions and cost reductions as a function of lower speeds. Other questions to be clarified are: which cost items should be included in the assessment, only ship-owner relevant cost or the total cost for the cargo owner; what is the value of shorter versus longer transport time and how can the relationship it be understood; what is the effect of including shipbuilding emissions in the assessment and how can they be quantified; are there differences between vessels types or are the differences more related to that different vessel types are built for different speeds.

2.9 Voyage optimization

The starting point for a voyage optimization system will in general be the shortest feasible route between port of departure and port of arrival, and then weather, current and wave data in combination with the vessel characteristic can be used to find the deviations and speed combinations which minimize resistance and fuel consumption for the given freight market. Such selection of routes between ports to find the optimum voyage, when current and weather conditions are taken into account, is often referred to as weather routing. McCord et al. (1999) concluded in a case study that 11% fuel savings could be achieved for a 16-knot vessel by utilizing ocean currents while Lo et al. (1991) estimated a significant reduction in world fleet fuel consumption by utilizing ocean currents. Since the added resistance caused by waves is very sensitive to the sea spectrum (Strom Tejsen et al., 1975), models which can be used to calculate added resistance and hence fuel consumption as a function of sea condition and vessel speed in combination with weather and wave forecasts, will enable large cost and emission reductions. Weather routing studies have also been performed and significant fuel savings are indicated by Perakis and Papadakis (1989) and Papadakis and Perakis (1990). However, little research has been done during the last decade to utilize the major improvements achieved during this period in weather forecasting techniques, algorithmic developments and computing power, as well as development in hull and propulsion technology.

2.10 Energy Management

Emission reductions through energy management are an expression which covers at least three different themes. Buhaug et al. (2009) use it to cover all actions which minimize energy usage of auxiliary machines and hotel loads, and for maintenance of main engine and cleaning of hull and propeller. The classification society Det Norske Veritas (DNV), use it about activities advising shipowners on ways to achieve reductions in fuel consumption, and subsequently often verify the reductions through on-board measurements. Turan et al. (2012) use it about introducing new technologies such as LED lightning to reduce the basic consumption. And for centralised power management systems that optimise the energy distribution of the ship power plant to minimise the energy consumption by monitoring, directing and controlling. The energy saving potential of energy-management measures depends on how efficiently the vessel is operated and on the share of auxiliary power consumption of the total energy consumption.

2.11 Summarizing state of the Art

The state of the art section shows that it is possible to reduce fuel cost and emissions from maritime transport. A total of nine main alternative reduction options have been described which all can contribute to emission reductions. Some of the options, like wind assisted ships or solar cell technology are applicable on parts of the world fleet. Others options like concept, speed and capability are general and applicable for the whole fleet. In addition there are options which have not been described such as anti-fouling for reducing hydrodynamic resistance or engine tuning. However compared to the main options they are of less importance and in general part of normal vessel maintenance.

Summarizing all these options, it appears to be sufficient to satisfy the high end of the required 50% – 85% reduction target by 2050 set by the IPCC (2007). All these options are cost effective for fuel prices at present levels (2012) which are around 600 USD per ton of heavy fuel oil and around 900 USD per ton of marine diesel oil. However while the first percentage reductions for any of these options are cost effective and hence profitable, the cost for additional reductions increases per percentage saved, until we reach the point where the cost exceeds the savings. Achieving the full reduction potential for any of the options will hence mean that the cost for the last percentage of reductions far exceeds the cost reductions achieved through fuel savings. This is in line with previous studies which have documented that it is possible to reduce emissions with up to 75% (Buhaug et al., 2009). And that the cost efficient potential is in the range of 25% – 45% per freight unit transported (Buhaug et al., 2009; Faber et al., 2009; DNV 2010; IMAREST, 2011). The highest reduction percentages correspond to a fuel price at the present level (2012) while the lowest to fuel price levels down to roughly half the present level. Basically this means that the consensus view of previous studies is that the greenhouse gas emission reductions in 2050, based on business as usual scenarios, will be half of what is required according to IPCC (2007).

Another approach to estimate 2050 emission figures could be to base them on historical performance. The historical figures show 1% or less annual average efficiency improvement through technologies and economies of scale since 1950, which implicates that emission per freight unit transported may be 35% – 45% lower in 2050 than today. And which also is unsufficent to meet the required 50% – 85% reductions by 2050 as set by IPCC (2007).

3. Context and research design

The title of this thesis is *Strategies and measures for reducing maritime CO_2 emissions*. A strategy is a plan of action designed to achieve a specific goal which in this thesis is to reduce maritime CO_2 emissions. The plural form strategies are used since the state of the art study has shown that a large number of options exist for reducing maritime CO_2 emissions. Measures are in this context used for actions required to implement the strategies which enables reduction of maritime CO_2 emissions

One of the objectives for this research has been to investigate if the available strategies and measures for improving energy efficiency on its own could enable emission reductions by up to 85% per freight unit transported by 2050. This is a reduction by a factor of 5 to 6 and a seemingly substantial challenge. The question is thus how to realize the required greenhouse gas reductions, and at the same time meeting sea-transport system mission objectives. A fundamental criterion to enable this is to establish the main drivers for making ships more energy efficient and environmentally friendly and the relationship between the main drivers.

In previous studies (Buhaug et al, 2009; Faber et al, 2009; DNV 2010; IMAREST, 2011), the main criterion in focus have been cost, and the focus have been on documenting that it is possible to reduce fuel cost and emissions in a cost effective manner, i.e. emissions can be cut with net cost savings. Another fundamental criterion is profit because ship owners are in shipping to make a descent profit or to maximize the profit. In a simplified model cost reductions will contribute to profit increases since profit is the difference between income and cost. However quite often reducing cost also reduces income and then it becomes more complicated. One example is cost reductions through slow speeding which increases total transport time where the customer might demand freight rates reductions, which reduces income. If cost reductions are larger than income reductions this is still profitable, however the opposite might also be the case. Another example is that with a good freight market the additional income when vessel speed is increased will generally be larger than the additional cost. Russell et al. (2010) has investigated the relationship between cost, income and profit and concludes that it is important to identify and assess the impact of the range of decisions faced by individual shipowners and collectively based on current and future market conditions, and conclude that it is important to take profit and opportunity cost into consideration.

Hence it follows that the most efficient measure for reducing CO_2 emission is to identify the strategies which makes it economically profitable for ship owners and their customers to reduce CO_2 emissions. Both for shipowners focusing on an ongoing operation with long-term vessel ownership and for those focused on asset play, with buying and selling vessels driven by profit and opportunity assessments.

Main research questions which initially were asked were:

- RQ1 - What strategies and measures are available
- RQ2 - What are the characteristics of these strategies and measures
- RQ3 - What are the most promising strategies for further investigation
- RQ4 - How to operationalize the good strategies

- RQ5 - Will implementing the good strategies be sufficient to achieve the required reductions

These five research questions forms the cornerstones of this thesis. The two first ones: RQ1 - *What strategies and measures are available* and RQ2 - *What are the characteristics of these strategies and measures* have briefly been answered in the state of the art section. The third one: RQ3 - *What are the most promising strategies for further investigation* has served as the decision point for where I should focus my resources and do further investigations. And the outcome of these studies is presented through the journal papers. The fourth one RQ 4 - *How to operationalize the good strategies* has been part of each of these studies and is presented through the journal papers. The fifth one RQ5 - Will implementing the good strategies be sufficient to achieve the required reductions will be based on the results of research questions: RQ1, RQ2, RQ3 and RQ4 and will be answered in the concluding section.

3.1 Delimitation

This thesis, focus on strategies and measures for reducing maritime CO_2 emissions within the sector as such. These emissions can also be reduced outside the sector through market based measures or instruments (MBM) through buying emission quotas, which basically means that the shipping sector pays other sectors for reducing their emissions. Buying quotas outside the sector has not been part of this work since this thesis focus on reductions within the sector. Neither is the emission effect of using a larger share of biofuels included. The main reason is that total benefits of using first generation biofuels is marginal (Bengtson et al., 2012), this will improve significantly with second generation biofuel, but such emission reduction will not be a result of work within the shipping sector. Potential emission reductions through a use of a larger share of Low carbon fuels such as LNG or Hydrogen has neither been part of this scope. Both have clear benefits due to a lower greenhouse gas impact when the best technology is used such as making hydrogen from renewable energy, and very low emissions of sulfur oxides, nitrogen oxides and particles. However they can be used as fuels across many sectors which all can enjoy these benefits. Renewable sources such as solar or wind in particular has clear benefits. However if wind should have been included, that would require models to quantify the benefits of different wind assist options for different ship types on different routes. While including solar cell technology would require a study considering the maximum deck area for installing solar cell panels for different vessel types, as well as the operational profile and the geographical area where the different vessel types operates.

Neither has gas exhaust gas CO_2 reduction or any other specific technologies for reducing emissions been included. The explanation is not lack of emission reduction potential, but the focus of this thesis which is emission reductions through improving energy efficiency.

3.2 Research Process

The research carried out in this thesis can be described as a step by step process. The process began with a literature review to get a deeper understanding for the subject and to generate ideas for the research presented in this thesis. The first outcomes of this literature review was that I realised that the maritime sector might have to reduce emissions by up to 85% per freight unit transported by 2050, which is a substantial challenge. The second outcome was that if all emission options previously studied were added up, such a reduction is feasible. And the third were the big gap between the large potential for emission reductions and the annual historical improvements of energy efficiency per freight unit transported of less than 1% per year. On this basis I concluded that it was important to understand the interest and the role of the stakeholders and the sea-transport system mission objectives to identify the main drivers for making ships more energy efficient and environmentally friendly. The methodological strategy to achieve this has included both the micro and macro perspective of shipping.

The macro perspective includes understanding the role of sea transport and how it has enabled increased trade and utilization of comparative advantages. In the old days, shipping was a unified business. After 1870s, the shipping business gradually changed due to a clearer distinction between tramp and liner shipping. The evolution since then has been an increase in vessel types, sizes and business concepts. This complexity has been increased with a strong focus on logistics and sea transport as a part of logistics chains. When analysing, two completely different pictures can be drawn. The first is that shipping is a highly specialised business where container vessels serves the container market, the RoRo vessels serves the RoRo market and so on, which implies that the market is segmented and that strategies and measures for reducing maritime CO_2 emissions should focus on each of them individually. The second is that most cargo types can be transported by different ship types or more correctly handling technologies and that shipping competes with other transport modes. This implicates that the focus should be on strategies and measures for reducing overall emissions. My approach has been to analyse different ship types and their performance individually to enable comparisons across vessel types and technologies and also across transport modes.

The micro perspective of my research includes understanding the main priorities of the shipowners and how their cost and profit model drives their decisions. Typical cost considered has consisted of the direct costs of the vessel, its fuel, terminal handling, hinterland transport and the capital cost of the goods transported. While more recently there has been a growing interest in including environmental impact.

The state of the art study served as the initial basis for identifying the most promising strategies. For each of the promising strategies studies was undertaken as described in the individual journal papers. The structure of each of these studies consists of:

- Formulation of the research questions
- Describing previous work within the field
- Describing the research gap and the contribution of this research
- Model development

- Model application to enable quantitative assessments of alternative options
- Analyzing results
- Discussion of results and conclusions

3.3 What are the most promising strategies for further investigations

The third research question: RQ3 - *What are the most promising strategies for further investigation* has served as the decision point for where I should focus my resources and do further investigations. It also represents the link between the State of the art study and the main PhD research as shown in Figure 1. In the figure the title of the thesis is placed on the top, with an arrow pointing to the two first research questions. A two way arrow are used to show the interaction between the two first research questions and the available strategies with one way arrows pointing to research question 3 which is the decision point. The options chosen for further research were:

- Concept, speed and capability
- Hull and super structure
- Power and propulsion systems
- Fleet management, logistics and incentives
- Voyage optimization

These emission reduction options covers a wide area from vessel design to its operation, however what they have in common is that none of them are based on new technologies or innovations as such. Instead the focus is on new or amended applications of known technologies. A two way arrow is used to show the interaction between research question RQ2 and RQ4 and the chosen strategies, with one way arrows pointing to research question 5.

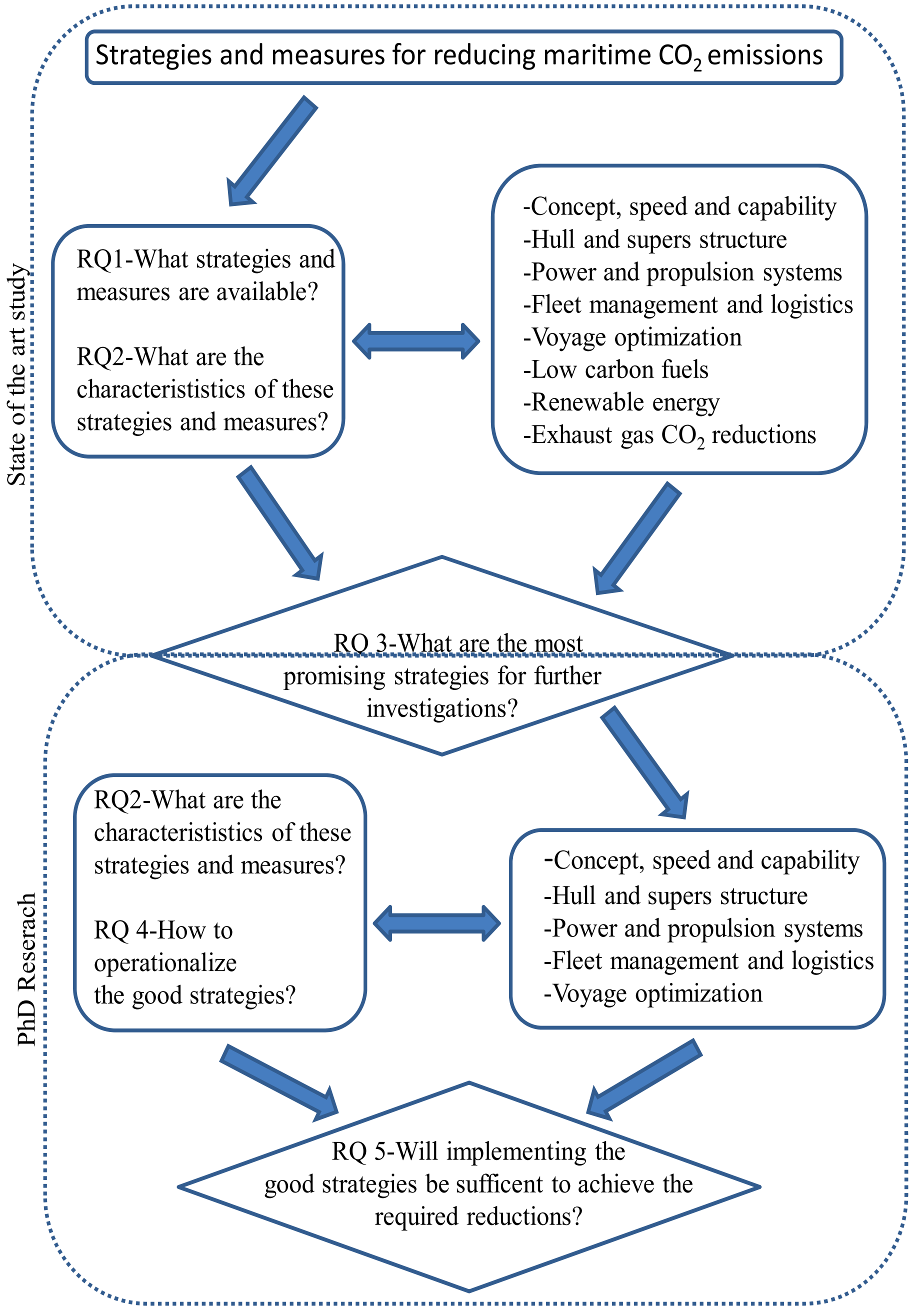

Figure 1: PhD Work - Strategies and measures for reducing maritime CO_2 emissions

If these emission reduction options had been completely independent from each other they could have been investigated separately, however there are combination and synergy effects. And due to this all the performed studies investigates at least two emission reduction strategies. The following section gives a brief introduction to each of the studies and explains the relationship to the most promising emission reduction strategies.

The first study *Green Maritime Logistics and Sustainability* (Lindstad et al, 2012) presents a methodology for assessing the environmental impact of maritime transport and transport in general with specific focus on greenhouse gas emissions. The methodology is based on a model which simulates how different vessels types are used in different trades. The model covers all vessels built for cargo freight, .i.e. general cargo, dry bulk, reefer, container, crude oil, oil products, chemicals, road units (RoRo), liquefied natural gas (LNG), liquefied pressurized gas (LPG) and sea-river vessels. The model is based on a combination of exact and estimated data. The exact data is the world fleet as listed in the 2007 Lloyd Fairplay database, now the IHS database (www.ihs.com) divided into vessel type and size groups. The reference year 2007 was selected because it was the last year before the financial recession started in 2008, the freight markets were good and vessels operated at speeds close to their design speed, and it was the reference year for the *Second IMO GHG study 2009* (Buhaug et al., 2009). The development of the model started with an analysis of the dry bulk shipping segment, focusing on how the vessels were used and freight flows, including movement patterns (origin and destination) of the main dry bulk commodities transported. In the model, vessel data, operational pattern per vessel type and freight tonnage are matched. This enables calculation of average operational gram CO_2 per freight unit transported which corresponds to the Energy Efficiency Operational Indicator (EEOI) as discussed by IMO. The model has enabled assessment of different trade scenarios, assessment of how different vessel types and their handling technologies compete for some of the cargo types, assessment of the relationships between vessel size and emissions, assessment of freight work and emissions per vessel type. These assessments are not presented as a part of the *Green Maritime Logistics and sustainability* study (Lindstad et al., 2012), but the model are used as part of the assessments in the other studies performed. The paper starts with an introduction to green maritime logistics and sustainability, followed by a framework for measuring greenhouse gas emissions for transport systems. The third section presents the assessment model, and in the fourth section the methodology is used to compare greenhouse gas emissions per freight unit transported for rail and road freight with the sea freight emissions as a function of vessel type and size. In relation to the main emission reduction strategies this paper has focused on issues in relations to:

- Concept, speed and capability
- Fleet, management, logistics and incentives

The second study: *Reductions in greenhouse gas emissions and cost by shipping at lower speeds* (Lindstad et al., 2011), presents investigations on the effects of speed reductions on the direct emissions and cost of maritime transport, for which the selection of ship classes was made to facilitate an aggregated representation of the world fleet. The ship classes in focus in this study were bulk (wet and dry), container and RoRo vessels all above 15 000 dead-weight (DWT). The objective of the developed model was to calculate costs and emissions as a function of vessel speed from very low speeds up to design speeds, which usually are 90% to 95% of the vessel maximum speeds. A main challenge in the model development was to establish the power requirement as a function of vessel speed, hull, propeller and sea state. This because traditionally, research on hulls shapes and propeller has designed them for still-water, design cargo load and design speed condition (Faltinsen et al., 1980), and this despite that a calm sea is quite the exception in shipping (Lloyd, 1988). Due to this vessels are generally speed tested fully loaded or at the design load (which could be 15% – 30% less than full load) under calm water conditions to verify the maximum speed, and to establish the relationship between speed and power for speeds from 75% of max and upward. This despite today's widespread slow steaming. The developed model was first used to identify the emissions and cost for individual ship classes as a function of speed, discuss and assess these, and then combine them to evaluate the emission reduction potential and costs for the global fleet. In relation to the main emission reduction strategies this paper has focused on issues in relations to:

- Concept, speed and capability
- Hull and superstructure
- Power and propulsion systems
- Fleet, management, logistics and incentives

The third study *Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market* (Lindstad et al., 2013) assesses shipping profits, costs, and emissions as a function of speed, sea and freight market condition. Compared to the second study, *Reductions in greenhouse gas emissions and cost by shipping at lower speeds* (Lindstad et al., 2011) the additional variables introduced are freight rates, profit and sea conditions per voyage. The main model extensions were to model propulsion efficiency as a function of sea conditions in addition to vessel speed and models enabling calculations of income and profit in addition to the traditional cost calculations. The vessel types in focus was ocean-going dry-bulk, break-bulk and wet bulk (tank) vessels. Combined these vessels types represents nearly 75% of world’s total sea freight work. The model was first used to assess vessel speed as a function of voyage priorities such as profit maximization, cost minimization and emission minimization. Then the model was used to assess, profit, cost and emissions as a function of sea conditions and freight market. And finally the emission reduction potential when the model was combined with weather forecasts was investigated. The paper as such is the shortest of the papers in this thesis. The original paper submitted to the journal was of the same length as the other articles; however the editor wanted a short paper with main focus on the model and its application. Compared to the original version the main changes are that the introduction was reduced by two thirds, the model description was shortened and in the concluding section all comparisons with previous research was taken out. However, what was important was kept. In relation to the main emission reduction strategies this paper has focused on issues in relations to:

- Concept, speed and capability
- Power and propulsion systems
- Fleet, management, logistics and incentives
- Voyage optimization

The fourth study: *The importance of economies of scale for reductions of greenhouse gas emissions from shipping* (Lindstad et al., 2012a) investigates the effects of economies of scale on the direct cost and emissions from shipping. In the study emissions from the current fleet (2007) is compared with what can be achieved by increasing average vessel size. The starting point for the modeling work is the model which simulates how different vessel types are used in different trades as described in the first paper, *Green Maritime Logistics and Sustainability* (Lindstad et al., 2012). This model was extended by including cost and capex data to enable economic assessments in combination with the initial emission, capacity and trade assessments. The aims of the analysis were first to identify the emissions and cost for individual ship classes for the existing fleet, and then to investigate the effects of economies of scale on the direct emissions and costs of maritime transport as a function of vessel size and fleet mix for the entire fleet. The comparison was based on 2007 levels of trade and predictions for 2050. In relation to the main emission reduction strategies this paper has focused on issues in relations to:

- Concept, speed and capability
- Hull and superstructure
- Fleet, management, logistics and incentives

The fifth study *Comparing the cost and emissions of maritime and air transport* (Lindstad and Strømman, 2011) presents a combined assessment of the cost and emissions of freight transport including both oceangoing vessels and aircrafts. The main objective of the developed model was to calculate emissions and costs for sea-freight and air-freight as a function of their characteristics and the cargoes they transport, with focus on cargo segments that currently are transported by both modes. To date, discussion on transport emission reductions at the international level has focused on separate reduction measures for sea and air transport, neglecting that they partly compete for the same cargo and passengers. And when comparisons have been made, assessments between transport modes have been based on comparing emissions and cost per transported ton. Using cargo weight in ton as the comparing unit is question-marked. And based on a thoroughly discussion cubic meter is instead used, since the majority of the cargo for which air and sea competition exist is light weighted. As part of the study the decision criteria for choosing between air and sea freight is investigated. The study includes an assessment of emission reductions achievable when the focus is on reducing total sea transport emissions and when the focus is on reducing total air and sea emissions. In relation to the main emission reduction strategies this paper has focused on issues in relations to:

- Concept, speed and capability
- Power and propulsion systems
- Fleet, management, logistics and incentives

The sixth study *Reductions in cost and greenhouse gas emissions with new bulk ship designs enabled by the Panama Canal expansion* (Lindstad et al, 2013a) presents an assessment of cost and emissions as a function of alternative bulk vessel design. Historically, fuel costs have been small compared with the fixed costs of a bulk vessel, its crewing and management. Today, however fuel cost accounts for more than 50% of the total cost. In combination with the introduction of stricter energy efficiency requirements for new vessels, such high costs might make design improvement a necessity for all new bulk vessels. This in contradiction to traditional bulk vessel designs, where the focus has been on maximizing the cargo-carrying capability at the lowest possible building cost and not on minimizing the energy consumption.

In the study cost and power model was developed to enable comparison of standard vessel designs with those of alternative designs. This enabled comparison of standard Panamax designs with more slender designs where the cargo capacity was kept constant by increasing vessel width only and by increasing both length and width. The employed power model includes real sea conditions as opposed to still water, and the economical assessment has been carried out for a low, medium and high fuel price. In relation to the main emission reduction strategies this paper has focused on issues in relations to:

- Concept, speed and capability
- Hull and superstructure
- Power and propulsion systems
- Fleet, management, logistics and incentives

Table 3 summarizes the relationship between the six studies (papers) and the investigated emission reduction options as described above. In the first column we find the name of each study while the investigated emission reduction options are placed in the headings of column two to six. The X marks shows which emission reduction options are investigated in each of the studies.

Table 3: The six studies and the investigated emission reduction options

	Concept, speed and capability	Hull and super-structure	Power and propulsion systems	Fleet management, logistics and incentives	Voyage optimization
Paper 1:Green Maritime Logistics and Sustainability	X			X	
Paper 2: Reductions in greenhouse gas emissions and cost by shipping at lower speeds	X	X	X	X	
Paper 3: Assessment of profit cost and emissions by varying speed as a function of sea conditions and freight market	X		X	X	X
Paper 4: The importance of economies of scale for reductions of greenhouse emissions from shipping	X	X		X	
Paper 5: Comparing the cost and emissions of maritime and air transport	X		X	X	
Paper 6: Reductions in cost and greenhouse gas emissions with new bulk ship designs enabled by the Panama canal expansion	X	X	X	X	

3.4 Research Questions, Exogenous and Endogenous variables for each study

For each of these studies specific research questions were asked in addition to the five main research questions:

- RQ1 - What strategies and measures are available
- RQ2 - What are the characteristics of these strategies and measures
- RQ3 - What are the most promising strategies for further investigation
- RQ4 - How to operationalize the good strategies
- RQ5 - Will implementing the good strategies be sufficient to achieve the required reductions

The purpose of the specific research questions has been to fully answer the main research questions. To give an example to answer 'RQ2 – What are the characteristics of these strategies and measures' the following specific research questions was formulated:

- What are the relationship between vessel speed, emission and cost, and what is the impact of introducing real sea conditions, and how to model this relationship?
- What are the relationship between vessel speed, profit, cost and emission and what is the impact of introducing real sea conditions?
- What are the relationship between vessel size and transport cost and emissions and how to model this relationship?
- How can emission and cost be modeled to enable comparison of air and sea freight?
- How can these relationships be modeled to enable comparison of designs with focus on vessel length, width and hull for varying fuel price?

In each of these studies models were developed to answer the specific research questions. When models are used for assessment that requires variables as input to the models the external defined input variables are termed exogenous variables. Exogenous comes from the Greek words "exo" and "gignomi", which refers to an action or object coming from outside a system. The result of these assessments is outcome values termed endogenous variables. Endogenous also comes from the Greek and means generated from within the system.
Table 4 shows the specific research questions asked in each of these seven studies, the exogenous defined variables for each study and the resulting endogenous variables for each study.

Table 4: Research questions, exogenous and endogenous variables for each study.

Study	Research Questions	Exogenous variables	Endogenous variables
Paper 1: Green Maritime Logistics and sustain-ability	• How can transport chains be modelled? • What are the principles for measuring and comparing GHG emissions and what are the main variables across transport modes? • What are the operational patterns of the fleet and how to build models to compare GHG emissions as a function of vessel types and sizes? • Why are comparisons across transport modes and across ship types important?	• Type of cargo carrier • Size of cargo carrier • Operational pattern • Utilization • Speed	• Emission
Paper 2: Reductions in green-house gas emissions and cost by shipping at lower speeds	• What are the relationship between vessel speed, emissions & cost and what is the impact of introducing real sea conditions. And how to model? • What is the effect of including emissions from shipbuilding in the assessments? • What is the value of shorter versus longer transport times and how can the relationship be modelled? • What are a realistic potential for emission and cost reductions by shipping at lower speeds and what cost items should be included?	• Vessel type and size • Vessel cost • Operational pattern • Utilization • Sea conditions • Fuel price • Shipbuilding emissions	• Cost • Emission • Speed
Paper 3: Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market	• What are the relationships between vessel speed, profit, cost & emission and what is the impact of introducing real sea condition. And how to model? • Can emission, cost and profit models be used in combination with weather forecasts to enable additional savings through better voyage routings? • Can profit be increased by varying speed as a function of freight market and sea conditions? • What are a realistic potential for cost & emission reductions by varying speed?	• Vessel type and size • Vessel cost • Freight rates • Utilization • Sea Conditions • Fuel price	• Profit • Cost • Emissions • Speed

Paper 4: The importance of economies of scale for reductions in greenhouse gas emissions from shipping	• What are the relationships between vessel size and transport cost and emissions and how to model? • What are the operational pattern of the seagoing fleet and how to build models to compare GHG emissions as a function of vessel types and size? • Why are comparisons across ship types and sizes important? • What are the pros and cons for a larger utilization of economies of scale in maritime transport? • What are the potential for cost and emission reductions by economies of scale?	• Vessel types and sizes • Vessel cost • Operational pattern • Utilization • Design Speed	• Cost • Emissions
Paper 5: Comparing the cost and emissions of maritime and air transport	• What is the current market share of air freight versus fast sea transport, and for which cargo types do they compete? • How can emissions and cost be modelled to compare air and sea? • What are the criteria's for selection of air versus sea freight & how to model? • What are the potential for emission reduction by focusing on reducing total air and sea freight emissions instead of treating them separately?	• Cargo carrier types and size • Cost of cargo carriers • Fuel price • Utilization • Operational speed	• Cost • Emission
Paper 6: Reductions in cost and greenhouse gas emissions with new bulk ship designs enabled by the Panama canal expansion	• Can emissions and cost be reduced by more slender bulk ship designs enabled by the Panama Canal expansion? • How is the fuel price affecting the traditional approach of designing and optimizing vessels for a design speed close to its maximum speed? • How can these relationships be modelled to enable comparison of designs with focus on vessel length, width and hull slenderness for varying fuel prices? • What is the reduction potential by building more slender bulk ships?	• Vessel size and type • Variation of main parameters • Required power at design speed • Fuel price • Vessel cost	• Cost • Emissions • Slenderness of hull

4. The Research papers

This section contains the six papers which are the major contribution to this thesis. Of which five are accepted and printed as described by the references. All papers are written by me and I am the corresponding and first author for all of them. The contributions from my co-authors are as described per paper in this introduction.

Paper 1: Green Maritime Logistics and Sustainability
Lindstad, H., Asbjørnslett, B., E. Pedersen, J., T. 2012, Green Maritime Logistics and Sustainability. In Song D., W, Panayides, P., M. (Eds.) Maritime Logistics: Contemporary Issues (2012), Page 227 – 243, Emerald, ISBN 978-1-78052-340-8.

- Professor Bjørn Egil Asbjørnslett supervised the paper and discussed concepts and arguments with me.
- Dr. Jan Tore Pedersen discussed the concepts and arguments with me.

Paper 2: Reductions in greenhouse gas emissions and cost by shipping at lower speeds
Lindstad, H. Asbjørnslett, B., E., Strømman, A., H., 2011. Reductions in greenhouse gas emissions and cost by shipping at lower speeds. Energy Policy 39 (2011), Page 3456-3464.

- Professor Anders Hammer Strømman supervised the paper, discussed the concepts and arguments with me.
- Professor Bjørn Egil Asbjørnslett discussed the concepts and arguments with me.

Paper 3: Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market
Lindstad, H. Asbjørnslett, B., E., Jullumstrø, E., 2013. Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market. Transportation Research Part D 19 (2013), Page 5-12.

- Professor Bjørn Egil Asbjørnslett supervised the paper and discussed concepts and arguments with me.
- Egil Jullumstrø contributed with hydrodynamic data, towing tank and practical experience, discussed the concepts and arguments with me.

Paper 4: The Importance of economies of scale for reductions of greenhouse gas emissions from shipping
Lindstad, H. Asbjørnslett, B. E., Strømman, A., H., 2012a, The Importance of economies of scale for reductions in greenhouse gas emissions from shipping. Energy Policy 46 (2012), Page 386-398.

- Professor Bjørn Egil Asbjørnslett co supervised the paper, discussed the concepts and arguments with me.
- Professor Anders Hammer Strømman co supervised the paper discussed the concepts and arguments with me.

Paper 5: Comparing the cost and emissions of maritime and air transport
This paper was submitted to Energy Policy in December 2011 and it came back from first review in February 2013. It took such a long time since the journal had problems finding reviewers in combination with disagreeing reviews. Compared to the first submitted version, adjustment has been made to accommodate for comments by the reviewers. The plan (when my PhD- thesis was submitted in March) was to resubmit this version to another journal. However after some thoughts and consultation I decided instead to resubmit a much shorter version with less focus on policy which was done in end of April 2013. Personally I prefer the version included in this thesis because it gives the reader a more complete picture.

- Professor Anders Hammer Strømman supervised the paper, discussed the concepts and arguments with me.

Paper 6: Reductions in cost and greenhouse gas emissions with new bulk ship designs enabled by the Panama Canal expansion
Lindstad, H., Jullumstrø, E., Sandass, 2013. Reduction in cost and emissions with new bulk ships designed enabled by the Panama Canal expansion. Energy Policy 59 (2013), Page 341–349

- Egil Jullumstrø contributed with hydrodynamic data, towing tank and practical experience, discussed the concepts and arguments with me
- Inge Sandaas introduced me to the STAWAVE method for calculating added resistance in waves and contributed with hydrodynamic data and practical experience. Calculated the power based on Holtrop to compare with power predictions based on the developed model.

4.1 Paper 1

Lindstad, H., Asbjørnslett, B., E. Pedersen, J., T. 2012, Green Maritime Logistics and Sustainability. In Song D., W, Panayides, P., M. (Eds.) Maritime Logistics: Contemporary Issues (2012), Page 227 – 243, Emerald, ISBN 978-1-78052-340-8.

4.2 Paper2:

Lindstad, H. Asbjørnslett, B., E., Strømman, A., H., 2011. Reductions in greenhouse gas emissions and cost by shipping at lower speeds. Energy Policy 39 (2011), Page 3456-3464.

Energy Policy 39 (2011) 3456–3464

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Reductions in greenhouse gas emissions and cost by shipping at lower speeds

Haakon Lindstad [a,b,*], Bjørn E. Asbjørnslett [a], Anders H. Strømman [a]

[a] Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway
[b] Norwegian Marine Technology Research Institute (MARINTEK), NO-7450 Trondheim, Norway

ARTICLE INFO

Article history:
Received 5 October 2010
Accepted 17 March 2011
Available online 19 April 2011

Keywords:
Maritime transport
Speed reductions
Greenhouse gas emissions

ABSTRACT

CO_2 emissions from maritime transport represent a significant part of total global greenhouse gas (GHG) emissions. According to the International Maritime Organization (Second IMO GHG study, 2009), maritime transport emitted 1046 million tons (all tons are metric) of CO_2 in 2007, representing 3.3% of the world's total CO_2 emissions. The International Maritime Organization (IMO) is currently debating both technical and market-based measures for reducing greenhouse gas emissions from shipping. This paper presents investigations on the effects of speed reductions on the direct emissions and costs of maritime transport, for which the selection of ship classes was made to facilitate an aggregated representation of the world fleet. The results show that there is a substantial potential for reducing CO_2 emissions in shipping. Emissions can be reduced by 19% with a negative abatement cost (cost minimization) and by 28% at a zero abatement cost. Since these emission reductions are based purely on lower speeds, they can in part be performed now.

0. Introduction

Anthropogenic emissions of greenhouse gases contribute to global warming, and augmentations in temperature to more than 2 °C above pre-industrial levels are likely to have catastrophic consequences at a global level (Walker and King, 2008). These implications are well documented by IPCC and acknowledged by our politicians. It is estimated that greenhouse gas emissions need to be reduced by around 50–85% in 2050, compared with current levels, in order to achieve a stabilization of the temperature at 2 °C above pre-industrial levels (IPCC, 2007).

While the marine sector has a non-binding commitment under the current Kyoto protocol regime, Article 2.2 of the former invites Annex I countries to the protocol to pursue the limitation or reduction of greenhouse gas emissions from shipping through the IMO. So far, however, the Annex I countries have had little success in limiting or reducing greenhouse gas emissions from international maritime transport. The main reason seems to be differences in the views of Annex I and non-Annex I countries when it comes to the interpretation of Article 2.2 and regarding the applicability of the IMO's principle of a non-discriminatory regulation of all ships engaged in international trade to a climate policy instrument (Faber et al., 2009). However, IMO has made some progress and the current debate is addressing how much the sector can be expected to reduce emissions, and should be obliged to reduce, as well as in what manner these diminutions can be achieved.

According to the IMO (Second IMO GHG study, 2009), maritime transport emitted 1046 million tons of CO_2 in 2007, representing 3.3% of the world's total emissions. These emissions are assumed to increase by 150–250% in 2050 if no action is taken (i.e., business as usual scenarios with a tripling of world trade). Similar growth prospects have also been reported by OECD (2010) and Eyring et al. (2009). These greenhouse gas emission growth figures stand in sharp contrast to the required total global reductions (IPCC, 2007). Nevertheless, it is a controversial issue how the annual greenhouse gas reductions shall be taken across sectors. Given a scenario where all sectors accept the same percentage reductions, the total shipping emissions in 2050 may be no more than 15–50% of current levels based on the required 50–85% reduction target set by the IPCC (2007). Moreover, provided that the demand for sea transport follows the predicted tripling of world trade, it can easily be deduced that the amount of CO_2 emitted per ton nautical mile (1 nm = 1.852 km) will then (as a minimum) have to be reduced from 25 to 4 g of CO_2 per ton nautical mile by 2050.

This is a reduction by a factor of 5 and a seemingly substantial challenge. The question is thus how to make it come about. There is indeed a documented potential to reduce greenhouse gas emissions in a cost-effective manner. In other words, emissions can be cut with net cost savings (DNV, 2009; Longva et al., 2010). Ships have typically been built to operate at a specific design speed: for large dry bulk vessels this speed is 13–16 knots, while large container vessels have service speeds of 24–26 knots.

---

[*] Corresponding author at: Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway. Tel.: +47 92801521.
E-mail address: Haakon.Lindstad@ntnu.no (H. Lindstad).

0301-4215/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2011.03.044

Nomenclature

B	vessel beam (maximum width) of the vessel at the waterline, m
C	cost per freight unit, USD/ton nautical mile
C_{HFO}	cost for heavy fuel oil per ton, USD/ton
C_{IR}	the annual interest rate as calculated by industry or financial institutions, %
C_M	export value per ton of transported cargo, USD/ton
C_{MDO}	cost of marine diesel oil per ton, USD/ton
D	roundtrip distance (1 nm = 1.852 km), nautical miles (nm)
C_{aw}	drag coefficient for the wave resistance, non-dimensional
C_T	total drag coefficient, non-dimensional
ε	the amount of CO_2 emitted per million ton nautical mile, ton
F	fuel consumption F for a roundtrip, ton
F_s	fuel used during sailing F_s, ton
$F_{p\&s}$	fuel used in port and slow zones (canals and in and out of ports), ton
g	the gravity force, m/s^2
$H_{1/3}$	significant wave height, m
j	propeller constant that is speed independent, non-dimensional
k	propeller constant that is speed dependent, non-dimensional
K	propeller (propulsion) efficiency as a function of the vessel speed, non-dimensional
$K_e = 3, 17$	emitted CO_2 when one unit of fuel is burnt, based on Endresen et al. (2007), g/g = 1
$K_f = 190$	the amount of fuel used per work unit produced, g/kWh
L	length of the ship at the waterline, m
M	weight (in tons) of the cargo onboard the vessel, ton
P	total power required, kWh
P_{aux}	power required for auxiliary machines, kWh
P_s	power required for still water, kWh
$P_{p\&s}$	power requirement in port and slow zones, kWh
P_w	additional power required for waves, kWh
ρ	density of water, kg/m^3
S	wetted surface of the vessel, m^2
T	time used per roundtrip (days, hours, min)
TC	time charter cost of the vessel per day, USD/day
u	wave speed in relation to vessel speed (1 knots = 1852 m/h), knots
v	vessel speed (1 knots = 1852 m/h), knots
v_d	the design speed for which the vessel is optimized (this speed is usually 90–95% of the maximum speed), knots

The core insight is straightforward: the power output required for propulsion is a function of the speed to the power of three. Hence, in very simple terms, when a ship reduces its speed, its fuel consumption is reduced. For this reason, several authors have incorporated speed optimization when optimizing fleet scheduling (Bausch et al., 1998; Fagerholt, 2001; Norstad et al., in press).

Ship scheduling and routing concerns the optimal assignment of available cargoes to a set of ships in the fleet, where "optimal" signifies either lifting (transporting) all cargoes while minimizing costs or maximizing profit by only assigning profitable cargoes. Speed reductions also affect the size and mix of a fleet of vessels serving a liner network, and this is known as fleet size mix and routing problems (Christiansen et al., 2007; Fagerholt and Lindstad, 2000). Here, the objective is to find the number and types of vessels as well as a set of feasible routes in order to minimize the total costs.

While the above-mentioned studies have been motivated by the opportunity for cost savings or profit maximization, there has emerged a growing interest in the relationship between speed and emission reductions. Corbet et al. (2009) considered whether the lowering of speed can be a potentially cost-effective CO_2 mitigation option for ships calling at US ports. They found that a fuel tax of about 150 USD/ton would lead to average speed-related CO_2 reductions of approximately 20–30%. Moreover, Sea at Risk and CE Delft (2010) primarily investigated how the overcapacity in major shipping markets in 2009 could be utilized for slow steaming and hence emission reductions. It was estimated that emissions of dry bulk, tanker and container vessels can be reduced by about 30%, relative to the situation in 2007, by employing an oversupply to reduce the speed.

Psaraftis and Kontovas (2010) studied the implications of various emission reduction policies for maritime logistics, and the slow steaming of container vessels in particular. They concluded that lower speeds have environmental benefits, but if the value of the goods is high, its capital cost in addition to the potential loss of sales would favor higher speeds. The modeling approach used in these studies (Corbet et al., 2009; Sea at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010) has involved the assumption of constant total transport volumes. This implies that when speed is reduced, additional vessels will be required to maintain the annual transport capacity. While there are some differences regarding which cost elements that are included, the basic method consists in calculating the fuel savings when speed is reduced versus the cost for additional vessels to maximize profit or minimize cost. In this study, both the cost of the shipping lines and that for the cargo owners, including the capital cost for the goods transported has been calculated. The additional value of including both these parameters is to obtain an enhanced understanding of the speed preferences of a cargo owner versus a shipping line.

The fuel and emission calculations in these studies (Corbet et al., 2009; Sea at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010) have been based on still water conditions. In the present study, the added resistance created by wave and wind (sea state) has been included in the power model to reflect the realities from very low speeds up to the design speed, which usually is 90–95% of the maximum speed. This enables the model to calculate the potential emission reductions that can be achieved as a function of speed, dictated by various priorities such as operation at the designed service speed, cost minimization and emission minimization for the various ship classes.

Furthermore, these results have been combined to provide an assessment of the overall potential for short and long term emission reductions through changes in the operation of the global maritime fleet. The employed model is described in Section 1, its application and the data are presented in Section 2, and the obtained results are discussed in the final section with respect to their implications to design policy.

1. Model description

The main objective of the developed model is to calculate costs and emissions for individual ship classes as a function of speed, dictated by various priorities such as operation at the designed service speed, as well as cost and emission minimizations. The system boundaries focus on the vessels and their use, for which reason the landside of the terminal and the port is excluded. The model consists of four main equations, of which the power Eq. (1) is the most important. It describes the power requirement as a function of vessel speed, hull, propeller and sea state. Traditionally, research on hull shapes and propellers has designed them for still-water, design cargo loads and design speed conditions (Faltinsen et al., 1980), and this despite that a calm sea is quite the exception in shipping. Lloyd (1998) has studied how additional wind and wave resistance increases the power needed as compared to what is required for calm water conditions. The results showed that the resistance rises rapidly with a significant wave height, that the greatest increase relative to the calm water resistance occurs at low speeds and that the contribution from wind is quite small in comparison to the effect of waves.

Based on the above considerations, the power model developed takes into account the propeller efficiency, the power needed for still water conditions, the additional power required for waves and that needed for the auxiliary engines (independent of vessel speed), as expressed by Eq. (1). Comparing this formula to well-established practice, the still water power is calculated in a standard manner (Lewis, 1988), the additional power for waves (Lloyd, 1998) has been modified to enable calculation of the additional average resistance for a full year (the factor $\frac{1}{2}$) and the auxiliary is in standard form. On the contrary, a new notation based on the work by Minsaas (2006) and Lloyd (1998) was required to give a good representation of propeller efficiency from zero speed up to service speed, which is usually 90–95% of the maximum speed

$$P = \underbrace{\frac{1}{\eta(j+k\sqrt{v/v_d})}}_{K}\left(\underbrace{\left(\frac{\rho C_T S v^3}{2}\right)}_{P_s}+\underbrace{\left(\frac{1}{2}\frac{c_{aw}\rho g(H_{1/3}/2)^2B^2}{L}(v+u)\right)}_{P_w}\right)+\underbrace{P_{aux}}_{P_{aux}} \tag{1}$$

Here, K gives the propeller (propulsion) efficiency as a function of the vessel speed and η gives the efficiency at the design speed v_d. Typically, η values will reside in the range from 0.6 to 0.7. When speed v is reduced, the propeller efficiency K drops according to the constants j and k (where $j+k=1$). The still water power is given by P_s, where ρ is the density of water, C_T is the total drag coefficient, S is the wetted surface and v is the speed. The wave power is given by P_w, where the $\frac{1}{2}$ expresses the average wave force working on a vessel during a typical roundtrip for which the voyage consists of parts with head waves, side waves and aft waves and where the effect of the aft waves has a small positive contribution to the forward speed compared to the added resistance created by the head waves. In its formula, ρ is the density of water, C_{aw} is the drag coefficient for the wave resistance, g is the vertical force, $H_{1/3}$ is the significant wave height for which the amplitude is half of the height, B is the width of the ship at the waterline, L is the length of the ship at the waterline, v is the vessel speed and u corresponds to the speed of the waves in relation to that of the vessel. The auxiliary power needed for running pumps and for producing electricity for lighting as well as all the supporting systems of the ship, P_{aux}, is a function of the vessel type and size, and also of the cargo it carries. Moreover, it is generally independent of vessel speed.

The fuel consumption F for a roundtrip involves the fuel used during sailing F_s and fuel used in port and slow zones $F_{p\&s}$, as expressed by

$$F = F_s + F_{p\&s} = K_f\left(\left(\frac{PD}{v}\right)+(P_{p\&s}T_{p\&s})\right) \tag{2}$$

Here, P represents the required power, D is the roundtrip distance, v is the actual vessel speed and K_f is the amount of fuel (in grams) per produced kWh. Moreover, $P_{p\&s}$ corresponds to the power requirement in port and slow zones and $T_{p\&s}$ is the time in port and slow zones per roundtrip. The difference compared to Second IMO GHG study (2009) is that the formula calculates the fuel as a function of speed where the added resistance from waves and efficiency of propulsion has been included in addition to the calm water resistance.

The amount of CO_2 emitted per ton nautical mile ε is calculated as follows (Second IMO GHG study, 2009):

$$\varepsilon = \left(\frac{F}{DM}\right)K_e \tag{3}$$

where F is the total amount of fuel consumed during the roundtrip as described in Eq. (2), K_e is the emitted CO_2 per unit of fuel burnt and DM is the freight service in distance-weight units (ton nautical mile), for which D is the distance and M is the average weight (tons) of the cargo on a given roundtrip.

The cost per ton nautical mile, C, comprise the fuel cost, the time charter cost of the vessel and the capital cost of the transported goods, as expressed by

$$C = \frac{1}{DM}\left((F_sC_{HFO}+F_{p\&s}C_{MDO})+TCT+\left(MC_M\frac{1}{2}T\left(1+\frac{C_{IR}}{365}\right)\right)\right) \tag{4}$$

The first factor, i.e., $1/DM$, transforms the cost from a total cost per roundtrip to a cost per ton nautical mile to enable comparisons of freight cost per unit for vessels of different sizes and types employed in various trades. The fuel cost is then calculated as the amount used during sailing F_s multiplied by the cost for heavy fuel oil C_{HFO} plus the fuel used in port and slow zones $F_{p\&s}$ multiplied by the price of marine diesel oil C_{MDO}. Until quite recently, deep-sea vessels could operate without using marine diesel oil at all. However, with stricter environmental legislations in Europe and in North America, it can be assumed that marine diesel oil will soon be required when navigating in all ports and slow zones. The cost of the vessel is calculated as the time charter cost per day, TC, multiplied by the voyage length, T, measured in days. The capital cost of the transported goods is obtained by the average amount of transported cargo M, the export value per ton of transported goods, C_M, the time used for the one way voyage which is half the roundtrip time $\frac{1}{2}T$ and the linearly distributed capital cost of transported goods $(1+(C_{IR}/365))$. Here, C_{IR} is the annual interest rate as calculated by industry or financial institutions. When the speed is reduced below the service speed (90–95% of maximum speed), two of these three cost terms will increase, and one will decrease, while the total freight work per roundtrip remains constant. The cost terms that are raised when the speed is reduced are the time charter and the capital cost while the fuel cost decreases due to a reduced power requirement (according to Eq. (1)) and fuel consumption (according to Eq. (2)).

Summing up, combining Eqs. (1)–(3) renders it possible to describe the greenhouse gas emissions associated with a specific operational mode expressed, while Eq. (4) provides the costs.

In order to obtain consistent fleet level results, it is important to also address the issue of environmental impacts of shipbuilding. To this end, Life Cycle Assessment (LCA) is the leading methodology for evaluation of environmental impact. In our case we have applied the Environmental Extended Input Output Life Cycle Assessment on-line tool (www.eiolca.net) provided by Carnegie Melon University and the obtained results includes the relative impacts of various types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain. Thus, the effect of producing a seagoing vessel would involve emissions at the shipyard, from mining metal ores, from the steel mill or the aluminum plant, and from the manufacture of engines and electronic parts.

2. Application and analysis

The aim of the analysis is to first identify the emissions and costs for individual ship classes as a function of speed, discuss and assess these, and then combine them to evaluate the emission reduction potential and costs for the global fleet.

2.1. Selection of ship classes for the study

The selection of ship classes for this study was made to facilitate an aggregated representation of the world fleet based on ton-nautical miles produced by the various classes and coverage of ship classes operating within different speed areas. The outcome of this selection was to include bulk, RoRo and container vessels above 15 000 dead-weight (the measure in ton for how much weight a ship can carry at most). Combined, these classes represent 80% of global sea transport.

The chosen vessel types operate within three speed regimes and were expected to exhibit varying responses in terms of costs and emissions resulting from reductions in operating speed. In terms of their utility, RoRo vessels are used for the transport of cars, trucks, heavy machines, forest products and project cargo, and typically have dead-weights between 15 000 and 40 000 tons with service speeds around 20 knots.

Their cargo capacity is also expressed in standard car units and number of lane meters.

Container vessels are employed for the transport of containers filled with a wide range of products and commodities, from high-value items like electronics, to low-value products as well as scrap steel and paper for recycling. Even if the containers look quite standardized, there are different sizes and types and as a result all containers are calculated as multiples of the standardized twenty feet unit (TEU) which has a length of 6.1 m, a width of 2.4 m and a height of 2.6 m, to enable load planning and capacity calculations. Typical dead-weights range from 40 000 to 160 000 tons equivalent to 3500 to 14 000 TEU, and service speeds are around 25 knots.

Bulk vessels are built for carrying either dry or wet cargoes, and the ore-bulk-oil carriers are capable of carrying both. The main dry bulk commodities include iron ore, coal, grain, alumina and aggregates while crude oil is the dominant wet bulk commodity. Measured in freight work, these 6 commodities add up to 60% of the global sea transport work measured in ton nm. Typical dead-weights range from 40 000 to 300 000 tons and service speeds are 13–16 knots.

2.2. The data set used in the analysis

In the performed calculations, both container and RoRo vessels were employed in trade between Asia and Europe, where the distance was 11 000–12 000 nautical miles. The bulk vessels were utilized in typical raw material trades from Australia to China, implying a distance of 4500 nautical miles. The modeling approach assumed that the total transport volumes were constant so as, when the speed is reduced, additional vessels will be required in order to maintain the annual transport capacity. Although speed limitations lead to reductions in operational emissions down to a minimum level, the emissions from shipbuilding increase due to the need for additional vessels.

At the present time, moderate speed reductions can be implied without additional vessels being built since there is an oversupply of vessels (Sea at Risk and CE Delft, 2010). However, in the long run, emissions from shipbuilding have to be included in the assessment to identify the speeds that minimize total emissions. Since the applied Environmental Extended Input Output Life Cycle Assessment on-line tool is based on US cost levels, which are high compared with new building prices in Asia, it was assumed that the price for US-built vessels of all categories would be twice the actual new building prices (CAPEX). Such an assumption led to a result of 42 900 tons of CO_2 emitted for building a Panamax Bulk vessel, where the weight of the vessel itself, without any cargo, fuel or supplies was 10 000 tons (more than 95% of this weight was steel). It can be argued that 4.3 kg CO_2 per kg ship is rather high, but at least such a value would ensure that the CO_2 effect for building additional vessels would not be underestimated. For the building of a RoRo vessel and a container vessel, the Environmental Extended Input Output Life Cycle Assessment with the same assumption gave 70 000 and 75 000 tons of CO_2, respectively.

All figures pertaining to cost were taken in US dollars (USD) and the price per ton for the two fuels used was $C_{HFO}=400$ and $C_{MDO}=600$. The time charter (TC) rate was based on new building prices (CAPEX), and the annual TC was set to 12% of the new building price and the daily TC was obtained by dividing the annual TC by 350 days. The capital cost of the goods transported, was calculated as a function of their ex-works value per ton and the interest rate for the capital required. Different accounting principles can be used to set the ex-works value, however we have set it based on the accounting principles that it shall reflect the manufacturing cost including the raw materials plus the profit of the manufacturer, while we have used average world market prices for commodities like crude oil, iron ore, coal and grain. The average ex-works value of the cargo onboard the RoRo and the container vessels was set to 5000 USD/ton, while 250 USD/ton was used for the bulk cargo. The interest was taken as 5% per annum.

The main characteristics of the vessels were the following: RoRo vessel—8000 standard car units, 28 000 dwt, CAPEX 82 million USD, TC/day 28 000 USD, CO_2 from shipbuilding 70 000 ton, main engine 18 500 kWh and service speed 20.5 knots; container vessel—6000 TEU, 80 000 dwt, CAPEX 88 million USD, TC/day 30 000 USD, CO_2 from shipbuilding 75 000 ton, main engine 60 000 kWh and service speed 25 knots; and bulk vessel—72 000 dwt, CAPEX 50 million USD, TC/day 17.000 USD, CO_2 from shipbuilding 42 900 ton, main engine 9800 kWh and service speed 14.5 knots.

For all the trades, the vessel dead-weight utilization was set to 50% on a roundtrip basis, as determined based on a bulk vessel loaded 100% one way and returning empty. For RoRo and container vessels, the following figures were utilized: 25–50% one way and 50–75% on the return trip. All these ship types may achieve higher yearly dead-weight utilizations, but the fact of employing identical utilization percentages rendered the comparisons and conclusions transparent.

For the resistance due to waves, the significant wave height used was 2.5 m. This is quite close to the average value that would be obtained for all ocean areas if a full calculation were to be carried out. This increases the average power requirement compared with still water conditions for all the vessels, and while the impact is only 2–3% for container vessel moving at the service speed of 25 knots, it increases to 5% at 19 knots and 15% at 12.5 knots. Since speed reductions also gives reductions of propulsion efficiency, while the auxiliary consumption is speed independent, the net effect is a calculated power reduction to 20% compared with what is required to achieve service speed (the power equation) and to 12% if only still water resistance (based on constant propulsion efficiency) and auxiliary are included. Reducing speed by 50% also gives the same reduction of freight work per hour and the emission per ton nautical mile becomes 40% of the emissions at the service speed (the power equation), compared with 24% if only still water and auxiliary power is included. For bulk vessels, which moves slower, the impact of including the average wave resistance increases the power requirement by 15% when traveling at a service speed of 14.5 knots. When the speed is reduced with 50% to 7.25 knots, the emissions per ton nautical mile become 54% of emissions at the service speed (with the power equation) compared with 30% if only still water and auxiliary power are included. For RoRo vessels, which travel at a service speed of 20.5 knots, the emission reductions are smaller than for container vessels and larger than for bulk vessels.

2.3. *Results regarding speed and cost*

The results for the individual ship classes are presented in Fig. 1. The figure contains two separate parts for each of the three vessel types with a common vertical axis. The vertical axis represents the cost in USD for the transport work measured per million ton nm as a function of vessel speed on the right-hand side of the figure, and the same cost as a function of emissions on the left-hand side. By plotting the results this way, it is possible to obtain the emission reduction as a function of the speed reduction.

All the graphs present a dotted and a dashed line; the former includes the cost elements time charter, TC, and fuel oil cost, FC, while the dashed line also takes into account the capital cost of the transported goods, CC. Moreover, the graphs to the left contain a solid line, which includes the life cycle emissions associated with the increased number of vessels required to serve a constant flow of goods as speeds are reduced (in addition to the direct emissions from operation). The graphs to the right demonstrate a minimum cost for a speed lower than the design speed. Furthermore, the section of the curve on the left-hand side of this point is inefficient in terms of cost versus speed, assuming a positive utility assigned to increased speed. This was found for cost curves both including and excluding the value of goods.

When the value of the cargo was added, it caused the entire curve to shift upwards and to the right. Following this, the cost optimum speed increased when the value of the cargo was included. The magnitude of this shift was given by the ratio of capital cost of the goods relative to the time charter and fuel costs. As can be observed, the ship classes demonstrated different behaviors in this respect. The cost optimal speed for bulk ships changed very little with the inclusion of the cargo value, from 12.5 to 13 knots, while the cost curves shifted only marginally upward with the minimum cost changing from 3400 to 3550 USD per million ton nm. For reference, the design speed was 14.5 knots.

For the two other ship classes, the changes were much more significant. For RoRo vessels, the design speed was 20.5 knots, while the cost optimum speed was 16.8 and 19 knots, respectively, excluding and including goods capital costs. The changes were even more significant for container ships for which the design speed was 25 knots, while the cost optimum speed was 15.6 and 18 knots excluding and including goods capital costs. For the latter case, the costs at optimum were 10% lower than at the design speed.

2.4. *Results regarding minimizing emissions and Pareto optimality*

The graphs on the left side show the trade-off curves between costs and emissions as a function of vessel speed on the right-hand side. All graphs have three distinct lines. The dotted line represents time charter plus fuel cost and direct emissions from operation. The dashed line includes the costs for time charter, fuel, goods capital cost and direct emissions. The solid line corresponds to the same cost elements as the dashed line but also includes the emissions associated with shipbuilding. This is required for consistency, since the number of ships must be increased as the sailing speed is reduced in order to maintain the same flow of goods. The curves demonstrate that a reduction of the speed below the design speed reduces emissions. The emission reduction is the largest for the first percentage of speed reduction, whereas when the speed is further reduced, the marginal emission reduction gradually becomes smaller until it reached zero for the speed that gives the lowest emissions per ton nautical mile. Further reductions in speed lead to increase of emissions per ton nautical mile.

When plotting emission against cost, a Pareto distribution was obtained, where both emissions and cost increased when the speed was reduced below the minimum emission speed. The dotted line shows this relationship when fuel and the time charter cost is included. When the capital cost of goods was taken into account, the curve moved upwards as shown by the dashed line, and when emissions from shipbuilding were taken into account, the solid lines were caused to shift upwards (cost increase) and to the right (emission increase).

According to these results, the emission optimum speed increased when shipbuilding was included. The magnitude of these shifts in emissions was given by the specific shipbuilding emissions and the additional vessels required, whereas the shift in cost was based on cargo values. As can be observed, the ship classes demonstrated different behaviors in this respect. When minimizing emissions for bulk ships, the speed increased from 6 to 7.2 knots, adding up to 8 ton CO_2 per ton nm when shipbuilding was included in the assessment. At this speed, emissions from shipbuilding constituted 20% of the total, while at the design speed of 14.5 knots, emissions added up to 12.4 ton CO_2 per ton nm of which shipbuilding was 6% of the total. For container vessels, the speed when minimizing the emissions increased from 7.2 to 8.4 knots adding up to 13.9 ton CO_2 per ton nm when shipbuilding was included in the assessment. At this speed, emissions from shipbuilding corresponded to 11% of the total, while at the design speed of 25 knots, emissions added up to 36.4 ton CO_2 per ton nm of which shipbuilding represented 2%. For RoRo vessels, the speed when minimizing the emissions increased from 7.2 to 8.4 knots when shipbuilding was included in the assessment, adding up to 20.9 ton of CO_2 of which 20% came from shipbuilding. On the other hand, at the design speed of 20.5 knots, the emissions were 38.7 ton CO_2 per ton nm of which shipbuilding constituted 5%.

To summarize, when the focus was to minimize emissions, a speed reductions (compared to the design speed) down to 50% for bulk, 59% for RoRo and 67% for container vessels gave emission reductions of 35%, 46% and 62% for the three vessel types. Minimizing emissions led to cost increases and represents the left border of the Pareto optimal curve, while a minimization of cost, also causing emission reductions, corresponds to the right border. Although emission and cost minimization represents the left and right border values on the Pareto curve, the third point of specific interest was the emission when the cost equaled the design speed level. Here, there occurred an emission reduction with a zero abatement cost. This point was found for the following speeds (with the reductions as compared with the design speed in brackets): 17.7 knots (13%) for RoRo, 12.5 knots (13%) for bulk and 12 knots (52%) for container vessels. The emission reductions were 17% for RoRo, 14% for bulk and 53% for container vessels.

2.5. *Results for the global fleet*

Table 1 summarizes the bottom-up results for each of the vessel groups to a macro level in order to calculate emissions for the whole world fleet as a function of varying priorities.

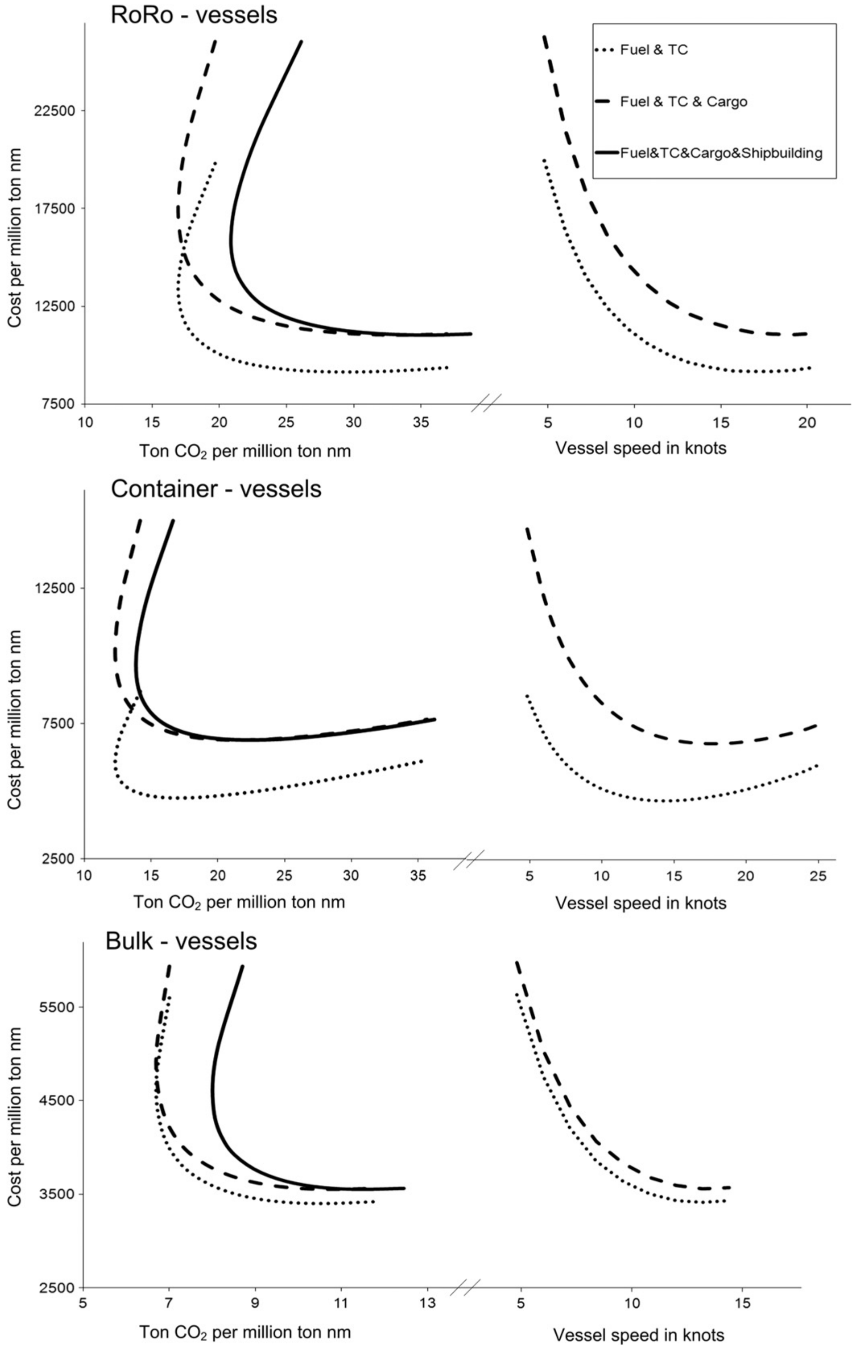

Fig. 1. Emission and cost as a function of vessel speed.

The employed fleet database was the 2007 world fleet as published in the Sea-web database by Lloyds Register Fairplay (now IHS-Fairplay) and the fuel consumption and operational patterns per vessel group were those published by Lindstad and Mørkve (2009).

As can be seen from the table, the world fleet was divided into five groups; RoRo, bulk, container, other cargo vessels and other vessels. The vessel group 'other cargo vessels' includes product and chemical tankers, gas carriers, reefers, general cargo vessels and Ro–Pax vessels which transport both cargo and passengers.

Table 1
Annual emissions as a function of varying priorities.

Vessel type and CO_2 emission in million tons	Design speed	Minimizing cost	Abatement cost = 0 USD/ton	Abatement cost = 20 USD/ton	Abatement cost = 50 USD/ton	Minimizing CO_2
RoRo	39	36	33	30	26	21
Container	269	169	118	109	105	103
Bulk	289	259	250	231	215	187
Other cargo vessels	368	286	247	228	213	191
All other vessels	157	157	157	157	157	157
Total	1122	907	804	755	716	659
% of AS IS		81	72	67	64	59

This is a mixed group with vessel speeds ranging from less than the bulkers, to faster than the container vessels, and it was assumed that the emission reduction percentages for the various priorities would correspond to the average of those of RoRo, container and bulk vessels. For other vessels comprising service boats, fishing boats, offshore service vessels, cruise vessels and leisure yachts built for other purposes than cargo transport, constant emissions were assumed.

The table displays that emissions including shipbuilding, when operated at the design speed, are 1120 million ton CO_2 per year of which 76 million tons come from shipbuilding. When the cost is minimized, the emissions are reduced by 19% to 850 million ton with an 8% increase of the fleet. When the focus is changed from cost to emission minimization, four points of interest emerge; emissions minimized under the condition of the cost not exceeding that at the design speed (zero abatement cost), potential emission reductions with an abatement cost of 20 USD/ton, potential emission reduction with an abatement cost of 50 USD/ton and maximizing emission reductions regardless of the abatement cost.

When emissions are minimized for a cost equal to design speed (zero abatement cost), emissions are reduced by 28% to 804 million ton CO_2 with a 19% increase of the fleet. With an abatement cost of 20 USD/ton, the CO_2 emissions can be reduced by 357 million ton, which gives a 33% reduction. If the abatement cost is increased to 50 USD/ton, the emissions can be reduced with 406 million ton of CO_2, corresponding to a 36% reduction. If emission reductions are maximized, the emissions are reduced by 41% to 659 million ton CO_2 with an abatement cost of more than 100 USD/ton CO_2 and a fleet increase of 54%.

3. Discussion and conclusions

The results from the model demonstrated that there is a substantial potential for reducing CO_2 emissions in shipping, since a decrease of 19% can be obtained with a negative abatement cost and since a diminution of 28% would be possible at a zero abatement cost. Achieving minimum emissions of 59% of the current level would lead to cost increases and hence a positive abatement cost based on current prices for fuel and the cost of building new vessels. Since these emission reductions are purely based on lower speeds, as opposed to on new technology, some of them can be achieved straight away. However, in order for the full potential to be realized, more vessels need to be built to maintain the total transport capacity.

3.1. Sensitivity analysis

When comparing the obtained results to data from other studies, they were found to be within a similar range as those presented by Corbet et al. (2009) and Sea at Risk and CE Delft (2010). If fuel prices increase, the profitable (19%) and free-of-charge (28%) abatement cost options will also increase, whereas they will be lowered with a price reduction on fuel. This statement regarding the fuel price agrees with the results obtained by Corbet et al. (2009), however none of the other studies has focused on this aspect. Based on strict requirements whereby the maximum sulphur content of standard marine fuel oil (HFO) undergoes a step-wise reduction from 3.5% to 0.5% within the next 10 years, marine fuel oil will become more expensive even if oil prices should remain at the current level.

The other main exogenous variable where sensitivity is an issue is the capital cost of the transported goods. In the present analysis, the value of 250 USD/ton was used for bulk commodities to reflect the mix of coal and iron ore at export prices below 100 USD/ton, alumina, fertilizer, grain and other commodities from 150 USD/ton and upwards, and crude oil at 400 USD/ton. It can be argued that the value of 250 USD/ton is both too high and too low, but 13 knots gives the lowest cost for all cargo values between 100 and 400 USD/ton. For the RoRo segment, 5000 USD/ton was used to reflect the combination of new cars in all price ranges, new trucks and heavy machinery with the transport of used cars as well as industrial project cargoes and forest products. One can point out that this value is rather high and if it is reduced by 50% to 2500 USD/ton, 18 knots becomes the speed that gives the lowest cost compared to 19 knots with 5000 USD/ton. Container lines also transport a mix of cargo with a wide range of value per ton, but their operations are frequently analyzed solely on the basis of the high-value goods that are transported. Such an analysis was performed by Psaraftis and Kontovas (2010) who used 30 000 USD/ton. Although the container segment transports products within this price range, it could be argued that a majority of container cargoes presents costs outside it. At the lower end of the container segment can be mentioned cargoes such as paper for recycling and scrap steel, while in the 100–1000 USD/ton range, one finds grain, rice, canned fruits, forest products, steel for manufacturing, ceramic tiles and various other building materials.

It can also be claimed, as was done in this study, that this cargo mix gives an average of 5000 USD or less per ton on a container vessel, and even then, the inventory cost is 20% for a container vessel sailing at the design speed. This value increases to 25% when the speed is reduced from 25 to 18 knots. With a cargo value of 30 000 USD/ton, the capital cost of the goods would be 70% of the total transport cost at the service speed, thereby rendering any speed reductions unprofitable.

We have also considered if port and logistics inefficiencies in general will influence on our conclusions. However, since the assumption is that the total transport volumes are constant, the implication when speed is reduced is that each vessel will do fewer roundtrips and less port calls, but total number of roundtrips and port calls per year will remain unchanged, and speed reductions will then not influence port inefficiencies.

3.2. *How to achieve speed reductions*

A key issue is how to achieve the speed reductions that will lower emissions. Discussions have already taken place both within UNFCCC and through the Marine Environmental Protection Committee of IMO. The main measures that have been discussed involve an Energy Efficiency Design Index (EEDI) and Market Based Instruments (MBIs) in the form of emissions trading, a fuel levy, or a combination of the two (Lindstad et al., 2010). While the Energy Efficiency Design Index will only reduce emissions from new vessels, which suggests that even after 12–15 years, only half of the fleet will be covered, the Market Based Instruments will have an immediate full effect. The Market Based Instruments are based on the assumption that higher fuel prices will incite operators to reduce speeds, and studies such as that of Corbet et al. (2009) have investigated how the fuel price influences speed decisions taken by the shipping lines, with the conclusion that higher fuel prices result in speed reductions.

The data from the present investigation indicates that things may be more complex and that the impact of fuel prices on speed decisions has been overestimated. Such a statement is based on Pareto solutions - where cost and emissions are optimized - being found for speeds below current service speeds (reference level). From the shipping markets, it is also well known that in a good market, ship-owners will tend to operate at full speed in order to maximize income at both high and low fuel prices. Reduced speeds, on the other hand, are used to save costs and reduce available capacities in a depressed market. The above could indicate that it may be important to understand ship-owners' preferences, as well as those of their customers, in order to enable speed reductions.

It could be an option to introduce utility theory to handle such complex relationships. In economics, utility is a measure of relative satisfaction and in logistics place utility is used for the relative satisfaction of having the right products at the right places at the right time. One objective of introducing utility theory would be to model the relative value of shorter transport times, in order to obtain a better understanding of the price premium that customers would be willing to pay for maintaining short lead times based on fast transport. An alternative approach to using utility theory could be to model the relative value of transport time based on a survey. Even if the focus in this study has been on the cost, the additional cost given by speeds that exceed the speed which gives the lowest cost can be seen as the price premium currently paid by customers to maintain short lead times. In a study carried out for IMO Anger et al. (2010) argued that the willingness to pay for short lead times was high, and their conclusion was that the increase in fuel price due to Market Based Instruments would have to be 800% in order to stabilize emissions at the current level, given the expected growth in world trade until 2050.

We believe that Market Based Instruments at this level would probably be unacceptable, since they - even if they contribute to the required reduction in shipping - might well result in undesired increases in emissions due to a reduction of trade transactions based on comparative advantages, including access to raw materials, a skilled work-force, capital and a competitive cost level, but also the ability to exploit renewable energy sources (Duchin, 2005; Strømman and Duchin, 2006; Strømman et al., 2008). On this basis, the conclusion would be that while high Market Based Instruments would undoubtedly reduce fuel oil consumption in shipping, a major shortcoming is that this is a mechanism that does not distinguish between trade transactions contributing to lower emissions and those that do not.

Another option could be speed reductions enforced through speed limits. This is a measure used worldwide for road transport to reduce accidents and energy consumption, but a maritime application has not been among the main measures considered by IMO for greenhouse gas reductions. Speeds limits can be implemented as absolute limits not to be exceeded at any point during the sailing, or as an average speed limit measured between waypoints in ports of departure and arrival through existing identification and tracking system (AIS) technologies.

Introducing speed limits would reduce the transport work performed by the sailing fleet of vessels. To uphold the given transport work capacity in the market, the absolute fleet of vessels would have to be increased accordingly, as shown in Table 1. This signifies that the speed limits will have to be gradually lowered to enable the shipyards to add the extra capacity needed. However, parts of this extra capacity needed to enable speed reductions are already in place due the current oversupply of vessels (Sea at Risk and CE Delft, 2010).

Further, speed limits may affect supply chains, competition in the shipping market, and safety. For the supply chains, it has been claimed that lower speeds will require changes in the supply chains which would be deemed unacceptable by cargo owners and their customers. However, such changes appear to have been successfully implemented to accommodate slow steaming (lower speeds) during the current recession. An explanation could be that while supply chain management in general focuses on reducing total lead times and maximizing utility, it also renders it possible to make the required adjustment to any changes, such as longer transport times. From the point of view of competitiveness in the sea transport markets, speed limits could introduce changes to the market playing field as known today. This is a point where a broad and deep discussion is required, and we are not able to fully cover this in the present paper.

An initial question is whether a speed limit should be set as one fixed limit for all vessels, or differentiated. A 'one speed for all vessels' scheme might be an 'easy way out', but it will also have challenges. In order for a one-limit scheme to lead to reductions for all vessel types the speed will have to be reduced down to 8–12 knots which might double the transport times of general cargo. On the other hand, one challenge with differentiated speed limits is that the current classification of vessels is made based on cargo handling systems and not on the cargo they transport. This means that the RoRo, container and open hatch vessels, which cover the speed range from 16 to 25 knots, and transport what may be termed 'general cargo', are classified differently. Feasible ways to handle differentiated speed limits such as 18 knots for passengers, 14 knots for general cargo and 10 knots for bulk products could be to decide that the speed limit is given for each voyage by the main cargo types on the vessel. An alternative solution could be to make 10 knots the general limit and enforce a significant fuel levy per knot above 10 knots to allow faster sailings up to the maximum speed allowed. Introducing speed limits should also give a positive contribution to safety, since the measure will contribute to speed reductions in congested fairways. Any scheme for speed limits should however not disable vessels from being built with a power and propulsion system which gives speed reserves needed for escaping pirates and maintaining complete control in harsh weather.

As a conclusion, this study has demonstrated that emissions from shipping can be reduced from 1122 million ton CO_2 per year to 804 million ton CO_2, which corresponds to a 28% reduction at zero abatement cost, by lowering speeds. If the abatement cost is increased, the emission reduction potential is raised to 33% with 20 USD/ton CO_2 and to 36% with 50 USD/ton CO_2. Since these reductions are purely based on lower speeds, they can in part be performed straight away and it is our judgment that limits are the best means of bringing down speeds to the desired levels for all ship types.

Acknowledgments

We are grateful to Egil Jullumstrø, naval architect and hydrodynamic expert in MARINTEK, for his contribution with valuable comments regarding power requirements when vessels operate at speeds below service speeds. Many thanks also to Christopher Paalson, senior consultant and manager of IHS Fairplay, for contributing with new building costs for vessels and their daily time charter equivalents.

References

Anger, A., Barker, T., Pollitt, H., Lindstad, H., Lee, D., Eyring, V., 2010. International Shipping and Market Based Instruments. International Maritime Organization (IMO).

Bausch, D.O., Brown, G.G., Ronen, D., 1998. Scheduling short term marine transport of bulk products. Maritime Policy & Management 25 (4), 335–348.

Christiansen, M., Fagerholt, K., Ronen, D., Nygren, B., 2007. Maritime transportation. In: Barnhart, C., Laporte, G. (Eds.), Handbook in Operations Research and Management Science. Elsevier.

Corbet, J.J., Wang, H., Winebrake, J.J., 2009. The effectiveness and cost of speed reductions on emissions from international shipping. Transportation Research D 14, 593–598.

DNV, 2009. DNV Pathways to low carbon shipping, Abatement potential towards 2030, 〈www.dnv.com〉.

Duchin, F., 2005. A world trade model based on comparative advantage with m regions, n goods, and k factors. Economic Systems Research 17 (2), 141–162.

Endresen, O., et al., 2007. A historical reconstruction of ships' fuel consumption and and emissions. Journal of Geophysical Research-Atmospheres 112 (D12).

Eyring, V., Isaksen, I.S.A., Berntsen, T., Collins, W.J., Corbett, J.J., Endresen, Ø., Grainger, R.G., Moldanova, J., Schlager, H., Stevenson, D.S., 2009. Transport impacts on atmosphere and climate: shipping. Atmospheric Environment, 1–37.

Faber, J., Marowska, A., Nelissen, D., Davidson, M., Eyring, V., Cionni, I., Selstad, E., Kågeson, P., Lee, D., Buhaug, Ø., Lindstad, H., Roche,P., Humpries, E., Graichen, J., Cames, M., 2009. Schwarz Technical support for European action to reducing Greenhouse Gas Emissions from international transport, 2009, Oude Delft 180 2611 HH Delft—The Netherlands.

Fagerholt, K., 2001. Ship scheduling with soft time windows—an optimization based approach. European Journal of Operational Research 131, 559–571.

Fagerholt, K., Lindstad, H., 2000. Optimal policies for maintaining a supply service in the Norwegian Sea. Omega 28, 269–275.

Faltinsen, O.M., Minsaas, K.J., Liapis, N., Skjørdal, S.O., 1980. Prediction of resistance and propulsion of a ship in a Seaway. In: Proceeding of the 13th Symposium on Naval Hydrodynamics, Tokyo, the Shipbuilding Research Association of Japan, 1980, pp. 505–529.

IPCC, 2007. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva.

Lewis, E.D., 1988. Principles of Naval Architecture, vol. II. The Society of Naval Architects and Marine Engineers, ISBN: 0-939773-01-5.

Lindstad, H., Asbjørnslett, B.E., Pedersen, J.T., 2010. Reduction of greenhouse gases from shipping through technical measures or marked based instruments. In: Conference Proceeding IAME 2010, Lisbon Portugal.

Lindstad, H., Mørkve, O.T., 2009. A methodology to assess the energy efficiency and the environmental performance of maritime logistics chains. In: Conference Proceedings International Marine Design Conference, 2009. ISBN:978-82-519-2438-2.

Lloyd, A.R.J.M., 1998. Seakeeping, Ship Behaviour in Rough Weather, 1998, ISBN: 0-9532634-0-1.

Longva, T., Eide, M.S., Skjong, R., 2010. A cost–benefit approach for determining a required CO_2 Index level for future ship design. Maritime Policy & Management 37 (2), 129–143.

Minsaas, K.J., 2006. Naval Hydrodynamic Propeller Theory. Department of Marine Hydrodynamics, Norwegian University of Science and Technology (UK-2006-80/III).

Norstad, I., Fagerholt, K., Laporte, G., Tramp ship routing and scheduling with speed optimization. Transportation Research Part C: Emerging Technologies, in Press, Corrected Proof, Available online 12 June 2010, ISSN 0968-090X, doi:10.1016/j.trc.2010.05.001.

OECD, 2010. OECD Globalization, Transport and the Environment978-92-64-07290-9.

Psaraftis, H.N., Kontovas, C.A., 2010. Balancing the economic and environmental performance of maritime transport. Transportation Research Part D.

Second IMO GHG study, 2009. International Maritime Organization (IMO) London, UK, April 2009; Buhaug, Ø.; Corbett, J.J.; Endresen, Ø.; Eyring, V.; Faber, J.; Hanayama, S.; Lee, D.S.; Lee, D.; Lindstad, H.; Markowska, A.Z.; Mjelde, A.; Nelissen, D.; Nilsen, J.; Pålsson, C.; Winebrake, J.J.; Wu, W.–Q.; Yoshida, K.

Sea at Risk and CE Delft, 2010. Sea at Risk and CE Delft, 2010. 〈http://www.seas-at-risk.org/〉.

Strømman, A.H., Hertwich, E.G., Duchin, F., 2008. Shifting trade patterns as a means of reducing global carbon dioxide emissions, a multiobjective analysis. Journal of Industrial Ecology 13, 1.

Strømman, A.H., Duchin, F., 2006. A world trade model with bilateral trade based on comparative advantage. Economic System Research 18 (3), 281–297.

Walker, G., King, D., 2008. The Hot Topic: How to Tackle Global Warming and Still Keep the Lights On. Bloomsbury, London.

4.3 Paper3:

Lindstad, H. Asbjørnslett, B., E., Jullumstrø, E., 2013. Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market. Transportation Research Part D 19 (2013), Page 5-12.

Transportation Research Part D 19 (2013) 5–12

Contents lists available at SciVerse ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market

Haakon Lindstad [a,b,*], Bjørn E. Asbjørnslett [a], Egil Jullumstrø [b]

[a] Norwegian University of Science and Technology, Trondheim, Norway
[b] Norwegian Marine Technology Research Institute, Trondheim, Norway

ARTICLE INFO

Keywords:
Profit and opportunity cost
Maritime weather routing
Greenhouse gases
Shipping and environment

ABSTRACT

This paper assesses shipping profits, costs and emissions by speed and as a function of sea and freight market conditions. Traditionally, seagoing vessels have been designed to operate at standardized, maximum economic speeds based on hydrodynamic considerations. High fuel costs and increased environmental concerns have challenged this practice. While speed reductions may reduce costs and emissions, most studies are based on still water conditions despite these being the exceptions. In addition, shipping lines operate in a commercial market with the objective of making profit and not solely on cost reductions. Our results show that significant cost and emissions reductions can be achieved and that the maximum economic speeds based on hydrodynamic considerations even in a good freight market are lower than the design speeds.

1. Introduction

With increasing fuel costs and more public focus on maritime transport emissions, reducing fuel cost and emissions has become a necessity for shipping lines. Historically, fuel costs were small compared with the fixed cost of the vessel, its crewing and management, while today it accounts for more than 50% of the cost. Traditionally, seagoing vessels have been designed and optimized to operate at maximum economic speeds based on hydrodynamic considerations. These design speeds have been standardized for vessels of similar type and size. The core insight is straightforward: the power output required for propulsion is a function of the speed to the power of three. For this reason, there has emerged a growing interest in the relationship between speed and emission reductions.

Traditionally, fuel and emission calculations in these studies have been based on still water conditions or an average sea state, although Lloyd (1988) has shown that high wind and wave resistance increases the power needed. The results show that the resistance rises rapidly with increasing wave height and that the peak resistance occurs in head waves when the average length of the waves is close to the length of the vessel. This signifies that a Panamax-size bulk vessel, with a dead weight of 72,000 tons and built for a design speed of 14–15 knots, will see its speed reduced by 2–3 knots with 4-m head waves and by 6–9 knots with 8-m head waves. In energy and emission terms, 4-m head waves confer a 25–35% increase in energy and emission while 8-m head waves lead to an increase of more than 100% compared to still water conditions.

Since seagoing vessels operate under all sea conditions, models need to allow calculation of the resistance and fuel consumption as a function of sea condition and vessel speed. Within the shipping sector, most abatement analysis in shipping has been based on a cost approach. Russell et al. (2010), however suggests that this fall short when it comes to identifying,

---

[*] Corresponding author at: Norwegian University of Science and Technology, Trondheim, Norway. Tel.: +47 92801521.
E-mail address: Haakon.Lindstad@ntnu.no (H. Lindstad).

1361-9209/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.trd.2012.11.001

characterizing and assessing the impact of current and future market conditions, and that there is a need to take profit and opportunity cost into consideration.

2. Model description

Existing analysis tends to calculate emissions, cost and revenue as functions of sea conditions and vessel characteristics for speeds ranging from zero to the design speed. The system boundaries focus on vessels sailing from port to port. The model consists of five main equations, of which the power element is the most important. This takes into account propeller efficiency K, the power needed for still water conditions P_s, the extra power required for waves P_w, the power needed for wind P_a, and the necessary auxiliary power P_{aux}, as a function of a vessel's speed and cargo load; Eq. (1). To the power required for still water and aerodynamic resistance (Lewis, 1988) is added wave resistance (Lloyd, 1998), the auxiliary power calculation is in standard form.

An alternative based on Hollenbach and Friesch (2007) and Orsic and Faltinsen (2012) and others offers a representation of propeller efficiency from zero up to the design service speed of a ship as a function of sea conditions. The propeller efficiency drops when the engine output is reduced and when the significant wave height increases:

$$P = K(P_s + P_w + P_a) + P_{aux} \tag{1}$$

$$K = \eta(v, H_{1/3}) = max\left(\frac{1}{\eta(j + k \cdot \sqrt{\frac{v}{V_d}})}, \frac{1}{\eta(1 - r \cdot H_{1/3})}\right)$$

$$P_s = \frac{\rho \cdot C_{ts} \cdot S \cdot v^3}{2} \cdot \left(\frac{M \cdot m}{DWT} + (1 - m)\right)$$

$$P_w = \frac{C_w \cdot \rho \cdot g \cdot \left(\frac{H_{1/3}}{2}\right)^2 \cdot B^2}{L} \cdot (v + u)$$

$$P_a = \frac{C_a \cdot \rho_a \cdot A \cdot (v + u_a)^3}{2}$$

where K is the propeller (propulsion) efficiency as a function of the vessel speed and sea condition, and η is the propulsion efficiency at the design speed V_d and for a calm sea $H_{1/3}$. Typically, η values range from 0.6 to 0.7. When the speed is reduced as by $\sqrt{}(v/v_d)$, the propeller efficiency K drops according to the constants j and k (where $j + k = 1$). When the wave height $H_{1/3}$ increases by r. $H_{1/3}$ the efficiency drops according to the constant r.

The still water power is given by P_s, where ρ is the density of water, C_{ts} is the still water drag coefficient, S is the wetted surface, v is the vessel speed, M is the cargo on board the vessel, DWT is the maximum weight the vessel can carry and m is the cargo weight constant for the vessel which gives the ratio between the power requirement when fully loaded, partly loaded and in ballast. The additional power for wave resistance is given by P_w, where C_w is the drag coefficient for the wave resistance, ρ is the density of water, g is the vertical force, $H_{1/3}$ is the significant wave height for which the amplitude is half of the height, B is the width of the ship at the waterline, L is the length of the ship at the waterline and u corresponds to the speed of the waves in relation to that of the vessel.

The additional power for wind resistance is given by P_a where C_a is the drag coefficient for the aerodynamic, ρ_a is the density of air, A is the surface area projected for the wind and u_a corresponds to the speed of the wind in relation to that of the vessel. The auxiliary power needed for running pumps and for producing electricity for lighting as well as all the supporting systems of the ship, P_{aux}, is a function of the vessel type and size, and also of the cargo it carries. Moreover, it is independent of vessel speed.

The cost per ton/nautical mile (ton/nm), C, comprises the fuel cost and the time charter cost of the vessel, as expressed by equation:

$$c = \frac{1}{D \cdot M}\sum_{i=0}^{n}\left(\frac{D_i}{v_i} \cdot \left((K_f \cdot P_i \cdot C_{Fuel}) + \frac{Capex\,v_{k_1k_2}}{24}\right)\right) \tag{2}$$

The first factor, i.e., $1/(D \cdot M)$, transforms the cost from a cost per voyage to a cost per ton/nm for which D is the voyage distance and M is the cargo weight in tons. During a voyage, the sea conditions will vary and this is handled by dividing each voyage into sailing sections with a distance D_i for each sea condition. Then, the total for the voyage is given by the summation of the sailing sections from 0 to n.

The second factor $\left(\frac{D_i}{v_i}\right)$ gives the hours in each section of the voyage. The hourly fuel cost per section is given by $(K_f \cdot P_i \cdot C_{Fuel})$; where K_f is the fuel required per produced kW h and C_{Fuel} is the cost per fuel unit. In addition to fuel, the cost of operating a vessel comprises financial items, depreciation and operating cost expressed as $Capexv_{k1k2}$. Here, $Capexv$ is the new building price of the vessel, k_i% of $Capexv$ gives the daily fixed costs which include financial costs such as depreciation and return of capital, and k_2% of $Capexv$ gives the daily variable cost. When the speed is reduced below the service speed (90–95% of the maximum speed), the fuel cost decreases for calm and moderate sea conditions due to a reduced power requirement (Eq. (1)), whereas the $Capexv_{k1k2}$ cost will increase due to additional days per voyage. With the current high fuel cost per unit in historical terms and the moderate new building prices, the reduction in fuel cost for moderate speed reductions below the design speed is much larger than the additional $Capexv_{k1k2}$ cost of the vessel.

The CO_2 emitted per ton/nm ε is calculated:

$$\varepsilon = \frac{1}{D \cdot M} \sum_{i=0}^{n} \frac{D_i \cdot K_f \cdot P_i \cdot K_e}{v_i} \tag{3}$$

where K_ε is the CO_2 per unit of fuel consumed.

The income per ton/nm comprises a daily rental rate for the vessel paid by the customer and fuel paid by the customer from which the capital cost of the transported goods are deducted as expressed by Eq. (4). It is common to base the rental rate for a voyage on a contractual speed that includes weather margins and to include additional fuel usage for wind and waves. On the other hand, a deduction of capital cost of the goods was not part of a standard shipping contract in the past, but recently, as a result of slowing steaming to save fuel, part of that saving might be offset against the financial cost of the goods transported on the vessels.

$$I = \frac{1}{D \cdot M} \sum_{i=0}^{n} \left(\frac{D_i}{24 \cdot v_c} \cdot \left((FC_c + TC_c) - \frac{v_c}{v_i} \cdot \left(M \cdot C_M \cdot \frac{C_{IR}}{365} \right) \right) \right) \tag{4}$$

The second factor, i.e., $D_i/(24 \cdot v_c)$, gives the contractual duration of each sailing section in days where v_C is the contractual speed for the voyage and 24 is the hours per day. The first term, i.e., $(FC_C + TC_C)$, gives the fuel and time charter income; where FC_C is the fuel income and TC_C is the time charter income per day at contractual speed. The second term contains the capital cost of the transported cargo i.e., $\frac{v_c}{v_i}\left(M \cdot C_M \cdot \frac{C_{IR}}{365}\right)$, where C_M is the export value per ton of transported goods and C_{IR} is an annual interest rate.

Profit is determined by Eq. (4) minus Eq. (2) and can be expressed either as a profit per ton/nm, $Profit_{nm}$, or as profit per day, $Profit_{day}$:

$$Profit_{nm} = 1 - C, \quad Profit_{day} = (1 - C) \cdot \frac{D \cdot M}{\sum_{i=0}^{n} \frac{D_i}{24 \cdot v_i}} \tag{5}$$

In an industrialized setting the main focus will typically be on profit per freight unit Profit_{nm}, while shipowners operating in a competition market with many individual actors are more focused on maximizing profit per vessel per day Profit_{day}. For example in a good shipping market with high time charter rates, the profit per thousand ton/nm when the vessel is sailing at 10 knots is $1.49 per thousand ton/nm yielding a daily profit of $12,500. If the speed is increased to 12 knots the profit drops to $1.37 per ton/nm, which is an 8% reduction per ton/nm. However, since the freight work increases with 20%, the profit per day increases with 12% to $14,000 a day. So, if additional cargoes are available, the profit is maximized with a speed of 12 knots whereas if no additional cargoes are available profit is maximized with a speed of 10 knots.

3. Analysis

We focus on ocean-going dry bulk, break bulk and wet bulk vessels, which accounted for nearly 75% of sea freight in 2007. Table 1 provides base data for these, and other vessels, CO_2 emissions.

The average bulk vessel according to the table has a dead weight (dwt) of 72,000 tons, a design speed of 14.6 knots and an installed power of 10,300 kW, representing vessels with a size going from 15,000 up to more than 300,000 dwt, an engine between 6000 and 25,000 kW and speeds from 13 up to 16 knots. Instead of using the average bulk vessels, we use the bulk vessel type that is closest to the average, dry bulk Panamax vessels. Such ships are the largest bulk vessels capable of passing through the Panama canal, and there are1477 of them with an average dwt of 72,000 ton, design speeds of 14.4 knots and installed power of 9800 kW (Lindstad et al., 2012). The annual operating cost of a vessel, $Capexv_{k1k2}$, is calculated based on the 2011 new-building cost of $40 million where $k_1 = 8\%$ covers the fixed and $k_2 = 4\%$ the variable costs. The cost of fuel, C_{Fuel}, is based on an average consumption pattern of 90% heavy fuel oil at 600 $/ton and 10% marine diesel oil at 900 $/ton, giving costs of 630 $/ton based on average 2011 prices. Panamax vessels are employed in North Atlantic trades between US East Coast and European ports along the English Channel, with 3600 nautical miles a typical voyage.

Table 1
Annual freight carried and CO_2 emitted by vessel type.

Vessel type	Vessels	Average vessel size in dwt (ton)	Speed (knots)	Average engine size (kW)	Freight carried (billion ton nm)	CO_2 emitted (million ton)	Gram CO_2 per freight unit (gram per ton nm)
Bulk vessels over 15,000 dwt	10,900	72,000	14.6	10,300	30,000	364	12
Container vessels	4400	34,000	20.3	22,500	7500	261	35
All other vessels	29,700	5000	12.7	3800	3500	195	56
World cargo fleet	45,000	24,000	13.9	5000	41,000	820	20

Table 2
Vessel speed as a function of sea condition and freight market.

Sea state	Percentage of voyage	Distance	Design speed	80% of design speed	Profit maximization speed	Cost minimizing speed	Emission minimizing speed
Loaded head waves							
0–2 m	37	1332	14	11	13	10	7
2–5.5 m	55	1980	13	11	12	10	7
5.5–14 m	8	288	7	7	7	7	7
Loaded following waves							
0–2 m	37	1332	14	11	13	10	7
2–5.5 m	55	1980	14	11	12	10	8
5.5–14 m	8	288	13	11	10	10	10
Loaded side waves							
0–2 m	37	1332	14	11	13	10	7
2–5.5 m	55	1980	13	11	12	10	7
5.5–14 m	8	288	10	10	10	10	7
Ballast head waves							
0–2 m	37	1332	15	11	14	10	7
2–5.5 m	55	1980	14	11	14	10	7
5.5–14 m	8	288	7	7	7	7	7
Ballast following waves							
0–2 m	37	1332	15	11	14	11	7
2–5.5 m	55	1980	15	11	14	11	8
5.5–14 m	8	288	13	11	12	10	10
Ballast side waves							
0–2 m	37	1332	15	11	13	11	9
2–5.5 m	55	1980	14	11	12	11	9
5.5–14 m	8	288	11	11	11	11	9
Distance and average sailing days per voyage		3600	11	14	12	15	20
Average speed			13	11	12	10	8

Table 3
Profit, cost and emissions as a function of sea conditions and freight market.

	Design speed	80% of design speed	Profit maximization speed	Cost minimizing speed	Emission minimizing speed
Average speed	13	11	12	10	8
Daily income high TC_C ($)	49,800	39,300	45,500	36,900	26,800
Daily income $TC_C \approx$ cost ($)	37,400	29,400	35,200	27,600	19,900
Daily income low TC_C ($)	31,200	24,400	28,500	22,900	16,400
Cost per day ($)	36,930	26,330	31,470	24,450	19,600
Profit per day high TC_C ($)	12,900	13,000	14,000	12,500	7200
Profit per day $TC_C \approx$ cost ($)	500	3100	3700	3200	300
Profit per day low TC_C ($)	−5700	−1900	−3000	−1600	−3200
Average freight work in 1000 ton nm per day with 50% annual utilization	11,122	8871	10,208	8373	6210
Income per 1000 ton nm with high TC_C ($)	4.48	4.43	4.46	4.41	4.32
Cost per 1000 ton nm ($)	3.32	2.97	3.08	2.92	3.16
Profit per 1000 ton nm with high TC_C ($)	1.16	1.47	1.37	1.49	1.16
CO_2 emissions in kg per 1000 ton nm with 50% yearly utilization	10.7	7.4	8.8	6.8	5.1
CO_2 emission reduction compared to design speed (%)		30	17	37	52

Table 4
Cost and emission reductions applying model in combination with weather forecasts.

	Average weather	Rough weather	Rough weather and weather routing	Design speed	80% of design speed	Profit maximizing speed	Cost minimizing speed	Emission minimizing speed
	Distance in nm			Speed in knots				
0–2 m wave height	1332	288	288	14	11	13	10	7
2–5.5 m wave height	1980	1332	3924	13	11	12	10	7
5.5–14 m wave height	288	1980	288	7	7	7	7	7
	Distance in nm per voyage			Sailing days per voyage				
Base case	3600			12	14	13	16	21
Rough weather		3600		17	18	17	19	21
Rough weather and weather routing			4500	15	18	16	19	27
				Cost per 1000 ton nm ($)				
Base case				1.9	1.8	1.9	1.7	1.8
Rough weather				2.8	2.9	2.9	2.7	2.7
Weather routing-rough weather				2.5	2.3	2.4	2.3	2.4
Cost reduction compared to design speed with weather routing (%)				11	17	14	19	14
				CO_2 emissions in kg per 1000 ton nm				
Base case				6.4	5.1	5.8	4.6	3.6
Rough weather				9.4	9.3	9.6	8.6	8.1
Weather routing-rough weather				8.4	6.9	7.6	6.2	4.9
Emission reduction compared to design speed with weather routing (%)				11	27	19	34	48

Wind and weather data for the North Atlantic are based on average sea and wind data from Bales et al. (1981). For each voyage the conditions vary and it is therefore important to establish cost and emission data for the most typical sea condition and for the sea conditions which are the most demanding for the vessels. The most typical sea condition involves a significant wave height between 2 and 5.5 m, which the vessels will experience 55% of the time, and a significant wave height between 0 and 2 m, which the vessels will experience 37% of the time.

Waves with a wave height of 7–8 m offer the most demanding conditions for a dry bulk Panamax vessel because the length of the waves is close to that of the vessel that maximizes it movement. We have therefore chosen to use 1-m waves as a proxy for a significant wave height of zero and 2 m, 4-m waves as a proxy for a significant wave height of 2–5.5 m and 8-m waves as a proxy for a significant wave height of 5.5–14 m, which occurs 8% of the time.

We focus on head, follow and side waves for significant heights of 1, 4, 8 m, with calm water performance as the benchmark. The main observations are that the 1-m significant wave height provided only a marginal difference with regard to cost and emissions compared to calm water conditions. The 4-m significant wave height increase emissions and cost with 30% compared to calm water conditions for head waves, 20% for side waves and 15% for following waves at the design speed, but no increase was observed when the speed was reduced to 8–10 knots. This is because by lowering its speed with following waves, the vessel could better use the push created by the waves. An 8-m wave height increases costs and emissions of about 150% compared to calm water conditions for head waves, 60% for side waves and no increase for following waves.

Typical examples of speed decisions as a function of freight market include the design speed, 80% of the design speed, profit maximization, cost minimization and emission minimization. A priority on the design speed reflects that the voyage and contract shall be executed as fast as possible while 80% of the design speed is used to reflect a standard slowing steaming option. Profit maximization signifies executing the voyage with the speeds that provide the greatest profit. Cost minimization means to execute the voyage with the speeds that lead to the lowest cost. Finally, emission minimization means that the main priority shall be to minimize emissions at any cost.

The priorities for each voyage are often a function of the freight contract between the cargo owner and the shipping line. These priorities might not be the best option, especially when the individual benefits or the benefits are compared. To illustrate that varying priorities lead to different costs, profits and emissions, we have used the model on North Atlantic trades with distances, wind and sea conditions as described. To get a complete picture, the calculations are based on three round trips. The contractual fuel usage is based on shortest sailing distance between ports of departure and arrival at contractual speed, and independently of actual vessel speed and sailed distance, included 15% extra consumption to compensate for wind and waves; the time charter income per voyage is based on contractual speed; and calculations are based on a high daily level twice the cost, a level close to break-even, and a low level covering about 50% of the cost. The capital cost of the goods onboard the vessels are valued at $250 per ton and with a 5% interest rate deducted. Because the time used for entering and leaving port, as well as for loading and discharging is independent of vessel speed, it is not included.

Table 2 shows speed as a function of sea condition for each priority for the dry bulk Panamax vessel. The first column gives the sea condition and loading condition, the second gives the length of the voyage for each sea condition and loading condition and the following columns show the speed for each priority as a function of voyage requirement. An important observation is that for head wave conditions, the speed dropped and with 8-m waves the model revealed that the speed should be kept at a maximum achievable level for all priorities. For the other sea conditions, the speed recommendation varied up to more than 100% between the lowest and the highest speeds. The two last lines give the average speed and average sailing days per voyage based on an average of six voyages for each of the priorities. The average speed was 13 knots for the design speed, 11 knots for the 80% of design speed, 12 knots when the priority was to maximize profit, 10 knots when minimizing cost and 8 knots when minimizing emissions.

Calculating the average cost per day and ton/nm for the six voyages for each of the priorities and comparing them with the incomes at high, break-even and low freight rates enables comparison of profitability as a function of voyage requirements and market rates (Table 3). The results show that the design speed priority gave a lower profit per day and per ton/nm than profit maximization both at high and market rates close to break-even. At market rates close to break-even, profit maximization also led to slightly higher profits than cost minimization. With low market rates, the cost minimization priority offers the least cost and the greatest profitability. These profit assessments are based on the assumption that a ship owner operating in a shipping market with free competition can assume that his individual behavior does not influence the demand and supply situation. If we instead take a more industrialized approach, by assuming that the decisions of each shipowner influence the market, Table 3 shows that the speed priority that minimizes the cost also maximizes the profit per ton/nm. When emissions are considered, the reduction compared to design speed is 17% with profit maximization, 37% with cost minimization and 52% with emission minimization.

The model can be applied in combination with weather data to investigate potential cost and emission reductions (Strøm-Tejsen et al., 1973). We focus on head wave conditions because they have the most unfavorable impact on vessels. To illustrate the results of applying the model on head wave voyages, we use weather data for a typical stormy period where the distribution of waves are 8% for 1-m, 37% for 4-m and 55% for 8-m waves compared to the average yearly distribution of 37%, 55% and 8% (Table 4). This distribution change to 6.5%, 87%, and 6.5% by deviating from the shortest route and extending the voyage from 3600 nm to 4500 nm. Even with such a large deviation, the emissions and costs were reduced for all freight market scenarios. These reductions are significantly larger both for profit maximization and cost minimization compared to the design speed. This based on cost reduction with profit maximization of 14% and cost minimization of 19% versus 11% for the design speed priority. Moreover, emission reduction values were 19% for the profit maximization priority and 34% for the cost minimization priority versus 11% for the design priority.

4. Conclusions

We have developed a model to assess profit, cost and emissions by varying speed as a function of sea conditions and freight market. The results demonstrate that significant cost and emission reductions can be achieved by varying speed as a function of sea conditions and freight market. Moreover, the maximum economic speeds based on hydrodynamic considerations even in a good shipping market with focus on profit maximization were lower than the design speed. Finally the model, in combination with weather data, enables voyage routings to be defined that give significant cost and emission reductions.

References

Bales, S.L., Lee, W.T., Voelker, J.M., Taylor, D.W., 1981. Standardized Wave and Wind Environments for NATO Operational Areas, NATO Report A414501, Brussels.

Hollenbach, U., Friesch, J., 2007. Efficient hull forms – what can be gained. In: 1st Int. Conf. on Ship Efficiency, Hamburg.

Lewis, E.D., 1988. Principles of Naval Architecture, vol. II. The Society of Naval Architects and Marine Engineers, Jersey City.

Lindstad, H., Asbjørnslett, B.E., Pedersen, J.T., 2012. Green maritime logistics and sustainability. In: Song, D.W., Panayides, P.M. (Eds.), Maritime Logistics: Contemporary Issues, Emerald, Bingley.

Lloyd, A.R.J.M., 1998. Seakeeping, Ship Behaviour in Rough Weather.

Orsic, J.P., Faltinsen, O.M., 2012. Estimation of ship speed loss and associated CO_2 emissions in a seaway. Ocean Engineering 44, 1–10.

Russell, B.A., Wang, H., Zeinali, M., 2010. Marginal abatement costs of CO_2 emissions reduction and market-based mechanisms and the pricing of credits. <http://www.corporateclimate.net/green-transportation-climate/logistics-supply-chain/74-cost-for-a-ship-to-reduce-co2-emissions-or-increase-efficiency.html>.

Strøm-Tejsen, J., Yeh, H.Y.H., Moran, D.D., 1973. Added resistance in waves. Transaction of the SNAME 78, 109–143.

4.4 Paper 4:

Lindstad, H. Asbjørnslett, B. E., Strømman, A., H., 2012a, The Importance of economies of scale for reductions in greenhouse gas emissions from shipping. Energy Policy 46 (2012), Page 386-398.

Energy Policy 46 (2012) 386–398

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The importance of economies of scale for reductions in greenhouse gas emissions from shipping

Haakon Lindstad [a,b,*], Bjørn E. Asbjørnslett [a], Anders H. Strømman [a]

[a] *Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway*
[b] *Norwegian Marine Technology Research Institute (MARINTEK), NO-7450 Trondheim, Norway*

ARTICLE INFO

Article history:
Received 15 August 2011
Accepted 29 March 2012
Available online 19 April 2012

Keywords:
Maritime transport
Economies of scale
Greenhouse gas emissions

ABSTRACT

CO_2 emissions from maritime transport represent 3.3% of the world's total CO_2 emissions and are forecast to increase by 150%–250% by 2050, due to increased freight volumes (Second IMO GHG study, 2009). Fulfilling anticipated climate requirements (IPCC, 2007) could require the sector to reduce emissions per freight unit by a factor of five or six. The International Maritime Organization (IMO) is currently debating technical, operational and market-based measures for reducing greenhouse gas emissions from shipping. This paper also investigates the effects of economies of scale on the direct emissions and costs of maritime transport. We compared emissions from the current fleet (2007), with what can be achieved by increasing average vessel size. The comparison is based on the 2007 levels of trade and predictions for 2050. The results show that emissions can be reduced by up to 30% at a negative abatement cost per ton of CO_2 by replacing the existing fleet with larger vessels. Replacing the whole fleet might take as long as 25 years, so the reduction in emissions will be achieved gradually as the current fleet is renewed.

1. Introduction

The environmental consequences of increasing international trade and transport have become important as a result of the current climate challenge. Products are increasingly being manufactured in one part of the world, transported to another country and then redistributed to their final country of consumption. Since 1990, growth in world trade, of which more than 80% is carried by seagoing vessels (measured by weight), has been higher than ever before and transport volumes have nearly doubled. CO_2 emissions from maritime transport rose from 562 million tons (all tons are metric) in 1990 to 1046 million tons in 2007 (Second IMO GHG study, 2009), which is an 86% increase. This is a high rate of growth, compared to the total global growth in CO_2 emissions from 20,941 million tons in 1990 to 28,846 million tons in 2007 (IEA 2009), which is a 38% increase. Maritime transport emissions are anticipated to increase further by 150%–250% until 2050 on the basis of "business as usual" scenarios with a tripling of world trade (Second IMO GHG study, 2009). Similar growth prospects have also been reported by OECD (2010) and Eyring et al. (2009). These greenhouse gas (GHG) emission growth figures are in sharp contrast to the total reduction of 50%–85% by 2050 that will be necessary to keep the global temperature rise below 2 °C (IPCC, 2007). Just how the annual greenhouse gas reductions should be shared among sectors is a controversial issue, but given a scenario where all sectors accept the same percentage reductions, and that the demand for sea transport follows the predicted tripling of world trade, it can easily be deduced that the amount of CO_2 emitted per ton nautical mile will have to be reduced by at least 85%. This is a reduction by a factor of 5 to 6, which represents a substantial challenge. The question is thus how to make it come about.

Previous studies have documented that it is possible to reduce GHG emissions in a cost-effective manner, i.e. emissions can be cut with net cost savings (DNV, 2010; Longva et al., 2010). These studies can be grouped into two categories; those that investigated the total improvement potential (Second IMO GHG study, 2009; DNV, 2010) and those that looked at what can be achieved by focusing on one or more measures, such as the relationship between speed reduction and emissions (Corbet et al., 2009; Sea at Risk and CE Delft, 2010; Lindstad et al., 2011). The background for the focus on speed reductions is that ships have typically been built to operate at a specific design speed. For large bulk vessels this design speed is around 14 knots (25 km/h), while large container vessels have design speeds of up to 27 knots (50 km/h). The key insight is that the power output required for propulsion is a function of speed to the power of three. This simply

---

[*] Corresponding author at. Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway. Tel.: +47 92801521.
E-mail addresses: Haakon.Lindstad@ntnu.no, Haakon@marintek.sintef.no (H. Lindstad).

0301-4215/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enpol.2012.03.077

means that when a ship reduces its speed, its fuel consumption is reduced. The studies that focus on the relationship between speed reductions and emissions have indicated potential reductions of as much as 28% at zero abatement cost and 33% at a cost of 20 USD per ton CO_2 (Lindstad et al., 2011), while the studies of the total improvement potential (Second IMO GHG study, 2009; DNV, 2010) suggest a total reduction potential in the range of 50%–75% without taking gains through economies of scale into consideration.

This contrasts with the fact that historically, emission and cost reductions have been achieved through building larger vessels, commonly termed "economies of scale", and to a lesser degree through the adoption of new technology. In shipping, economies of scale (EOS) usually refer to benefits obtained when smaller vessels are replaced by larger ones. To make qualified suggestions about the effect of increasing average vessel size, knowledge of the current situation is a prerequisite. While rail and road are fairly standardized, with more or less given figures for capacity and speed per unit, the existing maritime fleet consists of vessels of many types and sizes ranging from a few hundred tons to up to hundreds of thousands of tons, while their maximum speed ranges from less than 10 knots (18 km/h) to more than 30 knots (55 km/h), and distances ranges from a few nautical miles (nm) to more than 10,000 nm (18,000 km). Some vessels can only transport one specific product, such as crude oil or LNG. Others, such as product tankers and chemical tankers can transport a wide range of liquid products. The most flexible vessels today are container vessels, which were initially used for transport of finished goods packed in containers, but now also transport raw materials and semi-finished goods. And while container vessels operate as common carriers in liner services calling at a regularly published schedule of ports (like a bus service), most seagoing cargo is still transported by vessels in tramp operation (like a taxi service), where their schedule is a function of cargo availability and customer requests. While a common carrier refers to a regulated service where any company may book transport according to general published rules of the operator, a tramp service in general is a private business arranged between the cargo owner and the operator of the vessel according to a specific contract called a charter party.

Previous studies of economies of scale have tended to focus on the financial benefits of building larger vessels within one particular shipping segment, such as container vessels (Cullinane and Khanna, 2000; Notteboom and Vernimmen, 2009) or LNG Transport (Oil and Gas Journal (2008)).

The International Maritime Organization (IMO) is currently debating technical, operational and market-based measures for reducing greenhouse gas emissions from shipping. In July 2009 the principles for a mandatory Energy Efficiency Design Index (EEDI) and a Ship Energy Efficiency Management Plan (SEEMP) were agreed, and two years later in July 2011 (Resolution MEPC.203 (62)), the EEDI and SEEMP were adopted as parts of the MARPOL Convention (the International Convention for the Prevention of Pollution from Ships). The EEDI uses a formula to evaluate the CO_2 emitted by a vessel per unit of transport as a function of vessel type and size. The formula has been established by grouping vessels built during the past 10 years into vessel types such as container and dry bulk, and then generating the average values and baselines as a function of size and type by a standard excel regression model. Common to all vessel types is that as vessel sizes increase, their emissions decrease. However, the EEDI gives baseline requirements, in which the required emissions reduction when vessel size is doubled is only 14% for a container vessel, 20% for a general cargo vessel, 30% for a dry bulker, 31% for a tanker such as a crude oil carrier and 33% for RoRo car carriers (Roll-on Roll-off vessel). In-depth discussions have challenged a number of aspects of these curves, and it is a fact that while the existing fleet of large container vessels achieve EEDI values well below their current EEDI requirements, large tankers and RoRo vessels lie well above them. The consequence of this is that when the EEDI requirements in the coming 20 years become as much as 30%–35% stricter than they are today, large container vessels can quite easily satisfy them, while it may become much more difficult for large dry bulk, tank and RoRo vessels to satisfy the requirements through technical improvents. It is not within the scope of this paper to offer a detailed technical discussion of the EEDI. However, these examples demonstrate that EEDI can be further developed, and that it is worth investigating how to utilize and encourage economies of scale as an integrated part of EEDI and mitigation policies in general.

While economies of scale are a well-established concept in shipping, this study is the first to investigate the potential reductions in costs and emissions that can be achieved for the whole fleet. The results of the investigation are utilized to suggest how future EEDI and other IMO emission reduction requirements should be set in order to achieve maximum emission reductions through economies of scale. We first establish the employment and performance of the existing fleet (2007), and then compare it with what can be achieved by increasing average vessel size. The comparison is based on the 2007 levels of trade and predictions for 2050.

The model is described in Section 1, its application and the data are presented in Section 2, and the results obtained are discussed in the final section with respect to their implications for policy development.

2. Description of model

The main objective of our model is to calculate emissions and costs for the global fleet as a function of vessel size and fleet mix, with a specific focus on the effect on economies of scale. The system boundaries are set on the vessels themselves and how they are used, for which reason the landside of the terminal and port is excluded. The model is based on a combination of empirical and estimated data. The empirical data are taken from the world fleet as listed in December 2007 in the Lloyds Fairplay database (now the IHS Fairplay database), divided into vessel type and size groups. For each vessel type and size group the operational profile was established on the basis of studies of how vessels in each group are used and the cargoes they carry.

The model consists of four main equations. The first establishes the annual operational profile and freight work of each vessel type and size group. The second calculates annual fuel consumption based on the operational profile and freight work done. The third calculates the amount of CO_2 emitted per nautical mile (nm) sailed, based on the annual fuel consumption and the annual freight work. The fourth equation calculates cost per ton nm.

The annual operational profile in days, T, of a vessel consists of days per cargo voyage multiplied by number of cargo voyages plus days per voyage in ballast multiplied by number of voyages in ballast as expressed by Eq. (1):

$$T = \left[\left(\frac{D_c}{v_c} + T_{l\&d} + T_{s\&w} \right) \middle| N_c + \left(\frac{D_b}{v_b} + T_{s\&w} \right) \middle| N_b \right] \tag{1}$$

where the first term gives the annual number of days used on cargo voyages, where D_c is the distance, v_c is the speed on the cargo voyages, $T_{l\&d}$ is time taken to load and discharge cargo, $T_{s\&w}$ is the time used in slow zones and waiting, N_c is annual number of cargo voyages. The second term gives the annual number of days used on voyages in ballast, which means repositioning the vessel by sailing without any cargo to the next loading port. The annual number of cargo and ballast voyages per vessel type and size used in this study are based on Lindstad et al. (2012). The ratio between cargo voyages and ballast voyages ranges from 1:1 for crude oil transport which is a typical tramp trade to 1:0 in liner trades performed by container vessels or RoRo vessels Christiansen et al. (2007). The explanation is that crude oil carriers transport crude only and hence have to return empty to the oil source after delivery at the refinery, while container vessels and RoRo vessels can transport almost any cargo as long as it can be packed in containers or lifted or rolled on board the vessels. In the formula, D_b is the distance, v_b is the speed on the ballast voyages, $T_{s\&w}$ is the time in slow zones and waiting, N_b is annual number of voyages in ballast.

The annual fuel consumption F of a vessel is the total fuel used on cargo voyages and on ballast voyages, as expressed by Eq. (2):

$$F = K_f \left| \left[\left[\left(\left(\frac{P_c|D_c}{v_c} \right) + P_{l\&d}|T_{l\&d} + P_{s\&w}|T_{s\&w} \right) \middle| N_c \right] + \left[\left(\left(\frac{P_b|D_b}{v_b} \right) + P_{s\&w}|T_{s\&w} \right) N_b \right] \right] \right. \quad (2)$$

where the first term gives the fuel used on cargo voyages, the second term gives the fuel used on ballast voyages and K_f is the amount of fuel (in grams) per produced kWh. In the first term, P_c represents the power used to achieve the speed on cargo voyages, where the power output required for propulsion (when sailing) is a function of the speed to the power of three, which implies that when a ship reduces its speed below its design speed its fuel consumption per nm is reduced. When speed is further reduced the propulsion efficiency drops, the relative impact of wind and waves increases and the net effect is that when the speed drops below 6–9 knots the emissions per nm increase (Lindstad et al., 2011). Then D_c is the distance of the cargo voyages and v_c is the speed on cargo voyages. $P_{l\&d}$ Is the power requirement when loading and discharging and $T_{l\&d}$ is the time used, $P_{s\&w}$ is the power requirement in slow zones and waiting and $T_{s\&w}$ is the time used. In the second term, P_b represents the power used to achieve the speed on ballast voyages, D_b is the distance of the ballast voyages and v_b is the speed on the ballast voyages. $P_{s\&w}$ is the power requirement in slow zones and waiting and $T_{s\&w}$ is the time used. The vessel speeds are based on the speed data per vessel as given by the IHS-Fairplay database, where the speed in general is based on the speed of the vessel when fully loaded, using 75% of its maximum continuous power rating (MCR) under still-water conditions. When sailing in ballast or partly loaded, less than 75% of MCR is needed to achieve the design speed. However, since calm water is the exception in shipping rather than the rule, additional power is required to maintain the design speed when the resistance increases due to wind and waves. Based on these considerations and on a dialog with ship owners, we have used the following values to achieve the design speed; 95% MCR on cargo voyages for bulk, tank and all other vessels modeled with ballast voyages, 80% MCR on their ballast voyages and 90% MCR for container and RoRo vessels. When ship owners slow steam (i.e. reduce speeds below the design speed) to reduce overcapacity in one or more shipping segment these MCR percentages will be lower. Since these speed reductions are usually of the same magnitude for all vessels of similar types, they do not influence the relative difference between small and large vessels within a shipping segment.

The annual amount of CO_2 emitted per ton nautical mile ε is calculated as follows
(Second IMO GHG study, 2009):

$$\varepsilon = \left(\frac{F}{D_c|M|N_c} \right) \middle| K_e \quad (3)$$

where F is annual fuel consumption per vessel as described in Eq. (2), K_e is the CO_2 emitted per unit of fuel burnt and $D_c|M|N_c$ is the annual freight work measured in tons per nautical mile, for which D_c is the distance of the cargo voyage, M is the weight of the cargo and N_c is annual number of cargo voyages.

The cost per ton nautical mile C comprises the annual freight work, the cost of fuel and the annual time charter cost of the vessel as expressed by

$$C = \frac{1}{D_c|M|N_c} \left[(F|C_{Fuel}) + (Capex_v|(k_1 + k_2) + k_3) \right] \quad (4)$$

The first factor, i.e.: $D_c|M|N_c$, transforms the cost from an annual cost per vessel in order to enable comparisons of freight cost per unit for vessels of different sizes and types employed in various trades to be drawn. The cost of fuel is then calculated by multiplying the annual amount of fuel F from Eq. (2) by the average cost of fuel C_{Fuel}, which is calculated based on an average consumption pattern of 90% heavy fuel oil (HFO) and 10% marine diesel oil (MDO). Using one fuel price is a simplification. However, since this mix is given by different geographical environmental requirements and not vessel types it is a proxy which does not really influence the conclusions. Examples of such geographical requirements are the requirement to use low sulphur oil as MDO, or expensive cleaning of the exhaust gas if HFO is used, in the Baltic and North Seas. The annual cost of operating a vessel is based on current new-building prices and where the cost consists of financial items, depreciation and operating costs, expressed as: $(Capex_v|(k_1 + k_3) + k_3)$. Where $Capex_v$ is the new-building price of the vessel, k_1% of $Capex_v$ are fixed costs, which consist of financial cost including depreciation and return on own capital, k_2% of $Capex_v$ plus a basic amount k_3 is the variable cost. To summarize, combining Eqs. (1)–(3) enables us to estimate greenhouse gas emissions due to economies of scale as a function of vessel type and size, while Eq. (4) estimates the costs involved.

3. Application and analysis

The aims of the analysis were first, to identify the emissions and costs for individual ship classes for the existing fleet, and then, to investigate the effects of economies of scale on the direct emissions and costs of maritime transport as a function of vessel size and fleet mix for the entire global fleet.

3.1. Selection of types of vessel and size groups

This study includes all cargo vessels as listed in the IHS-Fairplay database (www.ihs.com) in December 2007, but excludes vessels which are built for a combination of passenger and cargo, such as Ro-Pax vessels which transports passengers, cars and cargo on board trailer units. In terms of emissions, the vessels that are excluded emit 20% of the total CO_2 emitted by maritime transport. This means that the vessels included according to our calculations emitted 820 million tons of CO_2 in 2007. This is within the same range as the total emissions calculated for these vessels by the IMO 2009 GHG study. The cargo vessels can be grouped into the three subgroups of dry bulk, general cargo and tank, based on cargo type and on how the cargo is handled and transported, although there is some overlap (competition for cargoes) between dry bulk and general cargo and between general cargo and tankers. The following section offers a brief introduction to the different vessel types and the cargoes that they carry.

Dry bulk commodities are in solid form and can be handled mechanically by grabs, conveyor belts, bucket units or pneumatic systems. Typical dry bulk commodities are iron ore, coal, grain, cement, fertilizers and aggregates. General cargo is all cargo types which cannot be handled by grabs, conveyor belts, pumps or pipeline systems. General cargo is transported by general cargo vessels, container vessels, reefer vessels and Ro-Ro vessels. Container vessels are purpose-built for transport of standardized containers. However, since containers are of different types, e.g. reefer, tank, bulk and standard, container vessels can carry not only general cargo, but also dry bulk commodities and petroleum products and chemicals. General cargo vessels are typically used for transport of pallets, bulk products in Big Bags, forest products, steel and aluminum, but also containers. Reefer vessels carry perishables such as fruit and fresh food and frozen products, while Ro–Ro vessels are used for new and used cars, heavy vehicles and project cargo, but also trailer units with cargo and goods. Wet bulk cargoes typically consist of liquefied products and gas that are mainly transported in wet bulk tankers, such as crude oil, liquefied petroleum gas (LPG) and liquefied natural gas (LNG), or a family of similar products such as refined oil products by product tankers and chemical products by chemical tankers.

Each of these types of vessel includes vessels of various sizes; however, while the largest reefers are around 20,000 dead weight tons (dwt), the largest crude oil tankers are more than 300,000 dwt. The dead weight is the measure in metric tons of how much weight a ship can carry. To model the existing operational patterns, all vessel types were divided into two to six size groups where the small vessels for all vessel types are those between 0 and 15,000 dwt. The smallest vessel typically operates in short sea trades or coastal shipping trades (Second IMO GHG study, 2009). For all vessel types, the largest vessels are grouped together. For reefers, where the largest vessels are only 20,000 dwt this gives only two size groups, while six size groups are needed to describe the operational trade pattern of dry bulkers, whose largest vessels have an average size of 172,000 dwt. This process enabled us to calculate values for the smallest vessel, the largest and the average within each group. Table 1 summarizes the main characteristics of the operational patterns of both dry bulk vessels and all other types of cargo vessels. The table shows vessel type and size in the first column, number of vessels in the second column, average dead weight per vessel in the third column, net payload per vessel in the fourth where the weight of the bunkers and the tare weight of the cargo containment units has been subtracted from the dead weight (Container and Ro–Ro). These are followed by average utilization, average design speed, duration of cargo voyages, annual number of cargo voyages, annual number of ballast voyages, average engine size, annual freight work done, which is the sum of all quantities carried measured in weight over all the distances, annual CO_2 emitted and grams CO_2 per ton nm. To familiarize the reader with the table we take dry-bulk Capesize vessels as an example (first line in Table 1). The average size of a Capesize vessel is 172,000 dwt and when bunker oil, water and supplies have been loaded they can load 169,000 t, a capacity that is utilized 97% on average. The main Capesize trades are from Australia to Japan/Korea/China in Asia or to Western Europe, and from Brazil to Asia and Western Europe. The average sailing distance is 7500 nm one way, the design speed is 14 knots and the time used from start of loading until end of discharge is 33 day, including average waiting times. Capesize vessels sail an average of six voyages with cargo and five in ballast a year, due to imbalance of trades. A combination of cargo and ballast voyages is usual in all tramp trades. While in liner trades, represented by container and Ro–Ro vessels, there are no ballast voyages, but also lower utilization, since very few of these vessels are fully loaded on a roundtrip basis.

The main observations from Table 1 are that the largest vessels are mainly used on the longest voyages while the smallest are mainly used on the shortest voyages. Most freight work is performed by the largest vessels, including Panamax size groups, while the ‘coastal vessels’ below 15,000 dwt perform some 5% of all sea transport work. The largest vessels of all types emit less CO_2 per ton nm, where the ratio of largest to smallest is 1:13 in dry bulk (7–91 g of CO_2 per ton nm) and 1:3 in the container segment (28–80 g of CO_2 per ton nm). This implies that increasing average vessel sizes will help to lower emissions. However, we would point out that the relationships between ship size and emission is not linear, but rather reflects a power–law relationship with diminishing marginal emission reductions as vessel size increases. To illustrate this, as the dry bulk vessel size increases from 26,000 to 46,000 dwt, the emissions per ton nm are reduced by 33%, while an increase from 46,000 to 72,000 dwt offers only a further 17% reduction.

3.2. Reduction in greenhouse gas emissions through economies of scale

As we pointed out in the Introduction, economies of scale in shipping is the term usually used to refer to the benefits obtained by replacing smaller vessels by larger vessels. The potential of economies of scale to reduce greenhouse gases and costs can be evaluated by calculating the average for existing vessels and comparing it with what can be achieved by replacing the existing fleet with larger vessels. We point out that the rise in vessel size is an ongoing process, which gradually increases the average vessel size by introduction of new vessels which are larger than the existing ones and by replacing old vessels which are being scrapped with similar or a larger size one. Examples of such increases are the new Chinamax dry bulkers (400,000 dwt) which will be more than twice the average size of today’s largest bulkers; the Capesize vessels (172,000 dwt). Similarly, the new Maersk’s triple-E class container vessels (216,000 dwt) will be twice the average size of today’s largest container vessels. When these larger vessels are introduced, more ports will be served by feeder vessels. However, since the feeder distances are much shorter than the deep-sea distances, the increase in emissions due to this change will still be much smaller than the savings on the deep-sea legs. Feeder vessels and their operations are perhaps best known as an integrated part of the ocean services provided by the big container lines. However, feeder vessels and operations are already used in a number of different trades, where cargoes are collected and/or delivered at a number of ports by smaller vessels and brought to larger ports served by ocean-going vessels. Although in theory new vessels can be much bigger than existing vessels, there will be limitations, due to draft and port restrictions both for ocean going vessels and for feeder and coastal vessels in smaller ports. And when physical constraints themselves do not set the limits, national rules for pilotage and port fees will in some cases result in significant cost increases and operational disadvantages when a ship exceeds a certain size. Examples are ships exceeding a length of 200 m in Japanese ports or a given dead weight size in Norwegian ports. A general consequence of such rules is that vessels are either kept below the limits or built significantly larger. Moreover, logistics requirements and the size and cost of carrying stocks will tend to work against using vessels that are too large. The explanation is that with constant freight volumes, the introduction of larger vessels will tend to reduce sailing frequencies, and when sailing frequencies are reduced the total lead time from factory gate to customer will be longer.

Given all these considerations and the predictions for trade growth until 2050, we use the average size of today’s largest vessels (2007) of each type as shown in Table 1 to calculate what can be achieved by economies of scale. For dry bulkers this means Capesize vessels with an average size of 172,000 dwt. For container vessels it means 8500 TEU vessels with an average size of 106,000 dwt. In comparison, the current average sizes are

Table 1
Operational patterns and quantity of CO_2 emitted per ton nm as a function of vessel size and type.

Vessel type	**Number of vessels**	**Average vessel size in dwt (ton)**	Net payload capacity (ton)	Utili-sation when loaded	Distance per voyage (nm)	Speed (knots)	Duration of cargo voyage (days)	Number of cargo voyages	Duration of balast voyage (days)	Number of balast voyages	Average engine size (kW)	Freight work (**billion ton miles**)	CO_2 emitted (**gram per ton nm**)
Dry bulk Capesize 120′+	**782**	**172,000**	169,000	97%	7500	14	33	6	30	5	15,430	**5770**	**7**
Dry Bulk 80–120’	**119**	**94,000**	92,000	97%	6500	14	29	7	26	5	1970	**480**	**10**
Dry Bulk Panamax 60–85’	**1447**	**72,000**	71,000	95%	5500	14	28	8	25	5	9800	**4290**	**10**
Dry Bulk Handymax 35–60’	**1937**	**46,000**	45,000	95%	5,000	14	25	9	22	5	8210	**3730**	**13**
Dry Bulk Handysize 15–35’	**1920**	**26,000**	25,000	90%	3000	14	16	15	14	7	6660	**1940**	**20**
Dry Bulk coastal 0–15’	**1318**	**4300**	4000	85%	787	12	6	36	5	20	1950	**130**	**91**
General Cargo 15′++	**1215**	**25,000**	24,000	90%	3000	15	16	15	13	8	8080	**1180**	**24**
General Cargo 0–15’	**16,065**	**3100**	2800	85%	500	12	5	46	4	24	1580	**1200**	**59**
Container 8500 TEU +	**206**	**106,000**	85,000	70%	11,000	25	31	11	27	0	67,370	**1480**	**28**
Container 5500–8500 TEU	**175**	**80,000**	64,000	70%	11,000	25	31	11	27	0	60,280	**950**	**33**
Container 3000–5500 TEU	**1068**	**55,000**	44,000	70%	7000	23	24	14	20	0	37,210	**3220**	**34**
Container 2000–3000 TEU	**789**	**33,000**	27,000	70%	2500	21	10	32	9	0	20,000	**1190**	**34**
Container 1000–2000 TEU	**832**	**21,000**	16,400	70%	1,000	19	8	45	6	0	12,660	**430**	**49**
Container 0–1000 TEU	**1328**	**9100**	7300	70%	650	17	6	49	5	0	6230	**220**	**80**
Reefer 15′++	**22**	**16,000**	14,500	90%	4000	21	14	16	12	10	14,970	**20**	**61**
Reefer 0–15’	**1204**	**5200**	4700	90%	1501	16	7	29	5	19	4830	**250**	**81**
RoRo 35′++	**20**	**45,000**	36,000	70%	8500	18	30	12	27	0	20,30	**50**	**27**
RoRo 15’–35’	**409**	**20,000**	15,800	70%	1800	19	11	33	9	0	14,170	**260**	**54**
RoRo 0–15’	**1981**	**4200**	3400	70%	437	14	4	80	4	0	4980	**160**	**227**
Crude oil 200′++	**506**	**295,000**	289,000	99%	9000	15	42	4.5	37	4.5	24,830	**5860**	**7**
Crude oil 120–200’	**356**	**152,000**	147,000	99%	6000	15	29	6	26	6	17,160	**1990**	**10**
Crude oil 75–120’	**660**	**103,000**	100,000	99%	2500	15	16	12	14	12	12,730	**1880**	**15**
Crude oil 15–75’	**410**	**52,000**	50,000	98%	897	15	11	18	9	18	9090	**350**	**27**
Crude oil 0–15’	**121**	**3600**	3500	98%	300	12	6	25	5	25	1930	**3**	**114**

Products 75'++	47	112,000	108,000	85%	5000	15	29	9	24	4	14,580	180	13
Products 15–75'	737	46,000	37,100	85%	3637	15	23	10	20	5	8960	1030	24
Products 0–15'	4122	2500	2100	85%	149	11	12	20	10	12	2930	30	95
Chemical 40'++	533	48,000	45,000	85%	5,000	15	25	11	21	3	9360	1070	18
Chemical 15–40'	839	28,000	22,200	85%	2897	15	21	12	18	4	7820	710	33
Chemical 0–15'	2496	4900	4000	85%	435	12	7	31	5	16	2270	140	118
LNG 60'++	229	76,000	75,000	99%	8000	20	31	6	27	6	27,090	820	33
LNG 15'–60'	26	38,000	30,700	99%	3923	18	21	10	18	10	14,910	30	47
LNG 0'–15'	10	8600	8200	99%	700	16	9	18	8	18	5800	1	113
LPG 45'++	118	53,000	51,000	99%	5000	17	21	9	18	9	13,400	270	22
LPG 15'–45'	128	27,000	21,500	99%	2031	16	13	15	11	15	10,060	100	39
LPG 0–15'	857	3500	2800	99%	320	13	5	34	4	34	2550	40	172
Total	45,000	24,000				14						41,000	20

52,000 dwt for dry bulkers and 34,000 dwt for container vessels. The assumed 2050 fleet of dry bulkers will then consist of Chinamax dry bulkers, dry bulkers with a size between Chinamax and Capesize, the current Capesize vessels, a new bulk size around 125,000 dwt utilizing the new Panama lock extension from 2014, and vessels from 50,000 dwt and downwards to serve smaller ports and trades. With an average lifetime of 25 years per vessel the benefits of building larger vessels will appear gradually, but the whole fleet could still be renewed before 2050.

The economies of scale calculations were performed in two steps, as shown in Table 2. First, for 2007 we compared the average performance of each vessel type based on the current pattern of operation, with what it would have been if the average vessel size had increased from the current average (2007 fleet) up to the average size of the largest vessels used today (2007). To exemplify for dry bulk, the current average size (2007 fleet) is 53,000 dwt while the average size of the largest type of dry bulkers, the Capesize vessels is 172,000 dwt. This based on the assumption that the mathematical average vessel within each group represents the average values for each vessel type. Secondly, we did the same for 2050, based on anticipated freight work and volumes per vessel type. Our 2050 projections for freight volumes and freight work are based on growth in GDP in line with the IPCC (2007) B1 scenario, growth in freight work, which is 80% of the growth in GDP and growth in container shipping, which will continue to be three times as high as in other shipping segments (Second IMO GHG study, 2009). Similar growth predictions for container ships trade and emissions have also been made by the Ocean Policy Research Foundation (2008). Compared with other IPCC (2007) scenarios, the B1 scenario, which has an annual growth of 3.1%, lies between high-growth scenarios such as A1T (4%) and low-growth scenarios like B2 (2.4%). With these assumptions, freight work will grow from 41,000 billion ton nm in 2007 to 109,000 billion ton nm in 2050.

Table 2 shows that the total freight work performed in 2007 was 41,000 billion ton miles, produced by 45,000 vessels with an average size of 24,000 dwt. If the 2007 fleet had been replaced by an economies of scale (EOS) fleet with an average size of 98,000 dwt, the number of vessels would have fallen to 11,000. This would reduce CO_2 emissions per ton nm from 20 to 14 g, and reduce annual emissions from 820 million tons to 570 million tons CO_2 which is a 31% reduction. By 2050, the freight work based on the IPCC (2007) B1 scenario will have grown to 109,000 million tons. If this work had been performed by the 2007 fleet mix, 12,300 vessels would have been required, while only 23,000 vessels would be needed with an EOS fleet whose average size has increased from 98,000 dwt to 106,000 dwt due to the greater share of freight work performed by container vessels. The negative effect of the greater share of total freight work done by container vessels is that the quantity of CO_2 per ton nm mile increases compared to 2007 figures from 20 to 24 for the 2007 fleet and from 14 to 18 for the EOS fleet. However, increased environmental concern might slow down the anticipated strong growth in container shipping and hence give a freight distribution among vessel types in 2050 more in line with 2007 figures. If the average vessel size increases significantly but fails to reach 106,000 dwt the savings will be reduced, although by less than might be expected, since 50% of the reduction in emissions comes from the first doubling of average vessel size from 24,000 to 48,000 dwt, and the remaining 50% comes from increasing average vessels size from 48,000 to 106,000 dwt.

3.3. Reduction in costs through economies of scale

The potential for reducing costs through economies of scale was estimated using the same vessel size assumptions as for emission reduction in the previous section. This means

Table 2
Quantity of CO_2 emitted per ton nm as a function of vessel size and type.

Vessel type	Freight work (billion ton miles)	No. of vessels 2007 fleet	Average vessel size 2007 fleet (ton (dwt))	Average vessel size EOS fleet (ton (dwt))	No. of vessel EOS fleet	CO_2 emitted per freight unit 2007 fleet (gram per ton nm)	CO_2 emitted per freight unit EOS fleet (gram per ton nm)	Annual CO_2 emitted 2007 fleet (million ton)	Annual CO_2 emitted EOS fleet (million ton)
Key figures 2007									
Dry bulk	16,137	7523	53,000	172,000	2295	11.4	7.0	184	113
General cargo	2382	17,280	4600	25,000	3165	42.2	24.4	100	58
Reefer	258	1226	5400	16,100	412	84.8	65.3	22	17
Container	7501	4398	34,000	106,000	1418	34.8	28.2	261	212
RoRo	485	2410	7200	45,000	388	75.8	25.7	37	12
Crude oil	10,061	2053	143,000	295,000	994	9.7	7.0	98	70
Oil products	1257	4906	10,200	112,000	445	25.0	13.3	31	17
Chemicals	1919	3868	15,800	48,000	1281	25.4	17.8	49	34
LNG	852	265	70,000	76,000	243	33.9	33.3	29	28
LPG	401	1103	11,600	53,000	239	34.8	22.5	14	9
Sea river	16	1169	1136	7,466	178	31.3	11.5	3	1
Total freight	41,000	45,000	24,000	98,000	11,000	20.0	13.8	820	570
Key figures 2050									
Dry bulk	29,853	16,250	53,000	172,000	4725	11.4	7.0	340	208
General cargo	4,407	37,325	4600	25,000	5293	42.2	24.4	186	108
Reefer	477	2,648	5400	16,100	706	84.8	65.3	40	31
Container	46,131	32,721	34,000	106,000	6270	34.8	28.2	1 604	1301
RoRo	897	5,206	7200	45,000	403	75.8	25.7	68	23
Crude oil	18,613	4,434	143,000	295,000	1875	9.7	7.0	181	130
Oil products	2325	10,597	10,200	112,000	696	25.0	13.3	58	31
Chemicals	3550	8355	15,800	48,000	2064	25.4	17.8	90	63
LNG	1576	572	70,000	76,000	516	33.9	33.3	53	52
LPG	742	2382	11,600	53,000	381	34.8	22.5	26	17
Sea river	30	2163	1136	7466	329	31.3	11.5	6	2
Total freight	109,000	120,000	24,000	106,000	23,000	24.4	18.1	2 650	1970

calculating the average costs of existing vessels and then comparing them with the costs which can be achieved by building bigger vessels. When comparing costs, different cost-accounting principles can be employed, but irrespective of principles, some cost items will be variable and others fixed. A variable cost is an expense that fluctuates based on activity level, while a fixed cost does not fluctuate with activity level. For a ship-owner, vessels that are owned or are leased on long-term contract represents the main fixed cost, while the cost of fuel is a variable cost. Between these two cost types, we have the cost of crew and the management cost of operating the vessel, which is not a fully variable cost, but is still usually treated as a variable cost. Regarding cost accounting principles used in comparing the existing fleet with an EOS fleet, we have at least three options. The first is to compare the fleets on the basis of total variable and fixed costs for the required transport capacity, based on the cost of new-building in 2011. The second is to use the average second-hand price of the existing fleet in combination with the 2011 variable cost to compare with new-building of the EOS fleet. The third option is to take a marginal approach for the existing fleet, comparing only its variable cost against total variable and fixed cost for the EOS fleet. The first cost option gives us the relative cost advantage with an EOS fleet compared to the existing fleet in a long-term view. The second enables us to compare the competitiveness of the existing fleet against an EOS fleet gradually entering the market. The third option tells us whether the existing fleet will at least be able to cover its variable costs when the EOS fleet enters the market. It should be noted that freight rates and hence the transport cost in shipping have historically been highly volatile, ranging from low levels that do not even cover all variable costs to high levels that are more than 5 to 10 times the total costs. However, in a 25-year perspective, which is the average lifetime of a vessel, the profitability of major shipping companies will be similar to that of other large companies. We have calculated costs per ton nm using Eq. (4) with costs and percentages as outlined below. The cost of fuel C_{Fuel} is based on an average consumption pattern of 90% HFO at a price of 600 USD/ton and 10% MDO at a price of 900 USD/ton, which gives a fuel price of 630 USD/ton based on average 2011 prices. The annual time-charter equivalent cost per vessel is calculated on the basis of the 2011 new-building price $Capex_v$ as provided by IHS Fairplay (Table 3), and where 8% of $Capex_v$ covers the fixed cost, and 3% of $Capex_v$ plus a basic amount of 2000 USD per day, covers the variable costs. The basic amount takes into account the fact that even for small and cheap vessels there are some costs which have to be covered. In total, this is sufficient to pay for the operation of the vessel, its technical and operational management, its depreciation and the return on the capital employed.

We calculated economies of scale on the basis of these new building costs, operational patterns and transport work as established in the previous sections. This calculation was first performed in order to find the relative cost advantage using an EOS fleet relative to the existing fleet, based on full fixed and variable costs for both fleets as shown in Table 4.

Table 4 shows that costs per million ton nm with the 2007 fleet are lowest for crude oil carriers, with a cost of 3500 USD. In

Table 3
New-building cost per vessel as a function of vessel type and size.

Vessel type	Average vessel size 2007 fleet (ton (dwt))	Engine size 2007 fleet (kWh)	Average new building price 2007 fleet (Million USD)	Average vessel size EOS fleet (ton (dwt))	Engine size EOS fleet (kWh)	Average new building price EOS fleet (Million USD)
Dry bulk	52,500	8000	32	172,000	15,000	59
General cargo	4600	2100	11	25,300	8000	27
Reefer	5400	5000	15	16,100	15,000	29
Container	34,200	22,000	44	106,000	67,000	98
RoRo	7200	7500	32	44,600	20,000	93
Crude oil	142,900	15,000	65	295,200	25,000	98
Oil products	10,200	2700	15	112,100	15,000	57
Chemicals	15,800	4500	28	47,600	9000	54
LNG	70,100	25,000	162	76,300	27,000	170
LPG	11,600	4500	28	53,300	13,000	64

Table 4
Comparing total cost for the existing fleet (2007) with total costs for an EOS fleet in 2007 and 2050.

Vessel type	2007 Freight work (Billion ton miles)	2050 Freight work (Billion ton miles)	Cost with 2007 fleet (USD per million ton nm)	Cost with EOS fleet (USD per million ton nm)	Total cost in 2007 with 2007 fleet (Million USD)	Total cost in 2007 with EOS fleet (Million USD)	Total cost in 2050 with 2007 fleet (Million USD)	Total cost in 2050 with EOS fleet (Million USD)
Dry bulk	16,137	29,853	4200	2400	68,000	39,000	125,000	72,000
General cargo	2382	4407	22,400	9800	53,000	23,000	99,000	43,000
Reefer	258	477	28,400	19,200	7000	5000	14,000	9000
Container	7501	46,131	10,200	7800	77,000	59,000	471,000	360,000
RoRo	485	897	36,400	13,900	18,000	7000	33,000	12,000
Crude oil	10,061	18,613	3500	2500	35,000	25,000	65,000	47,000
Oil products	1257	2325	14,200	5100	1800	6000	33,000	12,000
Chemicals	1919	3550	12,700	8000	24,000	15,000	45,000	28,000
LNG	852	1576	12,500	12,200	11,000	10,000	20,000	19,000
LPG	401	742	17,200	9100	7000	4000	13,000	7000
Total	41,000	109,000			318,000	193,000	918,000	605,000
Cost in USD per million ton nm					7800	4700	8400	5600
Potential reduction with economy of scale						39%		34%

an EOS fleet, dry bulk vessels would have the lowest cost per million ton nm at 2400 USD, followed by crude oil tankers, with a cost of 2500 USD. Combining these unit costs with the freight work performed in 2007 and 2050 gives us the total costs in each year for both the 2007 fleet and the EOS fleet. In 2007, the total cost would be 318,000 million USD with the actual 2007 fleet and 193,000 million USD with the EOS fleet, which is a 39% reduction. In 2050, the total becomes 918,000 million USD with the 2007 fleet and 609,000 million USD with the EOS fleet, i.e. a 34% reduction. When 2007 and 2050 are compared the figures also show that the cost per million ton nm will be 10% higher in 2050 with the 2007 fleet and 20% higher with the EOS fleet. The reason is the foreseen growth in the total share of the freight work performed by container vessels, which have higher unit costs and emissions than the fleet average.

While this section has shown the benefits of replacing smaller vessels with larger ones when the existing vessels reach the end of their lifetime, additional calculations are needed offer recommendations for short- and medium-term decisions. Since we do not know the remaining value of the existing vessels, we make the assumption that it is significantly lower than the value of new-buildings and that the fixed cost per transported unit will be only 50% of the fixed cost per transported unit for a similar new-built vessel. Table 5 shows the results of this comparison, which is based on the 2007 freight work for all three cost options.

Table 5 shows that the total costs for the EOS fleet are lower than the variable costs of using the existing fleet. For dry bulkers this means that the variable costs for an average 2007 vessel is 3000 USD per million ton (4200 USD in total cost), while the total cost for an EOS dry bulker is 2400 USD per million ton. This implies that in trades that can accommodate larger vessels due to transport volumes and that are not limited by port restrictions, smaller vessels cannot compete against large new buildings. However, this does not imply that smaller vessels in general should be scrapped and replaced with larger new buildings, since smaller vessels will still be needed due to port limitations and the demand for transporting smaller volumes. But it does suggest that ship-owners should consider scrapping older vessels unless they match an EOS size, and replace them with newer second-hand vessels of similar or larger size, or with larger new-buildings. Regarding age, the average expected lifetime of cargo ships is around 25 years, while well-maintained vessels can operate longer. However, as a vessel becomes older, ordinary maintenance costs become larger, while costly upgrades may be needed in order to retain the class societies' certificates that are required to operate. In a good market with high freight rates, ship-owners can easily absorb these additional costs, while under normal market conditions, the profitability of keeping versus replacing an older vessel with a newer vessel will be evaluated at least annually. This is similar to the aviation industry, where airlines replace older aircraft which need overhauls and additional maintenance with newer aircraft with lower variable costs due to reduced fuel consumption and lower maintenance.

When we compare the significant cost savings made by increasing the average vessel size against the additional potential cost increases in ports related to infra- and supra- structure, for feedering and for increased stock, a few comments can be made. The first is that most ports can accommodate a certain rise in the average vessel size they serve without any modifications. Larger vessels like the Chinamax bulkers will only be used for trades between a limited numbers of ports. The second is that with the new Panama Canal locks from 2014, vessels can be much beamier and hence carry up to 50% more cargo and still be used in most ports that serve current Panamax vessels. The explanation of this is that the main restriction in most ports is the sea draft (measured from the surface of the water to the deepest part of

Table 5
Comparing the cost for the existing fleet (2007) with the full cost for an EOS fleet.

Vessel type	2007 Freight work (Billion ton miles)	Variable and fixed cost 2007 fleet based on —new buildings (1) (USD per million ton nm)	Variable and fixed cost 2007 fleet (2) (USD per million ton nm)	Variable cost only 2007 fleet (3) (USD per million ton nm)	Variable and fixed cost EOS fleet (USD per million ton nm)	Total cost with 2007 new built fleet (1) (Million USD)	Total cost with 2007 existing fleet (2) (Million USD)	Total variable cost 2007 fleet (3) (Million USD)	Total cost in 2007 with EOS-fleet (Million USD)
Dry bulk	16,137	4200	3600	3000	2400	68,000	58,000	48,000	39,000
General cargo	2382	22,400	19,300	16,100	9800	53,000	46,000	38,000	23,000
Reefer	258	28,400	25,500	22,500	19,200	7000	7000	6000	5000
Container	7501	10,200	9200	8100	7800	77,000	69,000	61,000	59,000
RoRo	485	36,400	30,000	23,500	13,900	18,000	15,000	11,000	7000
Crude oil	10,061	3500	3000	2500	2500	35,000	30,000	25,000	25,000
Oil products	1257	14,200	11,900	9600	5100	18,000	15,000	12,000	6000
Chemicals	1919	12,700	10,500	8200	8000	24,000	20,000	16,000	15,000
LNG	852	12,500	10,500	8500	12,200	11,000	9000	7000	10,000
LPG	401	17,200	14,200	11,200	9100	7000	6000	4000	4000
Total	41,000					318,000	275,000	228,000	193,000
Cost in USD per million ton nm						7800	6700	5600	4 700

the vessel) rather than beam or length. The third is that in some trades, the larger vessels used on the deep-sea legs will mean that fewer ports can be served, which will contribute to increased feedering. However both for dry bulk and container trade we might see the same as in aviation, where the largest Airbus A-380 aircraft is used on major routes with high frequencies like Singapore–London and Singapore–Frankfurt, while Singapore–Copenhagen is served by aircraft of half their size, three to four days a week. Translated to shipping, this means that major ports which cannot be served by mega-vessels will continue to be served directly by large vessels, while the ultra-large vessels will be used in major ports that can accommodate them. The fourth is that with the foreseen growth in trade, vessel sizes can be increased without reducing the sailing frequencies and without increasing the average days in stock for the commodities. The fifth is that port states can implement legislation in combination with a cost structure which will work as a barrier to the introduction of larger vessels. Although this challenge should not be ignored, we regard it primarily as a safety point. Our judgment is that due to completion between port states and ports, they will try to do whatever they can within the physical limitations to accept larger vessels as long as their safety threshold are met. Adding all this up, our conclusion is that compared to the potential savings of using significantly larger vessels, the additional cost are small.

3.4. Abatement costs with an EOS fleet

The main purpose of calculating abatement costs is to enable different emission reductions options both within shipping and between sectors to be compared. Since most abatement options come at a cost that exceeds the economical benefits, abatement costs tend to be positive. In the shipping sector, research has shown that there are emission reductions options which can be adopted at negative abatement cost (Second IMO GHG study, 2009; Faber et al, 2009; DNV 2010). However, Russell et al. (2010), claim that these studies fall short in identifying, characterizing and assessing the impact of the range of decisions faced by individual ship owners and collectively based on current and future market conditions, and that these studies do not take profit and opportunity cost into consideration. Our understanding is that previous work has been based on assuming an ongoing operation with long-term vessel ownership, ignoring that a large proportion of the shipping market is much more focused on asset play, with buying and selling vessels driven by profit and opportunity assessments. Taking the long-term view, abatement costs can be calculated by combining the cost savings and potential reductions in emissions produced by introducing larger vessels, as shown in Table 6. These abatement costs have been calculated on the basis of comparing the freight levels required to cover the fixed and variable costs of the 2007 fleet versus the EOS fleet, assuming that in the long run, freight rates for different commodities will reflect their different transport costs. These abatement costs lie within a range from −361 USD per ton CO_2 for container vessels to −739 USD per ton CO_2 for RoRo vessels. This is based on a scenario in which smaller vessels are replaced by larger vessels when they are scrapped, while scrapping relatively new small vessels to reduce emissions would give a positive abatement cost.

3.5. Sensitivity analysis of cost variables

Fuel prices and new building costs are the two main exogenous variables in the sensitivity analysis. The results regarding cost reductions through economies of scale in Section 3.3 are based on a fuel price of 630 USD/ton and 2011 new-building prices. However, both the fuel price, which is a function of the oil price, and

Table 6
Abatetment costs as a function of economies of scale.

Vessel type	Cost with 2007 fleet (USD per million ton nm)	Cost with EOS fleet (USD per million ton nm)	2007 Freight work (Billion ton miles)	2050 Freight work (Billion ton miles)	2007 Emission reduction with EOS fleet (Million ton CO_2)	2050 Emission reduction with EOS fleet (Million ton CO2)	Abetment cost per ton CO_2 (USD)
Dry bulk	4200	2400	16,137	29,853	42	78	−689
General cargo	22,400	9800	2382	4407	71	131	−423
Reefer	28,400	19,200	258	477	5	9	−472
Container	10,200	7800	7501	46,131	49	303	−361
RoRo	36,400	13,900	485	897	15	51	−739
Crude oil	3500	2500	10,061	18,613	24	27	−423
Oil products	14,200	5100	1257	2325	27	27	−415
Chemicals	12,700	8000	1919	3550	15	45	−620
LNG	12,500	12,200	852	1576	0	1	−598
LPG	17,200	9,100	401	742	5	9	−663
Total	7800	4700	41,000	109,000	250	680	

Table 7
Sensitivity analyses for cost variables.

Scenario	Average cost in 2007 with 2007 fleet (USD per million ton nm)	Average cost in 2007 with EOS fleet (USD per million ton nm)	Reduction in 2007 with EOS (USD per million ton nm)	Average cost in 2050 with 2007 fleet (USD per million ton nm)	Average cost in 2050 with EOS fleet (USD per million ton nm)	Reduction in 2050 with EOS (USD per million ton nm)
Base case, oil price = 630 USD/ton	7800	4700	3100	8400	5600	2800
Oil price 315 USD/ton	5700	3300	2400	5900	3800	2100
Oil price 1260 USD/ton	11,700	7400	4300	13,200	9100	4100
New building price 50% of today	6200	3800	2400	6900	4700	2200
New building price 200% of today	10,600	6400	4200	11,200	7300	3900

new-building prices have been extremely volatile during the past ten years. It is therefore relevant to test out the robustness of the conclusions by varying the 2011 costs of fuel and new-building from 50% of current levels to up to 200%. Table 7 shows that lower costs would reduce the cost difference between the 2007 fleet and the EOS fleet in absolute terms, while higher costs would increase it. However, since the saving with the EOS fleet ranges between 30 and 40%, we can conclude that economy of scale is a robust strategy that would be profitable at all foreseeable fuel and new-building prices.

4. Discussion and conclusions

The main objective of this paper was to investigate potential reductions in cost and emissions by utilizing economies of scale. The results demonstrate that emissions can be reduced by as much as 30% at a negative abatement cost by replacing the existing fleet with larger vessels. Replacing the whole fleet might take as long as 25 years, so the reduction in emissions will be achieved gradually as the current fleet is renewed.

When the results were compared with data from other studies of reductions in emissions and costs, they were found to be within a similar range as those for container vessels presented by Cullinane and Khanna (2000), Notteboom and Vernimmen (2009). Few studies of other vessel types exist, although figures are available that demonstrate the importance of economies of scale for emission reduction per freight unit since the Second World War (Second IMO GHG study, 2009). Our results confirm the potential for reducing emissions if we build bigger vessels in the future than we have done to date. Where abatement costs are concerned, our finding of minus 450 USD per ton CO_2 at a fuel price of 630 USD/ton is higher than previous studies have found (Second IMO GHG study, 2009; Faber et al, 2009; DNV 2010). When we compare the potential for emission reduction at a negative abatement cost, these studies indicates a reduction potential of around 30%, while our results suggest up to 30% from economies of scale alone. Since none of these studies have included the effect of economies of scale we conclude, on the basis of our results and those of Cullinane and Khanna (2000), Notteboom and Vernimmen (2009) that the importance of economies of scale has been underestimated by previous studies of abatement cost and reduction potential.

As mentioned in the Introduction, CO_2 emissions from maritime transport represent 3.3% of the world's total CO_2 emissions, and they are forecast to increase by 150%–250% until 2050, on the basis of "business as usual" scenarios with a tripling of world trade (Second IMO GHG study, 2009). In response to these challenges, the International Maritime Organization (IMO) is currently debating technical, operational and market-based measures for reducing greenhouse gas emissions from shipping. Progress has been made, and in July 2009 the principles of EEDI and SEEMP were agreed, while in July 2011, EEDI and SEEMP were adopted as part of the MARPOL Convention (Resolution MEPC.203 (62)). In a recent study commissioned by IMO (MEPC.63/INF.2), the potential reduction in emissions from EEDI and SEEMP versus business as usual scenarios was evaluated by Lloyds Register and DNV. The figures indicate that these two measures will reduce emissions per transported unit by almost 40% versus "business as usual" in 2050, and that EEDI would contribute 75% of the reduction. This is based on the assumption that more efficient technology is or will be available within the next few years. That the EEDI baselines fully represent the average for each ship type from very small to the largest vessels and that existing vessels will be replaced by vessels of similar size. In spite of these reductions, total emissions in 2050 are predicted to be twice the 2007 level, given a tripling of world trade.

It is our view that the study has taken an optimistic approach regarding the effect of new technology, but it is in line with previous assessments made by the Second IMO GHG study (2009). Regarding EEDI baselines, Greece has highlighted some of the problems for larger vessels (MEPC.62/6/19). The Greek evaluation shows that most modern large tankers currently lie well above the proposed baseline and that the same is true for large dry bulk vessels. This conclusion has also been drawn by IMarEST (MEPC.60/4/33) and by Kruger for RoRo vessels (GHG-WG.2/2/22). The treatment of larger vessels is clearly a challenge, since our study has shown that emissions can be reduced by up to 30% at negative abatement cost by replacing smaller vessels with larger ones. Since the effect of economies of scale is not included in the study by Lloyds Register and DNV, it comes in addition to what can be achieved with the EDDI and SEMP measures. Combined emissions could be reduced by more than 50%. However, the current treatment of larger vessels in EEDI is a challenge. This due to the fact that large dry bulk, tank and RoRo vessels built during the last 10 years lie on average around 10% above the current EEDI requirement, which implies that when the EEDI values in 2030 is reduced by a further 30%, the required improvement for these larger vessels will need to be 40%. Since the technology that will enable these reductions to be made is a function of vessel size and speed rather than of vessel type, EEDI reductions beyond what technology can give, can only be achieved by installing less power (smaller engines), thus reducing design speeds. A serious challenge is that power reductions on large dry bulkers and tankers can also have implications for safety, since their existing power levels partly are a function of what is required to keep the vessel under command in rough seas. On the other hand, large container vessels, which are already well below the requirements will need to improve by much less than 30%.

In a technical world, the obvious solution to maximizing emission reductions through combining economies of scale, EEDI and SEEMP would have been to improve the EEDI baselines by employing more advanced regression models in combination with technology assessments of current versus potential technologies. However, IMO's GHG discussions started on the basis of the non-binding commitment under the Kyoto protocol regime; progress has been slow and Resolution MEPC.203 (62) was not reached by consensus. So instead of making it complex, one solution might be to propose that when vessels reach a certain size, the EEDI requirement becomes a fixed value for all vessels above that size. One way to set this cut-off point for each ship type could be to set it so that 80% of vessels fall within the standard EEDI and 20% within the fixed area. Such an amendment of the EEDI scheme would bring several benefits; it would reward economies of scale and the associated emission reductions; large new-buildings would still have to be made much more energy-efficient than their older counterparts;, it would stop the debate in IMO about punishment of larger vessels, and it would offer more equal treatment of all vessels. Most importantly, it would enable larger vessels of all types to be built with sufficient power to maintain seaworthiness and maneuverability under all weather conditions.

Acknowledgments

We are grateful to Inge Sandaas, naval architect and business developer in UECC (United Car Carriers), for his valuable comments and input regarding economies of scale in shipping. Many thanks also to Christopher Paalson, director at IHS Fairplay, for contributing new-building prices and their daily time-charter equivalents.

Appendix. Nomeclature

C	cost per freight unit, USD/ton nautical mile (all tons are metric)
$(Capex_{v}\|(k_1+k_3)+k_3)$	annual cost of a vessel, where $Capex_{v}$ is the new-building price of the vessel, k_1% of $Capex_{v}$ is the fixed cost which consists of financial costs including depreciation and return on own capital, k_2% of $Capex_{v}$ plus a basic amount k_3 is the variable (operational) cost, USD
C_{HFO}	cost of heavy fuel oil, USD/ton
C_{MDO}	cost of marine diesel oil, USD/ton
D_b	distance per voyage in ballast, nm=nautical miles
D_c	distance per cargo voyage, nm=nautical miles
DWT	maximum cargo capacity of a vessel, tons
EOS	economies of scale
ε	quantity of CO_2 emitted per ton nautical miles, grams
F_b	fuel consumption on sailings in ballast, tons
F_c	fuel consumption on cargo sailings, tons
$F_{l\&d}$	fuel consumption during loading and discharging, tons
$F_{p\&s}$	fuel consumption in port and slow zones (e.g. canals and entering and leaving port), tons
$K_e=317$	CO_2 emitted per unit of fuel burnt; based on Endresen (2007)
$K_f=190$	quantity of fuel used per unit of work produced, g/kwh
M	weight of cargo, tons
N_c	annual number of cargo voyages
N_b	annual number of voyages in ballast
N_v	number of vessels
P_b	power required on voyages in ballast, kWh
P_c	power required on cargo voyages, kWh
$P_{l\&d}$	power required for loading and discharging, kWh
$P_{s\&w}$	power required in slow zones and when waiting, kWh
T_b	time used per ballast voyage, (days, hours, minutes)
T_c	time used per cargo voyage, (days, hours, minutes)
$T_{l\&d}$	time per voyage for loading and discharging, (days, hours, minutes)
$T_{s\&w}$	time per voyage in slow zones and waiting, (days, hours, minutes)
v_b	vessel speed on ballast legs(1 knot=1852 m/h), knots
v_s	vessel speed on cargo legs (1 knot=1852 m/h), knots

References

Corbet, J.J., Wang, H., Winebrake, J.J., 2009. The effectiveness and cost of speed reductions on emissions from international shipping. Transportation Research D 14, 593–598.

Cullinane, K., Khanna, M., 2000. Economies of scale in large containerships: optimal size and geographical implications. Journal of Transport Geography 8 (3), 181–195.

Christiansen, M., Fagerholt, K., Ronen, D., Nygren, B., 2007. Maritime transportation. In: Barnard, C., Laporte, G. (Eds.), Handbook in Operations Research and Management Science. Elsevier.

DNV, 2010. Pathways to low carbon shipping, Abatement potential towards 2030, 〈www.dnv.com〉.

Endresen, O., 2007. A historical reconstruction of ships' fuel consumption and emissions. Journal of Geophysical Research—Atmospheres 112 (D12).

Eyring, V., Isaksen, I.S.A., Berntsen, T., Collins, W.J., Corbett, J.J., Endresen, Ø., Grainger, R.G., Moldanova, J., Schlager, H., Stevenson, D.S., 2009. Transport impacts on atmosphere and climate: shipping. Atmospheric Environment, 1–37.

Faber, J., Marowska, A., Nelissen, D., Davidson, M., Eyring, V., Cionni, I., Selstad, E., Kågeson, P., Lee, D., Buhaug, Ø., Lindstad, H., Roche, P., Humpries, E., Graichen, J., Cames, M., 2009. Technical Support for European Action to Reducing Greenhouse Gas Emissions from International Transport. Oude Delft 180, 2611 HH Delft, The Netherlands.

IPCC, 2007. IPCC, Contribution of Working Groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change., IPCC, Geneva.

Lindstad, H., Asbjørnslett, B.E., Strømman, A.H., 2011. Reductions in greenhouse gas emissions and cost by shipping at lower speed. Energy Policy 39, 3,456–3464.

Lindstad, H., Asbjørnslett, B.E., Pedersen, J.T., 2012. Green Maritime Logistics and Sustainability. In: Song. D.W., Panayides, P.M. (Eds.), Maritime Logistics: Contemporary Issues, Emerald 2012, isbn: 978-1-78052-340-8, pp. 227–243.

Longva, T., Eide, M.S., Skjong, R., 2010. A cost-benefit approach for determining a required CO_2 Index level for future ship design. Maritime Policy and Management 37 (2), 129–143.

Notteboom, T.E., Vernimmen, B., 2009. The effect of high fuel costs on liner service configuration in container shipping. Journal of Transport Geography 17, 325–337.

Ocean Policy Research Foundation, 2008. The World's Changing Maritime Industry and a Vision for Japan. Ocean Policy Research Foundation.

OECD, 2010. OECD Globalization, Transport and the Environment, 2010, ISBN: 978-92-64-07290-9.

MEPC.60/4/33; MEPC.62/6/19; MEPC/62/6/19; MEPC.63/INF.2; Resolution MEPC.203 (62); 〈www.imo.org/KnowledgeCentre/InformationResourcesOnCurrentTopics/AirPollutionandGreenhouseGasEmissionsfromInternationalShippping/Pages/default.aspx〉.

Oil and Gas Journal, 2008. Qatar Gas Transport Co. will operate the first of a new class of super-large LNG vessels, the "Q-Max", having the capacity to carry 266,000 cu m of LNG, almost 80% more cargo than conventional LNG ships. 2008-07-16.

Russell, B.A., Wang, H., Zeinali, M., 2010. Marginal Abatement Costs of CO_2 Emissions Reduction and Market-Based Mechanisms and the Pricing of Credits. 〈www.corporateclimate.net/green-transportation-climate/logistics-supply-chain/74-cost-for-a-ship-to-reduce-co2-emissions-or-increase-efficiency.html〉.

Sea at Risk and CE Delft, 2010. Sea at Risk and CE Delft 2010 http://www.seas-at-risk.org/.

Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W.-Q., Yoshida, K., 2009. Second IMO GHG study 2009; International Maritime Organization (IMO) London, UK, April 2009.

4.5 Paper 5:

Comparing the cost and emissions of maritime and air transport

Comparing the cost and emissions of maritime and air transport

*Haakon Lindstad[1, 2] Anders H. Strømman [1]
[1]Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[2]Norwegian Marine Technology Research Institute (MARINTEK), Trondheim, Norway
E-mail: Haakon.Lindstad@ntnu.no, Tel: +47 92801521

ABSTRACT

This paper presents a combined assessment of the costs and emissions of freight transport including both ocean - going vessels and aircraft. The main motivation for the study has been the environmental consequences of the ever-increasing globalization of trade and transport. Current total transport emissions, now accounts for more than 20% of global anthropogenic greenhouse gas emissions (IEA, 2010). While road and rail are important for national and regional trade, more than 80% of international trade tonnage is performed by ocean - going vessels, while aviation is responsible for more than 50% measured in value. To date, discussion on transport emission reductions at the international level has focused on separate reduction measures for sea and air transport, neglecting the fact that they partly compete for the same cargo and passengers. Our model has been developed to enable comparisons of potential emission reductions to be made, focusing on the maritime and air-freight sectors separately and on scenarios involving reductions in total transport emissions and costs. The results show that emission reductions are maximized when the focus is on reducing total transport emissions.

Keywords: Transport; Greenhouse gas emissions; Comparative analysis

1. **Introduction**

International transport volumes are continuously increasing. While reaping the apparent benefits of globalization, the emissions stemming from the resulting sea and air transport are causing increasing concern. Products are increasingly being manufactured in one part of the world, transported to other countries and then redistributed to their final country of consumption. Since 1990, total transport emissions have grown faster than total emissions, and transport emissions now account for more than 20% of global anthropogenic greenhouse gas (GHG) emissions (IEA, 2010). While road and rail are important for national and regional trade, more than 80% of international trade measured in tons (all tons are metric) is performed by ocean-going vessels. And while the total tonnage transported by aircraft is small in comparison to ocean going tonnages, the value of the goods transported add up to a significant proportion of world trade.

Comparing greenhouse gas emissions, marine transport accounts for 3.3% of CO_2 emissions according to the *Second IMO GHG study 2009* (Buhaug et al., 2009) while aviation is responsible for 2.1% of the total (IATA, 2011). These emissions are expected to increase as a result of continued globalization, with growing trading and more passenger transport under “business as usual” scenarios (Buhaug et al., 2009; Lee et al., 2009; Sgouridis et al., 2011) , while fulfilling anticipated climate requirements might require significant reductions either within the sectors or through measures extending beyond them.

To date, discussion on transport emission reductions at the international level has focused on separate reduction measures for sea transport and air transport, neglecting the fact that they partly compete for the same cargo and passengers (i.e. partially in the same market). Examples of such cargo types are fast-moving consumer goods such as electronics, fashion products, sports gear, spare parts, tools, machines, expensive cars, perishable goods, but also missing items required to complete an order in manufacturing industry. And between the pure air transport or sea transport options, we find what is termed “Air & Sea”, whereby goods are transported first by sea and then by air or vice versa. A typical example of Air & Sea transport goes from Asia to the Middle East by sea transport and then by air transport to Europe. By combining these modes, the user gets freight that is faster than by sea transport alone but cheaper than by airfreight only. And for the passenger part, an example of the competition is domestic transport in Greece between major islands and the capital Athens, where the customers can choose between air transport, fast ferries and ordinary ferries. Given this integrated and partially overlapping market situation, it seems meaningful to assess and develop joint mitigation scenarios and policies.

An example of the current debate is the discussion of the International Maritime Organization (IMO) concerning speed reductions for all vessels and the potential emission reductions which can be achieved, without taking into account the possibility that longer sea transport times might increase air freight transport and hence emissions. The background for the discussion is that ships have typically been built to operate at a specific design speed: for large bulk vessels this speed is around 25 km/h (14 knots), while large container vessels have service speeds of up to 50 km/h (26 knots). The key insight is quite straightforward: the power output required for propulsion is a function of the speed to the power of three. This simply implies that when a ship reduces its speed, its fuel consumption is reduced. For this reason several authors have investigated the relationship between speed reduction and emission reductions (Corbett el al., 2009; Sea at Risk and CE Delft 2010; Psaraftis and Kontovas, 2010; Lindstad et al., 2011).

For aviation, the International Civil Aviation Organization (ICAO) has focused on quantifying the impact of aviation on the environment and on reducing its impact through technical, operational and market-based measures. While IMO has set no metric targets for reductions, ICAO (2010) has quantified a 2% annual fuel efficiency improvement until 2050 and suggested that total emissions should be stabilized from 2020 at their 2020 level. This based on continuous growth in traffic.

Most studies regarding emission reductions in the transport sector have focussed on reductions which can be achieved within one transport mode, such as aviation (Capoccitti et al., 2009) or sea transport (DNV, 2010), assessing it separately from the rest of the transport market. However, there are some exceptions; Hjelde (2011) compares the environmental performance of short-sea shipping and road haulage, while

Psaraftis and Kontovas (2010) compared sea and rail transport for fast-moving consumer goods between Asia and Europe. The advantage of including more than one transport mode, in the analysis, is that sub-optimal measures, where the reduction achieved by one mode is less than the increase in another mode can be identified. Ideally, such comparisons should be extended to include total emissions, from sourcing of raw materials and manufacturing in addition to the transport itself (Duchin, 2005; Strømman and Duchin, 2006; Strømman et al, 2008). Going down that path would involve substantial relocation of industries between countries and between regions based on powerful measures rewarding climate change mitigation agreed by United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations (UN). Although that may yet happen, for the time being, it would appear to be more feasible to persuade IMO and ICAO to debate measures not only within their own transport mode but instead focusing on reducing total emissions from air and sea transport.

The main objective of this paper is to contribute to development of joint mitigation strategies for air and sea freight. This is done based on analysis of two of the major international trades. We focus on the cargo segments that currently are transported by both modes. This enables us to assess potential issues associated with shifts of cargo volumes from sea going vessels to air following speed reductions in sea transport, and therefore to identify avoidable sub-optimal solutions in the maritime sector. To this end, we develop specific cost and emission models for both transport modes. The model is described in Section 1, its application and the underlying data are presented in Section 2, and the results are discussed in the final section with respect to their implications for policy design.

2. Description of model

The main objective of our model is to calculate emissions and costs for sea-freight and air-freight as a function of their characteristics and the cargoes they transport. This allows for the assessment of integrated scenarios in which the focus is on reducing total sea- and air- freight emissions and costs. The model comprises four main equations. The first (1) calculates the annual operational profile for the cargo carriers (ocean - going vessels or air-freighters). The second (2) calculates annual fuel consumption. The third (3) calculates the amount of CO_2 emitted per freight unit distance. The fourth (4) calculates cost per freight unit distance. In the description of the model, we have simplified the terminology by using voyage as the common term for flights and sea voyages, repositioning as a common term for repositioning and ballast voyages, ports as a common term for airports and ports, and cargo carrier as a common term for aircraft and ocean-going vessels.

The annual operational profile of a cargo carrier comprises days on cargo voyages, days on repositioning voyages and idle days as expressed by equation (1):

$$T = \sum_{i=1}^{N_c}\left(\frac{D_i^c}{v} + T_i^{l\&d} + T_i^w\right) + \sum_{i=1}^{N_b}\left(\frac{D_i^b}{v} + T_i^w\right) \quad (1)$$

Where, the first term on the right hand side of the equation gives the annual number of days used on cargo voyages, and where D_i^c is distance per voyage, v is speed per voyage, $T_i^{l\&d}$is time used for loading and discharging cargo per voyage, T_i^w is waiting time and N_c is annual number of cargo voyages. The second term gives the annual number of days used on repositioning voyages, whereD_i^b is distance per voyage, v is speed, $T_i^w$is waiting time and N_b is annual number of repositioning voyages.

Annual fuel consumption F comprises fuel used on cargo voyages F_c and fuel used on repositioning voyages F_b, and is given by equation (2):

$$\begin{aligned} F = F_c + F_b = & \sum_{i=1}^{N_c}\left(K_f \cdot \left(\frac{P_i^{Mt \cdot v} \cdot D_i^c}{v}\right) + F_i^{l\&d} + F_i^w\right) \\ & + \sum_{i=1}^{N_b}\left(K_f \cdot \left(\frac{P_i^{Mt \cdot v} \cdot D_i^b}{v}\right) + F_i^w\right) \quad (2) \end{aligned}$$

Here the first term gives annual fuel consumption for cargo-carrying voyages and the second term gives annual fuel consumption for the repositioning voyages, where N_c represents the number of cargo voyages, N_b the number of ballast voyages, K_f the amount of fuel in grams per produced kWh, $P_{M_t \cdot v}$ is the power required as a function of speed v and the total cargo carried M_t, including the fuel required, the empty weight of cargo containment units on board the cargo carrier and any other additional weight such as ballast water. D is the distance. $F_{l\&d}$ is the fuel used during loading and discharging and F_w fuel consumption while waiting.

The annual amount of CO_2 emitted per ton kilometer or cubic meter kilometer ε by the cargo carrier is calculated using equation 3 (Buhaug et al., 2009):

$$\varepsilon = \frac{F}{\sum_{i=1}^{N_c}(D_i^c \cdot M_i)} \cdot K_e \quad (3)$$

where F is annual fuel usage in tons, N_c is number of cargo voyages, K_e is the emitted CO_2 per unit of fuel burnt, D_i^c is distance per cargo voyage, M_i is the amount of paying cargo transported on a voyage which excludes the fuel used, cargo containment units and any ballast water. The cost per cubic meter kilometer (m^3km) or ton kilometer (ton km), comprises the cost of fuel, the daily financial and operational costs of the cargo carrier, airport or port fees, airspace or fairway fees and cargo handling, as expressed by equation (4):

$$\mathrm{C}_{D\cdot M}=\frac{1}{\sum_{i=1}^{N_c}D_i^c\cdot M_i}\cdot\left((F\cdot C_{Fuel})+TC\cdot T+\sum_{i=1}^{N_c}C_i^{hpf}+\sum_{i=1}^{N_b}C_i^{pf}\right)\quad(4)$$

The first factor, transforms the cost from an annual cost to a cost per freight unit distance. Inside the main bracket, the cost of fuel is calculated by multiplying the annual quantity of fuel F burned as calculated by equation (2) by the cost of fuel C_{Fuel}. TC is the daily operational and financial costs of the cargo carrier and T is days per year or total days if the cargo carrier has been in service for less than a year. The two last terms summarise handling, port and voyage fees C_i^{hpf} for the cargo voyages and the port and voyage fees C_i^{pf} for the repositioning voyages.

To summarise, combining equations 1, 2, and 3 enables us to describe the greenhouse gas emissions associated with a specific operational mode, while equation 4 provides the costs.

3. Application and analysis

The primary objective of this analysis is to assess the total emissions and costs of different scenarios for combination of sea and air transport on two major international trades. The ocean-going vessels and aircraft included in this study are transporting fast-moving consumer goods such as electronics, fashion products, sports gear, spare parts, tools, expensive machines and perishable goods between the main regions and continents of the world. Where sea transport is concerned, this usually means container vessels with a dead weight (dwt) of 25 000 tons and upward. Where the dead weight measured in ton express how much weight a ship can carry at most including fuel and supplies. And for aircraft it tends to mean wide-body aircraft such as the Boeing 747 or Airbus 380. Comparing air and sea transport requires cost and operational figures for trades in which real competition exists. For this purpose we have chosen to compare air and sea transport between Asia and Europe and Asia and North America, which accounts for more than 50% of all international air freight transport tonnage (Kupfer et al., 2011), while similar sea figures can be found for these trades of importance for container shipping lines. When comparing air and sea, the sea route distance between origin and destination will in general be longer than the air route. To give some examples; Shanghai – Seattle is 9200 km by air and 9400 km by sea, while Shanghai – New York is 11900 km by air and 19600 km by sea, Shanghai- Amsterdam is 8900 km by air and 19600 km by sea, Tokyo – Amsterdam is 9300 km by air and 21000 km by sea and Tokyo – St. Petersburg is 7600 km by air and 23000 km by sea. As these examples show, the ratios of air and sea distances for these trades goes from as little as 1:1 directly across the Pacific to as much as 1:3 for trades from North-east Asia to North-east Europe. The average ratio is not far from 1:2, which is in line with our estimated world average calculated based on trade patterns according to (Kupfer et al, 2011) and IATA (2011). In this study we have therefore chosen to compare air and sea freight for two cases. In both cases the distance by air is 10 000 km, while by sea it is 20 000 km in the first case and 10 000 km in the second. The first case thus represents the average of the trades in which sea and air compete while the second illustrates the situation for trades in which the distance is almost the same, such as certain cross-Pacific trades between Asia and West coast of North America.

3.1. Data-set used for air-freight

The data-sets used are based on the World Air Transport Statistics for 2010 published by IATA (2011), airfreight trade data from Kupfer et al. (2011), the 2010 cost and operational figures of CargoLux (www.cargolux.com), which is a fully specialized air freight company, and finally, operational and technical specifications of Boeing's 747 freighters (www.boeing.com).

IATA, the International Air Transport Association, is responsible for collecting the operational figures of all airlines in the world (including the airlines which are not members of IATA). In 2010 the world's airlines transported 2.3 billion passengers, who flew an average of 2000 km per trip and a freight amount which came to 180 billion ton km. Half of this freight was transported in the belly of passenger planes and the other half by pure freight aircrafts. Calculating emissions for pure passenger planes or pure freighter requires no allocation rules. However, since half of the freight goes in a combination with passenger, the IATA standard is to use a weight of 100kg for the weight of the passengers and their luggage, and the metric weight of the freight. With this weight-based approach, a relatively large share of the total emissions is allocated to the freight and the totals reported per ton km of freight is 1 200 g $CO_{2,}$ while the emissions per passenger kilometer is 120 g CO_2. Howit et al. (2011) discuss allocation principles between freight and passengers when airfreight is carried in the belly of passenger aircrafts instead of designated air freighters. They debate different allocation principles and that a certain amount of mass should be added to passenger facilities to account for passenger facilities on board such as seat and galleys (50 + 200kg), however they decide against it. Lindstad and Pedersen (2009) have discussed principles for the allocation of emissions on RoPax vessels which are built to transport passengers, their cars and freight on trailers between areas divided by sea such as in the Baltic, the North Sea and the Mediterranean. They have suggested that the benchmark could be what the emissions would have been with alternative solutions such as passenger air transport and pure sea cargo vessels.

Since half of all air freight goes by pure freighters we follow that path by calculating emissions for a pure air-freight operation. Within this segment we find major companies like DHL and FedEx, but since these operate in all transport modes, we decided to use CargoLux as the benchmark. In 2010 CargoLux operated a fleet of 14 standardized Boeing 747-Freigheters. Table 1 displays the main cost and operational figures of CargoLux and an emission per ton km of 517 g of CO_2, which is less than half of the IATA average freight emission figure of 1200 g of CO_2. It should be noted that the table is constructed based on available information and that it is not a reprint of any tables made by IATA or CargoLux.

Table 1: Key CargoLux figures (source: IATA and CargoLux)

Daily key figures CargoLux		
Ton km produced per day	km/day	14 500 000
Fixed and operational costs of fleet	USD/day	1 800 000
Airport & flying fees	USD/day	700 000
Fuel cost (average price paid 750 USD/ton)	USD/day	1 800 000
Fuel consumption	ton/day	2 400
Cost per ton of fuel	USD/ton	1 000
Flight hours per plane per day	Hours	16
Number of planes		14
Average figures per flight CargoLux		
Ton cargo per flight	ton	47
Cubic meters per flight	m^3	527
Cubic meter capacity per flight	m^3	720
Specific gravity	kg/m^3	90
Capacity utilization (based on cubic meters)	%	73%
CO_2 emissions per ton km	g/ton*km	517
CO_2 emissions per m^3 km	g/m^3*km	47

These results indicates either that it is much more energy-efficient to move freight by pure freighters or that the principles whereby emissions are allocated to passengers and freight on combined carriers should be changed. Changing the allocation principles would mean ascribing a larger share of fuel consumption to the passengers, which could be done through changing the allocation principles from being ton-based to volume-based. For passengers the number of passengers is usually given by the volume they occupy in the passenger section, while the cargo is usually reckoned in terms of volume, with an average weight/volume relationship of around 100 kg per m^3. This is also illustrated by the fact that the newest version of the Boeing 747-freighter, the 747-8F, which has a capacity of 857 m^3 can carry a maximum cargo load of 115 tons with a flying distance of 10 000 km. This equals an average weight per cubic meter of 135 kg (0.135 in density per volume unit) when both the volume and the weight capacity are fully utilized. If the non-stop flying distance is raised to 14 000 km, the maximum cargo load drops to 75 tons, since the plane has to carry more fuel when the flight distance is increased and the cargo capacity is correspondingly reduce. The volume capacity can still be fully utilized if the average cargo weight per cubic meter drops to 90 kg or less. The opposite is the case if the flight distance is reduced to 8 000 km or less, as the weight of cargo can be raised to 134 tons, with an average weight per cubic meter of 155 kg. Light cargo weights tend to be favoured by operators, since the fuel consumption per unit distance is a function of the take-off weight, where a 5% reduction in take-off weight gives a 5% reduction in fuel consumption for the whole voyage (Anderson, 2012). Furthermore, lighter cargo weights tend to cause less wear and tear on the aircraft and hence lower maintenance costs.

Regarding emissions and the costs of the flight itself, including airport handling and flying fees, the results for five representative loading conditions as a function of flight distance are presented in Figure 1, which is made up of two parts with a common vertical axis that represents the flight distance. In the figure the horizontal axis on the right-hand side represents costs as a function of flight distance, and emissions as a function of flight distance on the left hand side. The fuel consumptions in these calculations are based on Boeing's technical specifications and the theoretical framework and formulae's provided by Anderson (2012). For the cost elements we have used an hourly cost of 4 000 USD per hour, covering all costs related to the aircraft and to running the airfreight company, a jet fuel cost of 1 000 USD per ton and 25 000 USD per flight in flight and airport fees. The cost per flight is a function of flight time and fuel used based on an average flight speed of 850 km per hour, plus loading and discharge time per flight, for which we have assumed five hours, and flight and airport fees. The first loading conditions that we investigated relate to fully utilizing the volume capacity of 857 m^3 and the weight capacity of 115 ton for a distance of 10 000 km, the average flying distance for intercontinental operations between Asia and Europe and Asia and North America.

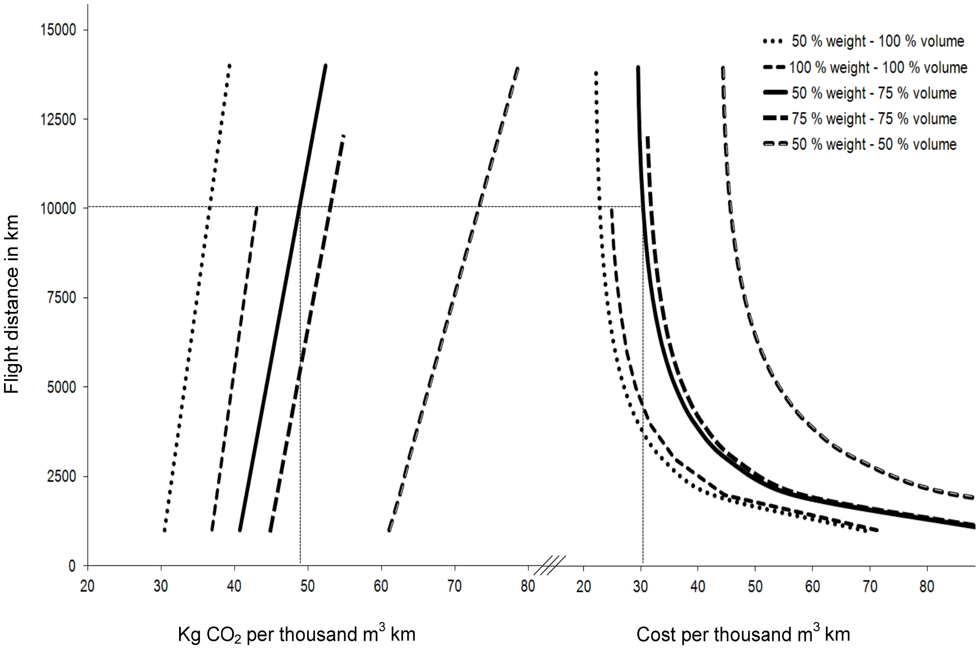

Figure 1: Air freight emissions and cost as a function of flying distance

A general observation which can be made from the figure is that fuel consumption and hence emissions increase with flying distance under all loading conditions. This is because when the flight distance increases, the plane needs to carry more fuel, which increases its take-off weight and hence the fuel consumption for the whole trip. For example, with 115 tons of cargo on board, the fuel consumption is 54 tons for a flying distance of 5 000 km, which gives an average consumption of 10.8 ton per 1 000 km. This is based on a take-off weight of 376 tons, a landing weight of 322 tons and an average flight weight of 349 tons. When the distance is raised to 10 000 km with a cargo weight of 115 tons the fuel consumption increases to 118 tons, i.e. an average consumption of 11.8 tons per 1 000 km. This is based on a take-off weight of 440 tons, a landing weight of 322 tons and an average flight weight of 381 tons. Another general observation is that under all loading conditions the cost per 1000 km is reduced when the distance increases.

With a distance of 10 000 km, the emissions per thousand cubic meter ranges from 37 kg in the case where 100% of the volume and 50% of the weight is utilized, 43 kg when 100% of volume and weight is utilized, 49 kg when 75% of the volume and 50% of weight is utilized, 53 kg when 75% of the volume and 75% of the weight is utilized and 74 kg when only 50% of the volume and 50% of the weight are utilized. These figures are similar to the average 2010 CargoLux figure of 47 kg per thousand cubic meters. For cost the values range from 23 to 46 USD per thousand cubic meters. If we exclude the alternative with 50% weight and volume utilization, since it is not economically sustainable, all the other loading conditions generate emissions of around 50 kg or less per thousand cubic meters at a cost of around 30 USD per thousand cubic meters. In order to retain traceability and ensure that the emission and cost values are not underestimated in the comparison with sea freight, we used the emissions and cost values for the loading condition that utilized 50% of the weight and 75% volume, i.e. 49 kg CO_2 per thousand cubic meters at a transport and handling cost of 30 USD per thousand cubic meters.

3.2 Data-set used for sea–freight

The general information about the world fleet is based on the vessel database and movement data published by IHS Solutions (2007, 2011), while specific data about new ultra-large container vessels are based on information provided by Maersk (www.maersk.com), which is the world's largest container line. All cost, emission and operational data are based on previous work by Lindstad and Mørkve (2009), Lindstad et al. (2011), Lindstad et al. (2012).

While aircraft operate at speeds of 800 - 850 kilometer per hour (km/h), vessel speeds depend on vessel type and size, where typical carriers of wet and dry bulk products operate at speeds of around 25 km/h while the fastest container vessels and RoRo and RoPax vessels have service speeds of up to 50 km/h. Although all of these fast vessel types compete with aircraft for freight transport, container vessels dominate this market for intercontinental transport. Container vessels are built to transport containers filled with a wide range of products and commodities, from high- and medium-value products for which they compete with the air-freighters, to low-value products such as newsprint, grain, rice and even scrap metal and waste paper. Although containers look quite standardized, there are different sizes and types, and as a result all containers are calculated as multiples of the standardized twenty-foot unit (TEU). In intercontinental trades, aircraft compete with container vessels with a capacity of 4000 TEU and above. The average vessel size in these trades has been increasing every year and Maersk is working on a project to start using 18 000 TEU vessels of more than 200 000 deadweight tonnage (dwt.) within the next few years where the deadweight tonnage is the measure of the maximum weight these vessels can carry. Apart from the increase in size, the main differences compared to current vessels are that the maximum speed will be slightly reduced, and that they will be optimized to sail most of their voyages at lower speeds than existing vessels. Since the required power for propulsion is a function of the speed to the third power, the motivation for reducing speed is to reduce fuel consumption, which also offers the environmental benefit of reduced emissions. Another alternative to the current concept could be that certain segments of the container fleet might sail even faster, to satisfy the requirements of cargo owners who wish to reduce transport time. Sailing faster would increase emissions and costs, but reduce lead times, and hence make sea transport more competitive with airfreight.

This study examines three different vessel concepts; 1 - The current fleet, represented by a 6500 TEU 80 000 dwt. vessel built for a service speed of 46 km/h (25 knots), 2 - A fast 6500 TEU vessel built for a service speed of 56 km/h (30 knots), 3 - An 18 000 TEU vessel built according to Maersk's specification and designed to operate in the speed range of 20 – 42 km/h (11 – 23 knots). The 6500 TEU vessel is the same container vessel as described by Lindstad et al. (2011), where the methodology and model for calculation of the required power as a function of cargo carried and vessel speed is described in detail. The main characteristics of the vessels are the following: 6500 TEU existing vessel, 80 000 dwt., Capex 88 million USD, TC/day=30 000 USD, main engine 60 000 kW and service speed of 46 km/h (25 knots). 6 500 TEU – fast vessel, 80 000 dwt., Capex 100 million USD, TC/day= 33 000 USD, main engine 110 000 kW and service speed of 56 km/h (30 knots). 18 000 TEU vessel, 216 000 dwt., Capex 190 million USD, TC/day=60 000 USD, main engine 110 000 kW built for service speeds of 20 – 42 km/h (11-23 knots). Both 6500 TEU vessels can obviously operate at lower speeds than 56 km/h or 46 km/h. For terminal handling, port fees, fairway and canal dues we use 600 USD per TEU per voyage.

For utilization figures and the relationship between volume capacity and weight, two loading conditions are of particular interest; the design condition based on fully utilizing the capacities, and the standard business operation. When fully loaded, the 6500 TEU vessel can carry 60 000 tons of cargo after we have subtracted the fuel (7000 tons) and the tare weight of the containers (13 000 tons) from the deadweight of 80 000 ton. Similarly, the available volume will be around 160 000 m^3, based on utilizing 80 – 85% of the volume per container unit, which is the maximum useful volume when we bear in mind that neither box sizes or pallets are optimized to fully utilize the container volume. This gives a relationship between volume and weight of 2.7 m^3 per 1 000kg and an average weight per cubic meter of 370 kg when both the volume and the weight capacity are fully utilized. The other loading condition of special interest is the empirical one for container business based on imbalances in trades, where the typical picture is that three out of ten containers are empty ones for repositioning. Based on 95% utilization of the TEU positions that gives an available volume of 110 000 m^3 and a maximum cargo weight of nearly 60 000 tons and a potential average cargo weight of nearly 550 kg per m^3 when both the volume and the weight are fully utilized. In reality, however, the average cargo which the container lines transports is not so heavy, and may be even less than the 370 kg per m^3 assumed by the design condition. While airfreight fully benefits from carrying lighter cargo, this only offers partial benefits for container vessels, since reductions in weight have to be partly compensated with ballast water to keep the propeller in the water and the center of gravity low, in order to ensure efficient propulsion and sea-worthiness. Based on 110 000 m^3, and an average weight of around 370 kg per m^3 that adds up to 40 000 tons of cargo. That implies 50% utilization of the weight capacity and 65% utilization of the volume, values which are quite close to the container line averages. We therefore use these as the average values for sea transport in the comparison.

The results of the comparisons of emissions and costs of the sea voyage for three different vessels are presented in Figure 2. The figure excludes fairway fees, port fees and terminal handling since they are a function of the whole voyage and not related to the distance, but they will be included in the comparison between air and sea transport. The figure contains two parts with a common vertical axis. The vertical axis represents the cost of transport per thousand cubic kilometers as a function of vessel speed on the right-hand side of the figure, and as a function of emissions on the left-hand side. Plotting the results in this way enabled us to obtain the reduction in emissions as a function of the lower speed. The graphs to the right demonstrate minimum cost for a speed which is lower than the design speed.

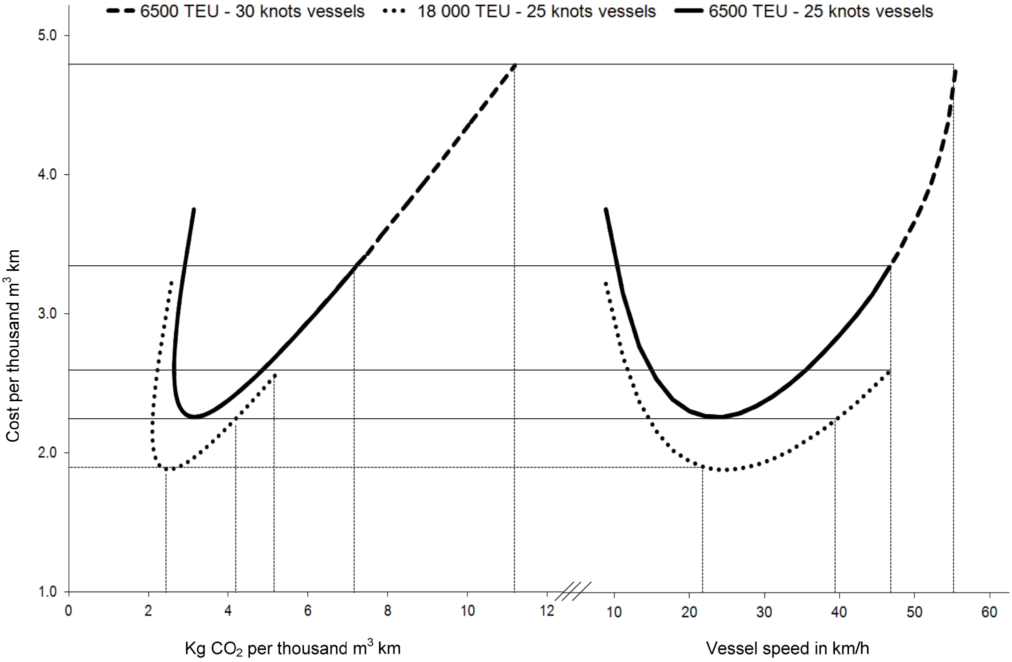

Figure 2: Sea transport emissions and costs as functions of vessel speed

One general observation is that the lowest emissions are achieved at vessel speeds in the range of 15 –18 km/h (8 – 10 knots) while the lowest costs are associated with vessel speeds around 22 – 25 km/h (12-14 knots). But since the reductions in emissions when speed is reduced below 22 km/h (12 knots) are marginal, we use this as the lowest speed in the comparison between sea and air transport in addition to the performance at 39 km/h (21 knots), 46 km/h (25 knots) and 56 km/h (30 knots).

3.3 Combined scenarios

The motivation for comparing air and sea container transport is that they partly compete for the same cargoes. We also even find solutions where the main intercontinental transport leg is divided into a sea leg followed by an airfreight leg, for example, sea transport from Asia to a port in the Middle East and then air freight to Europe. This gives a total transport time door to door of three weeks from Asia to Europe, compared to less than a week for airfreight alone and four to five weeks or more for transport solely by sea. Put simply, the choice of airfreight, sea freight or a combination of the two modes boils down to cost and profit assessments. This means that high-value products generally go as airfreight since the financial cost of carrying excess stocks due to longer transport times is larger than the additional transport cost. At the other end, it never pays to use airfreight for low-value goods even with very long transport times, except in an emergency. Product shelf life is another reason for using airfreight, not only for perishable goods such as fresh fish, seafood and strawberries, but also for new electronic products and new sports gear where a price premium can be obtained by bringing products faster to market. In other cases, the decision to use airfreight is taken to avoid lost revenue due to potential stock-outs. It is too complex to fully model all these relationships, which would involve the price that premium customers would be willing to pay to maintain short lead times based on fast transport. Instead, we take a simplified approach, in which we first calculate the current market share of airfreight versus sea freight based on statistics and existing trade patterns. We then calculate the current differences in total transport time between air and sea-freight. Finally, we quantify how market share increases if sea transport becomes slower (reduced service speeds) and how it decreases if sea transport becomes faster (higher speeds)

We calculate the current market share of airfreight and container transport on the basis of the current volumes and freight work done by air freighters and container vessels. The data sets used for air transport are based on the World Air Transport Statistics for 2010 from IATA (2011) and airfreight trade data from Kupfer et al. (2011). The datasets used for sea transport are based on UNCTAD (2011), Buhaug et al. (2009), IHS solution (2007, 2011), Lindstad et al. (2011) and Lindstad et al. (2012). Two conversions must be made to enable statistical data and hence market share for air- and sea-freight to be compared. The first one is conversion of the freight work to m^3km based on the average weight per cubic meter for air freight and sea freight, based on our findings in the previous sections, since the statistics are based on weight. For airfreight this is based on an average weight of 90 kg/m^3, which means that 11 m^3 of airfreight cargo weighs 1000 kg. For sea freight this is based on an average weight of 370 kg/m^3, which means that 2.7 m^3 weighs 1000 kg. The second conversion involves adjusting for the fact that the distance by sea is usually twice the distance by air, by multiplying the sea freight work by 0.5 in order to obtain a comparable freight work value. Table 2 shows the main inputs and the conversion factors which in combination give airfreight a market share of 10% and sea freight a market share of 90%.

Table 2: Conversion factors and key figures for comparing air and sea freight

		Air freight	Sea freight	Total
Freight work	billion ton km	180	13 884	14 064
Conversion factor ton to m^3		11.0	2.7	
Freight volume work	Billion m^3 km	1 980	37 487	39 467
Conversion factor for distance		1	0.5	
Adjusted Freight volume work	Billion m^3 km	1 980	18 743	20 723
Market share		10%	90%	100%

The next step is to calculate the difference in total transport time between air and sea freight when the air transport leg is about 10 000 km and the sea transport distance is about 20 000 km, such as between Asia and Europe and between Asia and the East Coast of the USA. When these services are operated at the design speed of around 46 km/h, the total time for a one-way voyage will be around 28 days, which in addition to the pure sailing time on the open sea includes reduced speed through canals and when entering and leaving ports, loading and discharging containers and waiting for canal passage, tides, and so on. For air transport it will be around two days, which includes the flight time of 12 hours plus five hours for loading and discharging, preparing the cargo for loading and waiting for the aircraft. For both sea and air modes, the collection and distribution of cargo mean additional time; however, if we assume that time to be equal for both options, the difference in transport time becomes 28 – 2 = 26 days. These 26 days of difference in transport time are then used as input to quantify how market share increases if sea transport becomes slower and decreases if sea transport becomes faster. The slow alternative is here based on replacing 6 500 TEU vessels with a service speed of 46 km/h with ultra-large 18 000 TEU vessels with a speed of 39 km/h, which will lengthen voyage time by seven days, due to longer sailing time and the longer time needed for loading and discharging. While the fast alternative is based on 6 500 TEU vessels sailing at 56 km/h and streamlined terminal operations, which reduces the difference from air freight by seven days from 26, making it 19 days. Regarding cost and cost differences, the airfreight cost is 30 USD per thousand m^3km for all alternatives. The sea transport costs, including port and fairway dues and cargo handling, add up to 7 USD per thousand m^3 km for the 18 000 TEU vessel with a speed of 39 km/h when we have adjusted for the fact that the sea distance is twice the air distance. The cost for the 6500 TEU, 46km/h version adds up to 9 USD per thousand m^3km and 12 USD per thousand m^3km for the 56 km/h version. This gives an added transport cost for air freight instead of sea freight in the range of 18 – 23 USD per thousand m^3 km, which gives 180 – 230 USD per m^3 between Asia and Europe or North America. This means that when the decision-makers decide to use air transport instead of sea transport, the cost savings on less stock in transit and transport, or lost contribution due to delayed or lost sales, is calculated or estimated to be more than 180

– 230 USD per thousand m^{3}km. Since both the cost of carrying stock and lost contribution are a function of the value of the goods, we use the study by Leachman (2008), in which he studied the declared value of imported container goods to US west coast. According to Leachman, 20% of the cargo has a value of more than 1 060 USD per m^3 (30 USD per cubic foot), 10% of the cargo has a value of more than 1 410 per m^3 (40 USD per cubic feet) and 4% has a value of more than 1 770 USD per m^3 (50 USD per cubic feet). Since the decision to use airfreight is taken either on the basis of cost or of lost or delayed contribution from sales, both of them can be expressed in cost terms as a function of product value, as shown in Figure 3.

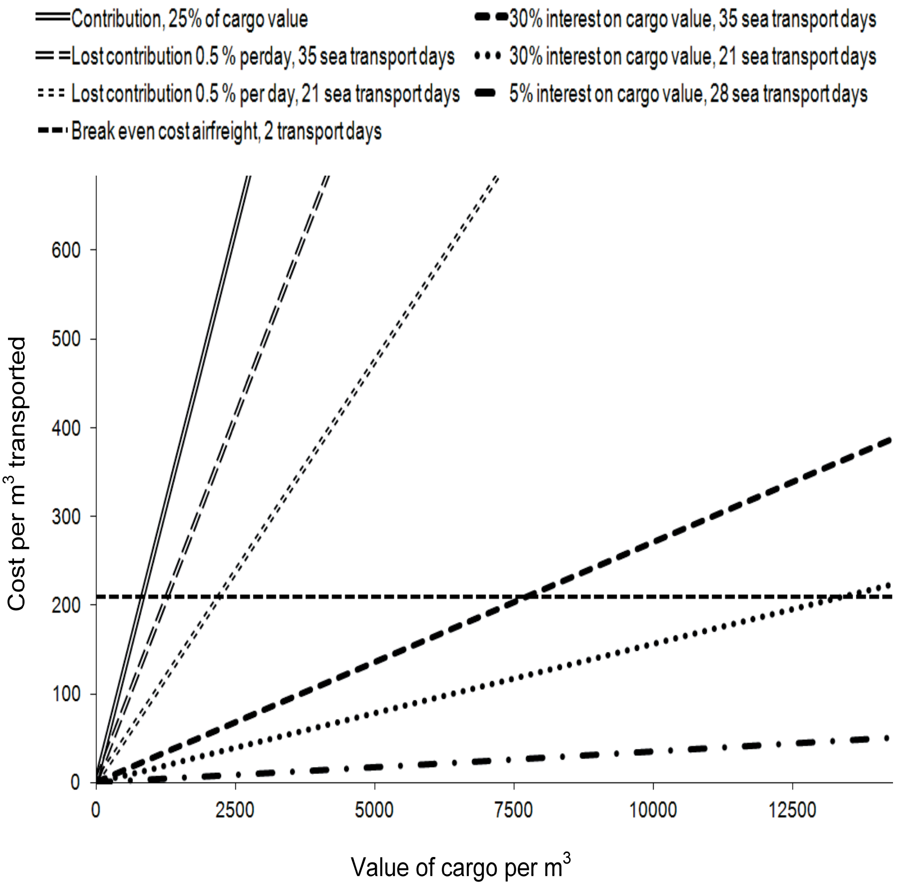

Figure 3: Decision criteria for choosing between air freight and sea freight

The main observations based on Figure 3 are that in all cases when the additional cost is less than 180 – 230 USD per m^3, sea freight is chosen, as is shown by the horizontal dashed line. This means that if the assessment is made on a purely cost basis, airfreight will never be an alternative if the interest cost of capital is as low as 5%; however, if the cost is as high as 30% it becomes competitive when the value of the goods exceeds 14 000 USD per m^3 for the fastest service and 8000 USD for the slowest service. If the assessment is made on the basis of contribution from sales, airfreight becomes competitive at product values as low as 1000 USD per m^3, which means that airfreight competes for at most 20% of the container volumes. From the figure we also see that the fast service has a cut-off point against airfreight at higher product values than the slow service, which means that slowing down all container vessels will contribute to a higher market share for air freight, and *vice versa*. To fully model these relationships would be a huge task; however we can conclude that the market share for airfreight is a function of both the difference in total transport time and the value of the goods transported. That conclusion is drawn on the basis of our data sets, in which we take 26 days as the reference point for a 10% market share where the market share will increase by 2% if the difference in transport time increases by seven days and decreases by 2% if the difference is reduced by seven days. If this line is followed down to a zero difference in transport time it does not cross zero, which is due to the fact that as the difference in transport times becomes smaller, airfreight is still used since customers are willing to pay a significant price premium even for marginal reductions in transport time.

As we described in the introduction, our model was developed to enable comparisons of potential emission reductions to be made that focus only on the maritime sector (sub-optimization), and of scenarios in which the focus is on reducing total sea- and air-freight emissions and costs (optimization). We therefore investigated five scenarios in addition to the current situation, of which the first three, i.e. scenario 1, 2 and 3 are typical examples of what currently is being discussed by the maritime community, motivated by the need to reduce maritime transport emissions. Regarding the current situation (Scenario 0), it should be noted that the current vessel average speed is below 25 knots due to overcapacity in the market and high fuel prices and low freight rates, but a common market assumption is that when the market recovers, the speed will increase again. Scenario 4 and 5 represent a more holistic approach that focuses on reducing total emissions from air and sea. The scenarios which have been considered are: scenario 0 (the current situation) with a 90% market share for container vessels, where 6500 TEU and 46 km/h are used as the base point reference; scenario 1 reducing the speeds of the current fleet to 39 km/h; scenario 2 replacing the 6500 TEU vessels with ultra-large 18 000 TEU vessels and maintaining the service speed at 46 km/h; scenario 3 reducing the speed of the 18 000 TEU vessels to 39 km/h; scenario 4 using the 6500 TEU vessels to transport 20% of the containers that have an average value of 1000 USD per m^3 and above and carrying the other 80% of the cargo at the very low speed of 22 km/h with the 18 000 TEU vessels; scenario 5 using 6500 TEU vessels operating at both 46 and 56m/h in addition to the 18 000 TEU operating at 22 km/h. The scenarios are tested on two cases. The first is based on that the sea distance is twice the air-distance and the relationship between difference in transport time and market share of airfreight, as shown in Table 3. In the second case we have assumed equal distances as for pure cross-Pacific trades and that the market share for air freight is constant and not a function of difference in transport time, as shown in Table 4. The shorter sea transport distance then involved reduces the difference in transport times between air and sea from 26 days to 15.5 days, which gives a market share of 7% for air freight based on the modeling assumption for the market share of air freight.

Table 3: Potential cost and emission reduction for average relationship between sea and air distance

	Speed	Carriers	Distance in km	Freight time in days	CO_2 emitted per distance unit	CO_2 per thousand m^3 km distance adjusted	Freight volume in % of total	Freight work distance adjusted	Annual CO_2 emissions in million	Total annual CO_2 emissions	Emission Reduction in %	Cost per thousand m^3 km	Cost per thousand m^3 km distance adjusted	Annual cost in billion USD	Total cost in billion USD per year	Cost Reduction in %
Unit	km/h		km	days	g/m^3km	g/m^3km	%	million m^3 km	million tons	million tons	%	USD/m^3 km		billion USD	billion USD	%
Current situation																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	10%	2 072	102			30.0	30.0	62		
Container	46	6500 TEU	20 000	28.0	7.1	14.2	90%	18 651	265	366		3.3	9.0	168	230	
Lower speeds - 1																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	11%	2 280	112			30.0	30.0	68		
Container	39	6500 TEU	20 000	31.5	5.7	11.4	89%	18 443	210	322	12%	2.8	8.0	148	216	6%
Economy of scale - 2																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	11%	2 280	112			30.0	30.0	68		
Container	46	18 000 TEU	20 000	31.5	5.2	10.4	89%	18 443	192	304	17%	2.5	7.4	136	205	11%
Lower speeds&Economy of scale - 3																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	12%	2 487	122			30.0	30.0	75		
Container	39	18 000 TEU	20 000	35.0	4.2	8.4	88%	18 236	153	275	25%	2.2	6.8	124	199	14%
Differentiated speeds&Economy of scale - 4																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	10%	2 072	102			30.0	30.0	62		
Container	46	6500 TEU	20 000	28.0	7.1	14.2	20%	4 145	59			3.3	9.0	37		
Container	22	18 000 TEU	20 000	52.5	2.3	4.6	70%	14 506	67	227	38%	1.9	6.2	90	189	18%
Higher speeds&Economy of scale - 5																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	8%	1 658	81			30.0	30.0	50		
Container	56	6500 TEU	20 000	21.0	11.0	22.0	22%	4 559	100			4.7	11.8	54		
Container	22	18 000 TEU	20 000	52.0	2.3	4.6	70%	14 506	67	248	32%	1.9	6.2	90	193	16%

Table 4: Potential cost and emission reduction when sea and air distance are equal

	Speed	Freight Carrier	Distance	Freight time	CO_2 emitted per distance unit	CO_2 emitted when distance adjusted	Freight volume in % of total	Freight work distance adjusted	Annual CO_2 emissions	Total annual CO_2 emissions	Emission reduction	Cost per thou-sand m^3 km	Cost per thousand m^3 km distance adjusted	Annual cost	Total annual cost	Cost reduct-ion
Unit	km/h		km	days	g/m^3km	g/m^3km	%	million m^3 km	million tons	million tons	%	USD/m^3 km		billion USD	billion USD	%
AS IS																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	7%	1 451	71			30.0	30.0	43.5		
Container	46	6500 TEU	10 000	17.5	7.1	7.1	93%	19 272	137	208		3.3	5.7	109.9	153	
Lower speeds - 1																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	7%	1 451	71			30.0	30.0	44		
Container	39	6500 TEU	10 000	20.0	5.7	5.7	93%	19 272	110	181	13%	2.8	5.2	100	144	6%
Economy of scale - 2																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	7%	1 451	71			30.0	30.0	44		
Container	46	18 000 TEU	10 000	20.0	5.2	5.2	93%	19 272	100	171	18%	2.5	4.9	94	138	10%
Lowe speeds&Economy of scale - 3																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	7%	1 451	71			30.0	30.0	43.5		
Container	39	18 000 TEU	10 000	22.5	4.2	4.2	93%	19 272	81	152	27%	2.2	4.6	88.7	132	14%
Differentiated speeds&Economy of scale - 4																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	7%	1 451	71			30.0	30.0	43.5		
Container	46	6500 TEU	10 000	16.0	7.2	7.1	23%	4 766	34			3.3	5.7	27.2		
Container	22	18 000 TEU	10 000	31.0	2.3	2.3	70%	14 506	33	138	33%	1.9	4.3	62.4	133	13%
Higher speeds&Economy of scale - 5																
Airfreight	850	747-Freighter	10 000	2.0	49.0	49.0	7%	1 451	71			30.0	30.0	43.5		
Container	56	6500 TEU	10 000	12.5	11.2	11.2	23%	4 766	53			4.7	7.1	33.8		
Container	22	18 000 TEU	10 000	35.0	2.3	2.3	70%	14 506	33	158	24%	1.9	4.3	62.4	140	9%

The most important results as shown by the tables are as follows: all the scenarios lead to reductions in total emissions and costs compared to the current situation for both cases and the reduction in emissions is larger than the cost reductions under all the scenarios. However for the first case, in which the market share of airfreight is modeled as a function of the difference in transport time, parts of the reduction in sea transport emissions are lost due to higher air-freight emissions. However, the difference in reductions between the two cases is quite small. The smallest emission reduction of 12 – 13% is obtained for scenario 1 when speed is reduced from 46 – 39 km/h, while emissions in scenario 2 are reduced by 17 – 18% if 6500 TEU vessels are replaced by 18000 TEU vessels, combining speed reduction with the introduction of much larger vessels (scenario 3) reduces emissions by 25 – 27%. Scenario 4 gives the largest emission reductions of 35 – 38% by combining speed differentiation of container vessels with economy of scale. In scenario 4, all container cargo which has a value of 1000 USD per m^3 or more and which adds up to 20% of the container cargo is transported by 6500 TEU vessels at 46 km/h. While cargo with a value of 1000 USD per m^3 or less, which generally cannot pay for air freight is transported by ultra-large 18 000 TEU vessels at 22 km/h in order to obtain the maximum reduction in emissions at low speeds and emission reduction as a function of economy of scale. In scenario 5 the speed of the fastest container vessels increases from 46 to 56 km/h while the ultra-large 18000 TEU vessels operate at 22 km/h. This lowers the market share of airfreight; however, the increase in sea transport emissions is larger than the reduction in airfreight emissions. The net result is a 32% decrease compared to the AS IS scenario, and it still produces a larger reduction in emissions than the scenario in which economy of scale is combined with lower speeds.

4. Discussion and conclusions

The main objective of this paper has been to contribute to development of joint mitigation strategies for air and sea freight. This is done based on analysis of two major international trades. The results of this analysis demonstrate that there is substantial potential for reductions, and that all the options discussed did reduce costs and emissions. However, the largest reductions can be achieved by realising that container vessels transport two different types of cargo. And that the larger proportion of these two consists of goods which are hardly ever considered for air freight, while for approximately 20% of the container cargo, air freight is an option. We therefore suggest to introduce a two-scheme service for container vessels, where the fastest vessels carrying approximately 20% of the total cargo should continue to operate at 46 km/h (25 knots) while the other 80% should be transported by ultra-large container vessels at a speed of around 22 km/h (12 knots). The fast vessels will then maintain the container vessels' market share versus air freight, while the slow ones will operate at quite similar speeds to those of tankers and bulk ships. Total emission reductions then add up to 35 – 38% with cost reductions in the range of 14 – 18%.

When we compared our results with data from other studies of reductions in emissions and costs the challenge is that most studies regarding emission reductions in the transport sector have focussed on reductions which can be achieved within one transport mode, such as aviation (Capoccitti et al., 2009) or sea transport (DNV, 2010), assessing it separately from the rest of the transport market. However we found the maritime reductions to be within a similar range as those presented by Corbet et al (2009), Seas at Risk and CE Delft

(2010) and Lindstad et al (2011). For airfreight, our results shows that the demand is increased when sea transport times becomes longer due to speed reductions and decreased when sea transport times are reduced due to higher speeds which are in line with (Sgouridis et al., 2011). Both for sea and air we have deliberately kept out the effect of using fuels with lower CO_2 impact, the effect of technology improvements and operational improvements since these will tend to result in the same scale of emission reductions for both modes of transport.

An increase in the price of crude oil will give a raise fuel costs for both sea and air transport, although the impact will be greater for air transport, due to its much higher fuel consumption per m^3km. However, while there is uncertainty about future crude oil prices, there will be a fuel cost increase for sea transport in any case, due to the required reduction in the sulphur content of marine fuel from todays 3.5% to 0.5%, which would probably lift the price from the current 650 USD per ton to around 1000 USD per ton, which is the same price as currently paid for jet-fuel and auto diesel.

Another key exogenous variable where sensitivity is an issue is the market share of air freight versus sea container freight, where the 10 % market share of airfreight, and 90% of sea freight used in this study has been established based on a conversion factor from weight to volume and by conversions of distances. The existing statistics are all in weight; however the competition between air and sea is mostly about light weighted cargo, where the cubic capacity of the carrier becomes the capacity restriction and not its weight carrying capacity. Since container ships are designed for heavy cargo while aircraft's are designed for light weighted cargo, our conclusion is that the comparison should be done based on emissions per volume and not per weight unit. When converting from weight to volume we have used an average weight of 90 kg/m^3 for the air cargo and 370 kg/m^3 for the sea cargo. Higher average volume weights of either of them will decrease the market share and lower volume weight of either of them will increase the market share. The distance conversion has been done based on the sea distance being twice the air distance in average. However if the real ratio is less than 1:2 it will decrease the market share of airfreight while a larger ratio increases it.

Differentiation of container vessel speed will be a major challenge to the whole container industry and there is no reason to believe that the actors will do it unless either competition in the freight market or regulations force them to do so. However, they could see it as a strategy to improve both their schedule adherence and their total environmental performance. Where schedule punctuality is concerned, only 50% of containers currently arrive on time (www.maersk.com), while introducing fast and a slow service differentiation would encourage operators to give the fast containers “business class” attention and fast tracking while delivery times for the slow containers will be set on the basis of robust schedules and cost-effectiveness. When comparing our results with current policies discussed by IMO, ICAO and UNFCCC, they have so far focussed on discussing emission reductions options for sea and air transport separately, neglecting the fact that they partly compete for the same freight cargoes and passengers. Neither IMO nor ICAO has either put focus on possible evasion effects of the measures debated and that reductions within one sector can give increases within another sector. In contrast to the current debate within IMO and ICAO, the results from our study shows that the largest emission reductions can be achieved, not by sub-optimizing as today but by focusing on reducing total sea and airfreight emissions.

REFERENCES

Anderson, J., D. 2012. *Introduction to FLIGHT.* New York McGraw-Hill,

www.boeing.com

Buhaug, Ø.; Corbett, J.J.; Endresen, Ø.; Eyring, V.; Faber, J.; Hanayama, S.; Lee, D.S.; Lee, D.; Lindstad, H.; Markowska, A.Z.; Mjelde, A.; Nelissen, D.; Nilsen, J.; Pålsson, C.; Winebrake, J.J.; Wu, W.–Q.; Yoshida, K., 2009. *Second IMO GHG study 2009.* International Maritime Organization, London, UK, April.

Capoccitti, S., Anshuman, K., Mildenberger, U., 2010. *Aviation Industry – Mitigating Climate Change Impacts through Technology and Policy,* Journal of Technology Management & Innovation 2010, Volume 5, Issue 2

www.cargolux.com

Corbet, J, J. Wang, H, Winebrake, J, J. 2009. *The effectiveness and cost of speed reductions on emissions from international shipping.* Transportation Research D, 14, 2009, 593-598.

DNV 2010. *Pathways to low carbon shipping, Abatement potential towards 2030,* www.dnv.com

Duchin, F., A., 2005. *A World Trade Model Based on Comparative Advantage with m Regions, n Goods, and k Factors,* Economic Systems Research Vol. 17, No.2, 2005, 141-162.

Eefsen, T., Cerup-Simonsen, B., 2010. *Speed, Carbon emissions and supply chain in container shipping,* Conference Proceeding IAME 2010, Lisbon Portugal

Endresen, O., Sorgard, E., Behrens, H., L., Brett, P., O., Isaksen, I., S., A., 2007. *A historical reconstruction of ships' fuel consumption and emissions.* Journal of Geophysical Research Atmosphere 112 (D12).

Eyring, V. Isaksen, I., S., A., Berntsen, T., Collins, W, J. Corbett, J, J. Endresen, Ø. Grainger, R, G. Moldanova, J. Schlager, H. Stevenson, D, S. 2009. *Transport impacts on atmosphere and climate.* Shipping, Atmospheric Environment. 2009. Page 1-37

Hjelle, H., M. 2010. *Short Sea Shipping's Green Label at Risk,* Transport Reviews, Volume 30, Issue 5, 2010, page 617 – 640

Howit, O., J., A., Carruthers, M., A., Smith, I., J., Rodger C., J., 2011. *Carbon dioxide emissions from international freight.* Atmosperic Environment Volume 45, issue 39 (2011), Page 7036-7045.

IATA, 2011. *WATS- World Air Transport Statistics.* ISBN 978-92-9233-582-3

ICAO, 2010. http://www2.icao.int/en/NewsRoom/Environment/Environment.pdf

IEA, 2009. *World Energy Outlook 2009,* International Energy Agency Publications, Paris

IPCC, 2007. *Contribution of Working Groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change*. 2007, IPCC, Geneva

Kupfer, F., Meersman, H.,Onghena, E.,Van de Voorde, E., 2011.*World air cargo and merchandise trade.* Critical Issues in Air Transport Economics and Business. Page 98 – 111, London, Routledge

Lee, D.,S., Fahey, D.,W. Forster, P., M., Newton, P.,J., Wit, R.,C., Lim, L., L., Owen, B., Sausen, R. 2009 *Aviation and global climate change in the 21st century,* Atmospheric Environment 43 (2009). Page 3520-3537

Leachman, R., C. 2008. *Port and modal allocation of waterborne containerized imports from Asia to the United States,* Transportation Research Part E 44 (2008). Page 313-331

Lindstad, H., Mørkve, O, T. 2009. *A Methodology to assess the Energy Efficiency and the Environmental Performance of maritime logistics chains.* Proceedings of the International Marine Design Conference – IMDC-2009, ISBN 978-82-519-2438-2.

Lindstad, H. Asbjørnslett, A. H. Strømman, 2011. *Reductions in greenhouse gas emissions and cost by shipping at lower speed.* Energy Policy 39 (2011). Page 3456-3464

Lindstad, H., Asbjørnslett, B., E., Pedersen, J., T. 2012. *Green Maritime Logistics and Sustainability*. Maritime Logistics: Contemporary Issues. Emerald Group Publishing Limited. ISBN: 978-1-78052-340-8

Lindstad, H. Pedersen, J., T., 2009. *Using maritime transport to meet climate goals in Europe and the challenges for the RoPax vessels.* Conference proceedings FAST 2009 Athens, Greece October 2009

Longva, T. Eide, M, S. Skjong, R. 2010. *A cost–benefit approach for determining a required* CO_2 *Index level for future ship design.* Maritime Policy & Management, Vol. 37, no. 2. Page 129–143

OECD, 2010. *OECD Globalization, Transport and the Environment*, 2010, ISBN 978-92-64-07290-9

Psaraftis, H, N. Kontovas, C, A. 2010. *Balancing the economic and environmental performance of maritime transport.* Transportation Research Part D 15 (2010). Page 458-462.

Sea at Risk and CE Delft. 2010. *Going Slow to Reduce Emissio*ns. http://www.seas-at-risk.org/

Second IMO GHG study 2009; International Maritime Organization (IMO) London, UK, April 2009; Buhaug, Ø.; Corbett, J.J.; Endresen, Ø.; Eyring, V.; Faber, J.; Hanayama, S.; Lee, D.S.; Lee, D.; Lindstad, H.; Markowska, A.Z.; Mjelde, A.; Nelissen, D.; Nilsen, J.; Pålsson, C.; Winebrake, J.J.; Wu, W.–Q.; Yoshida, K.

Sgouridis, S., Bonnefoy, P., A., Hansman, R., J., 2011. *Air transportation in a carbon constrained world: Long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation,* Transportation Research Part A 45 (2011). Page 1077-1091

Strømman, A.,H; Hertwich, E.,G.; Duchin, F., A., 2008. *Shifting Trade Patterns as a Means of Reducing Global Carbon Dioxide Emissions, A Multiobjective Analysis,* Journal of Industrial Ecology, Volume 13, Number1, 2008.

Strømman, A, H. Duchin, F., A., 2006. *A World Trade Model with Bilateral Trade Based on Comparative Advantage,* Economic System Research, Vol.18, No.3, 2006. Page 281-297.

4.6 Paper 6:

Lindstad, H., Jullumstrø, E., Sandass, 2013. Reduction in cost and emissions with new bulk ships designed enabled by the Panama Canal expansion. Energy Policy 59 (2013), Page 341–349

Is not included due to copyright

5. Contribution to State of the Art

This section will show how each of the studies has contributed to advancing state of the art.

The first study *Green Maritime Logistics and Sustainability* (Lindstad et al., 2012) presents a methodology for assessing the environmental impact of maritime transport and transport with specific focus on greenhouse gas emissions. The methodology is based on a model which simulates how different vessel types are used in different trades. The model developed enable assessment of different trade scenarios, assessment of how different vessel types and their handling technologies compete for some of the cargo types, assessment of the relationships between vessel size and emissions, assessment of freight work and average emissions per freight unit transported as a function of vessel type and size. Following this methodology total sea freight work was calculated to be 41 700 billion ton nm. Which was later rounded to 41 000 billion ton nm in the paper: *The importance of economies of scale for reductions in greenhouse gas emissions from shipping* (Lindstad et al., 2012a).

Comparing this study to well established practice, this study is not the first which builds capacity and demand models. However, the general approach has been to build models for one shipping segments and then perform in-depth analyses for instance of the container or the crude oil segment. Lately as a function of increased focus on sustainability models have been built to calculate fuel consumption and operational emission figures corresponding to the Energy Efficiency Operational Indicator (EEOI). To give an example, the *IMO 2009 GHG study* (Buhaug et al., 2009) used the seagoing fleet as listed in the Lloyds Fairplay database (ihs.com) and divided the vessels into subgroups per vessel type based on vessel sizes. Activity data collected by AIS systems was used to find total days at sea, service speed and days in port per year, but typical trading patterns and voyages was not established, only hours at sea and in port per subgroup. The transport work was calculated based upon assumptions regarding percentage at sea loaded, partly loaded and in ballast. Based on this methodology (Buhaug et al., 2009) the total sea freight work in 2007 was calculated to be 49 000 billion ton nm which is a high figure compared to 41 700 billion ton nm (Lindstad et al., 2012). This is also confirmed by the latest *Review of Maritime Transport* (UNCTAD, 2012) which estimates world's seaborne trade to have been 38 351 billion tons in 2007 and 42 794 billion tons in 2011. In such comparisons, approximately 5% should be added to the UNCTAD figures to include national sea trades, total then becomes 40 – 41 000 billion ton nm. These UNCTAD figures (UNCTAD, 2012) was first published in December 2012 and it was the first time ever that UNCTAD has published freight work figures in addition to the traditional ton figures, i.e. *Review of Maritime Transport 2011* (UNCTAD, 2011).

The second study: *Reductions in greenhouse gas emissions and cost by shipping at lower speeds* (Lindstad et al., 2011) presents investigations on the effects of speed reductions on the direct emissions and cost of maritime transport. The developed model enables calculation of costs and emissions as a function of vessel speed from very low speeds up to design speeds, which usually are 90% to 95% of the vessel maximum speeds. This enables the model to calculate the potential emission reductions that can be achieved as a function of speed, dictated by various priorities such as operation at the designed service speed, cost minimization and emission minimization for the various ship classes. The emission and cost model includes the added resistance created by waves, emissions related to shipbuilding and the opportunity to make the cost assessments both from a ship-owner and cargo-owners perspective.

Comparing this study to previous work, this study is not the first which investigates the emission reductions when vessels slow-steam i.e. reduces speed below their design speed. However, it is the first study which includes the added resistance from waves and the impact of shipbuilding. It is also the first study which investigates the emission and cost from very low speeds up to design speed. This has enabled calculation of emissions from priorities such as the speeds which minimizes cost and the speeds which minimizes emissions. In a previous study, Corbett et al. (2009) investigated how the fuel price influence speed decisions taken by the shipping lines. The conclusion was that higher fuel prices results in speed reductions, which supports the assumption that market based measures (MBM) incite operators to reduce speeds and hence emissions. The data from this study (Lindstad et al., 2011) indicates that this may be more complex, and that it may be important to understand ship-owners preferences, as well as those of their customers.

The third study *Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market* (Lindstad et al., 2013) assess profit, cost, and emission as a function of speed, sea and freight market condition. The main extension to the model developed in the second paper (Lindstad et al., 2011) is that the power model has been refined and that profit assessment has been included in the developed model in addition to the cost based assessment. This comes as a logical consequence of the conclusion from the second paper regarding the importance of understanding ship owner and customer preferences. The results demonstrate that significant cost and emission reductions can be achieved by varying speed as a function of sea conditions and freight market. And that maximum economic speed based on hydrodynamic considerations even in a good shipping market with focus on profit maximization is lower than the design speed. Finally it has been demonstrated that the developed model in combination with weather data enables weather routing contributing to further cost and emission reductions.

While the added resistance due to waves and the effects of wind is well recognized, this study is the first to present a model to assess emission, cost and profit as function of freight market and sea conditions. This for speeds from zero speed up to design speed, and in sea states from calm sea to rough sea. Previously published studies have generally focused on speed loss in moderate sea condition as a function of waves headings (Orsic and Faltinsen, 2012) or to publish power needed at specific sea conditions (Hollenbach and Friesch, 2007). When applying the developed model in combination with weather data the results are in line with Strom Tejsen et al. (1975) which found that larger cost and emission reductions are achievable.

The fourth study: *The importance of economies of scale for reductions of greenhouse gas emissions from shipping* (Lindstad et al., 2012a) investigates the effects of economies of scale on the direct cost and emission from shipping. The potential of economies of scale was evaluated by comparing the average for the existing fleet with what can be achieved by replacing the existing fleet with a fleet of fewer larger keeping total capacity unchanged. The results demonstrate that emissions can be reduced by as much as 30 % at a negative abatement cost.

While economies of scale are a well-established concept in shipping, this study is the first to investigate the potential reductions in cost and emissions that can be achieved for the whole fleet. Comparing the results with data from other studies of reductions in emission and cost, they were found to be within a similar range as those for container vessels presented by Cullinane and Khanna (2002) and Notteboom and Vernimmen (2009). Few studies of other vessel type exists, although figures are available that demonstrates the importance of economies of scale for emission reductions per freight unit since the Second World War (Buhaug et al., 2009).

The fifth study *Comparing the cost and emissions of maritime and air transport* (Lindstad and Strømman, 2011) presents an assessment of the cost and emissions of freight transport for oceangoing container vessels and aircrafts. The main objective of the developed model was to calculate emissions and costs for sea-freight and air-freight as a function of their characteristics and the cargoes they transport, with focus on cargo segments that currently are transported by both modes. The results shows that emissions could be minimized by introducing a two-scheme speed service for container vessels, where the fastest vessels carrying approximately 20% of the total sea cargo volumes should continue to operate at 46 km/h (25 knots) while the remaining 80% of the cargo should be transported by ultra-large container vessels at a speed of 22 km/h (12 knots). The fast vessels will then maintain the container vessels' market share versus air freight, while the slow ones will operate at similar speeds to those of tankers and bulk ships.

When comparing these results with data from other studies of reductions in emissions and costs the challenge is that most studies regarding emission reductions in the transport sector have focussed on reductions which can be achieved within one transport mode, such as aviation (Capoccitti et al., 2010) or sea transport (DNV, 2010), assessing it separately from the rest of the transport market. However, there are some exceptions; Hjelle (2011) compares the environmental performance of short-sea shipping and road haulage. Lindstad and Pedersen (2009) investigate using maritime transport to meet climate goals in Europe. Psaraftis and Kontovas (2010) compared sea and rail transport for fast-moving consumer goods between Asia and Europe and found that the demand for rail-freight increased when transport times at sea increased due to lower speed. For airfreight, our results shows that the demand increases when sea transport times becomes longer due to speed reductions and decreases when sea transport times are reduced due to higher speeds. This is in line with airfreight results reported by Sgouridis et al. (2011). Howit et al. (2011) discuss allocation principles between freight and passengers when airfreight is carried in the belly of passenger aircrafts instead of designated air freighters. They debate different allocation principles and that a certain amount of mass should be added to passenger facilities to account for passenger facilities on board such as seat and galleys (50 + 200kg), however they decide against it. While this study (Lindstad and Strømman, 2011) question mark using ton as the comparing unit and concludes that cubic meter should be used for comparison since the majority of the cargo for which air and sea compete is light weighted.

The sixth study *Reductions in cost and greenhouse gas emissions with new bulk ship designs enabled by the Panama Canal expansion* (Lindstad et al., 2012b) presents an assessment of cost and emissions as a function of alternative bulk vessel design. The main objective of the developed model was to enable assessment of cost and emissions for standard vessel designs with more slender designs. The employed power model reflects real sea conditions as opposed to still water, and the economical assessment has been carried out for a low, medium and high fuel price. The results show that when the block coefficient is reduced and the hull becomes more slender and hence more energy-efficient, the emission per transported unit drops. However building slimmer vessels generally increases building cost per cargo carrying capacity unit. This implicates that the saving on fuel cost has to be larger than the additional building cost, if slimmer vessels shall be built. At present fuel cost levels, i.e. 600 USD per ton of fuel, the lowest cost was found for designs with block coefficients around 0.75 which gives a slender hull form compared to 0.82 to 0.90 for a typical bulk or tank vessel.

Comparing these results with the traditional rules of thumb in ship design and operation, the contrast is quite large. Traditionally bulk vessels has been built with high block coefficients to maximize the cargo-carrying capacity, while our conclusion is that with today's fuel costs, i.e. 600 USD per ton of fuel, more slender designs with lower block coefficient give the lowest costs. In addition, the benefit for society is that more slender bulk designs will contribute to significant emission reductions. Regarding the expansion of the Panama Canal, the main focus in previous studies has been on the requirements of the container lines and their potential benefits (Panama Canal Authority, 2006; Payer and Brostella, 2007; Thomson, 2008). Much less has been published on the effects on design within other shipping segments. One exception is the study by Stott and Wright (2011) which addresses how larger vessels will permit economies of scale in dry bulk shipping and how the hull forms can be made more energy-efficient by alternating the main ratios between beam, draft and length.

To summarize the purpose of this section has been to show how each of the studies has contributed to state of the art.

6. Conclusions

In this section the knowledge gained and the results from the individual studies have been combined enabling assessment of their combined emission reduction potential. This is done by first presenting some of the important observations and results, followed by the assessment of the combined emission reduction potential, and a final part giving directions for future research within the area.

6.1 Important observations and results

Important observations are shown through the following four figures. To keep consistency and enable us to compare between the figures, the focus is on dry bulk vessels of different sizes and designs. The dry bulk vessels have been chosen since they accounts for nearly 40% of the world freight work. Bulkers and tankers have similar designs and these results are therefore valid for vessels representing 75% of the world sea borne freight work. Apart from the fact that container and RoRo vessels are built for higher speeds, and operate at a higher cost level per ton transported, the general forms of these curves are quite similar.

Three different dry bulk vessels are compared. The first is a standard Panamax built to maximize cargo carrying capacity through the Panama Canal, before the lock extension in 2014. The second vessel is a slender bulk vessel, compared to a standard Panamax the width has been increased by 30%, the length and the draft is unchanged and in combination this enables a reduction of block coefficients from 0.87 to 0.68 while the maximum cargo carrying capacity is kept equal at 80 000 ton. The third vessel is a Capesize of the Dunkerque class with a maximum cargo carrying capacity of 175 000 ton. Neither the slender bulk vessel nor the Capesize vessel can go through the existing Panama Canal, but both can go through the canal after the new locks opens in 2014. The fuel price used for the comparison is 600 USD per ton based on 2012 average prices and time charter rates (TC) set to 12 % of the new building prices. The new building price for the vessels are typical 2012 contract prices for new buildings to be delivered the coming years and they are: standard Panamax 30 million USD; slender bulk 31.5 million USD; Capesize 50 million USD. For all vessels, the dead weight utilization was set to 50% on a roundtrip basis, based on fully loaded one way and empty back. Compared to real business, this favors the largest vessel, i.e. the Capesize vessels, since the other vessels will have a higher utilization on a yearly basis as shown in the *Green Maritime Logistics and Sustainability Paper* Lindstad et al (2012) and *The importance of economies of scale for reductions in greenhouse gas emissions from shipping* (Lindstad et al. 2012a). However even if this had been included, the Capesize vessel would still give a lower cost per transported unit, and due to this I have chosen to compare with equal utilization levels to get a clean technical comparison. Compared to *Reductions in greenhouse gas emissions and cost by shipping at lower speeds* (Lindstad et al. 2011) it should be noted: that emissions from shipbuilding is not included in the assessments made in section 6.1 and 6.3 and neither is the capital cost of the goods transported (the financial cost for carrying stock); that the drop in propulsion efficiency at lower speeds and higher sea states in section 6 are based on state of the art technology and not average technology; that the new building cost for a Panamax vessel has been reduced from 50 million USD in 2010 to 30 million USD in 2012; and that fuel cost has increased from 400 USD per ton in 2010 to 600 USD per ton in 2012. This gives larger rewards for speed reductions, since the fuels share of total cost at design speed has increased and the time charter cost at lower speeds has been reduced. And larger emission reductions at lower speeds due to improved propulsion efficiency. Figure 2 shows the relationship between cost per ton nm and vessel speed as a function of vessel size and fuel cost.

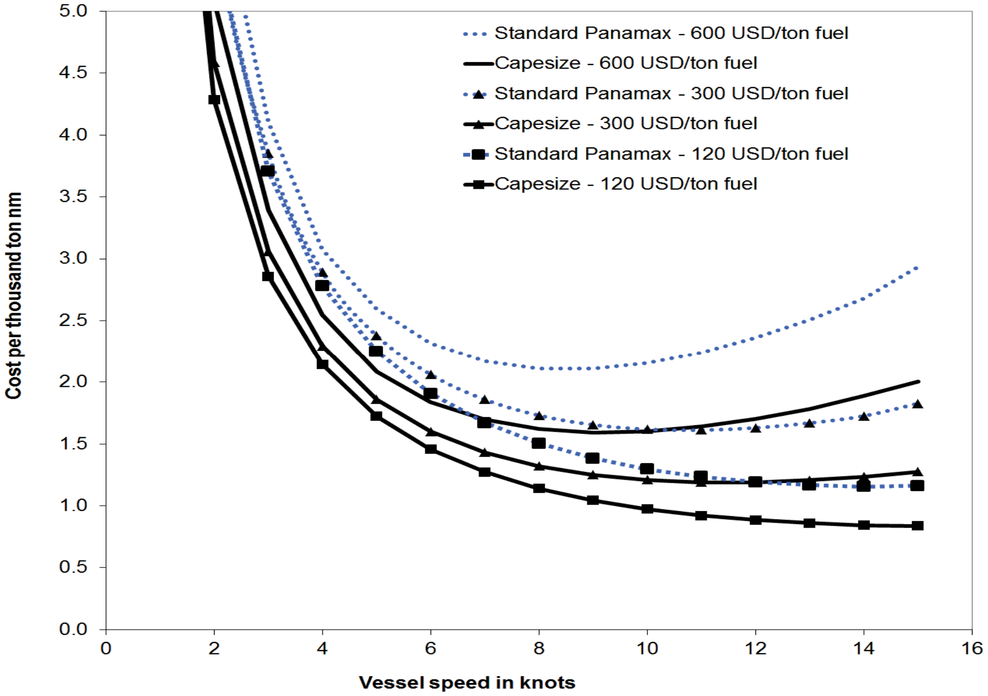

Figure 2: Cost as function of vessel size and fuel cost at calm water

Main observations are that if fuel cost is low, i.e. 120 USD per ton, corresponding to fuel price levels during the 1990 ties, the highest speed (15 knots) gives the lowest cost per freight unit transported. And vice versa, if the fuel cost is at present level, i.e. 600 USD per ton (2012), a speed of 8 - 10 knots gives the lowest cost per freight unit transported. If the fuel cost is somewhere between, i.e. 300 USD per ton, the curve flattens out for speeds above 10 knots. This implicates, that with a fuel cost of less than 300 USD per ton for dry bulkers and tankers, slow steaming which reduces emissions is unprofitable, while the profit from slow steaming increases for each dollar the fuel price increases above 300 USD per ton. Another observation is that the Capesize which has a cargo carrying capacity of more than twice the Panamax, i.e. 175 000 tons versus 80 000 tons, gives the lowest freight cost per freight unit transported for all fuel prices and speeds due to economies of scale.

Figure 3 shows that emissions per freight unit transported is a function of vessel speed, and has nothing to do with the fuel price as such. Hence, while the speed which gives the lowest cost will vary with the fuel price, the speed which gives the lowest emissions will be a function of vessel design and vessel size. Figure 3, contains two separate parts with a common vertical axis. The vertical axis represents the cost per ton nm as a function of vessel speed on the right hand side of the figure, and the same cost as a function of emissions on the left hand side for the standard Panamax vessel.

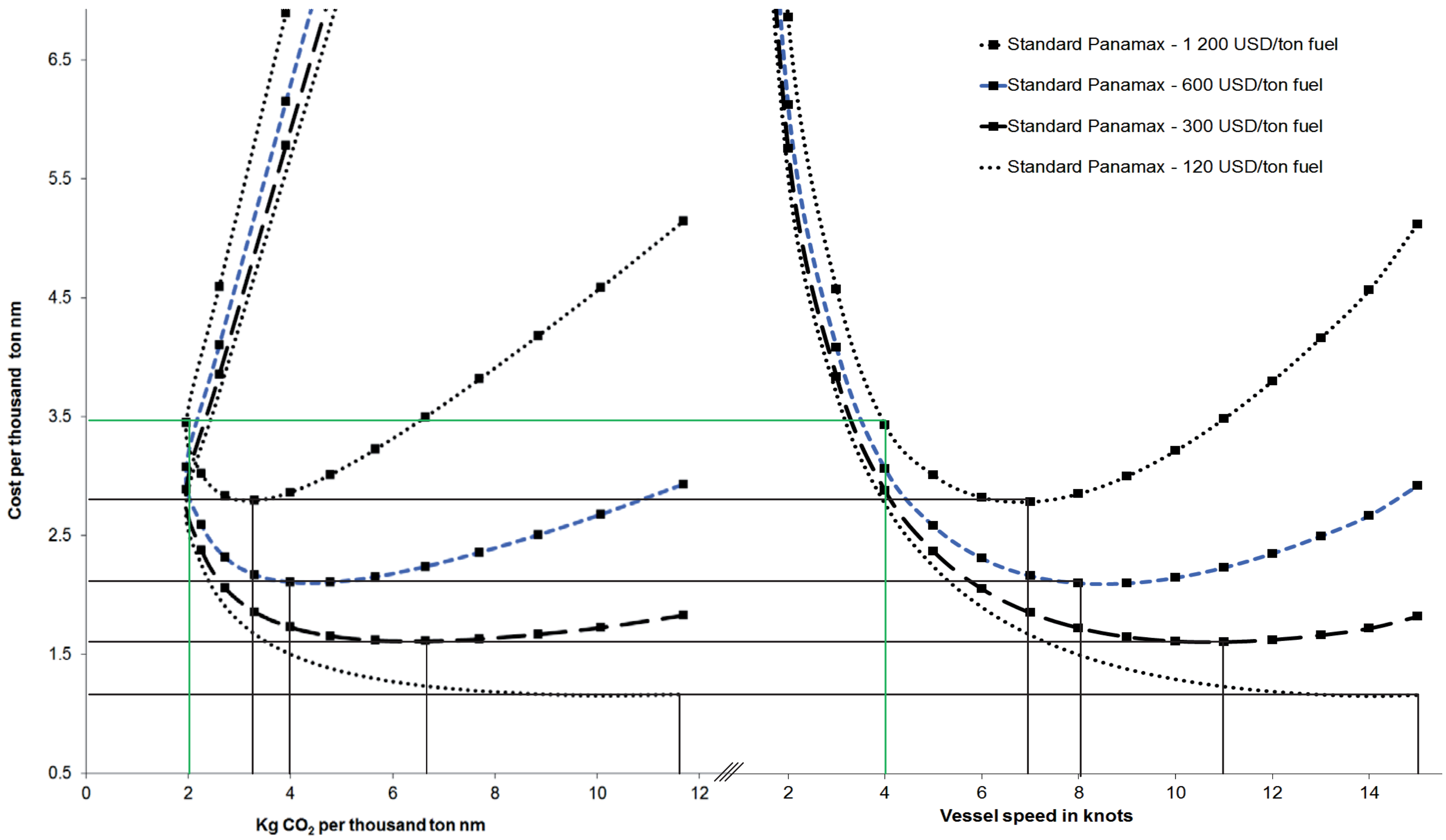

Figure 3: Emission and cost as a function of vessel speed and fuel cost at calm water

The figure shows that with a design speed of 15 knots at calm water conditions the vessel emits 11.5 kg of CO_2 per thousand ton nm independently of what the fuel price is. If the fuel cost is 120 USD per ton of fuel this speed gives the lowest transport cost, i.e. 1.2 USD per thousand ton nm. If the fuel cost is 300 USD per ton of fuel, 11 knots gives the lowest transport cost, i.e. 1.6 USD and emissions is reduced to 6.7 kg CO_2. If the fuel cost is 600 USD per ton of fuel, 8 knots gives the lowest transport cost, i.e. 2.2 USD and emissions is reduced to 4.0 kg CO_2. If the fuel cost increases to 1 200 USD per ton of fuel, 7 knots gives the lowest transport cost, i.e. 2.8 USD and emissions is reduced to 3.5 kg CO_2.
Figure 3 also demonstrates that 4 knots at calm water conditions is the speed which gives the lowest emissions, i.e. 2.0 kg per thousand ton nm as shown by the green lines in the figure. At 4 knots the cost will vary from 2.8 USD per thousand ton nm for the lowest fuel price up to 3.5 USD per thousand ton nm for the highest fuel price. Another observation is that with the highest fuel price, i.e. 1 200 USD per ton of fuel the cost at 4 knots (per ton nm) is lower than the cost at design speed.

Figure 4 shows the relationship between cost per ton nm and vessel speed as a function of vessel slenderness and fuel cost. Two vessels are compared. The first is the standard Panamax built to maximize cargo carrying capacity through the Panama Canal before the lock extension in 2014. The second is the slender bulk vessel, which can pass through the Panama Canal after the lock expansion in 2014. As previously described, the width of the slender bulk vessel has been increased by 30%, the length and the draft is unchanged and in combination this enables a reduction of block coefficients from 0.87 to 0.68 while the maximum cargo carrying capacity is kept unchanged at 80 000 tons.

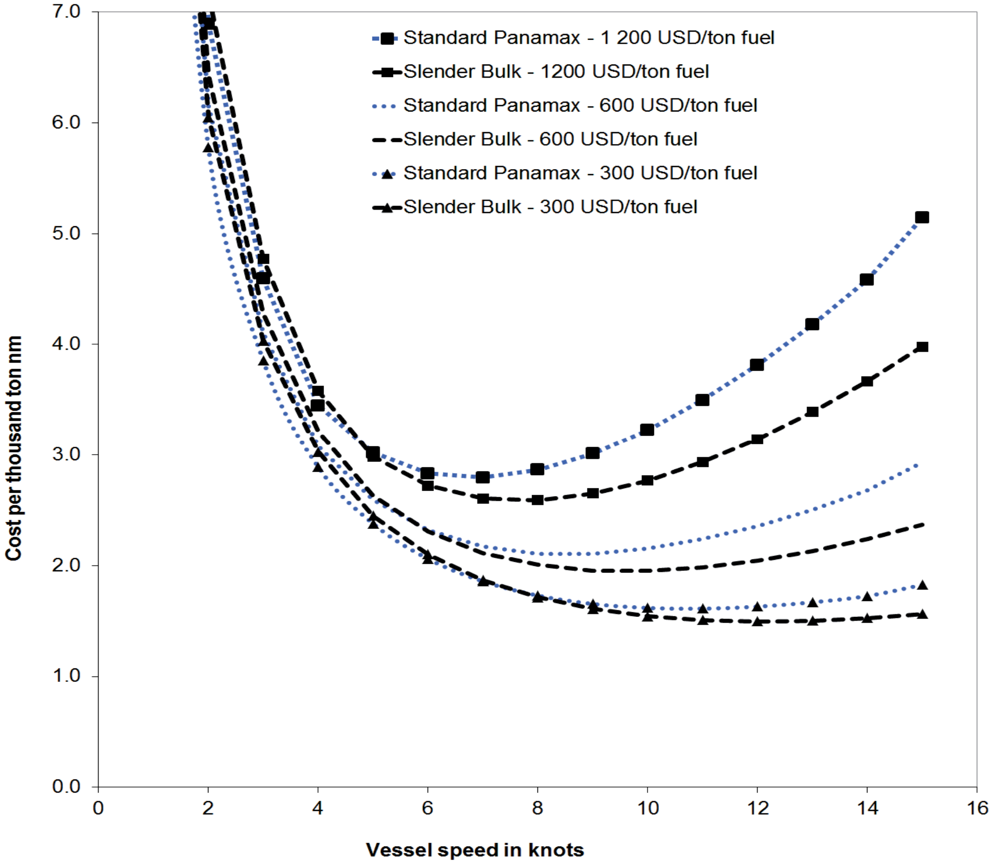

Figure 4: Cost as a function of vessel speed, vessel design and fuel cost at calm water

Main observations are that, the slender bulk vessel gives the lowest freight cost, for all the investigated fuel prices. This cost difference increases with the fuel price and with the speed, i.e. there are nearly no cost differences for speed under 6 knots or for the lowest fuel price.

Figure 5 illustrates the relationship between cost per ton nm and vessel speed as a function of vessel slenderness and sea state. Both vessels have a cargo carrying capacity of 80 000 tons and their specifications are as described for Figure 4.

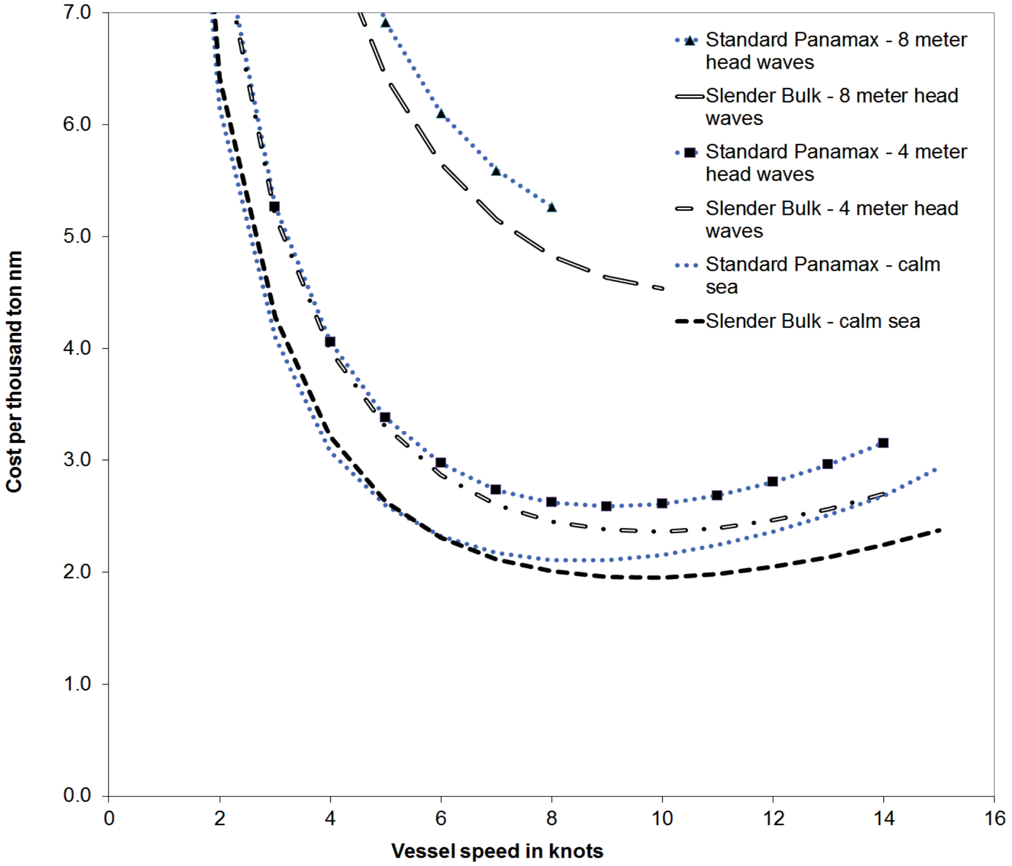

Figure 5: Cost as a function of vessel speed, vessel design and sea condition

The main observations are that the slender bulk vessel performs much better than the standard Panamax for all the investigated sea states. Another observation is that the slender bulk vessel in 4 meter significant head waves ($H_{1/3}$) operates at a cost comparable to the calm water performance of the standard Panamax (All wave heights in the figure are significant wave heights: ($H_{1/3}$))

To summarize based on these four figures in specific and the thesis in general the following observations and results should be noted:

- The importance of the fuel cost. With fuel cost above 300 USD per ton it becomes profitable to reduce speeds and hence emissions.
- The importance of economies of scale. It will generally be cost effective to use a larger vessel compared to smaller one if it can be used in the trade and fully utilized. In addition, economies of scale are not linked with the fuel cost, which means that it is cost effective for all fuel prices.

- The emission reduction potential is independent of the fuel cost. Which mean that while the speed which gives the lowest cost will vary with the fuel price, the speed which gives the lowest emissions will be a function of vessel design and size and vary only with the sea conditions.
- The importance of slender design. This means that if two vessels have the same cargo carrying capacity, the slenderest vessel will emit less CO_2 per freight unit transported. At present fuel cost, i.e. 600 USD per ton of fuel, it is profitable to build tank and bulk vessels more slender than today. This means to reduce block coefficients from typical values in 0.82 to 0.90 ranges, down to values around 0.75.
- Seagoing vessels should be designed and optimized to operate most efficiently at speeds in the range from 50% up to 100% of the requested design speed, i.e. 7 to 15 knots for bulkers and tankers. This for a representative number of sea conditions such as: calm water; 4 meter ($H_{1/3}$) head waves; 4 meter ($H_{1/3}$) following waves, 4 meter ($H_{1/3}$) side waves; and the head wave condition which represents the largest added resistance for the specific vessel, i.e. when the wave length is about equal to the length of the vessel. For a Panamax bulker that means 7 to 8 meter ($H_{1/3}$) head waves, for a Capesize that means 9 – 10 meter ($H_{1/3}$) head waves.
- The design speed should be based on an economic calculation and hence express the highest economic speed which is wise to drive a vessel of specific fullness. With today's high fuel costs, i.e. 600 USD per ton of fuel, this means speeds in the lower part of the speed boundary area. This in contradiction to the historic principles of basing it on speeds in the upper part of the boundary area as described in the state of the art section. If this gives a lower design speed than what is required, this implicates that the design should be made more slender.

6.2 Total combined emission reduction potential

One of the objectives of my research has been to investigate strategies and measures which could enable emissions reductions by up to 85% per freight unit transported by 2050. In combination with the foreseen tripling of world seaborne freight this could reduce total sea transport emissions in 2050 with 50% compared to the present levels. This foreseen growth in sea transport is based on global GDP growth according the IPCC (2007) B1 scenario and that sea transport will increase by 80% of the growth in GDP, which is the consensus estimate made by the *Second IMO GHG study 2009* (Buhaug et al., 2009). With these assumptions freight volume will grow from 41 000 billion ton nm in 2007 (Lindstad et al., 2012a) to 109 000 billion ton nm in 2050. These figures might appear high, but compared to freight work projections with high growth scenarios, the B1 scenario which has an annual growth of 3.1% represents a medium growth scenario between the high growth scenario A1T (4%) and low growth scenarios like B2 (2.4%).

If this increased freight work is transported with the current technology and vessels fleet mix (2007), the emissions will increase with the same percentage as the freight work. However 2050 emission levels will also be influenced by efficiency improvements, due to technical and operational improvements, and the market share of the different vessels types. Establishing the future market share of the different vessel types should idealistically be based on the forecasted tonnages of the different cargo types to be moved in 2050, which would imply a major effort. Due to this, it is more common to make such forecasts based on historical data in combination with expert judgments. The *Second IMO GHG study 2009* (Buhaug et al, 2009) applied this methodology. Based on the historical strong growth in container trades since the 1970ies, compared to other sea borne trades, they concluded that the annual growth in container trades would be two and a half to three times higher than the growth in the other shipping trades. This gives total sea transport cargo emissions of 2 650 million tons of CO_2 in 2050 for scenario 1 as shown in Table 5, if this freight work is performed by the same size distribution within each ship type as in 2007 fleet. This equals a 220% increase in emissions compared to the 820 million ton of CO_2 emitted in 2007 (Lindstad et al., 2012a). And increased emissions per freight unit transported since the increased in freight work is less than the increase in emissions, i.e. 170% increase in freight work. This due to the increased market share of container vessels which emit more than tankers and bulker per freight unit transported. For consistency it should be noted that none of the figures in this comparison includes emissions from vessels which are built for other purposes than freight transport, such as cruise, ferries, fishing, service or offshore vessels. In 2007 these vessels types emitted 220 – 230 million ton of CO_2 equivalent to 20 % of the total emissions (Lindstad et al., 2012a). The main argument for excluding them from the comparison is that there are no direct relationships between growth in trade and the size of the fishing or the cruise fleet, so these figures would have to be established by assessing the demand for different vessel types in 2050.

The assumption of continued strong growth in the market share of container vessels can be challenged based on market share developments since 2008. And that bulk and tank vessels in 2050 probably still will be more competitive for raw materials and oil products than container vessels. An alternative approach for a 2050 scenario would then be to assume that the foreseen seaborne trade according to the B1 scenario will be served with a fleet where the vessel types market shares in 2050 will be the same as today (2007). This gives total maritime transport emissions of 2 199 million tons of CO_2 in 2050 for scenario 2 as shown in Table 6 if this freight work is performed by the same size distribution within each ship type as in 2007. Instead of debating the likelihood of the first versus the second scenario, both will be used to try to answer the question, could the investigated strategies and measures reduce emissions by up to 85% per freight unit transported by 2050.

My studies have shown that the following strategies and measures have the largest emission reduction potential when emissions are measured in gram CO_2 per freight unit transported:

- Economies of scale
- Shipping at lower speeds
- More slender vessel designs
- Weather Routing
- Integrated air & sea policies

Total sea transport emissions can also be reduced through reductions in trade and transport volumes or through low carbon fuels, renewable energy or waste heat recovery. Debating the first of these options is outside the scope of this thesis, while the other ones were not selected for further investigations based on the state of the art study. For both the 2050 scenarios the base case figures are calculated by using the 2007 fleet to perform the 2050 freight work and then stepwise calculate emissions and potential emission reductions per measure, starting with economies of scale. The explanation for starting with economies of scale and then let shipping at lower speeds follow, is that reductions through economies of scale is an ongoing process in the same way as the market have recognized and reduced emissions through speed reductions. This compared to the other options which are less mature.

The savings per option is based on the performed studies, corrected for fuel price increases from the first paper based on 2010 prices of 400 USD per ton of heavy fuel oil to a 2012 level of 600 USD per ton of heavy fuel oil. Compared to the papers the following should be noted. Savings from economies of scale as calculated in *The Importance of economies of scale for reductions of greenhouse gas emissions from ships* (Lindstad et al., 2012a) for scenario 1 while the figures for scenario 2 was calculated for this comparison. Saving from shipping at lower speeds as calculated in *Reductions in greenhouse gas emissions and cost by shipping at lower speeds* (Lindstad et al., 2011) for an abatement cost of 50 USD per ton to compensate for the increase in fuel price from 2010 to 2012. Saving from more slender designs 24% for bulk and tank based on *Reductions in cost and greenhouse gas emissions with new bulk ship designs enabled by the Panama Canal expansion* (Lindstad et al., 2012b). And 24% for all other vessels apart for container vessels for which 12% is used. This due to container vessels in general being slenderer than bulk and tank vessels and hence having less potential for emission reductions through more slender designs. The savings from weather routing based on *Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market* (Lindstad et al., 2013), which indicates emission reduction of 19% – 48% with weather routing with rough weather in the north Atlantic. If we assume that weather routing is at least relevant for 20% of the voyages, this give an emission reduction potential 7% (Calculated based on average of 19% – 48% which is 35%, and that 20% of 35% is 7%). Saving from integrated air and sea policies are based on *Comparing the costs and emissions of maritime and air transport* (Lindstad and Strømman 2011) for scenario 1, while the figures for the scenario 2 was calculated for this comparison.

Based on this methodology the following results can be read out of Table 5 for scenario 1 which implies growth according to B1 scenario IPCC (2007) and fleet mix according to the *Second IMO GHG study 2009* (Buhaug et al., 2009).

Table 5: Scenario 1 - 2050 IPCC B1 and fleet mix as in *Second IMO GHG study 2009*

Vessel type	Freight work	CO_2 emissions					
		2050 BAU with 2007 fleet	Economies of scale fleet	Shipping at lower speeds	More slender designs	Weather routing	Integrated air&sea policies
	Billion ton nm	Million ton CO_2					
Dry bulk	29 853	340	208	155	118	109	109
General cargo	4 407	186	108	62	47	44	44
Reefer	477	40	31	18	14	13	13
Container	46131	1604	1301	473	416	387	301
RoRo	897	68	23	15	12	11	11
Crude oil	18613	181	130	97	73	68	68
Oil products	2325	58	31	23	18	16	16
Chemicals	3550	90	63	47	36	33	33
LNG	1576	53	52	39	30	28	28
LPG	742	26	17	12	9	9	9
Sea River	30	6	2	1	1	1	1
Totals	109 000	2 650	1 970	943	773	719	633
Gram CO_2 per ton nm		24.2	18.1	8.6	7.1	6.6	5.8
Emission reduction per measure			26%	52%	18%	7%	12%
Total reduction versus BAU			26%	64%	71%	73%	76%

Economies of scale reduces 2050 emissions with 26%, Shipping at lower speeds reduces emissions with 52%, More slender reduces emissions with 18%, Weather routing reduces emissions with 7%, Integrated air & sea policies reduces emissions with 12%. Combining all these emission reduction options the total reduction potential sums up to 76%.

The comparable figures for scenario 2 with fleet mix according to 2007 fleet and growth according to B1 (IPCC 2007) can be read out of Table 6.

Table 6: Scenario 2 - 2050 IPCC B1 scenario and equal growth all vessel types

Vessel type	Freight work	CO$_2$ emissions					
		2050 BAU with 2007 fleet	Economies of scale fleet	Shipping at lower speeds	More slender designs	Weather routing	Integrated air&sea policies
	Billion ton nm	Million ton CO$_2$					
Dry bulk	42 901	488	299	223	169	157	157
General cargo	6 333	267	155	89	68	63	63
Reefer	686	57	45	26	20	18	18
Container	19 942	693	563	204	180	167	130
RoRo	1 289	98	33	22	17	16	16
Crude oil	26 748	260	187	139	105	98	98
Oil products	3 342	83	44	33	25	23	23
Chemicals	5 102	129	91	67	51	48	48
LNG	2 265	76	75	56	43	40	40
LPG	1 066	37	24	18	14	13	13
Sea River	43	9	3	2	2	1	1
Totals	109 000	2 199	1 518	880	693	645	607
Gram CO$_2$ per ton nm		20.2	13.9	8.1	6.4	5.9	5.6
Emission reduction per measure			31%	42%	21%	7%	6%
Total reduction versus BAU		17%	43%	67%	74%	76%	77%

First observation to be made, are that this gives 2050 business as usual emissions which are 17% lower compared to scenario 1. The explanation is the higher market share of bulkers and tankers which emits less per unit transported than the container vessels. The emission reduction through economies of scale of 31% is larger than in scenario 1. The explanation is that in scenario 2, bulker and tankers have a large market share, which in combination with their larger emission reductions due to economies of scale (Lindstad et al., 2012a) gives larger emission reductions than in scenario 1. The emission reduction through shipping at lower speeds of 42% emission is smaller than in scenario 1. The explanation is that in scenario 1, the container vessels which has the largest emission reduction potential have a higher market share compared to bulkers and tankers (Lindstad et al., 2011). More slender designs reduce emissions with 21%. Weather routing reduces emissions with 7%. Integrated air and sea policies reduce emissions with 6%. Compared to the first scenario the emission reduction potential through more slender designs is higher due to a lower share of container vessels; while it is lower for integrated air and sea policies due to the same reason. Combining all these emission reduction options the total reduction potential ads up to 77%.

Summarizing these results they indicate an emission reduction potential of around 75% for the investigated emission options, and that the whole reduction is cost effective at the present fuel cost of 600 USD per ton. It is also worth nothing, that we get this result for both the investigated scenarios. This indicates that while the current bulker and tanker fleet operated at design speed are more energy efficient than the current container fleet operated at their design speed, this difference becomes much smaller if the majority of the container vessels reduce speed to comparable level with bulkers and tankers.

Potential emission reduction figures of this magnitude, i.e. 75% indicate a larger cost effective emission reduction potential than what have been found by previous studies (Buhaug et al, 2009; Faber et al, 2009; DNV 2010; IMAREST, 2011). A 75% reduction is also quite close to my objective of investigating available strategies and measures for improving energy efficiency by up to 85% per freight unit transported by 2050.

6.3 Future Research

The papers and this thesis are only one step enabling reductions of maritime CO_2 emissions. Further research in combination with tests and trials both in model and full scale is required for the following options:

- Shipping at lower speeds
- More slender designs
- Weather Routing

The shipping community has realized the benefit of speed reductions, however there is a need for testing out reliable methods to establish power and speed curves for any vessel from zero speed up to their design speed. This will enable that vessels are operated in the most cost and emission effective way for any sea condition and voyage priority. For more slender designs which are a less mature option, the challenge is not power predictions models, but it is the general market perception which says that bulk and tank vessels shall be built with shoe boxed shaped designs. To change this perception and the market behavior, additional studies in combination with the ability to advocate the importance of slender design will be important. For weather routing there is a need to perform full scale test in combination with voyage planning to convince the shipping community.

Neither economies of scale nor integrated air and sea policies are fully investigated, but compared to the other options, the work which is needed on these options is mainly at a policy level.

Personally I would like to go further into what could be achieved by combining operations and slender designs with specific focus on new designs enabled by the Panama Canal lock expansions. Since this is a natural extension to my thesis and a result of the synthesize process I will present the basic comparison enabled at this stage. Four vessels are compared. The first is a standard Panamax built to maximize cargo carrying capacity through the Panama Canal, before the lock extension in 2014. The second vessel is a slender bulk vessel, compared to a standard Panamax the width has been increased by 30%, the length and the draft is unchanged and in combination this enables a reduction of block coefficients from 0.87 to 0.68 while the maximum cargo capacity is kept equal at 80 000 ton. The third vessel, the Handy-Cape is 30% wider and 8% longer than the standard Panamax and it is built to maximize the cargo carrying capacity at the lowest building cost. This gives a maximum cargo carrying capacity of 120 000 tons. The fourth vessel is a Capesize of the Dunkerque class which can pass through the new locks when it is short loaded, which reduces the maximum cargo carrying capacity from 175 000 tons to 150 000 tons. The fuel price used for the comparison is 600 USD based on 2012 average prices and time charter rates (TC) set to 12 % of the new building prices. The new building price is typical 2012 contract prices for new buildings to be delivered the coming years and they are: standard Panamax 30 million USD; slender bulk 31.5 million USD; Handycape 40 million USD; Capesize 50 million USD.

Figure 6 shows cost and emissions as a function of vessel speed for each of these vessels with calm water conditions. Here the vertical axis represents the cost per ton nm as a function of vessel speed on the right hand side of the figure, and the same cost as a function of emissions on the left hand side.

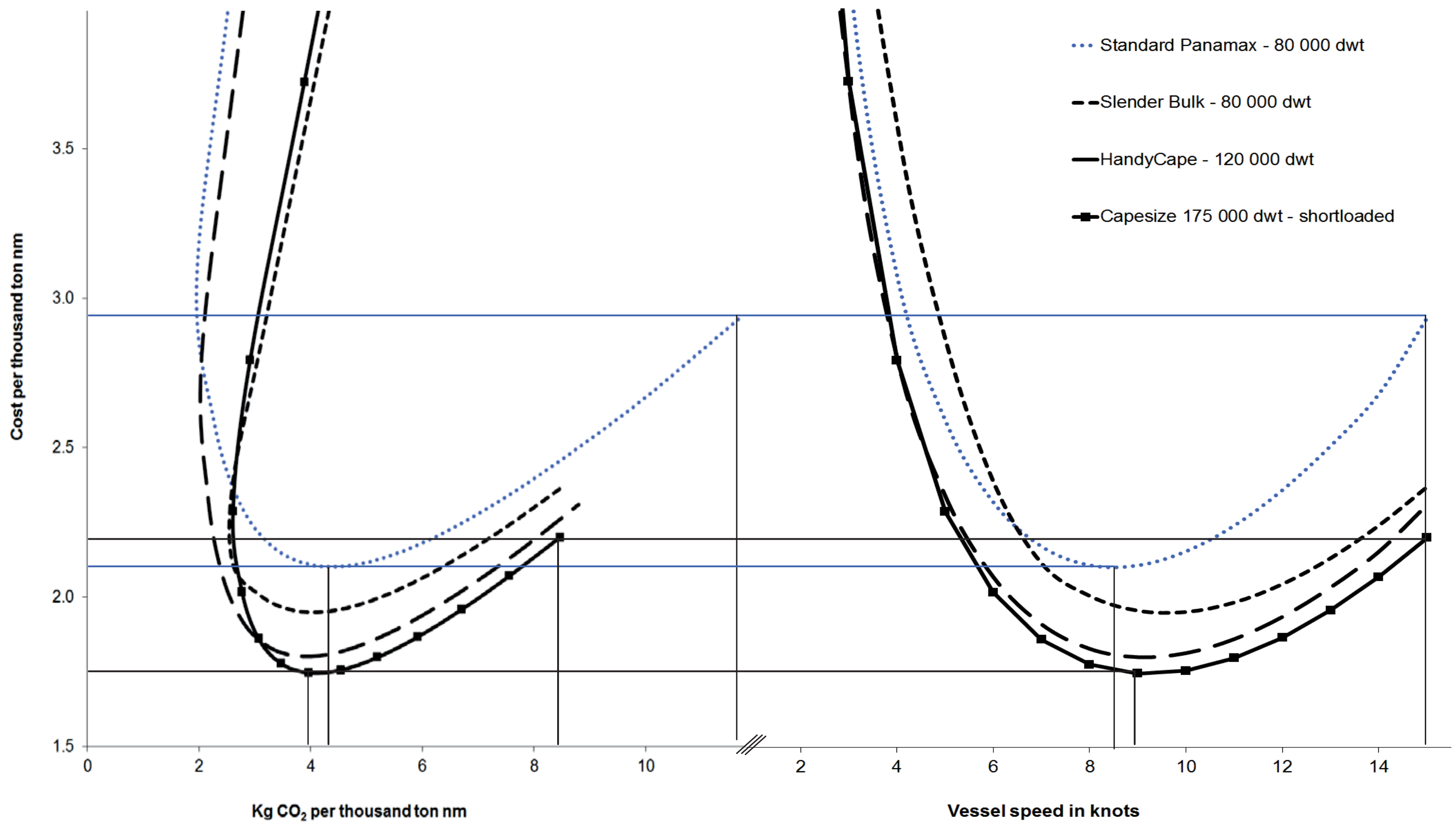

Figure 6: Emission and cost as a function of vessel speed, design and size calm water

The graphs to the right demonstrate a minimum cost for a speed lower than the design speed for all the investigated vessels. And the graphs on the left hand side demonstrate a minimum emission for a speed lower than the design speed. This means that reducing speed from the design speed around 15 knots down to the cost minimum speed of 8 to 9 knots for the standard Panamax reduces cost from 2.9 USD per thousand ton nm down to 2.1 USD per thousand ton mm and emissions from 11.5 kg CO_2 per thousand ton nm down to 4.5 kg CO_2 per thousand ton nm. For the Capesize such a speed reduction reduces cost from 2.2 USD per thousand ton nm down to 1.8 USD per thousand ton nm and emissions from 8.5 kg CO_2 per thousand ton nm down to 4.0 kg CO_2 per thousand ton nm. This indicates that reducing speed from design speed down to the cost minimizing speed gives cost reduction in the size of 15% – 25% per and emission reductions of 50% – 60%. Another observation is that the slender bulk vessel performs much better than the standard Panamax vessel. And when comparing between the slender bulk vessel and the Handy-Cape, the Handy-Cape is slightly better, but the difference is much smaller than what could be expected based on economies of scale effects (Lindstad et al 2012a).

In Figure 7 real sea conditions has been included in addition to calm water conditions focusing on vessels with cargo carrying capacity up to 120 000 tons (excluding the Capesize vessel). In this comparison 4 meter significant head waves ($H_{1/3}$) is used as a proxy for real sea conditions, based on typical sea condition in the North Atlantic (Bales et al., 1980). Waves will come from different directions which gives different power impact, however if an assessment shall be made based on two sea conditions only, 4 meter head waves ($H_{1/3}$) in addition to calm water conditions gives a good benchmark for comparison.

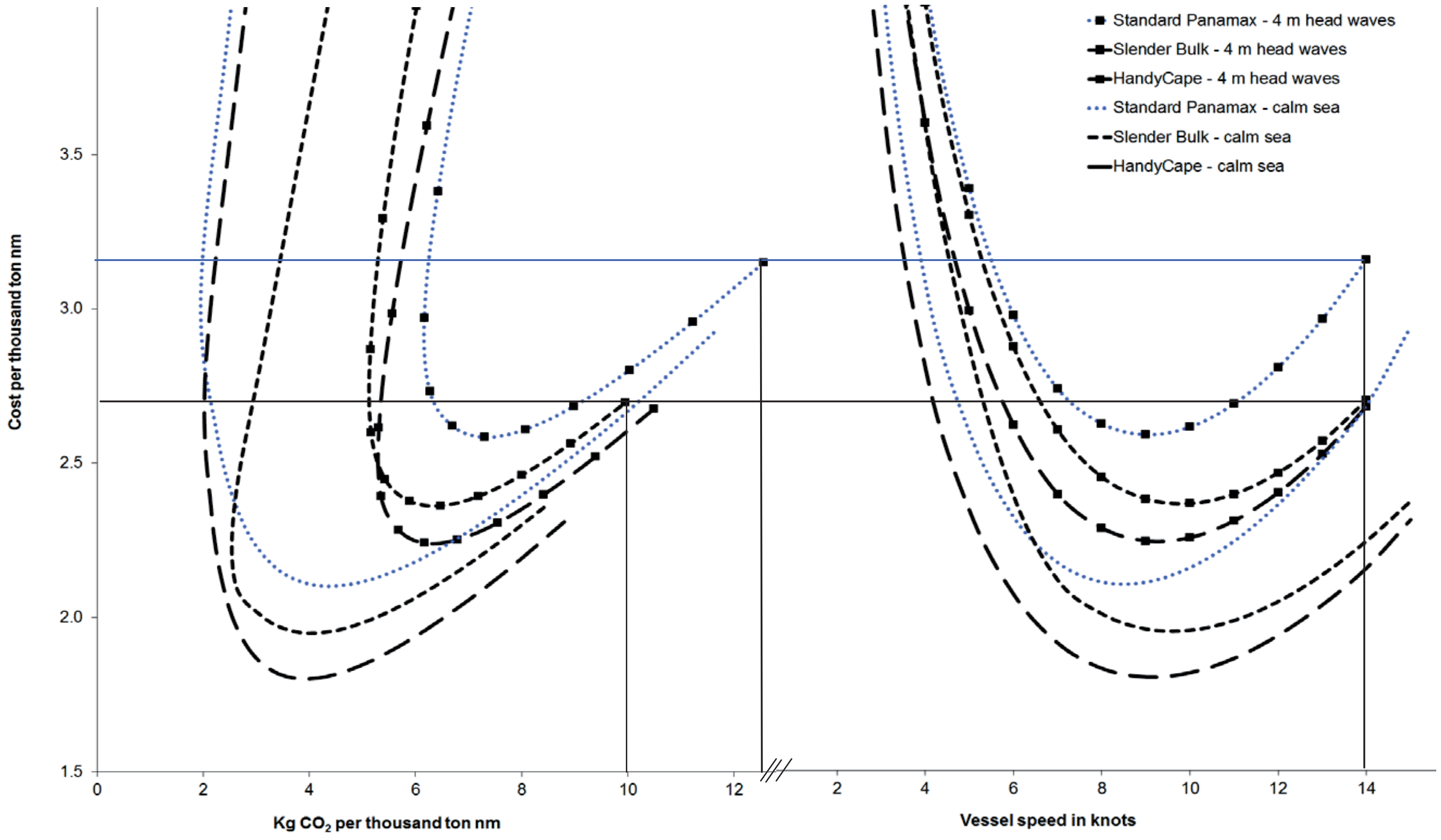

Figure 7: Emission and cost as a function of vessel speed, design, size and sea condition

In the same way as in Figure 6 the graphs to the right demonstrate a minimum cost for a speed lower than the design speed for all the investigated vessels. And the graphs on the left hand side demonstrate a minimum emission for a speed lower than the design speed. Both for calm sea and with 4 meter head waves ($H_{1/3}$). However this is as expected and what really should be noted is that the slender bulk vessel in 4 meter head waves ($H_{1/3}$) operates at a cost and emission level similar to what the standard bulk vessel achieves under calm water conditions. And when comparing between the slender bulk vessel and the Handy-Cape vessel in 4 meter head waves ($H_{1/3}$) the cost advantage the Handy-Cape had at calm water is now further reduced.

These results implicates that more focus should be put on investigating the benefits of slender designs and that shipowners should rather build slender bulk vessels than trying to become more competitive through only utilize economies of scale by building larger vessels. These slender bulk vessels will be even more competitive versus the Handy-Cape vessel in a future scenario where the expansion of the Panama Canal only marginally increases the standard bulk shipment sizes through the canal compared with the existing shipment sizes. A main argument for such a scenario is that there are size restrictions in the ports and fairways these vessels will be serving anyhow in addition to limitations in the supply chains. Examples of supply chain restrictions are physical constraints such as storage capacities and financial cost for carrying larger stocks.

With this section about further research I conclude my thesis.

7. References

Alvarez, J. F. 2009. *Joint routing and deployment of a fleet of container vessels,* Maritime Economics & Logistics. 11 (2009), Page 186-208.

Alvarez, J. F., Engebretsen, E., Longva, T., 2010. *The environmental impact of port queuing policies.* IAME July 2010, Lisbon Portugal.

Anger, A. Barker, T. Pollitt, H. Lindstad, H. Lee D. Eyring, V. 2010. *International Shipping and Market Based Instruments*, 2010, International Maritime Organization. London, UK

Archer, D., Brovkin, V. 2008.*The millennial atmospheric lifetime of anthropogenic CO_2*. Climatic Change, 90 (2008), Page 283–297.

Aribas, F. P. 2007. *Some methods to obtain the added resistance of a ship advancing in waves*, Ocean Engineering 34 (2007), Page 946-955.

Bales, S. L. Lee, W. T., Voelker, J.M., Taylor, D.W 1981. *Standardized Wave and Wind Environments for NATO Operational Areas*, NATO report A414501, 1981.

Bausch, D, O. Brown, G, G. Ronen, D. 1998. *Scheduling short term marine transport of bulk products,* Maritime Policy & Management, 25 (4) (1998), Page 335-348.

Bengtsson, S. Fridell, E. Andersson, K. 2012. *Environmental assessment of two pathways towards the use of biofuels in shipping*, Energy Policy, 44 (2012), Page 451-463.

Biello, D., 2009. *Worlds first fuel cell ships docks in Copenhagen.* www.scientificamerican.com.article

BP 2011, *Sustainability reporting 2011,* www.bp.com/sectiongenericarticle

Brett, P.,O., Boulououris, E., Horgen, R., Konnovessis D., Oestvik I., Mermiris G, Papanikolaou A., Vassalos D. A., 2006. *Methodology for the Logistics-Based Ship Design*, Proceedings 9th Int. Marine Design Conference-IMDC06, Ann Arbor-Michigan, May 2006.

Buhaug, Ø.; Corbett, J.J.; Endresen, Ø.; Eyring, V.; Faber, J.; Hanayama, S.; Lee, D.S.; Lee, D.; Lindstad, H.; Markowska, A.Z.; Mjelde, A.; Nelissen, D.; Nilsen, J.; Pålsson, C.; Winebrake, J.J.; Wu, W.–Q.; Yoshida, K., 2009. *Second IMO GHG study 2009.* International Maritime Organization, London, UK, April.

Capoccitti, S., Anshuman, K., Mildenberger U. 2010 *Aviation Industry – Mitigating Climate Change Impacts through Technology and Policy,* Journal of Technology Management & Innovation, Volume 5, issue 2 (2010).

Cho, S. C. Perakis, A. A., 1996, *Optimal liner fleet routing strategies,* Maritime Policy and Management, 23(1996), Page 249-259.

Christiansen, M. Fagerholt, K., Ronen, D., Nygren, B., 2007. *Maritime Transportation*, In Barnhart, C. and Laporte, G. eds. Handbook in Operations Research and Management Science, 2007, Elsevier.

Clauss, G.F., Siekmann, H. and Tampier B., G. 2007, S*imulation of the operation of wind-assisted cargo ships,* 102 Hauptversammlung der Shiffbautechnischen Gesellschaft, 21–23 November 2007, Berlin.

Corbett, J, J. Wang, H, Winebrake, J, J. 2009, *The effectiveness and cost of speed reductions on emissions from international shipping,* Transportation Research D, 14 (2009), Page 593-598.

Cullinane, K., Khanna, M. 2000. *Economies of scale in large containerships: Optimal size and geographical implications*. Journal of Transport Geography, 8 (3), Page 181-195.

Dadd, G. M., Hudson, D., A., Shenoi, R., A., 2011. *Determination of kite forces using three dimensional flight trajectories for ship propulsion.* Renewable Energy 36 (2011), Page 2667- 2678.

Dalsøren, S., Eide, M., Endresen, Ø., Mjelde, A., Gravir, G. and Isaksen, I. S. A. 2009. *Update on emissions and environmental impacts from the international fleet, the contribution from major ship types and ports*. Atmos. Chem. Phys., 9 (2009), Page 2171-2194.

Dimopoulos, G.G., Kakalis, N.M.P. 2010, *An integrated modeling framework for the design, operation and control of marine energy systems,* CIMAC 2010 Conference, Bergen Norway.

DNV, 2010. *Pathways to low carbon shipping, Abatement potential towards 2030*, www.dnv.com

Duchin, F. 2005. *A World Trade Model Based on Comparative Advantage with m Regions, n Goods, and k Factors*, Economic Systems Research Vol. 17, No.2 (2005), Page 141-162.

ECLAC. 2002. *Maritime Profile of Latin America and the Caribbean,* United Nations Economic Commission for Latin America and the Caribbean, www.eclac.cl/transporte/perfil.

Einang, P.M. 2007. "*Gas-fuelled ships"* CIMAC paper 261- Proceedings of the 25th CIMAC World Congress on Combustion Engines, Wien, Austria, 21–24 May 2007.

Emec, 2010. *Green Ship Technology Book*, Emec, 2010.

EN 16258:2012, *Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers),* http://www.evs.ee/products/evs-en-16258-2012

Endresen, O., Sorgard, E., Behrens, H., L., Brett, P.,O, Isaksen, I., S.,A., 2007. *A historical reconstruction of ships fuel consumption and emissions.* Journal of Geophysical Research Atmosphere 112 (D12).

Eyring, V., Stevenson, D.S., Lauer, A., Dentener, F.J., Butler, T., Collins, W.J., Ellingsen, K., Gauss, M. Hauglustaine, D.A. Isaksen, I.S.A. Lawrence, M. Richter, A. Rodriguez, J.M., Sanderson, M., Strahan, S.E., Sudo, K., Szopa, S., van Noije, T.P.C. and Wild, O. 2007. *Multi-model simulations of the impact of International shipping on Atmospheric Chemistry and Climate in 2000. Atmospheric Chemistry and Physics, 7 (2007), Page 757 -780*

Eyring, V., Corbett, J., J., Lee, D., S., Winebrake, J.J. 2007a. *Brief summary on the impact of ship emissions on atmospheric composition, climate and human health, IMO.org*

Eyring, V. Isaksen, I, S, A. Berntsen, T. Collins, W, J. Corbett, J, J. Endresen, Ø. Grainger, R, G. Moldanova, J. Schlager, H. Stevenson, D, S. 2009. *Transport impacts on atmosphere and climate*: Shipping, Atmospheric Environment, (2009) Page 1-37.

Faber, J., Marowska, A., Nelissen, D., Davidson, M., Eyring, V., Cionni, I., Selstad, E., Kågeson, P., Lee, D., Buhaug, Ø., Lindstad, H., Roche,P., Humpries, E., Graichen, J., Cames, M., Schwarz, 2009. *Technical support for European action to reducing Greenhouse Gas Emissions from international transport.* Oude Delft 180 2611 HH Delft – The Netherlands.

Fagerholt, K., 1999. *Optimal fleet design in a ship routing problem*. International Transactions in Operational Research, 6 (1999), Page 453-464.

Fagerholt, K. 2001 *Ship scheduling with soft time windows – an optimization based approach*. European Journal of Operational Research, 131 (2001), Page 559-571.

Fagerholt, K. Lindstad, H. 2000. *Optimal policies for maintaining a supply service in the Norwegian Sea*, Omega. 28 (2000), Page 269-275.

Fagerholt, K. Lindstad, H. 2007. TurboRouter: *An interactive optimization-based decision support system for ship routing and scheduling*. Maritime Economics&Logistics 9 (2007), Page 214 -233.

Fagerholt, K., Johnsen, T., A., V., Lindstad, H. 2009, *Fleet deployment in liner shipping* – A case study. Maritime Policy & Management, Volume 36 (5) (2009), Page 397- 410.

Fagerholt, K., Laporte, G., Norstad, I. 2010, *Reducing fuel emissions by optimizing speed on shipping routes.* Journal of the Operational Research Society 61 (2010), Page 523-529.

Faltinsen, O., M. Minsaas, K, J. Liapis, N. Skjørdal, S, O. 1980, *Prediction of Resistance and Propulsion of a Ship in a Seaway*. In Proceeding of 13th Symposium on Naval Hydrodynamics, Tokyo, the Shipbuilding Research Association of Japan, 1980, Page 505-529

FCSHIP-project, http://maritimetransportresearch.com/site/project/FP5_31

Green Ship of the Future, 2012, *Waste Heat Recovery Systems*, Green Ship of the Future, www.greenship.org

Guo, B., Steen, S. 2010. *Experiment on added resistance in short waves*, 28th Symposium on Naval Hydrodynamics, Pasadena, California, 12-17 September 2010.

Harlaftis, G., Theotokas, J., 2002, *Maritime business during the 20th Century*: Continuity and Change. In Grammenos, C., T. *The Handbook of Maritime Economics and Business*. Page 9-34. LLP ISBN 1-84311-195-0

Hirota, K., Matsumoto, K., Takagishi, K., Yamasaki, K., Orihara, H. and Yoshida, H., 2005, *Development of bow shape to reduce the added resistance due to waves and verification on full scale measurement.* International conference on marine research and transportation. 2005, Italy.

Hjelle, H., M. 2010. *Short Sea Shipping's Green Label at Risk,* Transport Reviews, Volume 30, Issue 5 (2010), Page 617 – 640.

Hollenbach, U., Friesch, J., 2007. *Efficient hull forms- What can be gained*, 1st Int. Conf. on Ship Efficiency, Hamburg

Howit, O., J., A., Carruthers, M., A., Smith, I., J., Rodger C., J., 2011, *Carbon dioxide emissions from international freight,* Atmosperic Environment Volume 45, issue 39 (2011), Page 7036-7045.

IMAREST, 2011, *Marginal Abatement Costs and Cost-Effectiveness of Energy-Efficiency Measures*, MEPC 62/5/2 and 62/7.

IPCC, 2007, *Contribution of Working Groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change*. 2007, IPCC, Geneva

Kotler, P., 1984, *Marketing Management*: Analysis, Planning, and Control, Prentice-Hall, 1984.

Kristensen, H., O., H., 2010. *Model for Environmental Assessment of Container Ship Transport*, SNAME Annual meeting 2010

Kumar, S. Hoffman, J., 2002, *Globalisation the Maritime Nexus*. In Grammenos, C.T. (editor): The Handbook of Maritime Economics and business. Page 35-64, LLP ISBN 1-84311-195-0

Lauer, A., Eyring, V., Hendricks, J., Jöckel, P. and Lohmann, U. 2007, *Global model simulations of the impact of ocean-going ships on aerosols, clouds, and the radiation budget,* Atmospheric Chemistry and Physics (2007) Pages 5061–5079.

Lee, D.,S., Fahey, D.,W. Forster, P., M., Newton, P.,J., Wit, R.,C., Lim, L., L., Owen, B., Sausen, R. 2009., *Aviation and global climate change in the 21st century,* Atmospheric Environment 43 (2009), Page 3520-3537.

Lindstad, H. 1987, *Economic optimal production apportionment in an industrial group with many factories.* M.Sc. thesis (Sivilingeniør – Hovedoppgave). 1987. Norges Tekniske Høyskole.

Lindstad, H. Pedersen, J.T., 2009. *Using maritime transport to meet climate goals in Europe and challenges for the RoPax vessels.* Conference proceedings FAST 2009 Athens, Greece, October 2009

Lindstad, H. Asbjørnslett, B., E., Strømman, A., H., 2011. *Reductions in greenhouse gas emissions and cost by shipping at lower speeds.* Energy Policy 39 (2011), Page 3456-3464. (Paper – 2)

Lindstad, H., Strømman, A., H., 2011. *Comparing the cost and emissions of maritime and air transport,* under first review for Energy Policy from December 2011 to February 2013. To be resubmitted. (Paper – 5)

Lindstad, H., Asbjørnslett, B., E. Pedersen, J., T. 2012, *Green Maritime Logistics and Sustainability*. In Song D., W, Panayides, P., M. (Eds.) Maritime Logistics: Contemporary Issues (2012), Page 227 – 243, Emerald, ISBN 978-1-78052-340-8. (Paper – 1).

Lindstad, H. Asbjørnslett, B. E., Strømman, A., H., 2012a, *The Importance of economies of scale for reductions in greenhouse gas emissions from shipping.* Energy Policy 46 (2012), Page 386-398. (Paper – 4).

Lindstad, H. Asbjørnslett, B., E., Jullumstrø, E., 2013. *Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market.* Transportation Research Part D 19 (2013), Page 5-12. *(*Paper – 3)

Lindstad, H., Jullumstrø, E., Sandass, 2013a. *Reduction in cost and emissions with new bulk ships designed enabled by the Panama Canal expansion*. Energy Policy 59 (2013), Page 341–349. (Paper – 6)

Lloyd, A., R., J., M. 1988. *Seakeeping, Ship Behaviour in Rough Weather***,** 1998, ISBN 0-9532634-0-1

Lloyds Fairplay (2007). Sea Web database www.lrfairplay.com

Lo, H. K., M., R., McCord, M., R., Wall, C., K. 1991, *Value of ocean current information for strategic routing.* European Journal of Operational Research 55, (1991), Page 124-135.

Madison, A., 2007. *Contours of the World Economy 1 – 2030 AD, Essays in Macro-Economic History*, Oxford University Press, 2007. ISBN 978-0-19-922721-1

MARPOL Convention, *International Convention for the Prevention of Pollution from Ships (MARPOL)* Adoption: 1973 (Convention), 1978 (1978 Protocol), 1997 (Protocol - Annex VI). http://www.imo.org.

McCord, M. R., Lee, Y., H., Lo, H., K., 1999, *Ship routing through altimetry-derived ocean currents.* Transportation Science 33(1) (1999), Page 49-67.

MOSES 2009. Nesheim, D., Lindstad, H., Pedersen, J., T., Holte, E. , *The MOSES blueprint,* DeliverableD43.8 Final Project Deliverable, Contract No. TREN/07/FP6TR/S07.71195/038585 MOSES, Marintek 2009

Norstad, I. Fagerholt, K. Laporte, G. 2010. *Tramp shipping routing and scheduling with optimization*. Transportation Research Part C 19 issue 5 (2010). Pages 853-865

Notteboom, T.E., Vernimmen, B., 2009. *The effect of high fuel liner service configuration in container shipping.* Journal of Transport Geography 17 (2009), Page 325–337.

OECD 2010, *OECD Globalization, Transport and the Environment,* 2010, ISBN 978-92-64-07290-9

OECD 2011, www.oecd.org

Ohlin, B., G., 1933. *Interregional and International Trade,* monograph, Stockholm, Sweden.

Orsic, J.P. Faltinsen, O. M., 2012. *Estimation of ship speed loss and associated* CO_2 *emissions in a seaway.* Ocean Engineering 44 (2012), Page 1 -10

Panama Canal Authority *2006. Proposal for the Expansion of the Panama Canal*. Panama Canal authority, 26.04.2006

Papadakis, N. A., Perakis, A.N. 1990, *Deterministic minimal time vessel routing*. Operations Research 38(3), (1990), Page 426-438.

Payer, H. G. Brostella, R. 2007. *The Panama Canal expansion and the Panamax vessel of the future*. Society of Naval Architects and Marine Engineer 114 (2007), Page 187-208.

Pedersen, J.T., Ottjes, J., Veeke, H., Lindstad, H., 1999. *IPSI A Revolutionary Concept for Intermodal Transport*. European Commission

Pedersen, T. A. 2009, *Bond graph modeling of marine power systems. NTNU,* Faculty of Engineering Science and Technology, Department of Marine Technology. (2009:56), PhD-thesis

Perakis, A. N., Papadakis. N. A., 1989. *Minimal time vessel routing in a time-dependent environment.* Transportation Science 23, (1989), Page 266-276.

Perkins, T, Dijkstra, G., Perini Navi team, Roberts, D. 2004 "*The Maltese Falcon: the realization*", Hiswa Symposium 2004.

Psaraftis, H, N. Kontovas, C, A. 2010. *Balancing the economic and environmental performance of maritime transport.* Transportation Research Part D 15 (2010). Page 458-462.
Resolution A.963 (23), www.imo.org

Resolution MEPC.203 (62), www.imo.org

Ricardo, D. 1817. *Principles of Political Economy and Taxation*, London

Russell, B., A., Wang, H., Zeinali, M. 2010, *Marginal Abatement Costs of CO_2 Emissions Reduction and Market-Based Mechanisms and the Pricing of Credits*. www.corporateclimate.net/green-transportation-climate/logistics-supply-chain/74-cost-for-a-ship-to-reduce-co2-emissions-or-increase-efficiency.html

Sea at Risk and CE Delft, 2010. *Going Slow to Reduce Emissions,* www.seas-at-risk.org

Sgouridis, S., Bonnefoy, P., A., Hansman, R., J., 2011, *Air transportation in a carbon constrained world: Long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation*, Transportation Research Part A - 45 (2011), Page 1077-1091

Silverleaf, A., Dawson, J., 1966. *Hydrodynamic design of merchant ships for high speed operation*. Summer meeting in Germany 12th – 16th of June, 1966. The Schiffbautechnische Gescaft E.V, The institute of marine engineers, The institute of engineers and shipbuilders in Scotland, The North East Coast Institution of Engineers and shipbuilders, The Royal institution of naval architects.

Skjølsvik, K.O., Andersen, A.B., Corbett, J.J., and Skjelvik, J.M. 2000. *Study of greenhouse gas emissions from ships,* MEPC 45/8: Report to International Maritime Organization on the outcome of the IMO Study on Greenhouse Gas Emissions from Ships. www.IMO.org.

Smith, A. 1776. *An Inquiry into the Nature and Causes of the Wealth of Nations*. London, UK.

Steen, S. and Faltinsen, O. M. 1988, *Added Resistance of a Ship Moving in Small Sea States*", PRADS'98, The Hague, Netherlands, September 1998, ISBN 0 444 82918 0

Stott, P., Wright, P., 2011. *Opportunities for improved efficiency and reduced CO2 emissions in dry bulk shipping stemming from the relaxation of the Panamax beam constraint.* Trans RINA, Vol. 153. Part A4, Intl J Maritime Eng. Oct-Dec 2011

Stopford, M. 2009. *Maritime Economics* 3rd edition. 2009. Oxon: Routlegde

Streamline project, 2010. www.streamline-project.eu

Strøm-Tejsen, J., Yeh, H., Y., H., Moran, D., D. 1973, *Added resistance in waves*, Transaction of the SNAME 78 (1973), Page 109 – 143.

Strømman, A., H., Hertwich, E., G., Duchin, F. 2008. *Shifting Trade Patterns as a Means of Reducing Global Carbon Dioxide Emissions, A Multiobjective Analysis*, Journal of Industrial Ecology, Volume 13, Number 1 (2008).

Strømman, A, H. Duchin, F. 2006. *A World Trade Model with Bilateral Trade Based on Comparative Advantage,* Economic System Research, Vol.18, No.3 (2006), Page 281-297

Sys, C., Blauwens, G., Omey, E., Van de Voorde, E., Witlox, F., 2008. *In Search of the Link between Ship Size and Operations.* Transportation Planning and Technology, August 2008. Vol. 31, No. 4 pages 435 – 463

TNO, 2004. *GES - A system for propulsion and energy system studies*, TNO, Delft, Netherlands.

Thomson, 2008. *Panamax gets larger*. Motor Ships 88 (1045), 2008

Turan, O. 2012, *INGRES - Intelligent green ships towards Zero emission.* EU proposal submitted for call SST.2013.1-2. Nov 2012. Glasgow, Great Britain

UNCTAD 2011, *Review of Maritime Transport 2011*. United Nations Conference on Trade and Development: New York and Geneva, ISBN 978-92-1-112841-3

UNCTAD 2012, *Review of Maritime Transport 2012*. United Nations Conference on Trade and Development: New York and Geneva, *ISBN 978-92-1-112860-4*

Van der Boom, 2010. *Ship Performance Analysis on Full Scale*, Workshop NMRI-MARIN June 24, 2010 http://www.marin.nl

Walker and King, 2008 Walker, G. King, D. *The hot topic: How to tackle global warming and still keep the lights on.* 2008, London: Bloomsbury

Westlake, A., 2012, *Solar-powered hybrid ship built to transport cars in Japan*, The Japan Daily Press Bringing Japan to Asia and to the World, http://japandailypress.com/solar-powered-hybrid-ship-built-to-transport-cars-in-japan

Wijnholst, N. and Wergeland, T. 2009. *Shipping Innovation*, IOS Press. ISBN 978-1-58603-943-1.

Wintecc project, 2007, www:ec.europa.eu/environment/life/news/newsarchive2007/november/index.htm

World Bank, 2011, *GDP*, www.data.worldbank.org

WTO 2011, *International Trade Statistics 2011,* World Trade Organisation, www.wto.org

8. Appendix: Previous PhD theses, Marine Technology, NTNU

Previous PhD theses published at the Departement of Marine Technology
(earlier: Faculty of Marine Technology)
NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Report No.	Author	Title
	Kavlie, Dag	Optimization of Plane Elastic Grillages, 1967
	Hansen, Hans R.	Man-Machine Communication and Data-Storage Methods in Ship Structural Design, 1971
	Gisvold, Kaare M.	A Method for non-linear mixed -integer programming and its Application to Design Problems, 1971
	Lund, Sverre	Tanker Frame Optimalization by means of SUMT-Transformation and Behaviour Models, 1971
	Vinje, Tor	On Vibration of Spherical Shells Interacting with Fluid, 1972
	Lorentz, Jan D.	Tank Arrangement for Crude Oil Carriers in Accordance with the new Anti-Pollution Regulations, 1975
	Carlsen, Carl A.	Computer-Aided Design of Tanker Structures, 1975
	Larsen, Carl M.	Static and Dynamic Analysis of Offshore Pipelines during Installation, 1976
UR-79-01	Brigt Hatlestad, MK	The finite element method used in a fatigue evaluation of fixed offshore platforms. (Dr.Ing. Thesis)
UR-79-02	Erik Pettersen, MK	Analysis and design of cellular structures. (Dr.Ing. Thesis)
UR-79-03	Sverre Valsgård, MK	Finite difference and finite element methods applied to nonlinear analysis of plated structures. (Dr.Ing. Thesis)
UR-79-04	Nils T. Nordsve, MK	Finite element collapse analysis of structural members considering imperfections and stresses due to fabrication. (Dr.Ing. Thesis)
UR-79-05	Ivar J. Fylling, MK	Analysis of towline forces in ocean towing systems. (Dr.Ing. Thesis)
UR-80-06	Nils Sandsmark, MM	Analysis of Stationary and Transient Heat Conduction by the Use of the Finite Element Method. (Dr.Ing. Thesis)
UR-80-09	Sverre Haver, MK	Analysis of uncertainties related to the stochastic modeling of ocean waves. (Dr.Ing. Thesis)

UR-81-15	Odland, Jonas	On the Strength of welded Ring stiffened cylindrical Shells primarily subjected to axial Compression
UR-82-17	Engesvik, Knut	Analysis of Uncertainties in the fatigue Capacity of Welded Joints
UR-82-18	Rye, Henrik	Ocean wave groups
UR-83-30	Eide, Oddvar Inge	On Cumulative Fatigue Damage in Steel Welded Joints
UR-83-33	Mo, Olav	Stochastic Time Domain Analysis of Slender Offshore Structures
UR-83-34	Amdahl, Jørgen	Energy absorption in Ship-platform impacts
UR-84-37	Mørch, Morten	Motions and mooring forces of semi submersibles as determined by full-scale measurements and theoretical analysis
UR-84-38	Soares, C. Guedes	Probabilistic models for load effects in ship structures
UR-84-39	Aarsnes, Jan V.	Current forces on ships
UR-84-40	Czujko, Jerzy	Collapse Analysis of Plates subjected to Biaxial Compression and Lateral Load
UR-85-46	Alf G. Engseth, MK	Finite element collapse analysis of tubular steel offshore structures. (Dr.Ing. Thesis)
UR-86-47	Dengody Sheshappa, MP	A Computer Design Model for Optimizing Fishing Vessel Designs Based on Techno-Economic Analysis. (Dr.Ing. Thesis)
UR-86-48	Vidar Aanesland, MH	A Theoretical and Numerical Study of Ship Wave Resistance. (Dr.Ing. Thesis)
UR-86-49	Heinz-Joachim Wessel, MK	Fracture Mechanics Analysis of Crack Growth in Plate Girders. (Dr.Ing. Thesis)
UR-86-50	Jon Taby, MK	Ultimate and Post-ultimate Strength of Dented Tubular Members. (Dr.Ing. Thesis)
UR-86-51	Walter Lian, MH	A Numerical Study of Two-Dimensional Separated Flow Past Bluff Bodies at Moderate KC-Numbers. (Dr.Ing. Thesis)
UR-86-52	Bjørn Sortland, MH	Force Measurements in Oscillating Flow on Ship Sections and Circular Cylinders in a U-Tube Water Tank. (Dr.Ing. Thesis)
UR-86-53	Kurt Strand, MM	A System Dynamic Approach to One-dimensional Fluid Flow. (Dr.Ing. Thesis)
UR-86-54	Arne Edvin Løken, MH	Three Dimensional Second Order Hydrodynamic Effects on Ocean Structures in Waves. (Dr.Ing. Thesis)

UR-86-55	Sigurd Falch, MH	A Numerical Study of Slamming of Two-Dimensional Bodies. (Dr.Ing. Thesis)
UR-87-56	Arne Braathen, MH	Application of a Vortex Tracking Method to the Prediction of Roll Damping of a Two-Dimension Floating Body. (Dr.Ing. Thesis)
UR-87-57	Bernt Leira, MK	Gaussian Vector Processes for Reliability Analysis involving Wave-Induced Load Effects. (Dr.Ing. Thesis)
UR-87-58	Magnus Småvik, MM	Thermal Load and Process Characteristics in a Two-Stroke Diesel Engine with Thermal Barriers (in Norwegian). (Dr.Ing. Thesis)
MTA-88-59	Bernt Arild Bremdal, MP	An Investigation of Marine Installation Processes – A Knowledge - Based Planning Approach. (Dr.Ing. Thesis)
MTA-88-60	Xu Jun, MK	Non-linear Dynamic Analysis of Space-framed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-61	Gang Miao, MH	Hydrodynamic Forces and Dynamic Responses of Circular Cylinders in Wave Zones. (Dr.Ing. Thesis)
MTA-89-62	Martin Greenhow, MH	Linear and Non-Linear Studies of Waves and Floating Bodies. Part I and Part II. (Dr.Techn. Thesis)
MTA-89-63	Chang Li, MH	Force Coefficients of Spheres and Cubes in Oscillatory Flow with and without Current. (Dr.Ing. Thesis
MTA-89-64	Hu Ying, MP	A Study of Marketing and Design in Development of Marine Transport Systems. (Dr.Ing. Thesis)
MTA-89-65	Arild Jæger, MH	Seakeeping, Dynamic Stability and Performance of a Wedge Shaped Planing Hull. (Dr.Ing. Thesis)
MTA-89-66	Chan Siu Hung, MM	The dynamic characteristics of tilting-pad bearings
MTA-89-67	Kim Wikstrøm, MP	Analysis av projekteringen for ett offshore projekt. (Licenciat-avhandling)
MTA-89-68	Jiao Guoyang, MK	Reliability Analysis of Crack Growth under Random Loading, considering Model Updating. (Dr.Ing. Thesis)
MTA-89-69	Arnt Olufsen, MK	Uncertainty and Reliability Analysis of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-70	Wu Yu-Lin, MR	System Reliability Analyses of Offshore Structures using improved Truss and Beam Models. (Dr.Ing. Thesis)
MTA-90-71	Jan Roger Hoff, MH	Three-dimensional Green function of a vessel with forward speed in waves. (Dr.Ing. Thesis)
MTA-90-72	Rong Zhao, MH	Slow-Drift Motions of a Moored Two-Dimensional Body in Irregular Waves. (Dr.Ing. Thesis)

MTA-90-73	Atle Minsaas, MP	Economical Risk Analysis. (Dr.Ing. Thesis)
MTA-90-74	Knut-Aril Farnes, MK	Long-term Statistics of Response in Non-linear Marine Structures. (Dr.Ing. Thesis)
MTA-90-75	Torbjørn Sotberg, MK	Application of Reliability Methods for Safety Assessment of Submarine Pipelines. (Dr.Ing. Thesis)
MTA-90-76	Zeuthen, Steffen, MP	SEAMAID. A computational model of the design process in a constraint-based logic programming environment. An example from the offshore domain. (Dr.Ing. Thesis)
MTA-91-77	Haagensen, Sven, MM	Fuel Dependant Cyclic Variability in a Spark Ignition Engine - An Optical Approach. (Dr.Ing. Thesis)
MTA-91-78	Løland, Geir, MH	Current forces on and flow through fish farms. (Dr.Ing. Thesis)
MTA-91-79	Hoen, Christopher, MK	System Identification of Structures Excited by Stochastic Load Processes. (Dr.Ing. Thesis)
MTA-91-80	Haugen, Stein, MK	Probabilistic Evaluation of Frequency of Collision between Ships and Offshore Platforms. (Dr.Ing. Thesis)
MTA-91-81	Sødahl, Nils, MK	Methods for Design and Analysis of Flexible Risers. (Dr.Ing. Thesis)
MTA-91-82	Ormberg, Harald, MK	Non-linear Response Analysis of Floating Fish Farm Systems. (Dr.Ing. Thesis)
MTA-91-83	Marley, Mark J., MK	Time Variant Reliability under Fatigue Degradation. (Dr.Ing. Thesis)
MTA-91-84	Krokstad, Jørgen R., MH	Second-order Loads in Multidirectional Seas. (Dr.Ing. Thesis)
MTA-91-85	Molteberg, Gunnar A., MM	The Application of System Identification Techniques to Performance Monitoring of Four Stroke Turbocharged Diesel Engines. (Dr.Ing. Thesis)
MTA-92-86	Mørch, Hans Jørgen Bjelke, MH	Aspects of Hydrofoil Design: with Emphasis on Hydrofoil Interaction in Calm Water. (Dr.Ing. Thesis)
MTA-92-87	Chan Siu Hung, MM	Nonlinear Analysis of Rotordynamic Instabilities in Highspeed Turbomachinery. (Dr.Ing. Thesis)
MTA-92-88	Bessason, Bjarni, MK	Assessment of Earthquake Loading and Response of Seismically Isolated Bridges. (Dr.Ing. Thesis)
MTA-92-89	Langli, Geir, MP	Improving Operational Safety through exploitation of Design Knowledge - an investigation of offshore platform safety. (Dr.Ing. Thesis)

MTA-92-90	Sævik, Svein, MK	On Stresses and Fatigue in Flexible Pipes. (Dr.Ing. Thesis)
MTA-92-91	Ask, Tor Ø., MM	Ignition and Flame Growth in Lean Gas-Air Mixtures. An Experimental Study with a Schlieren System. (Dr.Ing. Thesis)
MTA-86-92	Hessen, Gunnar, MK	Fracture Mechanics Analysis of Stiffened Tubular Members. (Dr.Ing. Thesis)
MTA-93-93	Steinebach, Christian, MM	Knowledge Based Systems for Diagnosis of Rotating Machinery. (Dr.Ing. Thesis)
MTA-93-94	Dalane, Jan Inge, MK	System Reliability in Design and Maintenance of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-93-95	Steen, Sverre, MH	Cobblestone Effect on SES. (Dr.Ing. Thesis)
MTA-93-96	Karunakaran, Daniel, MK	Nonlinear Dynamic Response and Reliability Analysis of Drag-dominated Offshore Platforms. (Dr.Ing. Thesis)
MTA-93-97	Hagen, Arnulf, MP	The Framework of a Design Process Language. (Dr.Ing. Thesis)
MTA-93-98	Nordrik, Rune, MM	Investigation of Spark Ignition and Autoignition in Methane and Air Using Computational Fluid Dynamics and Chemical Reaction Kinetics. A Numerical Study of Ignition Processes in Internal Combustion Engines. (Dr.Ing. Thesis)
MTA-94-99	Passano, Elizabeth, MK	Efficient Analysis of Nonlinear Slender Marine Structures. (Dr.Ing. Thesis)
MTA-94-100	Kvålsvold, Jan, MH	Hydroelastic Modelling of Wetdeck Slamming on Multihull Vessels. (Dr.Ing. Thesis)
MTA-94-102	Bech, Sidsel M., MK	Experimental and Numerical Determination of Stiffness and Strength of GRP/PVC Sandwich Structures. (Dr.Ing. Thesis)
MTA-95-103	Paulsen, Hallvard, MM	A Study of Transient Jet and Spray using a Schlieren Method and Digital Image Processing. (Dr.Ing. Thesis)
MTA-95-104	Hovde, Geir Olav, MK	Fatigue and Overload Reliability of Offshore Structural Systems, Considering the Effect of Inspection and Repair. (Dr.Ing. Thesis)
MTA-95-105	Wang, Xiaozhi, MK	Reliability Analysis of Production Ships with Emphasis on Load Combination and Ultimate Strength. (Dr.Ing. Thesis)
MTA-95-106	Ulstein, Tore, MH	Nonlinear Effects of a Flexible Stern Seal Bag on Cobblestone Oscillations of an SES. (Dr.Ing. Thesis)
MTA-95-107	Solaas, Frøydis, MH	Analytical and Numerical Studies of Sloshing in

		Tanks. (Dr.Ing. Thesis)
MTA-95-108	Hellan, Øyvind, MK	Nonlinear Pushover and Cyclic Analyses in Ultimate Limit State Design and Reassessment of Tubular Steel Offshore Structures. (Dr.Ing. Thesis)
MTA-95-109	Hermundstad, Ole A., MK	Theoretical and Experimental Hydroelastic Analysis of High Speed Vessels. (Dr.Ing. Thesis)
MTA-96-110	Bratland, Anne K., MH	Wave-Current Interaction Effects on Large-Volume Bodies in Water of Finite Depth. (Dr.Ing. Thesis)
MTA-96-111	Herfjord, Kjell, MH	A Study of Two-dimensional Separated Flow by a Combination of the Finite Element Method and Navier-Stokes Equations. (Dr.Ing. Thesis)
MTA-96-112	Æsøy, Vilmar, MM	Hot Surface Assisted Compression Ignition in a Direct Injection Natural Gas Engine. (Dr.Ing. Thesis)
MTA-96-113	Eknes, Monika L., MK	Escalation Scenarios Initiated by Gas Explosions on Offshore Installations. (Dr.Ing. Thesis)
MTA-96-114	Erikstad, Stein O., MP	A Decision Support Model for Preliminary Ship Design. (Dr.Ing. Thesis)
MTA-96-115	Pedersen, Egil, MH	A Nautical Study of Towed Marine Seismic Streamer Cable Configurations. (Dr.Ing. Thesis)
MTA-97-116	Moksnes, Paul O., MM	Modelling Two-Phase Thermo-Fluid Systems Using Bond Graphs. (Dr.Ing. Thesis)
MTA-97-117	Halse, Karl H., MK	On Vortex Shedding and Prediction of Vortex-Induced Vibrations of Circular Cylinders. (Dr.Ing. Thesis)
MTA-97-118	Igland, Ragnar T., MK	Reliability Analysis of Pipelines during Laying, considering Ultimate Strength under Combined Loads. (Dr.Ing. Thesis)
MTA-97-119	Pedersen, Hans-P., MP	Levendefiskteknologi for fiskefartøy. (Dr.Ing. Thesis)
MTA-98-120	Vikestad, Kyrre, MK	Multi-Frequency Response of a Cylinder Subjected to Vortex Shedding and Support Motions. (Dr.Ing. Thesis)
MTA-98-121	Azadi, Mohammad R. E., MK	Analysis of Static and Dynamic Pile-Soil-Jacket Behaviour. (Dr.Ing. Thesis)
MTA-98-122	Ulltang, Terje, MP	A Communication Model for Product Information. (Dr.Ing. Thesis)
MTA-98-123	Torbergsen, Erik, MM	Impeller/Diffuser Interaction Forces in Centrifugal Pumps. (Dr.Ing. Thesis)
MTA-98-124	Hansen, Edmond, MH	A Discrete Element Model to Study Marginal Ice Zone Dynamics and the Behaviour of Vessels

		Moored in Broken Ice. (Dr.Ing. Thesis)
MTA-98-125	Videiro, Paulo M., MK	Reliability Based Design of Marine Structures. (Dr.Ing. Thesis)
MTA-99-126	Mainçon, Philippe, MK	Fatigue Reliability of Long Welds Application to Titanium Risers. (Dr.Ing. Thesis)
MTA-99-127	Haugen, Elin M., MH	Hydroelastic Analysis of Slamming on Stiffened Plates with Application to Catamaran Wetdecks. (Dr.Ing. Thesis)
MTA-99-128	Langhelle, Nina K., MK	Experimental Validation and Calibration of Nonlinear Finite Element Models for Use in Design of Aluminium Structures Exposed to Fire. (Dr.Ing. Thesis)
MTA-99-129	Berstad, Are J., MK	Calculation of Fatigue Damage in Ship Structures. (Dr.Ing. Thesis)
MTA-99-130	Andersen, Trond M., MM	Short Term Maintenance Planning. (Dr.Ing. Thesis)
MTA-99-131	Tveiten, Bård Wathne, MK	Fatigue Assessment of Welded Aluminium Ship Details. (Dr.Ing. Thesis)
MTA-99-132	Søreide, Fredrik, MP	Applications of underwater technology in deep water archaeology. Principles and practice. (Dr.Ing. Thesis)
MTA-99-133	Tønnessen, Rune, MH	A Finite Element Method Applied to Unsteady Viscous Flow Around 2D Blunt Bodies With Sharp Corners. (Dr.Ing. Thesis)
MTA-99-134	Elvekrok, Dag R., MP	Engineering Integration in Field Development Projects in the Norwegian Oil and Gas Industry. The Supplier Management of Norne. (Dr.Ing. Thesis)
MTA-99-135	Fagerholt, Kjetil, MP	Optimeringsbaserte Metoder for Ruteplanlegging innen skipsfart. (Dr.Ing. Thesis)
MTA-99-136	Bysveen, Marie, MM	Visualization in Two Directions on a Dynamic Combustion Rig for Studies of Fuel Quality. (Dr.Ing. Thesis)
MTA-2000-137	Storteig, Eskild, MM	Dynamic characteristics and leakage performance of liquid annular seals in centrifugal pumps. (Dr.Ing. Thesis)
MTA-2000-138	Sagli, Gro, MK	Model uncertainty and simplified estimates of long term extremes of hull girder loads in ships. (Dr.Ing. Thesis)
MTA-2000-139	Tronstad, Harald, MK	Nonlinear analysis and design of cable net structures like fishing gear based on the finite element method. (Dr.Ing. Thesis)
MTA-2000-140	Kroneberg, André, MP	Innovation in shipping by using scenarios. (Dr.Ing. Thesis)

MTA-2000-141	Haslum, Herbjørn Alf, MH	Simplified methods applied to nonlinear motion of spar platforms. (Dr.Ing. Thesis)
MTA-2001-142	Samdal, Ole Johan, MM	Modelling of Degradation Mechanisms and Stressor Interaction on Static Mechanical Equipment Residual Lifetime. (Dr.Ing. Thesis)
MTA-2001-143	Baarholm, Rolf Jarle, MH	Theoretical and experimental studies of wave impact underneath decks of offshore platforms. (Dr.Ing. Thesis)
MTA-2001-144	Wang, Lihua, MK	Probabilistic Analysis of Nonlinear Wave-induced Loads on Ships. (Dr.Ing. Thesis)
MTA-2001-145	Kristensen, Odd H. Holt, MK	Ultimate Capacity of Aluminium Plates under Multiple Loads, Considering HAZ Properties. (Dr.Ing. Thesis)
MTA-2001-146	Greco, Marilena, MH	A Two-Dimensional Study of Green-Water Loading. (Dr.Ing. Thesis)
MTA-2001-147	Heggelund, Svein E., MK	Calculation of Global Design Loads and Load Effects in Large High Speed Catamarans. (Dr.Ing. Thesis)
MTA-2001-148	Babalola, Olusegun T., MK	Fatigue Strength of Titanium Risers – Defect Sensitivity. (Dr.Ing. Thesis)
MTA-2001-149	Mohammed, Abuu K., MK	Nonlinear Shell Finite Elements for Ultimate Strength and Collapse Analysis of Ship Structures. (Dr.Ing. Thesis)
MTA-2002-150	Holmedal, Lars E., MH	Wave-current interactions in the vicinity of the sea bed. (Dr.Ing. Thesis)
MTA-2002-151	Rognebakke, Olav F., MH	Sloshing in rectangular tanks and interaction with ship motions. (Dr.Ing. Thesis)
MTA-2002-152	Lader, Pål Furset, MH	Geometry and Kinematics of Breaking Waves. (Dr.Ing. Thesis)
MTA-2002-153	Yang, Qinzheng, MH	Wash and wave resistance of ships in finite water depth. (Dr.Ing. Thesis)
MTA-2002-154	Melhus, Øyvin, MM	Utilization of VOC in Diesel Engines. Ignition and combustion of VOC released by crude oil tankers. (Dr.Ing. Thesis)
MTA-2002-155	Ronæss, Marit, MH	Wave Induced Motions of Two Ships Advancing on Parallel Course. (Dr.Ing. Thesis)
MTA-2002-156	Økland, Ole D., MK	Numerical and experimental investigation of whipping in twin hull vessels exposed to severe wet deck slamming. (Dr.Ing. Thesis)
MTA-2002-157	Ge, Chunhua, MK	Global Hydroelastic Response of Catamarans due to Wet Deck Slamming. (Dr.Ing. Thesis)

MTA-2002-158	Byklum, Eirik, MK	Nonlinear Shell Finite Elements for Ultimate Strength and Collapse Analysis of Ship Structures. (Dr.Ing. Thesis)
IMT-2003-1	Chen, Haibo, MK	Probabilistic Evaluation of FPSO-Tanker Collision in Tandem Offloading Operation. (Dr.Ing. Thesis)
IMT-2003-2	Skaugset, Kjetil Bjørn, MK	On the Suppression of Vortex Induced Vibrations of Circular Cylinders by Radial Water Jets. (Dr.Ing. Thesis)
IMT-2003-3	Chezhian, Muthu	Three-Dimensional Analysis of Slamming. (Dr.Ing. Thesis)
IMT-2003-4	Buhaug, Øyvind	Deposit Formation on Cylinder Liner Surfaces in Medium Speed Engines. (Dr.Ing. Thesis)
IMT-2003-5	Tregde, Vidar	Aspects of Ship Design: Optimization of Aft Hull with Inverse Geometry Design. (Dr.Ing. Thesis)
IMT-2003-6	Wist, Hanne Therese	Statistical Properties of Successive Ocean Wave Parameters. (Dr.Ing. Thesis)
IMT-2004-7	Ransau, Samuel	Numerical Methods for Flows with Evolving Interfaces. (Dr.Ing. Thesis)
IMT-2004-8	Soma, Torkel	Blue-Chip or Sub-Standard. A data interrogation approach of identity safety characteristics of shipping organization. (Dr.Ing. Thesis)
IMT-2004-9	Ersdal, Svein	An experimental study of hydrodynamic forces on cylinders and cables in near axial flow. (Dr.Ing. Thesis)
IMT-2005-10	Brodtkorb, Per Andreas	The Probability of Occurrence of Dangerous Wave Situations at Sea. (Dr.Ing. Thesis)
IMT-2005-11	Yttervik, Rune	Ocean current variability in relation to offshore engineering. (Dr.Ing. Thesis)
IMT-2005-12	Fredheim, Arne	Current Forces on Net-Structures. (Dr.Ing. Thesis)
IMT-2005-13	Heggernes, Kjetil	Flow around marine structures. (Dr.Ing. Thesis
IMT-2005-14	Fouques, Sebastien	Lagrangian Modelling of Ocean Surface Waves and Synthetic Aperture Radar Wave Measurements. (Dr.Ing. Thesis)
IMT-2006-15	Holm, Håvard	Numerical calculation of viscous free surface flow around marine structures. (Dr.Ing. Thesis)
IMT-2006-16	Bjørheim, Lars G.	Failure Assessment of Long Through Thickness Fatigue Cracks in Ship Hulls. (Dr.Ing. Thesis)
IMT-2006-17	Hansson, Lisbeth	Safety Management for Prevention of Occupational Accidents. (Dr.Ing. Thesis)

IMT-2006-18	Zhu, Xinying	Application of the CIP Method to Strongly Nonlinear Wave-Body Interaction Problems. (Dr.Ing. Thesis)
IMT-2006-19	Reite, Karl Johan	Modelling and Control of Trawl Systems. (Dr.Ing. Thesis)
IMT-2006-20	Smogeli, Øyvind Notland	Control of Marine Propellers. From Normal to Extreme Conditions. (Dr.Ing. Thesis)
IMT-2007-21	Storhaug, Gaute	Experimental Investigation of Wave Induced Vibrations and Their Effect on the Fatigue Loading of Ships. (Dr.Ing. Thesis)
IMT-2007-22	Sun, Hui	A Boundary Element Method Applied to Strongly Nonlinear Wave-Body Interaction Problems. (PhD Thesis, CeSOS)
IMT-2007-23	Rustad, Anne Marthine	Modelling and Control of Top Tensioned Risers. (PhD Thesis, CeSOS)
IMT-2007-24	Johansen, Vegar	Modelling flexible slender system for real-time simulations and control applications
IMT-2007-25	Wroldsen, Anders Sunde	Modelling and control of tensegrity structures. (PhD Thesis, CeSOS)
IMT-2007-26	Aronsen, Kristoffer Høye	An experimental investigation of in-line and combined inline and cross flow vortex induced vibrations. (Dr. avhandling, IMT)
IMT-2007-27	Gao, Zhen	Stochastic Response Analysis of Mooring Systems with Emphasis on Frequency-domain Analysis of Fatigue due to Wide-band Response Processes (PhD Thesis, CeSOS)
IMT-2007-28	Thorstensen, Tom Anders	Lifetime Profit Modelling of Ageing Systems Utilizing Information about Technical Condition. (Dr.ing. thesis, IMT)
IMT-2008-29	Berntsen, Per Ivar B.	Structural Reliability Based Position Mooring. (PhD-Thesis, IMT)
IMT-2008-30	Ye, Naiquan	Fatigue Assessment of Aluminium Welded Box-stiffener Joints in Ships (Dr.ing. thesis, IMT)
IMT-2008-31	Radan, Damir	Integrated Control of Marine Electrical Power Systems. (PhD-Thesis, IMT)
IMT-2008-32	Thomassen, Paul	Methods for Dynamic Response Analysis and Fatigue Life Estimation of Floating Fish Cages. (Dr.ing. thesis, IMT)
IMT-2008-33	Pákozdi, Csaba	A Smoothed Particle Hydrodynamics Study of Two-dimensional Nonlinear Sloshing in Rectangular Tanks. (Dr.ing.thesis, IMT/ CeSOS)

IMT-2007-34	Grytøyr, Guttorm	A Higher-Order Boundary Element Method and Applications to Marine Hydrodynamics. (Dr.ing.thesis, IMT)
IMT-2008-35	Drummen, Ingo	Experimental and Numerical Investigation of Nonlinear Wave-Induced Load Effects in Containerships considering Hydroelasticity. (PhD thesis, CeSOS)
IMT-2008-36	Skejic, Renato	Maneuvering and Seakeeping of a Singel Ship and of Two Ships in Interaction. (PhD-Thesis, CeSOS)
IMT-2008-37	Harlem, Alf	An Age-Based Replacement Model for Repairable Systems with Attention to High-Speed Marine Diesel Engines. (PhD-Thesis, IMT)
IMT-2008-38	Alsos, Hagbart S.	Ship Grounding. Analysis of Ductile Fracture, Bottom Damage and Hull Girder Response. (PhD-thesis, IMT)
IMT-2008-39	Graczyk, Mateusz	Experimental Investigation of Sloshing Loading and Load Effects in Membrane LNG Tanks Subjected to Random Excitation. (PhD-thesis, CeSOS)
IMT-2008-40	Taghipour, Reza	Efficient Prediction of Dynamic Response for Flexible amd Multi-body Marine Structures. (PhD-thesis, CeSOS)
IMT-2008-41	Ruth, Eivind	Propulsion control and thrust allocation on marine vessels. (PhD thesis, CeSOS)
IMT-2008-42	Nystad, Bent Helge	Technical Condition Indexes and Remaining Useful Life of Aggregated Systems. PhD thesis, IMT
IMT-2008-43	Soni, Prashant Kumar	Hydrodynamic Coefficients for Vortex Induced Vibrations of Flexible Beams, PhD thesis, CeSOS
IMT-2009-43	Amlashi, Hadi K.K.	Ultimate Strength and Reliability-based Design of Ship Hulls with Emphasis on Combined Global and Local Loads. PhD Thesis, IMT
IMT-2009-44	Pedersen, Tom Arne	Bond Graph Modelling of Marine Power Systems. PhD Thesis, IMT
IMT-2009-45	Kristiansen, Trygve	Two-Dimensional Numerical and Experimental Studies of Piston-Mode Resonance. PhD-Thesis, CeSOS
IMT-2009-46	Ong, Muk Chen	Applications of a Standard High Reynolds Number Model and a Stochastic Scour Prediction Model for Marine Structures. PhD-thesis, IMT
IMT-2009-47	Hong, Lin	Simplified Analysis and Design of Ships subjected to Collision and Grounding. PhD-thesis, IMT
IMT-2009-48	Koushan, Kamran	Vortex Induced Vibrations of Free Span Pipelines, PhD thesis, IMT
IMT-2009-49	Korsvik, Jarl Eirik	Heuristic Methods for Ship Routing and Scheduling. PhD-thesis, IMT

IMT-2009-50	Lee, Jihoon	Experimental Investigation and Numerical in Analyzing the Ocean Current Displacement of Longlines. Ph.d.-Thesis, IMT.
IMT-2009-51	Vestbøstad, Tone Gran	A Numerical Study of Wave-in-Deck Impact usin a Two-Dimensional Constrained Interpolation Profile Method, Ph.d.thesis, CeSOS.
IMT-2009-52	Bruun, Kristine	Bond Graph Modelling of Fuel Cells for Marine Power Plants. Ph.d.-thesis, IMT
IMT 2009-53	Holstad, Anders	Numerical Investigation of Turbulence in a Sekwed Three-Dimensional Channel Flow, Ph.d.-thesis, IMT.
IMT 2009-54	Ayala-Uraga, Efren	Reliability-Based Assessment of Deteriorating Ship-shaped Offshore Structures, Ph.d.-thesis, IMT
IMT 2009-55	Kong, Xiangjun	A Numerical Study of a Damaged Ship in Beam Sea Waves. Ph.d.-thesis, IMT/CeSOS.
IMT 2010-56	Kristiansen, David	Wave Induced Effects on Floaters of Aquaculture Plants, Ph.d.-thesis, CeSOS.
IMT 2010-57	Ludvigsen, Martin	An ROV-Toolbox for Optical and Acoustic Scientific Seabed Investigation. Ph.d.-thesis IMT.
IMT 2010-58	Hals, Jørgen	Modelling and Phase Control of Wave-Energy Converters. Ph.d.thesis, CeSOS.
IMT 2010- 59	Shu, Zhi	Uncertainty Assessment of Wave Loads and Ultimate Strength of Tankers and Bulk Carriers in a Reliability Framework. Ph.d. Thesis, IMT/ CeSOS
IMT 2010-60	Shao, Yanlin	Numerical Potential-Flow Studies on Weakly-Nonlinear Wave-Body Interactions with/without Small Forward Speed, Ph.d.thesis,CeSOS.
IMT 2010-61	Califano, Andrea	Dynamic Loads on Marine Propellers due to Intermittent Ventilation. Ph.d.thesis, IMT.
IMT 2010-62	El Khoury, George	Numerical Simulations of Massively Separated Turbulent Flows, Ph.d.-thesis, IMT
IMT 2010-63	Seim, Knut Sponheim	Mixing Process in Dense Overflows with Emphasis on the Faroe Bank Channel Overflow. Ph.d.thesis, IMT
IMT 2010-64	Jia, Huirong	Structural Analysis of Intect and Damaged Ships in a Collission Risk Analysis Perspective. Ph.d.thesis CeSoS.
IMT 2010-65	Jiao, Linlin	Wave-Induced Effects on a Pontoon-type Very Large Floating Structures (VLFS). Ph.D.-thesis, CeSOS.
IMT 2010-66	Abrahamsen, Bjørn Christian	Sloshing Induced Tank Roof with Entrapped Air Pocket. Ph.d.thesis, CeSOS.

IMT 2011-67	Karimirad, Madjid	Stochastic Dynamic Response Analysis of Spar-Type Wind Turbines with Catenary or Taut Mooring Systems. Ph.d.-thesis, CeSOS.
IMT - 2011-68	Erlend Meland	Condition Monitoring of Safety Critical Valves. Ph.d.-thesis, IMT.
IMT – 2011-69	Yang, Limin	Stochastic Dynamic System Analysis of Wave Energy Converter with Hydraulic Power Take-Off, with Particular Reference to Wear Damage Analysis, Ph.d. Thesis, CeSOS.
IMT – 2011-70	Visscher, Jan	Application of Particla Image Velocimetry on Turbulent Marine Flows, Ph.d.Thesis, IMT.
IMT – 2011-71	Su, Biao	Numerical Predictions of Global and Local Ice Loads on Ships. Ph.d.Thesis, CeSOS.
IMT – 2011-72	Liu, Zhenhui	Analytical and Numerical Analysis of Iceberg Collision with Ship Structures. Ph.d.Thesis, IMT.
IMT – 2011-73	Aarsæther, Karl Gunnar	Modeling and Analysis of Ship Traffic by Observation and Numerical Simulation. Ph.d.Thesis, IMT.
Imt – 2011-74	Wu, Jie	Hydrodynamic Force Identification from Stochastic Vortex Induced Vibration Experiments with Slender Beams. Ph.d.Thesis, IMT.
Imt – 2011-75	Amini, Hamid	Azimuth Propulsors in Off-design Conditions. Ph.d.Thesis, IMT.
IMT – 2011-76	Nguyen, Tan-Hoi	Toward a System of Real-Time Prediction and Monitoring of Bottom Damage Conditions During Ship Grounding. Ph.d.thesis, IMT.
IMT-2011-77	Tavakoli, Mohammad T.	Assessment of Oil Spill in Ship Collision and Grounding, Ph.d.thesis, IMT.
IMT-2011-78	Guo, Bingjie	Numerical and Experimental Investigation of Added Resistance in Waves. Ph.d.Thesis, IMT.
IMT-2011-79	Chen, Qiaofeng	Ultimate Strength of Aluminium Panels, considering HAZ Effects, IMT
IMT-2012-80	Kota, Ravikiran S.	Wave Loads on Decks of Offshore Structures in Random Seas, CeSOS.
IMT-2012-81	Sten, Ronny	Dynamic Simulation of Deep Water Drilling Risers with Heave Compensating System, IMT.
IMT-2012-82	Berle, Øyvind	Risk and resilience in global maritime supply chains, IMT.
IMT-2012-83	Fang, Shaoji	Fault Tolerant Position Mooring Control Based on Structural Reliability, CeSOS.
IMT-2012-84	You, Jikun	Numerical studies on wave forces and moored ship motions in intermediate and shallow water, CeSOS.

IMT-2012-85	Xiang ,Xu	Maneuvering of two interacting ships in waves, CeSOS
IMT-2012-86	Dong, Wenbin	Time-domain fatigue response and reliability analysis of offshore wind turbines with emphasis on welded tubular joints and gear components, CeSOS
IMT-2012-87	Zhu, Suji	Investigation of Wave-Induced Nonlinear Load Effects in Open Ships considering Hull Girder Vibrations in Bending and Torsion, CeSOS
IMT-2012-88	Zhou, Li	Numerical and Experimental Investigation of Station-keeping in Level Ice, CeSOS
IMT-2012-90	Ushakov, Sergey	Particulate matter emission characteristics from diesel enignes operating on conventional and alternative marine fuels, IMT
IMT-2013-1	Yin, Decao	Experimental and Numerical Analysis of Combined In-line and Cross-flow Vortex Induced Vibrations, CeSOS
IMT-2013-2	Kurniawan, Adi	Modelling and geometry optimisation of wave energy converters, CeSOS
IMT-2013-3	Al Ryati, Nabil	Technical condition indexes doe auxiliary marine diesel engines, IMT
IMT-2013-4	Firoozkoohi, Reza	Experimental, numerical and analytical investigation of the effect of screens on sloshing, CeSOS
IMT-2013-5	Ommani, Babak	Potential-Flow Predictions of a Semi-Displacement Vessel Including Applications to Calm Water Broaching, CeSOS
IMT-2013-6	Xing, Yihan	Modelling and analysis of the gearbox in a floating spar-type wind turbine, CeSOS
IMT-7-2013	Balland, Océane	Optimization models for reducing air emissions from ships, IMT
IMT-8-2013	Yang, Dan	Transitional wake flow behind an inclined flat plate-----Computation and analysis, IMT
IMT-9-2013	Abdillah, Suyuthi	Prediction of Extreme Loads and Fatigue Damage for a Ship Hull due to Ice Action, IMT
IMT-10-2013	Ramìrez, Pedro Agustìn Pèrez	Ageing management and life extension of technical systems- Concepts and methods applied to oil and gas facilities, IMT

IMT-11-2013	Chuang, Zhenju	Experimental and Numerical Investigation of Speed Loss due to Seakeeping and Maneuvering. IMT
IMT-12-2013	Etemaddar, Mahmoud	Load and Response Analysis of Wind Turbines under Atmospheric Icing and Controller System Faults with Emphasis on Spar Type Floating Wind Turbines, IMT
IMT-13-2013	Lindstad, Haakon	Strategies and measures for reducing maritime CO_2 emissons, IMT