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Emission Control Areas: Effect on the Fleet Renewal Problem

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Submission date: June 2014
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Summary

An important strategic planning problem in shipping is the fleet renewal problem. The purpose for liner shipping companies is to minimize the company's costs while finding the best way in which to develop a fleet over time to service given trades. A number of restrictions and regulations must be regarded when making fleet optimization models, and one such concerns Emission Control Areas (ECAs). These are areas of the world seas where strict emission limits are set for SO_x and NO_x in exhaust gas from ships, introduced by the International Maritime Organization (IMO). The purpose of this thesis is to implement the changes to a fleet renewal model introduced by accounting for ECAs. To the author's knowledge there is no work considering the inclusion of ECAs in fleet renewal models in existing literature.

The inspiration for the fleet renewal models proposed in this thesis has been the collaboration research project MARFLIX. Information about the sizes and characteristics of vessels in the fleet, as well as trade information, has been provided by the liner shipping company Wallenius Wilhelmsen Logistics (WWL). This information is the basis for one of the test instances. The other two instances are reduced versions of the full WWL instance.

To investigate the effect on the fleet decisions of including speed optimization, a basic model with fixed speed and an extended model with variable speed are presented. The fleet decisions found from these models are compared, and the results show that speed optimization makes the fleet more flexible, which in turn leads to fewer changes to the fleet for a five year period. The deployment costs for the optimal fleets from the two models are found, and a reduction in the size of the fleet in the speed extended model leads to a cost decrease of 0.297 % and 0.330 %, for the full and medium test instances, respectively. These numbers are small in size, yet correspond to a significant amount of money as the magnitude of the total costs is several billion dollars.

Based on the results from the speed optimization analysis, the conclusion is drawn that including variable speed in a fleet renewal model is profitable. Hence, the speed extended model, hereby denoted as the original model, is the basis for the ECA extended model. To include the IMO regulations ECA compliant vessels are defined as vessels with emissions beneath the ECA limits. Non-compliant vessels must either switch to low sulphur fuel (MGO) when sailing inside ECAs or be retrofitted with a scrubber. Scrubbers are used for

exhaust gas cleaning, and operating with a scrubber allows the vessel to use heavy fuel oil while keeping the emissions beneath the ECA limits.

The emission limits must be followed by all vessels sailing inside an ECA. If the regulations are not considered when planning the future fleet, they must be when the deployment is determined. The results in this thesis suggest that taking ECAs into account when making the fleet renewal plan induces savings of 0.602 % for the full test instance and 0.712 % for the medium instance. The fleet is adjusted to be more suitable for deployment in ECAs, and retrofitting reduces sailing costs for the upgraded vessels.

There is high uncertainty related to some of the estimates made for the input values. To investigate possible future situations of demand, fuel price, and scrubber price analyses have been performed. The results from these show that a shift in demand towards ECAs, lower scrubber price, and higher MGO price lead to an increase in the number of retrofitted vessels, and a reduction of total costs when accounting for ECAs in the fleet renewal model. With a decrease in the MGO price the benefit of retrofitting vessels disappear, and the cost of fuel switch decreases. Taking ECAs into account when making the fleet renewal plan is nevertheless beneficial, primarily as it allows compliant vessels to be acquired rather than non-compliant.

The fleet in the small test instance is sufficiently large to service all trades without the need for fleet changes during the five year period. No savings occur with the original input values, and thus there is no benefit when including ECAs. It will however be profitable to retrofit vessels when the MGO price is increased and when scrubber price is decreased, which will lead to savings using the ECA extended model in this instance as well.

In some analyses there are no difference between the models in fleet changes for the first time period. In these cases there is no direct benefit of using the ECA extended model, but the trends shown in later time periods can nevertheless indicate a better long term plan than the one obtained in the original model.

When estimates for input values are made the model is easy to use, and the solving time for the full test instance is 11.9 seconds. These facts, in addition to the cost savings possible to obtain, show that there is great potential in using the ECA model for fleet renewal planning.

Sammendrag

Et viktig strategisk planleggingsproblem innen shipping er flåtefornyingsproblemet. Hensikten er å minimere rederiets kostnader ved å finne den beste måten å utvikle en flåte på over tid, forutsatt at gitte laster blir fraktet. En rekke restriksjoner og regler må tas hensyn til når modeller skal lages for flåteoptimering, og en av disse omhandler såkalte Emission Control Areas (ECA-er). Dette er områder av verdenshavene der strenge utslippskrav er satt for SO_x og NO_x i eksosgassen fra skip, introdusert av Den Internasjonale Skipsfartorganisasjonen (IMO). Hensikten med denne masteroppgaven er å implementere endringene i en flåtefornyelsesmodell som oppstår når ECA-er tas hensyn til. Så langt forfatterens kunnskap strekker finnes det ikke noe arbeid som omhandler inkludering av ECA-er i flåteoptimeringsmodeller i eksisterende litteratur.

Inspirasjonen for modellene som foreslås i denne oppgaven har vært forskningsprosjektet MARFLIX. Informasjon om størrelser og karakteristikker for skipene i flåten, samt informasjon om fraktavtaler, har blitt gitt av rederiet Wallenius Wilhelmsen Logistics (WWL). Denne informasjonen er grunnlaget for en av testinstansene. De to andre instansene er reduserte versjoner av WWLs fullstendige problem.

For å undersøke effekten av å optimere hastighet når flåtebeslutninger skal tas presenteres en basismodell med fast hastighet og en utvidet modell med variabel hastighet. De optimale flåtebeslutningene som fremkommer av disse modellene er sammenlignet, og resultatene viser at å optimere hastighet gjør flåten mer fleksibel, noe som igjen fører til færre endringer i flåten over en periode på fem år. Kostnaden for implementering av de optimale flåtene fra de to modellene er funnet, og en nedgang i størrelsen av flåten i den utvidete modellen fører til en reduksjon av totale kostnader på 0,297 % og 0,330 %, for henholdsvis den fullstendige og den mellomstore testinstansen. Disse endringene er små i størrelse, men tilsvarer en betydelig sum ettersom størrelsesordenen for de totale kostnadene er flere milliarder dollar.

Basert på resultatene fra analysen av hastighetsoptimering trekkes konklusjonen at variabel hastighet i en flåtefornyelsesmodell er lønnsomt. Derfor er modellen med hastighetsoptimering, herved betegnet som opprinnelig modell, brukt som grunnlag for modellen med ECA-utvidelse. For å inkludere IMOs forskrifter er ECA-kompatible skip definert som skip med utslipp under grensene for ECA-er. Ikke-kompatible skip må enten bytte til drivstoff med

lavt svovelinnhold (MGO) ved seiling innenfor ECA-er eller oppgraderes med en gasskrubber. Skrubberen brukes til eksosrensing, og et skip som opererer med en skrubber kan forbrenne tungolje og likevel holde utslippene under ECA-grensene.

Utslippsforskriftene skal følges av alle fartøy som seiler innenfor en ECA. Dersom regelverket ikke blir vurdert når fremtidig flåte planlegges, må det vurderes når utplasseringen av skipene gjøres. Resultatene i denne oppgaven tyder på at det å ta ECA-er i betraktning når planen for flåtefornyelse lages gir en besparelse på 0,602 % for den fullstendige testinstansen og 0,712 % for den mellomstore instansen. Flåten justeres for å tilpasses ECA-forskriftene, og ettermontering av skrubbere reduserer seilekostnader for de oppgraderte skipene.

Det er stor usikkerhet knyttet til noen av estimatene for inngangsverdiene i oppgaven. For å undersøke mulige fremtidige situasjoner for etterspørsel, drivstoffpriser og pris for skrubber er analyser utført. Resultatene fra disse viser at et skifte i etterspørselen mot ECA-er, lavere scrubberpris og høyere MGO-pris alle fører til en økning i antall oppgraderte skip, og en reduksjon av de totale kostnadene når ECA-er tas hensyn til i flåtefornyelsesmodellen. Med en nedgang i MGO-prisen forsvinner fordelen av ettermontering av skrubbere, og kostnadene for drivstoffskifte avtar. Å ta ECA-er i betraktning når flåtefornyelsesplanen legges er likevel gunstig, hovedsaklig grunnet muligheten til å anskaffe ECA-kompatible skip.

Flåten i den minste testinstansen er stor nok til å betjene alle befraktninger uten endringer i løpet av femårsperioden. Ingen kostnadsreduksjon oppnås med de opprinnelige inngangsverdiene, og dermed oppnås heller ingen fordel ved å inkludere ECA-er. Det vil imidlertid være lønnsomt å ettermontere skrubbere på skip når prisen på MGO økes og når skrubberprisen reduseres, noe som vil føre til besparelser ved bruk av den ECA-utvidete modellen også i den minste testinstansen.

I noen av analysene er det ingen forskjell mellom modellene vedrørende flåteendringer i den første tidsperioden. I disse tilfellene er det ingen direkte fordel ved å bruke den ECA-utvidete modellen, men trendene som vises for senere tidsperioder kan likevel indikere en bedre langsiktig plan enn den funnet i den opprinnelige modellen.

Når estimater for inngangsverdiene er laget er modellen enkel å bruke, og løsningstiden for den fullstendige testinstansen er 11,9 sekunder. Dette, i tillegg til kostnadsbesparelsene som er mulig å oppnå, viser at det er stort potensial i å bruke en modell med ECA-utvidelse for planlegging av flåtefornyelse.

Preface

This master thesis was written as part of an integrated Master of Science in Marine Technology at the Norwegian University of Science and Technology in the spring of 2014. The purpose of this thesis is to implement Emission Control Area regulations in a basic fleet renewal model and to investigate the results of such an implementation.

The thesis work has been challenging in several ways. I have learned that it is next to impossible to estimate the time needed for almost any task. I have given myself numerous surprises, both positive and negative, concerning how many days or weeks I need for completing one. My ability to overcome programming errors emerging both in the LaTeXand the Mosel language (seemingly illogical at first), has been significantly improved.

Discussions I have participated in concerning my work and other master students' thesis work have shown me that there are many subjects within the field of naval architecture and marine technology that I have very limited knowledge of. Yet they have also reminded me that many students with other specializations have the same feelings towards optimization and the Emission Control Area regulations. Most importantly, I have learned a lot about these subjects myself, and for that I am grateful.

I would like to thank my supervisor, Adjunct Professor Kjetil Fagerholt, and my co-supervisor, Postdoctoral Fellow Jørgen Glomvik Rakke, at the Department of Marine Technology, for their guidance during my thesis work. I would also like to thank Wallenius Wilhelmsen Logistics for proving information about their fleet and trades so a realistic test could be performed of the proposed model.

A big thank you is directed towards my sister and chemical engineer Hanne Kristine Sørgård. Not only is she an inspiration as a person and as an academic, but the work she has done by proofreading my thesis is highly appreciated.

I am also grateful for my supportive, funny, articulate, and skillful fellow students in office A2.011 at the Marine Technology Center, and for the rest of the class graduating in the spring of 2014.

The Mosel codes and the input files used to run the test instances in this thesis are confidential and cannot be found in the published part of this thesis. Three copies of the files have been given to my supervisor.

Trondheim, June 10, 2014

Ellen Helene Sørgård

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List of Abbreviations

NO_x	Nitrogen Oxides
SO_x	Sulphur Oxides
DNV	Det Norske Veritas
DP	Dynamic Programming
ECA	Emission Control Area
FSM	Fleet Size and Mix
HFO	Heavy Fuel Oil
IMO	The International Maritime Organization
IP	Integer Programming
LCTC	Large Car and Truck Carrier
LNG	Liquified Natural Gas
LP	Linear Programming
MARINTEK	The Norwegian Marine Technology Research Institute
MARPOL	The International Convention for the Prevention of Pollution from Ships
MIP	Mixed Integer Programming
NTNU	The Norwegian University of Science and Technology
PCTC	Pure Car and Truck Carrier
SCR	Selective Catalytic Reduction
VRP	Vehicle Routing Problem
WWL	Wallenius Wilhelmsen Logistics

Chapter 1

Introduction

In the world today, globalization, increased consumption, and economic growth contribute to a large demand for goods and for increased transportation. With around 80 % of the global trade volume, seaborne trade is the largest international trade market in the world (UNCTAD, 2012). The number of shipments and the world fleet has been growing the last few years, despite the financial crisis, and the world fleet grew by 4 % in 2011 (UNCTAD, 2012). Competition between transporters creates a need for the shipping companies to ensure efficiency and cost reduction when managing a fleet of vessels. Uncertainty in future demand, freight rates, and fuel prices tend to make long term decision making a complex task. Good decision tools can provide better and more cost efficient solutions for companies struggling to grow or to keep their position in a volatile and uncertain market.

One such tool is to make good models for the fleet size and mix (FSM) problem. In a FSM problem the purpose is to determine the optimal fleet of vessels, where the number of vessels in the fleet and their sizes are of interest. Finding how to develop a suitable fleet in the long term is called a fleet renewal problem. An initial fleet is given, and the task is to find the best decisions for the future, such as the way in which the company should purchase, charter, or scrap vessels. The use of well developed fleet decision models can make the task of managing a fleet easier and faster compared to the use of manual planning only.

When developing fleet decision models, as when planning manually, a number of restrictions and regulations must be accounted for, such as laws from local governments and international rules and regulations. One such regulation has been introduced by the International Maritime Organization (IMO). To restrict emissions to air in certain areas of the world seas, Emission Control Areas (ECAs) have been determined. This affects shipping companies' utilization of their fleets, as only ships with emissions beneath given limits are allowed to sail in these areas without sanctions. Implementing this aspect in a fleet renewal model increases the problem complexity because of added constraints concerning vessel and trade compatibility, additional ways to upgrade the fleet, and added costs. The ship owners have to take into account all costs related to upgrading their fleet, or parts of it, to comply with the regulations. Finding the best solutions for a fleet trading in ECAs is important as large costs are related to sailing in such waters, especially with a fleet that does not comply with the emission levels. Including the ECA regulations and their effect on the fleet renewal problem has not been discussed in existing literature. The aspect is addressed in this thesis in order contribute to the development of better and more useful decision support models.

1.1 FSM and fleet renewal problems

1.1.1 The global seaborne trade market

Some commonly used terms and theories in shipping are needed to create a background knowledge and a context for the rest of this thesis. In the following paragraphs some of the most important ones are described.

Shipping market cycles

One of the greatest challenges for ship owners is the uncertainty of the future demand situation. The market is highly volatile and changes rapidly, which makes it hard to make good estimates of future situations. As building ships could take years, it is of great importance to be able to make good estimates. When market changes occur, freight rates react fast and it can be essential to have an appropriate fleet in hand. The delay in ship building compared to the rapid changes in demand and freight rates result in a biased relationship leading to the rise of natural cycles in supply and demand.

Stopford (2009) describes three types of cycles in the shipping market: long-term and short-term cycles and seasonal cycles. These are affected by changes in the industry, the economic status in the world, and the natural cycle induced by seasonality of cargo.

Shipping modes

Lawrence (1972) introduces three categories of shipping: tramp, liner, and industrial. This classification has become the standard way of separating different types of shipping, and Christiansen et al. (2007) describe the modes as follows.

Tramp shipping is often compared to a taxi service. The shipping company operates on contract cargos that must be transported and finds other cargos in the spot market to maximize the profit.

Liner shipping is similarly compared to a bus line. In liner shipping there are fixed, published schedules stating the ports and cargos the ships will service.

In industrial shipping, the cargo owner is also the ship owner and the aim is to transport the cargo at the lowest cost possible.

Classification of planning

It is common to separate the planning problems in shipping based on the length of the planning horizon. The three categories often used are strategic, tactical, and operational planning.

Strategic planning involves long-term decisions that influence the fleet several months or years into the future. Determining fleet composition and renewal fall into this category.

In tactical planning, the utilization of the fleet is determined. The time horizon can span from a few weeks to several months, some times up to one year, and the decisions can include fleet deployment, routing and scheduling, and inventory ship routing.

Operational planning concerns the short-term decisions for the fleet. This involves day-to-day operations like stowage planning, speed selection, and weather routing.

1.1.2 The fleet size and mix problem

The large costs and revenue ship owners deal with calls for a good way to make decisions about how many ships to include in a fleet and what kinds of ships that would be most profitable. In addition, the decision of which ships that are going to service the different trades is of interest to support the capacity and tonnage demand. An important strategic planning problem is to determine the optimal types of ships for a fleet, their sizes, and how many ships of each type to include in a fleet. The purpose is to find the best fleet to service a given demand while optimizing utilization of the fleet capacity. This problem is in operations research called the fleet size and mix problem.

Traditionally, these decisions have been made based on experience and gut feeling. The solutions experienced maritime personnel derive are good, but probably not optimal. Large shipping companies often have an extensive fleet which is highly heterogeneous, and the decision makers need to have a great deal of information at hand to make good strategic decisions.(Christiansen et al., 2007)

Ship owners operate in a highly uncertain market. Due to long construction time for a vessel and fluctuations in the market, gaps between supply and demand are not uncommon. Local, regional, and global changes, e.g. in demand, oil prices, and economic status, make the seaborne trade market unpredictable. The fluctuations and uncertainty of the environment makes it even harder to make good fleet decisions.

Based on the reasons mentioned, there is a need for a better decision support system in many shipping companies. Such tools can be convenient both in strategic, tactical, and operational planning. In strategic planning, the category of focus for this thesis, fleet composition and management models can be used as support when deciding how to keep an advantageous fleet in the long term. Decision makers will commonly not rely exclusively on the result of an optimization model, but use the solutions obtained to compare different strategies and perform analyses to better be able to make good decisions. Optimization models are often a fast and relatively easy tool to provide a basis that decisions can be made upon. Solving for different scenarios and outcomes of e.g. fuel or construction prices and demand requires little time, and can provide the decision maker with alternative solutions of which he can choose one or use as a foundation for making his decision.

In a fleet renewal model fleet decisions are proposed for several time periods, often several years. When using such a model, the purpose is to find good decisions for the next time period. A reasonable way to use a fleet renewal model is to make decisions for the current time period based on results from the solution of the model, and each following time period run the model anew after updating the estimates for the future. To stick to a five year plan founded upon a fleet renewal model is risky as it is based on estimates that might not be accurate. The reason for solving for a longer period of time even though decisions for only one time period is to be made is that it can provide a broader overview of the market and the fleet in the future. What the solution to the model assumes about the future can report information about the direction in which the fleet should develop in the relevant time span to account for prospective changes in the future.

Types of FSM problems

The simplest FSM problems deal with how many vessels and the sizes of the vessels to include in a fleet to meet the demand. The problems can be subject to differences and extensions of many types, all of which make the problem more realistic, yet more complex and harder to solve. In the following paragraphs some of the most common differences and extensions of the problem is presented.

First of all, the FSM problem in a maritime setting is different from that of land based transportation. In a fleet of cars and trucks the number of vehicles are often large and the vehicles are similar in size. In maritime transportation there are fewer vessels, they are bigger, and they vary more in size. Hence, the fleet is in larger degree heterogeneous. The complexity of the vessel and the uncertainty in travel time is also higher in maritime transportation. In addition, there are often one or more depots in land based transportation, which is not usual in maritime transportation.(Hoff et al., 2010)

When cargo is to be transported, there are often time windows involved. There is an earliest and a latest start for when the cargo can be loaded and unloaded. This calls for the use of time constraints.

Most FSM models include the possibility to buy and sell vessels. In addition, some include the possibility of chartering in and out. This aspect makes the model more flexible, as the ship owner may use some vessels in one period of time and not in others, as the demand for transportation changes. Chartering vessels in and out results in less work for the ship owner than buying and selling vessels, and is a good way to handle short-term demand changes. Purchasing vessels instead of chartering in is nevertheless a better solution in many cases. Chartering in is quite expensive, and in the long run the net present value of purchasing a vessel becomes lower than that of chartering in if this is needed for longer periods of time. When chartering in, the option of getting vessels specialized for the need is harder, as a contrast to building a vessel and specifying all elements the ship owner needs or wants. In addition, the access to charter in vessels is limited, especially if the segment of shipping in which the company is operating requires specialized vessels.

If ship owners want a more long-term perspective on the utilization of the fleet, the FSM model can include more than one planning period. In these cases the uncertainty is greater than with one period and a deterministic model could be unrealistic. This can be solved using the rolling horizon principle. Stochastic modelling can be used to create forecasts for future events, and more information is revealed as time goes by. Decisions are made in each time period based on the available information. To evaluate the solution of a model, simulation can produce different scenarios where the solution is assessed. This is a helpful tool to appraise the solution when the outcome of future situations is not known.

Challenges for the FSM problem

One of the biggest challenges in making a mathematical model of the FSM problem is the uncertainty that lies within the shipping market(Pantuso et al., 2014a). Even if sophisticated methods for including uncertainty are developed, the decision maker has to deal with the fact that it is impossible to predict the future. According to Pantuso et al. (2014a), most models proposed in the literature are deterministic, and does not handle uncertainty at all. As very few maritime problems can be interpreted as deterministic, this leads to unrealistic simplifications. Strategic planning is especially sensitive to uncertainty because of the time frame, and predictions about the distant future is harder to make. Some papers discuss and propose models where uncertainty is explicitly handled, but the literature is scarce. Pantuso et al. (2014a) suggest that researchers focus more on models and analyses of the future demand and other factors to provide better tools for making good decisions about the future.

Pantuso et al. (2014a) state that the majority of the papers concern homogeneous fleets and single period problems, while reality shows that heterogeneous fleets are more common, and short-term planning is not always advantageous. In addition, they point out that more problems should be examined in which there is an initial fleet in stead of building one from scratch, alternative fixed costs when acquiring ships, as well as using FSM for asset play.

Another drawback, that is not mentioned in Pantuso et al. (2014a), is that there has been no research on how to include the ECA regulations in a FSM model. As the strict emission limits in ECAs will come into force in 2015, the scarce research on this field is not surprising. Yet it could lead to a big improvement seeing that a model including such areas would be more realistic than models not including them. When the regulations become stricter in 2015, the cost of not taking them into account could be high.

1.2 Emission Control Areas

The IMO is a specialized agency of the United Nations for maritime safety. It was established in 1948 to attend to safety at sea and prevent pollution of the maritime environment. IMO has 170 member states and comprise several committees which develop international legislations and regulations (The International Maritime Organization, 2014a,d). MARPOL is the International Convention for the Prevention of Pollution from Ships. The purpose of MARPOL's work is to prevent pollution at sea and minimize the spillage associated with accidents. The convention includes six technical Annexes which regulate special areas of pollution.(The International Maritime Organization, 2014c)

Annex VI, Prevention of Air Pollution from Ships, came into force in 2005. It sets limits for emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x) from ship exhaust. There are 73 contracting states, representing 94.7 % of the world tonnage (The International Maritime Organization, 2014b). A revised MARPOL Annex VI was adopted in 2008, stating stricter regulations for global emissions of SO_x, NO_x, and particulate matter. The ECAs were also introduced, aiming to further reduce emissions in designated areas of the seas. These areas were chosen based on the amount of sea traffic and the oceanographical and ecological condition in the areas.(The International Maritime Organization, 2014b)

MARPOL protects the ECAs by setting standards for emissions of sulphur oxides (SO_2 and SO_3), nitrogen oxides (NO and NO_2), and particulate matter in ship exhaust (The International Maritime Organization, 2014f). SO_x has a high water-solubility and humans

Table 1.1: Current and future limits (The International Maritime Organization, 2014b)

Current limits:

ECA sulphur limit	1.0 %
Global sulphur limit	3.5 %
New builds	NO_x tier II

Future limits:

ECA sulphur limit	2015: 0.1 %
Global sulphur limit	2020 (2025)*: 0.5 %
New builds	2016: NO_x tier III in ECA

*Subject to a feasibility review to be completed no later than 2018

absorb the gases when breathing in polluted air. This can cause severe damage to the lungs. SO_x can also react with hydrogen and oxygen to create sulphuric acid, which is an important component in acid rain. NO_x contributes to an environmental problem called hypertrophication, which is a term for several negative changes to ecosystems caused by addition of substances like nitrates to an area. NO_2 can also react with oxygen to form ground level ozone, which can cause harm to human health and is an important greenhouse gas.(Kågeson, 2005)

Figure 1.1 provides an overview of the existing ECAs, while table 1.1 summarizes the current and future ECA limits.

Different Tiers (levels) of control for NO_x emissions apply to ships based on the construction date, and the values of the limits are calculated based on the engine speed. Tier III will apply to ships operating in ECAs, while outside these areas Tier II is valid. Table 1.2 shows the emission limits for the different Tiers. n denotes the engine's rated speed in revolutions per minute (rpm), which is decisive for the emission limit. An example of limits for $n = 720$ rpm is given.(The International Maritime Organization, 2014e)

The controls for SO_x emissions are separated between sea transport inside and ouside of the ECAs. They primarily set limits to sulphur content of exhaust gas and the changes to the limits through time can be seen in figure 1.2.

1.2.1 ECA solutions

As can be seen in figure 1.2 todays average emissions of sulphur is well beneath the global limit. In MARPOL Annex VI it is stated that ships trading both within and outside of the ECAs are allowed to perform a fuel switch when entering or leaving an ECA. As it is more costly to sail with emissions beneath local limits, it would be preferable to sail normally

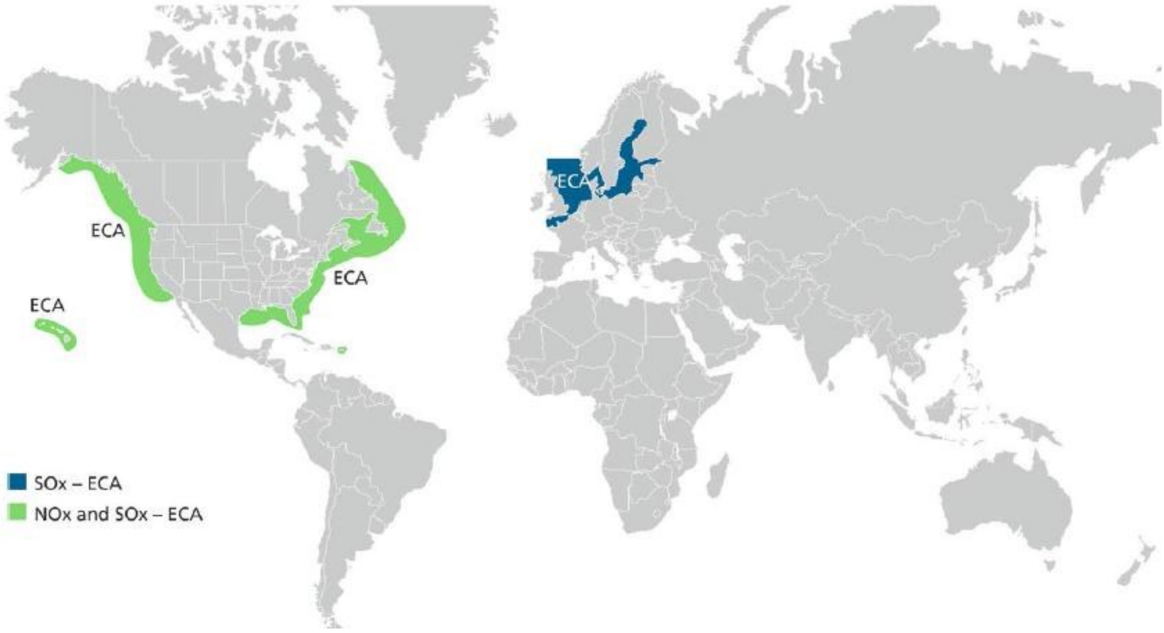

Figure 1.1: Existing Emission Control Areas (Balland, 2013)

Table 1.2: Tier Limits (The International Maritime Organization, 2014e)

Tier	Ship construction date on or after	Cycle emission limit (g/kWh)		
		$n \leq 130$	$130 \leq n \leq 1999$	$n \geq 2000$
I	1. January 2000	17.0	$45n^{-0.2}$ e.g. 720 rpm: 12.1	9.8
II	1. January 2011	14.4	$44n^{-0.23}$ e.g. 720 rpm: 9.7	7.7
III	1. January 2016*	3.4	$9n\ -0.2$ e.g. 720 rpm: 2.4	2.0

* Subject to a technical review to be concluded 2013 this date could be delayed, regulation 13.10

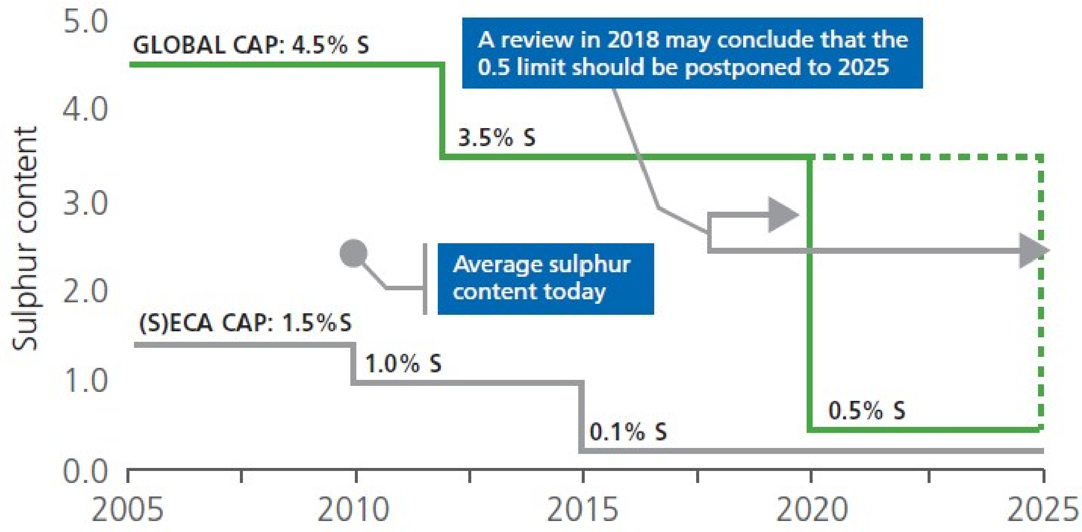

Figure 1.2: Sulphur content limits through time (Balland, 2013)

outside of the ECAs and switch to lower emissions entering the area. A drawback is that the risk of engine shutdown increases with fuel switch.(Balland, 2013)

The easiest way to comply with the IMO regulations is to avoid sailing in ECAs. This can be done by unloading in ports or onto other vessels outside the ECA border. As the ECAs comprise some of the most visited sailing areas, that option is rarely relevant as the solution is not very flexible and could be hard to carry out (Balland, 2013). There are, however, a few other options. In the following paragraphs these will be described.

SO_x compliance

There are primary and secondary methods to comply with the sulphur emission control limits. The primary method involves no formation of the pollutants, i.e. using fuel in which the sulphur limit is met. The secondary method is allowing the pollutants to be formed and to remove them prior to discharge of the exhaust into the air. In the latter method guidelines have been adopted to ensure proper exhaust gas cleaning, primarily by use of scrubbers.(The International Maritime Organization, 2014g)

Low sulphur fuel is available throughout the world with existing bunkering systems, and is a well known solution proven to be safe. The investment cost is relatively small, and the additional crew training would be limited, but the operational expenses would increase.(Hodne, 2013)

Scrubbers can be used for water washing of the exhaust gas and make it possible to continue running on heavy fuel oil (HFO) if fuel switch is not desired or possible. The investment cost is not very high, and the technology is developed and well established.(Hodne, 2013)

If scrubbers were to be installed it would require space. If retrofitted, the ship stability and structure should be reconsidered. The ship would not need additional tanks or fuel supply systems like it would with another type of fuel on board. Added maintenance would be needed. However, this applies to the decision of installing another fuel system as well.(Hodne, 2013)

NO_x compliance

There are several ways to reduce the emissions of NO_x, all of which with a varying degree of efficiency and compatibility. The most commonly used measure is selective catalytic reduction (SCR) systems. Other abatement measures are available as well and the most promising methods are water injection, exhaust gas recirculation, and internal engine adjustments (Wahlström et al., 2006). The NO_x emission limits only concern new builds, and the different systems will not be thoroughly described in this thesis.

LNG as fuel

Using Liquified Natural Gas (LNG) as fuel would result in reduced emissions both of SO_x, NO_x, CO_2, and particulate matter. It is proven to be safe and the operation is clean and vibration free.(Hodne, 2013)

LNG solutions are available, but the bunkering infrastructure could be a challenge. Even though infrastructure is being developed, for the time being there is limited availability throughout the world ports. In addition, LNG tanks require a lot of space on board and the crew would need additional training. The future LNG prices are also subject to high uncertainty.(Balland, 2013)

1.2.2 Costs of ECA compliance

In Madsen and Olsson (2012), a cost-efficiency analysis is carried out for ECA compliancy for a 5,200 dead weight ton Roll on-Roll off vessel sailing at 25 knots. Net present value for the costs of compliance in four different scenarios are found, including HFO with scrubber and SCR, LNG as fuel, low sulphur fuel with SCR, and low sulphur fuel with an assumed NO_x taxation. Their analysis show that the installation of a scrubber and a SCR system results in the lowest net present value, given a vessel lifetime of 20 years and a discount rate of 4 %.

The uncertainty in the compliance costs are apparent. A lot of the abatement technology is relatively new, and it is very costly. Further development and more frequent use of these and other measures during the next decade can be considered probable, which could possibly lead to lower costs both for investment, installation, and operation. In addition, as mentioned earlier, the future fuel prices are close to impossible to predict, and are subject to high uncertainty. Changes in these and other factors could possibly result in a different outcome of a cost-efficiency analysis.(Balland et al., 2013)

In the rest of this paper, it is assumed that the most easy and least costly way to comply with ECA regulations for SO_x is by installation of a scrubber or performing a fuel switch.

The remainder of this thesis is organized as follows. In Chapter 2 a description of the problem to be solved is presented, and relevant literature is examined in Chapter 3. Chapter 4 presents and describes the mathematical models developed in this thesis, while in Chapter 5 a computational study is performed. Concluding remarks are given in Chapter 6.

Chapter 2

Problem description

The basic fleet renewal problem compasses finding the best strategy for developing a fleet over time. As time passes, the purpose is to find the best renewal plan, with decisions comprising purchase, charter, and disposal of vessels. An initial fleet of vessels is given, with information about capacity, speed, fuel consumption, and charter rates. Operational trades are the trades to be serviced, and are specified by start and end region, distance, and frequency or volume demand. Ballast trades, where no cargo is shipped but where the empty vessels sail to another region, do not provide revenue but could be necessary. In addition, compatibility between different vessels and trades is analyzed. Based on estimated future demand and fuel prices the fleet decisions are to be made for the chosen period of time.

Including ECAs: Changes to the basic problem

In the basic problem the compatibility between vessels and trades are based on dimensions, capacity, and other factors deciding whether or not the vessel type is applicable for the trade. When ECAs are introduced, the vessel types must be partitioned also in terms of emission levels. If a vessel type is ECA compliant normal sailing will result in emissions beneath ECA limits. The vessels could have abatement technology on board, run on low sulphur fuel, or in other ways comply with the regulations without changing operations in ECAs. Non-compliant vessel types are those that need to make changes when entering ECAs, as the normal emissions are above the limits. If these vessel types are to sail in ECAs they need to perform a fuel switch when entering, and it is assumed that the switch will be from HFO to marine gas oil (MGO). A retrofitted vessel is one that is originally non-compliant, but have been retrofitted with a scrubber, so that they can sail in ECAs without performing a fuel switch.

The fleet renewal model with ECAs is to determine the same fleet decisions as in the basic

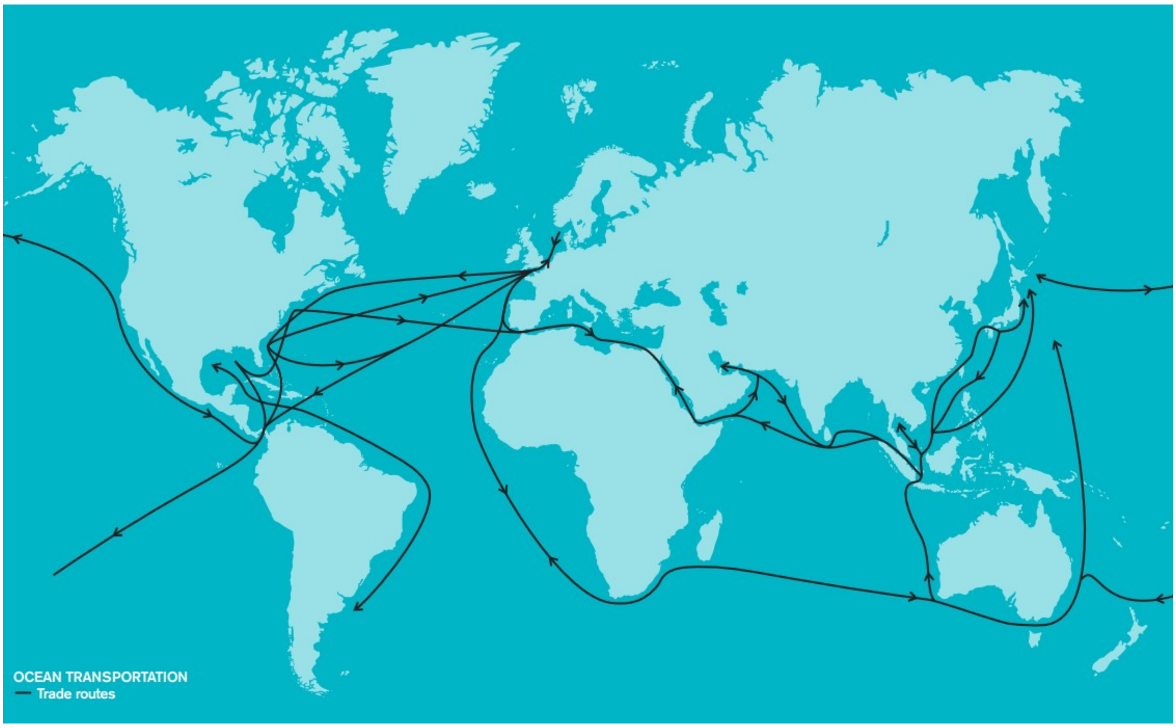

Figure 2.1: Ocean trade routes (Wallenius Wilhelmsen Logistics, 2014b)

model, with purchasing, chartering, and disposing of vessels. In addition the decisions of upgrading parts of the fleet must be considered. When a purchase is made the vessel type of choice can be either ECA compliant or non-compliant. New decisions also comprise retrofitting of non-compliant vessels to satisfy emission limits. When a vessel is retrofitted it has to be taken out of service. Hence, the available operational days for the vessels will be fewer if the retrofitting option is utilized. The lost time must be made up for, either by chartering in vessels or making sure that the available fleet can service all trades even without the vessels that are being retrofitted.

The deployment cost of the fleet will depend on which vessel types service the different trades. Non-compliant vessels sailing on non-ECA trades, retrofitted vessels, and compliant vessels can maintain normal operation, and in these cases the sailing costs are equal to what they would be without the ECAs. Non-compliant vessels sailing on ECA trades must perform a fuel switch, and as the price of MGO is higher than that of HFO, the sailing costs will be higher in ECAs.

The problem used for testing the models is given by the liner shipping company Wallenius Wilhelmsen Logistics (WWL). Their trade routes are shown in Figure 2.1 and Table 2.1.

Table 2.1: Trade routes and frequencies (Wallenius Wilhelmsen Logistics, 2014b)

Start region		**End region**	**Frequency**
Europe	-	US East Coast	Weekly
Europe	-	US West Coast	Every 15 days
Europe	-	US Gulf	Every 15 days
North America	-	Europe	Weekly
Asia	-	Europe (via Suez)	Weekly
Asia	-	North America	Every 10 days
Europe	-	South Africa	Every 15 days
South Africa	-	Europe	Every 45 days
Europe	-	Oceania	Every 10 days
South Africa	-	Oceania	Every 15 days
Oceania	-	Asia	Every 10 days
North America	-	Middle East	Monthly
North America	-	Asia	Every 15 days
North America	-	Oceania	Every 10 days
US Gulf	-	South America	Every 15 days
South America	-	US Gulf	Every 15 days
China Express (Japan-Korea-China)			Every 15 days
SEA Express (Thailand-Singapore-Indonesia)			Every 15 days

MGO usage

As a vessel performs a fuel switch, the amount of MGO needed to obtain the same speed as before will not be equal to the amount of HFO needed before the fuel switch. To remain at constant speed, the energy received from the combustion of the fuel must be constant. The calorific value of a fuel denotes the amount of energy acquired from burning one mass unit of the fuel. The calorific value of HFO is lower than that of MGO, and the amount of MGO used will be less than that of HFO if the same energy output is desired. This is shown in equations (2.1)–(2.4), where E is the energy output, m is the mass of the fuel, and h_n is the calorific value. The combustion process will be equal for both cases.

$$E = m \times h_n \tag{2.1}$$

$$E_{HFO} = E_{MGO} \tag{2.2}$$

$$m_{HFO} \times h_{n,HFO} = m_{MGO} \times h_{n,MGO} \tag{2.3}$$

$$m_{MGO} = \frac{h_{n,HFO}}{h_{n,MGO}} \times m_{HFO} \tag{2.4}$$

The amount of MGO needed is around 5 % less than that of HFO for constant energy output. This value is subject to change depending on the quality of the fuel types used.

The fuel costs at sea are calculated as the fuel consumption in tons per day multiplied with the fuel price per ton and the number of days at sea. The percentage of each trade that lies within an ECA is estimated and it is assumed that a vessel switches fuel when entering or leaving the ECA. The amount of time spent in an ECA is the basis for calculating the amount of MGO and HFO used on each trade, and the formulas used for calculating fuel cost at sea can be seen in equations (2.5)–(2.6).

$$C^S_{normal} = FC_{HFO} \times P_{HFO} \times D^S \tag{2.5}$$
$$\begin{aligned} C^S_{fuelswitch} = {} & FC_{HFO} \times P_{HFO} \times D^S \times (1 - F_{ECA}) \\ & + FC_{HFO} \times F_{mass} \times P_{MGO} \times D^S \times F_{ECA} \end{aligned} \tag{2.6}$$

Here, C^S is the fuel costs at sea, and FC_{HFO} is the given HFO consumption in tons per day at sea. P_{HFO} and P_{MGO} is the price of respectively HFO and MGO per ton and D^S is the number of days at sea. F_{ECA} is the amount of time traveled within an ECA on the given trade and F_{mass} is the factor with which the mass of HFO is replaced with MGO.

Time for retrofit

To facilitate modelling and comprehension, it is assumed that vessels are retrofitted in the beginning of each time period. An alternative could be to define that if in one time period the best solution is to use a retrofitted ship, the retrofitting should be carried out in the preceeding time period. That way the vessel is ready for sailing in the beginning of the current time period. This alternative could be preferred if the amount of vessels to be retrofitted in one time period is large, so that a lot of the fleet capacity is taken out of service in the beginning of the relevant time period. With this alternative the retrofitting could be spread out in time over a whole year and thus avoid removing a large number of vessels at the same time from the fleet. This could also be a way to secure that prospective capacity restrictions on yards are not exceeded.

There is a trade off with regards to which method to use. The first alternative simplifies the problem, which is already complex, and is chosen based on this criteria. A simple way to avoid a lack of capacity in the fleet at the time of retrofitting and ensure that yards have sufficient capacity to carry out the retrofitting is to set a maximum number of retrofitting for each time period.

Chapter 3

Literature review

In this Chapter, relevant literature is presented. Papers concerning FSM and fleet renewal problems are discussed in Section 3.1, while Section 3.2 presents papers on the ECA problematics.

3.1 Fleet Size and Mix

A selection of articles on the FSM problem is presented in this Section. For a more complete survey of FSM literature see Pantuso et al. (2014a). The focus of this part of the literature review will be on liner shipping problems which consider fleet size and mix and fleet renewal, as these are the topics most relevant for the problem of this thesis.

In Pantuso et al. (2014a) 12 articles are found that discuss liner shipping only. Out of these 12 most address container shipping, while others concern passenger transportation. As container ships dominate the liner segment of shipping (UNCTAD, 2012) the results are not surprising. However, liner problems can, in most cases, be transferred between the different cargo types.

According to Pantuso et al. (2014a) the first paper on the strategic FSM problem was published by Everett et al. (1972). They propose a linear programming (LP) problem to determine the optimal sizes and designs for the US merchant marine fleet of tankers and bulkers. In the following decades several different models and solution methods have been proposed.

In Salhi et al. (1992) the fact that most vehicle routing and fleet composition models used a fixed unit running cost for all vehicle types is challenged. They introduce simple modifications to some well known heuristics, showing the effect of including different costs for different types of vessels. They use the savings approach, where the savings of joining two costumers are calculated, and the tour-partitioning based approach, where the heuristic finds the shortest path using partitioning of a graph with all feasible vehicle routes. The results of the models with cost modifications show superior solutions compared to the ones from the original models with fixed unit running costs.

Fagerholt (1999) finds the optimal fleet for a real liner shipping problem. He determines all feasible routes for the largest ship and solves a set partitioning problem to find both the optimal fleet and the corresponding routes.

Lane et al. (1987) use a forward-looking heuristic to create a set of schedules associated with each ship in a liner service in the Pacific Sea. Finding the optimal solution, the model also finds the optimal fleet size and mix.

Sigurd et al. (2005) address the establishment of a fleet to service a given set of trades between ports in Norway and Central Europe. Up to 15 different vessels is to be constructed, and the aim is to produce a fleet which minimizes the costs for a shipping company while satisfying all requirements from the costumers. Constraints such as time windows for pick-up and delivery, recurring visits, and voyage separation are considered, and the solution is found with a branch-and-price heuristic.

The inherent uncertainty of the shipping market is addressed in several papers concerning stochastic programming. Meng and Wang (2010) use a chance constraint for each of the routes in a case to find the optimal fleet size and mix to satisfy an uncertain demand. They assume that the demand is normally distributed, and the integer programming (IP) model proposed is to guarantee that the demand is met with at least a given probability. 10 sets of cargo demand scenarios are generated based on benchmark demand patterns on a hypothetical case, and the optimal fleet and deployment plan is found for each of the scenarios. The problem is extended to include demand uncertainty in transshipment in Meng et al. (2012). A two-stage stochastic IP model is formulated and a solution algorithm is proposed.

In a fleet renewal problem the fleet size and mix for multiple time periods is to be determined by finding the optimal way of purchasing and disposing of vessels. Wijsmuller and Beumee (1979) present an investment and replacement model based on LP. While finding the best replacement schedule the fleet mix can be adjusted and the fleet size can vary between periods.

Nicholson and Pullen (1971) describe a fleet renewal and management problem for maximizing long-term assets for a company. Over a 10 year period a given fleet is to be renewed due to major changes in technology, and while vessels are sold others are chartered in to ensure sufficient capacity in the fleet. A priority for which vessels to sell is determined, and dynamic programming (DP) is used to find the optimal replacement strategy.

An algorithm for solving renewal problems combining both LP and DP is proposed by Xinlian et al. (2000). The purpose is to find the optimal way to add and lay up vessels by minimizing the costs over three years. They conclude that the model is more realistic than a LP model and saves computational time compared to a mixed integer programming (MIP) model.

Fleet utilization and renewal by purchasing newbuilds and scrapping vessels is considered in Jin and Kite-Powell (2000). They maximize the profit for a manager of a homogeneous fleet of vessels using an optimal control model. The decisions are based on a replacement strategy which determines when it is no longer economical to keep a vessel in the fleet due to the increase in operational costs with the aging of the vessel.

In Meng and Wang (2011) a multi-period liner ship fleet planning problem is studied. Different scenarios for the fleet size and mix are proposed by the liner shipping company. In each planning period a MIP problem is solved to maximize the profit. The demand is estimated for each planning period. The long-term fleet development and deployment plan is found by using a shortest path algorithm to solve the DP model for the multi-period problem. The authors also address the decision problem of whether to charter in or to purchase vessels.

Price and demand volatility is considered in Alvarez et al. (2011). A basic MIP model is extended for a multi-period fleet sizing, renewal, and deployment problem, taking into account the uncertainty in the market. The aim is to find optimal solutions while experiencing random variations in prices for selling and purchasing vessels as well as for demand. The model is tested on a realistic case for a bulk shipping company and can provide decision support for companies with varying risk tolerance degrees.

Pantuso et al. (2014b) take the uncertainty in the shipping market into account by presenting a stochastic programming model for the fleet renewal problem. The purpose is to analyze if the solution to the stochastic model proposes better decisions than that of a deterministic model using average data. The costs are minimized given a probability for each scenario, and comprise acquiring of new builds, purchase of second-hand ships, revenue of ships sold, chartering costs, and operational costs. Random variables are discretized to create a scenario tree. The results from the analysis show that while deterministic models perform well in finding the types of vessels to acquire, the size of the fleet is improved when using the proposed stochastic model.

In a deployment problem the task is to assign vessels in a given fleet to the trades that are to be serviced. The deployment of the fleet is relevant for the fleet renewal problem as it influences the choices of changes made to the fleet. This thesis does not focus on fleet deployment, but a deployment plan is necessary to create an overview of the advantages and shortcomings of a fleet, and is therefore included. A thorough literature review on fleet deployment, routing, and scheduling has been conducted by Christiansen et al. (2004) and Christiansen et al. (2013).

Although several of the articles presented in this Section is relevant for the problem this thesis addresses, none of them consider the effect of ECAs in fleet planning.

3.2 Emission Control Areas

The different ways to comply with the ECA regulations have been discussed in several papers, some of which are presented here. Some articles describe the different measures to be taken, while others apply an optimization tool for making decisions about which measures to implement to comply with the regulations.

Han (2010) describes different strategies for ECA compliance, and separates the measures into three categories: technological, operational, and market-based measures. He identifies the major air pollution sources and the most important rules and regulations of air pollution in the maritime sector, and presents different mitigation strategies. Technological strategies involve upgrading the engines and propulsion systems to be more energy efficient and to emit less pollutants. Operational strategies include making changes to the operation of the vessel and the systems on board, like speed reduction and fuel change, and are mostly relevant in and near ports. Market-based measures such as economical incentives for lower emissions, emission trading programs, and emission fees provide a third way to reduce emissions.

Green logistics is a term used to describe problems which focus on environmental issues as well as economics. Sbihi and Eglese (2010) give a description of the field and address how combinatorial optimization can be used in green logistics with a focus on reverse logistics, waste management, and vehicle routing problems (VRPs).

There are several articles in the literature concerning how to optimize sailing speed to reduce fuel consumption and hence, emissions. Most of these are on the subject of VRPs. Lindstad et al. (2013) optimize speed by developing a model using information about sea conditions, freight market, and vessel design to vary power. By focusing on hydrodynamic and freight market aspects, they find that the optimal economical speed often is lower than the design speed found when considering still water conditions. The results show that both costs and emissions can be reduced by operating at this calculated speed.

Kuo and Wang (2011) aim to determine routes for which the emissions from a routing plan will be minimized. Their model uses distances, speed, and cargo weight to calculate the fuel consumption, which is to be minimized by the use of tabu search. They find that this approach significantly reduces fuel consumption and emissions compared to models that aim to minimize traveling distances.

Eguia et al. (2013) also address the fact that the environmental focus is becoming more important and should be considered in addition to economics when deciding how to operate a fleet of vessels. A heuristic is developed and validated by benchmark problems, where environmental issues like emissions, vibrations, noise, and accidents are minimized by representing these elements as costs in the objective function of a VRP. For a more complete survey of green VRPs, see Lin et al. (2014).

Madsen and Olsson (2012) compare different strategies for compliance with the ECA regulations and find the most cost-effective of these, looking at both new builds and retrofit. Using an example vessel and a route in the Baltic Sea they consider four different scenarios for compliance both with NO_x and SO_x regulations. The net present value of the investment and operational costs is calculated for each of the scenarios. They conclude that installation of a scrubber and a SCR system is favorable for the case.

An optimization model is developed by Balland et al. (2012) which aims to minimize costs while choosing air emission controls for a vessel to comply with the ECA regulations. Each emission control should be compatible both with the vessel type, the mission of the vessel, and the existing controls on the vessel. Some controls will interact with others, both in terms of costs and emission reduction, while others may be mutually exclusive. These effects are taken into account, and the results show that the interaction between controls needs to be addressed. Possible future changes in costs related to the measures and their interaction are also pointed out, and could possibly change the outcome of the cost minimization.

To introduce the uncertainty of emission reductions by different controls, Balland et al. (2013) propose a stochastic optimization model for installation of air emission controls to comply with the ECA regulations. The model finds the most cost-efficient installation procedure over a time horizon by modeling different scenarios. The model is a two-stage IP model which takes into account the cost and emission reduction interaction between the controls as described in Balland et al. (2012) and seeks to minimize the implementation costs for a set of controls.

The literature concerning green house gases is extensive. For instance, Bektas and Laporte (2011) propose a solution to the pollution routing problem which addresses both fuel consumption and green house gas emissions. As the ECA regulations do not concern total emissions of green house gases more literature discussing these will not be presented here.

As indicated in this Chapter, both fleet renewal problems and the ECA problematics are addressed in the literature. The lack of papers concerning both topics is however prominent, and the effect ECAs have on fleet decisions is not investigated.

Chapter 4

Mathematical Models

In this Chapter the mathematical formulations of the proposed models are presented and explained. Section 4.1 presents the basic formulation of a fleet renewal problem. Speed optimization is introduced in Section 4.2, and ECAs in Section 4.3.

4.1 Basic model

In this Section a model to the basic fleet renewal problem is presented. Without extensions of any kind, the model seeks the optimal decisions for the renewal of an initial fleet, comprising purchase and chartering of vessels. The deployment of the fleet is found to provide a foundation for determining the capacity needed in the fleet.

Sets and indices

$\mathcal{V}$	Set of vessel types indexed by v
$\mathcal{T}$	Set of time periods indexed by t
$\mathcal{R}$	Set of regions indexed by r
$\mathcal{I}$	Set of trades indexed by i. $\mathcal{I} = \mathcal{I}^O \cup \mathcal{I}^B$
$\mathcal{I}^O$	Set of operational trades. $\mathcal{I}^O \subseteq \mathcal{I}$
$\mathcal{I}^B$	Set of ballast trades/sailings. $\mathcal{I}^B \subseteq \mathcal{I}$
$\mathcal{I}_v$	Set of trades to which vessel type v is compatible
$\mathcal{I}_r^S$	Set of trades starting in region r
$\mathcal{I}_r^L$	Set of trades ending in region r
$\mathcal{V}_i$	Set of vessel types that are compatible with trade i

Parameters

F_{it}	Required minimum frequency of voyages on operational trade i in time period t
D_{it}	Volume requirement for trade i in time period t
Q_v	Capacity of vessel v
T_{vi}	Sailing time (in days) on operational or ballast trade i for vessel v
T^A_{vt}	Number of available vessel days for one vessel of type v in time period t
N_{vt}	Number of vessels of type v in fleet plan in time period t
$\overline{N}_t$	Maximum number of vessels that may be purchased in time period t
$\overline{I}_t$	Maximum number of vessels that may be chartered in in time period t
C_{vit}	Total fuel and port/canal costs of sailing vessel type v on trade i in time period t
C^{TC}_{vt}	Time charter cost for using vessel type v in the fleet in time period t
C^{IN}_{vt}	The cost of chartering in a vessel of type v in time period t

Variables

x_{vit}	The number of times vessels of type v sail operational trade i in time period t
x^B_{vit}	The number of times vessels of type v sail ballast trade i in time period t
y_{vt}	The number of vessels of type v that are used in time period t
w_{vt}	The number of vessels of type v that are chartered in in time period t
p_{vt}	The number of vessels of type v that are purchased in time period t

Objective function

$$\min \sum_{v\in\mathcal{V}}\sum_{i\in\mathcal{I}^O}\sum_{t\in\mathcal{T}} C_{vit}x_{vit} + \sum_{v\in\mathcal{V}}\sum_{i\in\mathcal{I}^B}\sum_{t\in\mathcal{T}} C_{vit}x^B_{vit} + \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} C^{TC}_{vt}y_{vt} + \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} C^{IN}_{vt}w_{vt} \quad (4.1)$$

The objective function (4.1) minimizes the total costs, consisting of sailing costs for operational and ballast trades, time charter costs, and costs for vessels chartered in.

Constraints

$$\sum_{v\in\mathcal{V}_i} x_{vit} \geq F^O_{it}, \qquad t\in\mathcal{T}, i\in\mathcal{I}^O, \quad (4.2)$$

$$\sum_{v\in\mathcal{V}_i} Q_v x_{vit} \geq D_{it}, \qquad t\in\mathcal{T}, i\in\mathcal{I}^O \quad (4.3)$$

Constraints (4.2) and (4.3) make sure that the frequency and volume demand requirements are met for all operational trades.

$$\sum_{i \in \mathcal{I}_r^S \cap \mathcal{I}^O \cap \mathcal{I}_v} x_{vit} + \sum_{i \in \mathcal{I}_r^S \cap \mathcal{I}^B \cap \mathcal{I}_v} x_{vit}^B = \sum_{i \in \mathcal{I}_r^L \cap \mathcal{I}^O \cap \mathcal{I}_v} x_{vit} + \sum_{i \in \mathcal{I}_r^L \cap \mathcal{I}^B \cap \mathcal{I}_v} x_{vit}^B, \qquad v \in \mathcal{V}, t \in \mathcal{T}, r \in \mathcal{R} \tag{4.4}$$

Constraints (4.4) ensure flow conservation by stating that for each vessel type and time period, the number of vessels ending in a region must be equal to the number of vessels starting in the same region.

$$\sum_{i \in \mathcal{I}^B \cap \mathcal{I}_v} T_{vi} x_{vit}^B + \sum_{i \in \mathcal{I}^O \cap \mathcal{I}_v} T_{vi} x_{vit} \leq T_{vt}^A (y_{vt} + w_{vt}), \qquad v \in \mathcal{V}, t \in \mathcal{T}, \tag{4.5}$$

Constraints (4.5) state that the sailing time for both operational and ballast trades cannot exceed the available time for each vessel type.

$$y_{vt} = N_{vt} + \sum_{t'=1}^{t} p_{vt'}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, \tag{4.6}$$

$$\sum_{v \in \mathcal{V}} p_{vt} \leq \overline{N}_t, \qquad t \in \mathcal{T}, \tag{4.7}$$

$$\sum_{v \in \mathcal{V}} w_{vt} \leq \overline{I}_t, \qquad t \in \mathcal{T}, \tag{4.8}$$

Constraints (4.6) define the number of vessels in the fleet, while constraints (4.7) and (4.8) make sure that the number of vessels that are purchased and chartered in cannot exceed the maximum number of vessels available for purchasing and chartering.

$$x_{vit} \geq 0, \text{(and integer)}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, i \in \mathcal{I}^O \cap \mathcal{I}_v, \tag{4.9}$$

$$x_{vit}^B \geq 0, \text{(and integer)}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, i \in \mathcal{I}^B \cap \mathcal{I}_v, \tag{4.10}$$

$$y_{vt}, w_{vt}, p_{vt} \geq 0, \text{and integer}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, \tag{4.11}$$

The last constraints, (4.9), (4.10), and (4.11), are non-negativity and integer constraints for all variables.

4.2 Speed optimization

Including speed optimization allows the vessels in the model to use a set of speeds instead of only one predefined speed. This makes the model more realistic and offers more flexibility to

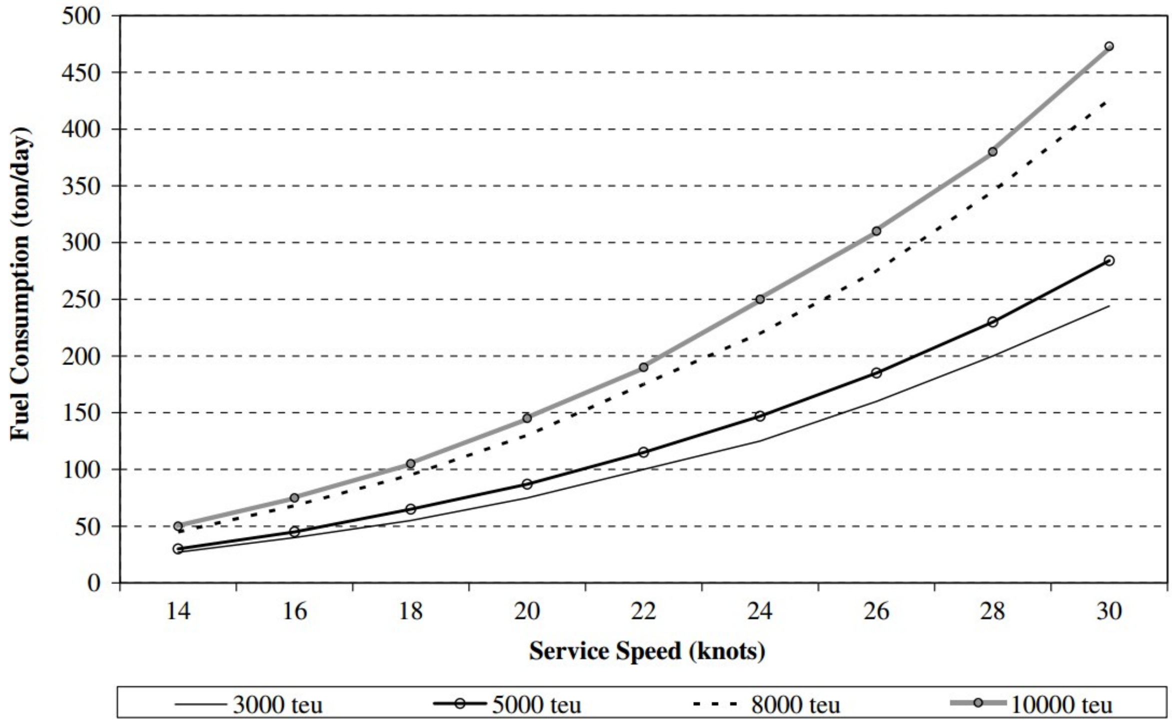

Figure 4.1: Example, daily fuel consumption for four types of container ships at different service speeds (Notteboom and Vernimmen, 2009)

the solution. Variable speed can be used as a way of adjusting the transportation capacity of the given network. If the demand is low the vessels can slow down to reduce fuel consumption, and hence fuel costs, while remaining in operation. The vessels can alternatively sail faster when demand is high or to compensate for other factors such as delays, accidents, or other things that make the transportation capacity reduced for shorter or longer periods of time.

Fuel costs rise with increased fuel consumption, which is dependent on the speed with which the vessel is sailing. Figure 4.1 shows the daily fuel consumption of four vessels based on their service speed. The graph is based on information from container vessels, but the shape of the graph is similar for any kind of vessel (Notteboom and Vernimmen, 2009). Fuel consumption can be approximated as a cubic function of speed over the set of service speeds available for a vessel (Fagerholt et al., 2010). Linear combinations of the specific relationship can be used to find the fuel consumption at any given speed.

By allowing the speed to vary more economical and environmental friendly solutions can also be found. As fuel consumption and hence emission levels are proportional with sailing speed, finding the optimal speed for a fleet can reduce both operational costs and environmental impact. In fact, Norstad et al. (2011) find the average fuel consumption to decrease by 14 %

when introducing speed as a decision variable in a routing and scheduling model.

The model is extended to include speed optimization by adding a set of available speeds for each vessel type, $\mathcal{S}_v$. The index s is added to the sailing variables, so a variable x_{vits} denotes the number of times vessel type v sail trade i in time period t at speed s. In addition the parameters T_{vi} and C_{vit} is given an index s for the sailing time and sailing cost, respectively, of servicing trade i with vessel type v at speed s.

The full model is presented in Appendix A.

4.3 Adapting the model to ECA requirements

Only vessels with sufficiently low emission levels of SO_x are able to sail in ECAs. The extended optimization model is to determine which vessels are allowed to service the different trades, making sure that an ECA trade is not serviced by a vessel with too high emissions. If the available fleet is not capable of servicing all trades, or the costs of doing so are high, vessels need to be upgraded with emission controls to satisfy the regulations. The model is to determine how many of each vessel type to retrofit or purchase to make the fleet able to satisfy the demand on each trade.

To adapt the basic model to ECA requirements the vessel types in the fleet are separated based on ECA compliance, and the sailing time in ECAs is determined for each trade. This provides a basis for defining the compatibility between the trades and the vessels. Vessels that are not ECA compliant can either perform a fuel switch in ECAs or be retrofitted. The costs and out-of-service time for retrofitting are introduced as parameters in the model. When vessels are retrofitted they are taken out of service, and this downtime must be accounted for in the model to make sure that there is sufficient time both for servicing the given trades and for completion of the retrofitting. If a scrubber is installed in one time period the model must ensure that the scrubber is installed in the following time periods as well. New decision variables are needed for sailing on a trade with both an ECA compliant vessels and with a retrofit vessel.

Sets and indices

$\mathcal{V}$	Set of vessel types indexed by v
$\mathcal{T}$	Set of time periods indexed by t
$\mathcal{R}$	Set of regions indexed by r
$\mathcal{I}$	Set of trades indexed by i. $\mathcal{I} = \mathcal{I}^O \cup \mathcal{I}^B$
$\mathcal{I}^O$	Set of operational trades. $\mathcal{I}^O \subseteq \mathcal{I}$
$\mathcal{I}^B$	Set of ballast trades/sailings. $\mathcal{I}^B \subseteq \mathcal{I}$
$\mathcal{I}^E$	Set of trades that lie partly within ECAs. $\mathcal{I}^E \subseteq \mathcal{I}$
$\mathcal{I}_v$	Set of trades to which vessel type v is compatible
$\mathcal{I}_r^S$	Set of trades starting in region r
$\mathcal{I}_r^L$	Set of trades ending in region r
$\mathcal{V}_i$	Set of vessel types that are compatible with trade i
$\mathcal{V}^E$	Set of vessel types that are ECA compliant

Parameters

F_{it}^O	Required minimum frequency of voyages on operational trade i in time period t
D_{it}	Volume requirement for trade i in time period t
Q_v	Capacity of vessel v
T_{vi}	Sailing time (in days) on operational or ballast trade i for vessel v
T_v^R	Installation time (in days) for retrofitting a vessel of type v
T_{vt}^A	Number of available vessel days for one vessel of type v in time period t
N_{vt}	Number of vessels of type v in fleet plan in time period t
$\overline{N}_t$	Maximum number of vessels that may be purchased in time period t
$\overline{I}_t$	Maximum number of vessels that may be chartered in in time period t
C_{vit}	Total fuel and port/canal costs of sailing vessel type v on non-ECA trade i, or on ECA trade i with compliant or retrofitted vessel in time period t
C_{vit}^{FS}	Total fuel and port/canal costs of sailing vessel type v on ECA trade i using fuel switch in time period t
C_{vt}^{TC}	Time charter cost for using vessel type v in the fleet in time period t
C_{vt}^{IN}	The cost of chartering in a vessel of type v in time period t
C_{vt}^R	The cost of retrofitting a vessel of type v in time period t

Variables

x_{vit}	The number of times vessels of type v sail trade i in time period t
x^{E}_{vit}	The number of times ECA compliant vessel of type v sail trade i in time period t
x^{R}_{vit}	The number of times retrofitted vessel of type v sail trade i in time period t
x^{B}_{vit}	The number of times vessels of type v sail ballast trade i in time period t
x^{BE}_{vit}	The number of times ECA compliant vessel of type v sail ballast trade i in time period t
x^{BR}_{vit}	The number of times retrofitted vessel of type v sail ballast trade i in time period t
y_{vt}	The number of vessels of type v in the fleet in time period t
w_{vt}	The number of vessels of type v that are chartered in in time period t
p_{vt}	The number of vessels of type v that are purchased in time period t
u_{vt}	The number of vessels of type v that are being retrofitted in time period t
z_{vt}	The total number of vessels of type v that are retrofitted in time period t

Objective function

$$\begin{aligned}
\min & \sum_{v\in\mathcal{V}^E}\sum_{i\in\mathcal{I}^O}\sum_{t\in\mathcal{T}} C_{vit}x^{E}_{vit} + \sum_{v\in\mathcal{V}^E}\sum_{i\in\mathcal{I}^B}\sum_{t\in\mathcal{T}} C_{vit}x^{BE}_{vit} \\
& + \sum_{v\in\mathcal{V}\setminus\mathcal{V}^E}\sum_{i\in\mathcal{I}^O}\sum_{t\in\mathcal{T}} C_{vit}x^{R}_{vit} + \sum_{v\in\mathcal{V}\setminus\mathcal{V}^E}\sum_{i\in\mathcal{I}^B}\sum_{t\in\mathcal{T}} C_{vit}x^{BR}_{vit} \\
& + \sum_{v\in\mathcal{V}\setminus\mathcal{V}^E}\sum_{i\in\mathcal{I}^O\setminus\mathcal{I}^E}\sum_{t\in\mathcal{T}} C_{vit}x_{vit} + \sum_{v\in\mathcal{V}\setminus\mathcal{V}^E}\sum_{i\in\mathcal{I}^B\setminus\mathcal{I}^E}\sum_{t\in\mathcal{T}} C_{vit}x^{B}_{vit} \\
& + \sum_{v\in\mathcal{V}\setminus\mathcal{V}^E}\sum_{i\in\mathcal{I}^O\cap\mathcal{I}^E}\sum_{t\in\mathcal{T}} C^{FS}_{vit}x_{vit} + \sum_{v\in\mathcal{V}\setminus\mathcal{V}^E}\sum_{i\in\mathcal{I}^B\cap\mathcal{I}^E}\sum_{t\in\mathcal{T}} C^{FS}_{vit}x^{B}_{vit} \\
& + \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} C^{IN}_{vt}w_{vt} + \sum_{v\in\mathcal{V}\setminus\mathcal{V}^E}\sum_{t\in\mathcal{T}} C^{R}_{vt}u_{vt} + \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} C^{TC}_{vt}y_{vt}
\end{aligned} \tag{4.12}$$

The objective function (4.12) minimizes the total costs, consisting of sailing costs for all trades, time charter costs, costs for vessels chartered in, and vessel retrofitting costs. The sailing costs are partitioned into four groups, where the first comprises sailings performed by compliant vessels and the second comprises sailings performed by retrofitted vessels. Groups three and four are sailings performed by non-compliant vessels, on ECA trades using fuel switch and non-ECA trades, respectively.

Constraints

$$\sum_{v \in \mathcal{V}_i} (x_{vit} + x_{vit}^E + x_{vit}^R) \geq F_{it}^O \qquad t \in \mathcal{T}, i \in \mathcal{I}^O, \tag{4.13}$$

$$\sum_{v \in \mathcal{V}_i} Q_v(x_{vit} + x_{vit}^E + x_{vit}^R) \geq D_{it}, \qquad t \in \mathcal{T}, i \in \mathcal{I}^O, \tag{4.14}$$

Constraints (4.13) and (4.14) make sure that the frequency and volume requirements are met for all operational trades.

$$\begin{aligned} &\sum_{i \in \mathcal{I}_r^S \cap \mathcal{I}^O \cap \mathcal{I}_v} x_{vit} + \sum_{i \in \mathcal{I}_r^S \cap \mathcal{I}^B \cap \mathcal{I}_v} x_{vit}^B = \\ &\quad \sum_{i \in \mathcal{I}_r^L \cap \mathcal{I}^O \cap \mathcal{I}_v} x_{vit} + \sum_{i \in \mathcal{I}_r^L \cap \mathcal{I}^B \cap \mathcal{I}_v} x_{vit}^B, \qquad v \in \mathcal{V} \backslash \mathcal{V}^E, t \in \mathcal{T}, r \in \mathcal{R}, \end{aligned} \tag{4.15}$$

$$\begin{aligned} &\sum_{i \in \mathcal{I}_r^S \cap \mathcal{I}^O \cap \mathcal{I}_v} x_{vit}^E + \sum_{i \in \mathcal{I}_r^S \cap \mathcal{I}^B \cap \mathcal{I}_v} x_{vit}^{BE} = \\ &\quad \sum_{i \in \mathcal{I}_r^L \cap \mathcal{I}^O \cap \mathcal{I}_v} x_{vit}^E + \sum_{i \in \mathcal{I}_r^L \cap \mathcal{I}^B \cap \mathcal{I}_v} x_{vit}^{BE}, \qquad v \in \mathcal{V}^E, t \in \mathcal{T}, r \in \mathcal{R}, \end{aligned} \tag{4.16}$$

$$\begin{aligned} &\sum_{i \in \mathcal{I}_r^S \cap \mathcal{I}^O \cap \mathcal{I}_v} x_{vit}^R + \sum_{i \in \mathcal{I}_r^S \cap \mathcal{I}^B \cap \mathcal{I}_v} x_{vit}^{BR} = \\ &\quad \sum_{i \in \mathcal{I}_r^L \cap \mathcal{I}^O \cap \mathcal{I}_v} x_{vit}^R + \sum_{i \in \mathcal{I}_r^L \cap \mathcal{I}^B \cap \mathcal{I}_v} x_{vit}^{BR}, \qquad v \in \mathcal{V} \backslash \mathcal{V}^E, t \in \mathcal{T}, r \in \mathcal{R}, \end{aligned} \tag{4.17}$$

Flow conservation for normal, compliant and retrofit sailings is taken care of by constraints (4.15), (4.16), and (4.17), respectively.

$$\sum_{i \in \mathcal{I}^B \cap \mathcal{I}_v} T_{vi}(x_{vit}^B + x_{vit}^{BR}) + \sum_{i \in \mathcal{I}^O \cap \mathcal{I}_v} T_{vi}(x_{vit} + x_{vit}^R) + T_v^R u_{vt} \leq T_{vt}^A(y_{vt} + w_{vt}), \qquad v \in \mathcal{V} \backslash \mathcal{V}^E, t \in \mathcal{T}, \tag{4.18}$$

$$\sum_{i \in \mathcal{I}^B \cap \mathcal{I}_v} T_{vi} x_{vit}^{BE} + \sum_{i \in \mathcal{I}^O \cap \mathcal{I}_v} T_{vi} x_{vit}^{E} \leq T_{vt}^A (y_{vt} + w_{vt}), \qquad v \in \mathcal{V}^E, t \in \mathcal{T}, \tag{4.19}$$

$$\sum_{i \in \mathcal{I}^B \cap \mathcal{I}_v} T_{vi} x_{vit}^{BR} + \sum_{i \in \mathcal{I}^O \cap \mathcal{I}_v} T_{vi} x_{vit}^{R} + T_v^R u_{vt} \leq T_{vt}^A z_{vt}, \qquad v \in \mathcal{V} \backslash \mathcal{V}^E, t \in \mathcal{T}, \tag{4.20}$$

Constraints (4.18), (4.19), and (4.20) state that the sailing time together with retrofitting time cannot exceed the available time for each of the vessel types non-compliant, compliant and retrofit.

$$y_{vt} = N_{vt} + \sum_{t'=1}^{t} p_{vt'}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, \tag{4.21}$$

$$z_{vt} = \sum_{t'=1}^{t} u_{vt'} \qquad v \in \mathcal{V} \backslash \mathcal{V}^E, t \in \mathcal{T}, \tag{4.22}$$

$$\sum_{v \in \mathcal{V}} p_{vt} \leq \overline{N}_t, \qquad t \in \mathcal{T}, \tag{4.23}$$

$$\sum_{v \in \mathcal{V}} w_{vt} \leq \overline{I}_t, \qquad t \in \mathcal{T}, \tag{4.24}$$

Constraints (4.21) and (4.22) define the number of vessels in the fleet and the number of vessels that are retrofitted at given time periods, while constraints (4.23) and (4.24) make sure that the number of vessels that are purchased and chartered in cannot exceed the maximum available purchase and charter in vessels.

$$x_{vit}, x_{vit}^E, x_{vit}^R \geq 0, \text{(and integer)}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, i \in \mathcal{I}^O \cap \mathcal{I}_v, \tag{4.25}$$

$$x_{vit}^B, x_{vit}^{BE}, x_{vit}^{BR} \geq 0, \text{(and integer)}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, i \in \mathcal{I}^B \cap \mathcal{I}_v, \tag{4.26}$$

$$y_{vt}, w_{vt}, p_{vt}, u_{vt}, z_{vt} \geq 0, \text{and integer}, \qquad v \in \mathcal{V}, t \in \mathcal{T} \tag{4.27}$$

The last constraints, (4.25), (4.26), and (4.27), are non-negativity and integer constraints for all variables.

Chapter 5

Computational study

To analyze the proposed models several computational experiments have been performed. In Section 5.1 the different test instances are presented. In Section 5.2 results for the basic model and the speed extended model are compared, and in Section 5.3 the effect of the fleet decisions when including ECAs is studied. Section 5.4 presents further analyses of the ECA extended model with possible changes to input data.

5.1 Test instances

The basic model formulation is based on a FSM model from a collaboration research project between the Norwegian Marine Technology Research Institute (MARINTEK), the Norwegian University of Science and Technology (NTNU), Det Norske Veritas (DNV), and WWL, called MARFLIX. The project aims to develop and test decision support models for the FSM problem through quantitative methods. The project is also the basis of the fleet and trade schedule information used to study the models in this thesis.

WWL was founded in 1999 as a collaboration between the two shipping companies Wallenius Logistics AB of Sweden and Wilhelmsen Ship Holding Malta Ltd. of Norway. The company delivers logistics and shipping solutions for manufacturers of rolling cargo such as cars, trucks, heavy equipment, and specialized cargo. WWL service 18 trading routes across six continents with a fleet of 61 vessels. The fleet consists of Pure Car and Truck Carriers (PCTC), Large Car and Truck Carriers (LCTC), and Roll on-Roll off (Ro-Ro) vessels.(Wallenius Wilhelmsen Logistics, 2008a,b,c)

The vessel input comprise data such as vessel capacities, speed choices available, fuel consumption, and charter rates. Trade routes with distances as well as frequency and volume demand are given, in addition to general parameters like port costs for different vessel types.

Fuel prices are estimated based on average values between European and east coast USA prices, as these are the places WWL usually bunker, given on bunkerworld.com in May 2014.

Most of the input values are provided by WWL, such as charter rates, time charter costs, retrofit costs, and time for retrofit. The time charter costs consist of daily expenses like maintenance, crew salary, and accoutrement, as well as devaluation. The charter in rate is equivalent to the time charter rate with some added cost as payment to the ship owner. WWL do not get much revenue from charter out, and the rate mainly covers daily expenses for having the vessel in the fleet. WWL have not retrofitted many vessels, but have provided estimated numbers for both the downtime and the associated costs of retrofitting.

Reasonable values for the number of vessels the company is able to charter in and out as well as purchase each year is proposed. As the Ro-Ro market is specialized, there is a limited number of vessels available in the market, and a limited number of companies interested in chartering in vessels if WWL wish to leave out vessels from their fleet. Based on this, the number of vessels available for chartering in is set to three, and two for chartering out. For purchase, a maximum of two vessels each year is set. In reality, purchasing two vessels each year could be unrealistic, but prospective results showing that this is a favorable strategy is indicative for capacity demand in the future. Some years reality could show that purchasing both more and less than two vessels is an option.

Three test instances have been studied: The full WWL case, with all vessels and all trades, and two smaller instances hereby denoted as the medium and the small test instance. Table 5.1 shows the initial fleets for the three test instances. The fleets are shown with aggregated numbers for all PCTC, LCTC and Ro-Ro vessels, as these are similar in size and characteristics. Altogether there are four LCTC, 13 PCTC, and four Ro-Ro vessel types. The complete initial fleets can be found in Appendix B. Initially, none of the vessels in the fleets are ECA compliant.

The models presented in this thesis have been implemented and solved using Xpress-IVE Version 1.24.00. The Mosel codes and the input files used to run the test instances are confidential and cannot be found in the published part of this thesis.

Table 5.1: Initial fleets, test instances

Vessel type	**# of vessels in fleet**		
	Full	**Medium**	**Small**
LCTC	13	12	10
PCTC	32	28	3
Ro-Ro	12	8	1

5.2 Comparison of basic model and speed extended model

When speed optimization is included in a fleet renewal model the interest does not lie in finding the speed with which the vessels should sail, but in finding how the fleet decisions and the quality of the solution are influenced when accounting for variable speed already on the strategic level.

If speed optimization is not considered when making the fleet renewal strategy, the company will optimize the speed when deployment plans are made and implemented. To demonstrate the savings that can be made by taking variable speed into account when determining the future fleet the deployment costs have been calculated both for the fleet renewal plan found with fixed speed and the one found with variable speed. Table 5.2 shows the resulting changes in the costs for deployment of the two different fleets for the five time periods, for the full and medium test instances.

The cost decrease of 0.297 % for the full instance can be said to make a difference as the costs are in the magnitude of several billion dollars for a five year period. Higher speed in the speed optimized model for the full and medium instances will make the sailing costs accordingly higher. The need to charter in and purchase vessels is lower, resulting in fewer vessels in the fleet, and as a result the time charter costs are significantly lower. This, together with lower charter in costs, is the primary reason for the decrease in total costs.

The results for the medium test instance is similar, with a total cost decrease of 0.330 %. All cost types have larger relative value in the medium than in the full instance. The increase in sailing costs and the decrease in time charter costs are higher, corresponding to larger numbers of purchased and chartered in vessels in the fixed speed model. The fact that the difference in number of vessels added to the fleet between the fixed and variable speed model is higher in the medium instance makes the total relative cost difference higher as well.

In the small instance the available fleet is sufficient to service all trades with time slack in both models, and as there are no changes in the fleet there will be no change in the deployment

Table 5.2: Changes in deployment costs, fixed vs. optimized speed

Type of cost	**Change**	
	Full	**Medium**
Trade sailings cost	1.473 %	2.540 %
Ballast sailings cost	2.973 %	3.392 %
Time charter cost	-2.988 %	-4.967 %
Total cost	-0.297 %	-0.330 %

Table 5.3: Fleet decisions, fixed vs. optimized speed, full

Fixed speed

t	Purchased	Chartered in	Chartered out
1	1 x PCTC 5	None	2 x PCTC 2
2	2 x PCTC 5	None	1 x PCTC 2 1 x PCTC 11
3	2 x PCTC 5	None	2 x PCTC 2
4	2 x Ro-Ro 3	1 x PCTC 4 1 x PCTC 5	1 x PCTC 2 1 x PCTC 11
5	2 x Ro-Ro 3	1 x PCTC 4 1 x PCTC 5	1 x PCTC 2 1 x PCTC 11

Optimized speed

t	Purchased	Chartered in	Chartered out
1	None	None	1 x PCTC 2 1 x PCTC 11
2	1 x LCTC 1	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1	None	1 x PCTC 2 1 x PCTC 11
4	2 x Ro-Ro 3	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 1 x Ro-Ro 3	None	1 x PCTC 2 1 x PCTC 11

cost. The results from the full and medium instances indicate that taking variable speed into account when making the fleet renewal plan is profitable.

Explanations to the cost changes will be discussed in the remainder of this Section.

In Table 5.3 the fleet decisions for the full test instance in each time period is presented, for fixed and optimized speed. The renewal strategies are somewhat similar, but several differences are distinct. In the optimized speed model no vessels are chartered in during the five time periods, compared to four in the fixed speed model. This shows the increased flexibility resulting from varying speed. This is also clear when looking at the first time period, where varying speed results in no additions to the fleet, as the vessels can sail faster and manage the demand without it being necessary or economical to purchase vessels. When speed is fixed purchase of a vessel is necessary.

In the fixed speed model the decisions of purchasing and chartering in vessels are driven primarily by the fact that the fleet cannot service all trades without added capacity in the fleet. In the variable speed model there is also an economical aspect as increased speed results in higher fuel costs. In some time periods, the available fleet might have sufficient capacity to service all trades, but the costs of sailing at high speeds make it profitable to invest in new vessels and decrease the speed of all or some of the vessels, especially in the long term.

In both models a need for more and bigger vessels become apparent in later time periods. Ro-Ro vessels are purchased rather than PCTC or LCTC vessels in both models, and charter in vessels are needed in the fixed speed model. This is a response to an increase in the transportation demand on the trades. In addition to increased demand, some vessels are scrapped during the five years, and they need to be replaced to obtain the same or a higher level of total fleet capacity.

Looking at the fifth time period it can be seen that when speed is fixed two Ro-Ro vessels are purchased, while when speed vary, one Ro-Ro and one LCTC vessel is purchased. WWL's fleet list (Wallenius Wilhelmsen Logistics, 2014a) shows that their Ro-Ro vessels are typically about 30 % larger than their LCTC vessels. This could indicate that when speed is fixed, the demand for capacity is the most important motivation for vessel purchase. The need for more capacity in the fleet could be smaller when speed vary. The focus could be on the trades on which the added capacity is really needed, and therefore the primary focus is not on acquiring as large vessels as possible. Another reason could be that the capacity need is not as great as in the variable speed model, and smaller vessels cost less to purchase and maintain in the fleet.

The charter out strategy is similar in both models, and PCTC 2 and PCTC 11 are chartered out. The fact that the solutions propose to charter out vessels at the same time as chartering in and purchasing vessels suggest that these vessel types are so expensive to use that it is less costly to charter them out and charter in other vessels to use. An alternative explanation could be that these vessels do not fit into the deployment plan as they do not have the suitable sizes or characteristics for the trades to be serviced.

In the medium test instance the difference in fleet decisions between the two models are similar as in the full instance. The results are shown in Table 5.4. Here, as well as in the full instance, more and bigger vessels are chartered in and purchased when speed is fixed compared to when it is variable. Another similarity is that the need for more capacity increases in later time periods, and the fleet grows over time. In the last two time periods of the fixed speed model only one vessel is chartered out. This is a reduction compared to the first three time periods, where the maximum number of vessels, two, are chartered out. In the last time periods it is not possible to acquire any more vessels, as both chartering in and purchasing is at the maximum number of three and two vessels, respectively. The need for capacity is so high that one of the vessels that are chartered out in the first three time periods, because of their high costs, needs to be utilized in the fleet and can not be

Table 5.4: Fleet decisions, fixed vs. optimized speed, medium

Fixed speed

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 1 x Ro-Ro 3	1 x LCTC 1 1 x PCTC 5	2 x PCTC 2
2	2 x Ro-Ro 3	1 x PCTC 5 1 x PCTC 8	2 x PCTC 2
3	2 x Ro-Ro 3	1 x LCTC 1 1 x PCTC 5 1 x PCTC 8	2 x PCTC 2
4	2 x Ro-Ro 3	1 x LCTC 1 1 x LCTC 2 1 x LCTC 3	1 X PCTC 2
5	2 x Ro-Ro 3	1 x LCTC 1 1 x LCTC 2 1 x LCTC 3	1 x PCTC 2

Optimized speed

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 1 x Ro-Ro 3	None	2 x PCTC 2
2	2 x Ro-Ro 3	None	2 x PCTC 2
3	2 x Ro-Ro 3	None	2 x PCTC 2
4	1 x LCTC 1 1 x Ro-Ro 3	1 x LCTC 1	2 x PCTC 2
5	1 x LCTC 1 1 x Ro-Ro 3	1 x LCTC 1	2 x PCTC 3

managed without. The large demand increase is also reflected in the fact that, contrary to in the full test instance, vessels are chartered in for the last time periods also when speed is optimized. This suggest that the demand has increased to a level where it is no longer sufficient or economical to handle all trades with the available fleet.

For both the full and the medium test instances, and for both fixed and variable speed, purchasing vessels is preferred over chartering in vessels. As the demand is strictly increasing, this is a rational decision for the long term view. Even though the costs of purchasing a vessel is high, chartering in is expensive and would lead to higher costs for the company over time. As mentioned earlier, purchasing vessels lets the company request specialized characteristics. When chartering in they would have to settle for whichever vessel is available in the market at that time. Even though the models do not take this into consideration, this is an important

Table 5.5: Difference in speed, fixed vs. optimized, full

Vessel type	Fixed speed	Selected speed
LCTC 1	17	19
LCTC 2	18	16/17
LCTC 3	17	18/19/20
LCTC 4	17	20
PCTC 1	17	14.5/15/16
PCTC 2	16	18.8
PCTC 3	16	17/18/19
PCTC 4	16	16/17/18
PCTC 5	17	15.2/16/17/18
PCTC 8	18	20
PCTC 9	18	20.5
PCTC 12	17	17/18/19
PCTC 13	18	20
Ro-Ro 1	18	16.5
Ro-Ro 2	18	17
Ro-Ro 3	19	17.5/18/19/20
Ro-Ro 4	19	18/19/20/21

benefit in purchasing rather than chartering in. Another issue is that it is not given that a vessel with the size or characteristics for which the company is seeking is possible to charter in at the time of need.

This fact is also reflected in the difference in vessel types between charter in and purchase. The assumption is made that it is uncommon to find Ro-Ro vessels available in the market for chartering in, and that this opportunity can not be counted on. PCTC and LCTC vessels are less specialized and the possibility of finding these vessel types is larger.

For the small test instances, the initial fleet is capable of handling all trades both in the case of fixed and variable speed. No vessels are chartered in or purchased, and the charter out strategy can be seen in Appendix C.

Table 5.5 shows how the selected speed from the modified model differs from the fixed speed set in the original model for the full test instance. Vessels for which more than one speed is selected sails with different speeds on different trades or in different time periods. The optimized speed is in some cases lower than fixed one, while in other cases higher. This shows the increase in flexibility obtained by including variable speed, where a vessel can slow down to lower fuel costs when time is available or speed up to manage more trades or to finish a trade in one time period. The speed output is similar for the medium test instance, and can be found in Appendix C. In the small instance there is more time slack, which results

Table 5.6: Difference in speed, fixed vs. optimized, small

Vessel type	Fixed speed	Optimized speed
LCTC 1	17	14/15/16/17/18
LCTC 2	18	14/15
LCTC 3	17	14/15/16/17
PCTC 1	17	14.5
PCTC 9	18	15/16

Table 5.7: Average speed, fixed vs. optimized speed, full

t	Fixed speed	Optimized speed
1	17.48	17.84
2	17.46	18.35
3	17.50	18.92
4	17.49	18.90
5	17.54	19.00

Table 5.8: Average speed, fixed vs. optimized speed, small

t	Fixed speed	Optimized speed
1	17.63	14.14
2	17.65	14.13
3	17.53	14.20
4	17.49	14.96
5	17.47	15.78

in lower speeds on almost all sailings compared to when the speed is fixed. This is shown in Table 5.6.

The average speed for all vessels in each time period is summarized in table 5.7 for the full test instance. For all time periods, the average speed is higher when the model finds the best speed practice. The trend when speed is optimized is that it increases over time, as a response to the increase in demand. As was shown in Tables 5.3 and 5.4, vessels are added to the fleet as a response to the demand increase. The fact that the average speed increases as well indicates that the demand increases more than the fleet capacity in each of the time periods. The increased average speed shown in Table 5.7 is in coherence with the results from the fleet decisions. When the fleet in the variable speed model handles all trades with less additions to the fleet, the rest of the vessels are forced to increase their speed. As increasing speed increases the sailing costs, the fact that the average speed is higher when speed varies correspond to the theory that the vessel types that are chartered out is uneconomical to use.

Similar results for the average speed is seen in the medium test instance, included in Appendix C. Table 5.8 shows the average speed for the small instance. As the time slack is larger here, the average speed is lower in all time periods. The trend is that the average speed increases over time, as for the other two instances, but is still strictly beneath the fixed speed.

5.3 Comparison of speed extended and ECA extended model

The results in Section 5.2 show that the speed extended model is preferred over the basic model both in terms of lower total costs and fewer changes to the fleet. The solving time for the full test instance increases from 1.1 to 1.9 seconds. This is a large relative increase, but given that the amount of time used to solve the case with varied speed is still small, the speed extended model is chosen as the basis when comparing results with and without ECAs. In the rest of this Chapter the term *original model* refers to the speed extended model.

In this Section, the changes to the fleet renewal plan when introducing ECAs are investigated. Contrary to the variable speed inclusion in a fleet renewal model, including ECAs restricts the model. This leads to higher costs for the fleet. Sailing with compliant or retrofitted vessels, or with non-compliant vessels on non-ECA trades, will give the same sailing costs as a model excluding ECAs given the same sailings. Using non-compliant vessels on ECA trades is more expensive as a fuel switch is required, and retrofitting costs also make the total cost higher than the cost of managing the fleet without ECA considerations.

Table 5.9: Cost changes when accounting for ECAs

Type of cost	**Change**	
	Full	**Medium**
Operational sailings costs	-1.008 %	-2.195 %
Ballast sailings costs	0.248 %	-0.814 %
Time charter costs	-0.123 %	1.547 %
Total cost	-0.602 %	-0.712 %

The fact that the costs increase does not mean that the ECA extended model should not be used, or that implementing the fleet decisions proposed by the original model will result in less costly operation. If ECAs are not considered when determining the optimal fleet and the appurtenant deployment, the ECA regulations must nevertheless be followed. The true costs will be higher than the solution from the original model indicates, as all vessels that are not ECA compliant is forced to perform a fuel switch when entering ECAs.

To demonstrate this, the costs of determining a fleet renewal plan without accounting for ECAs and then deploying that fleet with ECAs have been compared to the deployment of the fleet found when ECAs were considered. The savings of taking ECAs into account when making the fleet renewal strategy can be seen in Table 5.9. It shows that the total costs decrease with 0.602 % for the full test instance, which corresponds to about 35 million US dollars. Even though this is a large amount of money, the relative decrease in costs is small.

The operational sailings costs count for a large part of the cost decrease. These costs are about five times as large as the ballast sailings costs, so the decrease in the former more than makes up for the increase in the latter. For the medium test instance the time charter costs increase, corresponding to an increased number of vessels in the fleet as can be seen later in this Section. The large decrease in the sailings costs makes the total costs decrease by 0.712 %.

The renewal plan for the small instance is equal in the solutions to both models, and there will be no changes in the costs.

The changes in optimal fleet renewal decisions, as can be seen in Table 5.10, show the significance of the cost difference between having compliant and non-compliant vessels. The vessels purchased when ECAs are considered are of the same types as in the output of the original model, but they are all ECA compliant. As the vessel types, trades and demands are equal, the fact that the same sized vessels are purchased is logical. Acquiring compliant vessels allows the shipping company to use them on whichever trade they are needed, both in the current time period and in the ones to come. If the cost of purchasing a compliant vessel is not significantly higher than that of a non-compliant one, the benefit of having a compliant vessel is large.

Table 5.10: Fleet decisions, with and without ECAs, full

Original model

t	Purchased	Chartered in	Chartered out
1	None	None	1 x PCTC 2 1 x PCTC 11
2	1 x LCTC 1	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1	None	1 x PCTC 2 1 x PCTC 11
4	2 x Ro-Ro 3	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 1 x Ro-Ro 3	None	1 x PCTC 2 1 x PCTC 11

ECA extended model

t	Purchased	Chartered in	Chartered out
1	None	None	1 x PCTC 2 1 x PCTC 11
2	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11

Purchasing compliant vessels excludes these when possibly debating which vessels to retrofit if the need should appear. Vessels that are already compliant will never experience any down time due to retrofitting, which could be an issue for non-compliant vessels. Retrofitting more vessels in the future could become an option if the fleet should be altogether non-compliant or too expensive due to more areas of the seas being made into ECAs, or to other compliant or retrofitted vessels leaving the fleet. Acquiring more ECA compliant vessels may allow more non-compliant vessels to sail on trades that spend less time in ECAs, or sail with lower speed. With a greater part of the fleet being compliant, the non-compliant vessels might not be forced to trade in ECAs to fulfill requirements on these trades when there are not enough compliant vessels to service them all.

As is the case for the original model, the output from the ECA extended model shows that purchasing vessels are preferred rather than chartering in. This means that despite the

Table 5.11: Sailings on trades by purchased vessel types in time periods 4 and 5

Vessel type	**Trade**	**% in ECA**	**# of sailings**
LCTC 1 Compliant	EUNA 2	32	105.70
	NAEU	32	88.89
	EUNA 4	61	10.01
	ASEU 3	7	10.01
Ro-Ro 3 Compliant	ASNA	12	11.79
	NAOC	17	11.79

fact that compliant vessels are more expensive than non-compliant, is it still more costly to charter in vessels than to purchase them, as discussed in Section 5.2.

A few other alterations in the fleet renewal plans from the two different models are worth discussing. Firstly, in the second time period two vessels are purchased in the ECA model, as a contrast to only one in the original model. The initial fleet, the trades, and the demands are equal in both models, hence there is no need for additional capacity in the fleet. This could indicate that costs can be saved by purchasing another compliant vessel rather than letting a non-compliant vessel service more of the transportation demand. The savings of letting a compliant vessel service ECA trades and possibly reducing the speed of parts of the fleet make up for the costs of having one more vessel in the fleet.

In the forth time period one LCTC and one Ro-Ro vessel is purchased in the ECA model, as opposed to two Ro-Ro vessels in the original model. This could decipher that it is no longer only the total capacity of the fleet that is the focus when purchasing decisions are made, but also the trades on which more capacity is needed. Table 5.11 shows the trades serviced by the vessel types LCTC 1 Compliant and Ro-Ro 3 Compliant in the two last time periods, and the number of sailings on these. As can be seen, almost all sailings performed by LCTC 1 Compliant is in large part within ECAs, while the ones serviced by Ro-Ro 3 Compliant are in lesser parts within ECAs. This could indicate that in addition to purchasing vessels to add capacity to the fleet, it is important to acquire compliant vessels to service trades where large savings can be made by not using fuel switch.

Some of the same trends as in the full test instance can be seen for the medium instance in Table 5.12. The purchase strategies are identical for the two models, but all vessels purchased in the ECA model are compliant.

There are differences in the charter in strategies for the two models. As mentioned, the initial fleet, the trades, and the demands are equal in both models, and so the result shows that it is less costly to charter in compliant vessels than to utilize the available fleet with fuel switch. Some of the trades in which only a small part is within ECAs are removed in the medium test instance, making the average trade percent in ECAs 23.73 %, while in the

Table 5.12: Fleet decisions, with and without ECAs, medium

Original model

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 1 x Ro-Ro 3	None	2 x PCTC 2
2	2 x Ro-Ro 3	None	2 x PCTC 2
3	2 x Ro-Ro 3	None	2 x PCTC 2
4	1 x LCTC 1 1 x Ro-Ro 3	1 x LCTC 1	2 x PCTC 2
5	1 x LCTC 1 1 x Ro-Ro 3	1 x LCTC 1	2 x PCTC 3

ECA extended model

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant	2 x PCTC 2
2	2 x Ro-Ro 3 Compliant	None	2 x PCTC 2
3	2 x Ro-Ro 3 Compliant	1 x PCTC 8 Compliant	2 x PCTC 2
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	1 x PCTC 2 1 x PCTC 3

full instance it is 19.80 %. The difference is not large, but it could be enough to make it profitable to charter in compliant vessels in the medium and not in the full instance.

In the small instance neither the original nor the ECA extended model suggest that any vessels should be purchased or chartered in, as can be seen in Appendix D. The charter out strategy is equal in the output from both the original and the ECA extended model in all three test instances, showing that the vessel types PCTC 2, PCTC 3, and PCTC 11 are uneconomical to operate.

The output from the ECA extended model shows that all retrofitting is performed in the first time period. For the full test instance two vessels are retrofitted, both of the type LCTC 3. The same result is found in the medium instance, while in the small instance no vessels are retrofitted.

For all instances very few vessels are retrofitted. There are several reasons to why this number is not higher. Purchase and installation of scrubbers is costly, and it takes time. The vessels are taken out of service for 30 days. Should vessels be retrofitted, the benefit of sailing on ECA trades for the consecutive time periods would have to make up for the time spent and the costs. The current fuel prices combined with the retrofitting price make it more economical to use fuel switch than to retrofit more vessels. Even though the opportunity to retrofit are only exploited for two vessels, there is a benefit of including this opportunity in the model. The savings when the two vessels are retrofitted have been calculated, compared to not including retrofit in the model. A decrease has been found of 0.028 % for the full test instance, which corresponds to about 1.5 million US dollars. The savings for the medium instance is 0.016 %, or about 800,000 US dollars. These numbers are not very large, and the decision makers of the company will have to decide whether or not the inconvenience of retrofitting vessels is worth the decreased costs.

One reason for the chartering in of a vessel in the first time period in the medium test instance could be explained by the retrofitting strategy. Even though only two vessels are retrofitted the transportation capacity of the fleet is reduced when these are taken out of service for 30 days each. The down time could make the fleet unable to service all trades, and introduce the need for a chartered vessel. As the demand is strictly increasing, and no charter in vessels are needed in the second time period, this is a reasonable explanation.

The trades serviced by retrofitted vessels are illustrated in Table 5.13. The table shows how the vessels in type LCTC 3 are used on different trades and the trade percent in ECA for each of the trades. A trend is that trades that in large part lie within an ECA are serviced by retrofitted vessels, while the trades with small percentage in ECA are serviced by non-compliant vessels. The results are according to the theory, as it is less costly to sail with retrofitted vessels in ECAs, and for trades that only have small parts within ECAs it is less costly to switch fuel when entering than to perform expensive retrofitting.

Similar results can be seen in Appendix D for the medium test instance. For the small instance this is not applicable as no vessels are retrofitted.

When ECAs are included in the original model, the solving time increases with 626 %, from 1.9 to 11.9 seconds. The relative increase is significant, but the total solving time is not viewed as a reason to avoid the ECA extension.

In these models, a discount of 5 % on future costs is used. The fleet decisions for the first

Table 5.13: Example: Trades serviced by retrofitted vessels, full

LCTC 3	**# of vessels in fleet: 4**	**# of vessels retrofitted: 2**
Trades serviced	**Trade percent in ECA**	**Type of vessel used**
ASNA	12	Non-compliant
EUOC 1	6	Non-compliant
EUNA 2	32	Both types
NAEU	32	Retrofit
NAOC	17	Non-compliant

time period is most relevant, as the shipping company would run the model each year and not rely on the results from years in the past. If costs from all time periods were valued equally, the numerical result could be misleading with regards to the decisions in the first time period as costs accrued in later years are less important. Moreover, it is reasonable to assume a required rate of return in addition to price increase.

5.4 Analyses of ECA model with input changes

Many of the input values used in the test instances are estimates, and could be sources of errors in the results. As mentioned there is a great deal of inherent uncertainty in the shipping market, as well as both long-term and short-term market cycles. This leads to difficulties when making estimates about future demand. Future fuel prices are also subject to high uncertainty, as well as technology development and higher occurence of retrofitting could make the costs of scrubber installation decrease. To investigate the effect of possible future situations on the fleet renewal model, some analyses are presented in this Section.

The resulting fleet decisions, retrofit strategies and costs given by the solution when the input values are altered are compared to those from the solution of the ECA model with original input values, to show the changes induced. In addition, the costs of taking ECAs into account when making the fleet renewal strategy are found by comparing the costs of the new solution to that of the model without ECAs, but with the same input values.

5.4.1 Sensitivity with regards to MGO price

In this thesis the assumption is made that all vessels with emissions above the ECA limits must switch to MGO when sailing inside an ECA. As MGO is more expensive than HFO, this leads to higher fuel costs. The price difference between HFO and MGO represents the added costs of performing fuel switches and the benefit of retrofitting vessels. For simplicity, the relationship between the HFO and the MGO price is investigated here by changing the price of MGO only.

In the following the price of MGO is decreased by 20 % of the current value to discuss the changes that would occur in the model solution with this decrease.

The changes in the costs related to a decrease in the MGO price are shown in Table 5.14. For all three test instances there is a decrease in sailings costs. There are no retrofitted vessels in the small test instance, and the decrease in the MGO price results in lower fuel costs for all sailings. The costs in the full and medium instances increase somewhat due to the fact that fuel switch is performed on all sailings, compared to the case with original MGO price

Table 5.14: Cost changes, original vs. 20 % decreased MGO price

Type of cost	**Change**		
	Full	**Medium**	**Small**
Operational sailings costs	-2.496 %	-2.739 %	-5.970 %
Ballast sailings costs	-1.218 %	-0.540 %	-9.052 %
Time charter costs	0.145 %	-1.614 %	0 %
Total cost	-1.597 %	-2.435 %	-2.926 %

Table 5.15: Cost changes, 20 % decreased MGO price, with vs. without ECAs

	Change, original MGO price		
	Full	**Medium**	**Small**
Total cost	-0.602 %	-0.712 %	0 %
	Change, 20 % decreased MGO price		
	Full	**Medium**	**Small**
Total cost	-0.075 %	-0.258 %	0 %

where retrofitting is performed. The decreased sailings cost indicates that the saved MGO costs are larger than the lost benefit of not having any retrofitted vessels. In all three test instances there will be large savings if MGO prices are reduced, as would be expected.

The costs of not taking ECAs into account are calculated for the case of decreased MGO price, and are presented in Table 5.15. There are no retrofitted vessels and the fleet is equal in the small test instance, hence there is no cost change. For the full and medium instances, the cost changes are smaller than before the MGO price reduction, as the decreased MGO price makes the fuel costs for the two solutions more similar. There are, however, still savings to be made by accounting for ECAs when determining the fleet plan, mostly because of the possibility to purchase compliant vessels.

One effect of a decrease in the MGO price is that a fuel switch will be less costly and thus that the benefit of having ECA compliant vessels will be smaller. This becomes apparent when the test instances are tried with lower MGO price, as the results show that it is no longer profitable to retrofit vessels. The two vessels that were retrofitted originally is now utilized with fuel switch.

Apart from the decrease in retrofitting there are only small changes to the fleet decisions. In the small test instance the exact same decisions are made about both purchasing, and chartering in and out. Only a small change in the purchase strategy is found in the full instance, where one LCTC vessel is replaced with one Ro-Ro vessel in the fourth time period. The strategies for these instances can be found in Appendix E. For the medium instance there is a change in the purchasing and chartering in strategy, as shown in Table 5.16. In the first time period, no vessels are chartered in, compared to the one LCTC vessel

Table 5.16: Fleet decisions, original vs. 20 % decreased MGO prices, medium

Original MGO prices

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant	2 x PCTC 2
2	2 x Ro-Ro 3 Compliant	None	2 x PCTC 2
3	2 x Ro-Ro 3 Compliant	1 x PCTC 8 Compliant	2 x PCTC 2
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	1 x PCTC 2 1 x PCTC 3

20 % decreased MGO prices

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	2 x PCTC 2
2	2 x Ro-Ro 3 Compliant	None	2 x PCTC 2
3	2 x Ro-Ro 3 Compliant	None	2 x PCTC 2
4	2 x Ro-Ro 3 Compliant	1 x LCTC 3 Compliant	2 x PCTC 2
5	2 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant	1 x PCTC 2 1 x PCTC 3

in the original model. As no vessels are retrofitted in the case of decreased MGO price, no vessels are taken out of service and the fleet is capable of servicing all trades without the need for additional vessels to make up for time lost when retrofitting. In the last three time periods one less vessel is chartered in. As fuel switch is less expensive the benefit of adding a compliant vessel to the fleet is no longer large enough to compensate for the added costs the extra vessel carry. Rather than chartering in more vessels, larger Ro-Ro vessels are purchased to secure sufficient capacity in the last two time periods.

The price of MGO could alternatively increase. This is a more probable outcome should the MGO price change. When the strict emission limits in ECAs come into force in 2015 the demand for MGO could increase, and a possible reaction could be an increase in the price. Following is an analysis of the changes that occur when the MGO price increases by 20 %.

Table 5.17 summarizes the cost changes when the MGO price increases by 20 %. A natural result is that total costs increase. Equal fleet renewal decisions result in equal time charter costs for the small test instance, while a decrease is seen for the medium instance and an increase in the full instance due to changes in purchase and charter strategies.

Table 5.17: Cost changes with 20 % increased MGO prices

Type of cost	**Change**		
	Full	**Medium**	**Small**
Retrofitting costs	350 %	500 %	N/A
Operational sailings costs	-0.408 %	-1.683 %	-8.837 %
Ballast sailings costs	-1.945 %	0.699 %	-13.028 %
Time charter costs	1.811 %	-0.743 %	0 %
Total cost	1.150 %	-0.048 %	1.224 %

Table 5.18: Cost changes, 20 % increased MGO prices, with vs. without ECAs

	Change, original MGO price		
	Full	**Medium**	**Small**
Total cost	-0.602 %	-0.712 %	0 %
	Change, 20 % increased MGO price		
	Full	**Medium**	**Small**
Total cost	-1.923 %	-2.817 %	-5.678 %

For the full instance the sailings costs decrease as a result of a large number of retrofitted vessels. For the medium instance the same is seen for operational trades, while the ballast sailings costs are dominated by an increase brought by the higher MGO prices. This can be explained by looking at the trades serviced by retrofitted vessels. These vessels perform round trips like EUNA 2–NAEU, with no ballast sailing, and NAOC–ASNA, with ballast sailings only from Oceania to Asia. This means that the savings obtained by having retrofitted vessels are larger for the operational than for the ballast sailings.

The cost changes when accounting for ECAs when the fleet plan is made is shown in Table 5.18. The savings are larger in all test instances when MGO price is increased, as fuel switch sailings become more expensive. In the original model, all sailings within ECAs use fuel switch, while in the ECA model compliant vessels are purchased and retrofitting is performed. For the small test instance, there were no changes to the fleet when introducing ECAs with the original MGO price, but when it is increased vessels are retrofitted. This results in the savings made in the small instance.

The change in the MGO price leads only to a small change in the charter out strategy for the small test instance, which can be found in Appendix E. The changes in the fleet decisions for the medium test instance is shown in Table 5.19. Changes occur for both purchasing and chartering in. In the first time period there is a need for more capacity. This could be a reaction to an increase in the number of retrofitted vessels as shown in Table 5.21 later in this Section. A similar result can be seen for the full test instance, where one vessel is purchased in the first time period, as opposed to none in the case of original MGO price.

Table 5.19: Fleet decisions, original vs. 20 % increased MGO prices, medium

Original MGO prices

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant	2 x PCTC 2
2	2 x Ro-Ro 3 Compliant	None	2 x PCTC 2
3	2 x Ro-Ro 3 Compliant	1 x PCTC 8 Compliant	2 x PCTC 2
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	1 x PCTC 2 1 x PCTC 3

20 % increased MGO prices

t	Purchased	Chartered in	Chartered out
1	2 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2
2	2 x Ro-Ro 3 Compliant	None	2 x PCTC 2
3	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 3 Compliant	2 x PCTC 2
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2

The fleet changes for the full instance can be found in Appendix E.

Increased MGO price leads to larger sailing costs when fuel switches are performed. This is reflected by the retrofitting strategies for the test instances, shown in Tables 5.20–5.22. For all instances the number of retrofitted vessels is higher, with an increase of seven, ten and nine vessels for the full, medium, and small instances, respectively. The results substantiate the fact that when the MGO prices increase, the benefit of spending time and money on retrofitting increases as well.

According to information found from Petromedia Ltd. (2014), it is not uncommon that the price of MGO changes about 5 % in one day. Therefore, an increase of 20 % may not be considered radical. To investigate the changes occurring in the solution of the ECA model should a major price change happen, the analysis is also performed for a MGO price increase of 50 %.

Table 5.23 shows the cost changes from the output of the models with original and 50 % increased MGO price. Underlined numbers means that the result is similar to, yet larger

Table 5.20: Number of retrofitted vessels, original vs. 20 % increased MGO prices, full

Original MGO prices		
Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 3	4	2
20 % increased MGO prices		
Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 3	4	2
LCTC 4	2	1
PCTC 3	2	2
PCTC 8	2	1
PCTC 13	4	3

Table 5.21: Number of retrofitted vessels, original vs. 20 % increased MGO prices, medium

Original MGO prices		
Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 3	4	2
20 % increased MGO prices		
Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 3	4	3
PCTC 3	2	2
PCTC 8	2	2
PCTC 11	12	4
Ro-Ro 3	4	1

Table 5.22: Number of retrofitted vessels, 20 % increased MGO prices, small

Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 1	2	2
LCTC 2	4	4
LCTC 3	4	2
PCTC 1	2	1

Table 5.23: Cost changes with 50 % increased MGO price

Type of cost	**Change**		
	Full	**Medium**	**Small**
Retrofit costs	900 %	700 %	N/A
Operational sailings costs	-0.592 %	0.218 %	-9.734 %
Ballast sailings costs	-2.292 %	-0.164 %	-14.997 %
Time charter costs	1.811 %	1.094 %	0 %
Total cost	2.207 %	2.108 %	1.329 %

Table 5.24: Cost changes, 50 % increased MGO price, with vs. without ECAs

	Change, original MGO price		
	Full	**Medium**	**Small**
Total cost	-0.602 %	-0.712 %	0 %
	Change, 50 % increased MGO price		
	Full	**Medium**	**Small**
Total cost	-4.385%	-5.243 %	-9.881 %

in magnitude than, the ones found when the MGO price was increased with 20 %. The retrofitting costs have increased, while for the full and small test instances the sailings costs have decreased due to more use of scrubbers rather than fuel switch. The total costs are higher for all test instances, as would be expected when the MGO price increases. For the medium instance with a 20 % increase, the total costs shown in Table 5.17 were dominated by savings from sailings costs. As the MGO price was increased further, it can be seen that the total costs increase because of the higher number of retrofitted vessels and the increase in sailings costs.

The same trend, with similar changes as with a 20 % increase, but with higher magnitude, can be seen for the cost changes related to the inclusion of ECAs in the model. These are shown in Table 5.24. The results indicate that should the MGO price increase radically, there are large savings to be made by considering ECAs when determining the fleet plan.

The changes to the fleet concerning purchase and charter strategy is equal when the increase is 50 % to when it is 20 %. This can be seen in Appendix E. The effect of the additional price increase is otherwise strengthened, both for the retrofitting strategy and for the cost changes. In Appendix E the number of retrofitted vessels for each of the test instances can be seen. In the case of a MGO price increase of 20 % there were nine retrofitted vessels in the full and small instances, and 12 in the medium instance. When the MGO price is increased further, the numbers are 20 and 16, for the full and medium test instance, respectively. No additional vessels are retrofitted in the small instance.

5.4.2 Sensitivity with regards to demand

A change in the demand situation would influence the fleet utilization. To investigate the changes to the fleet a shift in the demand situation is estimated. An increase of 10 % is added to the demand on trades that spend above 15 % of the time in ECAs, while demand on trades that spend below 15 % of the time in ECAs is decreased by 10 %. This corresponds to a shift in demand towards the ECA regions, in other words towards Europe and North America, and away from Africa, Asia and Oceania.

The demand shift is carried out for the full and medium test instances. The small instance comprise only trades between Europe and North America, and a shift in demand is not applicable.

The cost changes when introducing the demand shift are shown in Table 5.25. The number of retrofitted vessels is higher, hence the costs are correspondingly higher. The time charter costs are lower due to a reduction in the number of vessels in the fleet and to a lack of charter in vessels in the medium test instance. The vessels purchased are smaller than the ones purchased in the case of original demand, and this also contribute to the decreased time charter costs.

Large savings occur for the sailings costs. This is partly due to lower fuel costs for retrofitted vessels, and partly due to a reduced number and reduced sizes of vessels in the fleet. A large part could possibly be explained by the fact that the trades on which the demand is decreased are longer in distance and sailing time than the ones where demand is increased. The transportation is in larger part concentrated in the area of the Atlantic Ocean, and the utilization of the fleet is improved as the ballast sailings are fewer. All of these factors contribute to less fuel consumed, which in turn leads to decreased costs.

Table 5.26 shows the cost changes from the original model compared to the ECA model, with original and shifted demand. For the full test instance the reduction of sailings costs is larger with shifted demand, yet the increase in retrofitting costs is larger as well. With shifted demand there is a small increase in time charter costs as opposed to in the case

Table 5.25: Cost changes with shifted demand

Type of cost	**Change**	
	Full	**Medium**
Retrofit costs	100 %	50 %
Operational sailings costs	-6.606 %	-7.047 %
Ballast sailings costs	-7.108 %	-7.126 %
Time charter costs	-2.883 %	-3.199 %
Total cost	-5.004 %	-5.542 %

Table 5.26: Cost changes, demand shift, with vs. without ECAs

Change, original demand		
	Full	**Medium**
Total cost	-0.602 %	-0.712 %
Change, shifted demand		
	Full	**Medium**
Total cost	-0.619 %	-1.017 %

of original demand, where there is a small decrease. These facts result in a slightly larger reduction of total costs when accounting for ECAs for the shifted demand situation.

For the medium test instance there is a larger increase in the time charter costs and in the retrofitting costs. However, the decrease in sailings costs is much larger, which leads to an increase in the total savings made by taking ECAs into account.

The change in fleet decisions is summarized in Table 5.27 for the full test instance. The strategies for chartering in and out is equal as before the demand shift, while some changes can be seen in vessels purchased. Fewer and smaller vessels are purchased, which can be an indication that the total demand for fleet capacity has decreased. As the trades with decreased demand are longer in distance, this is not unlikely. In the case of original demand, the Ro-Ro vessels purchased in the last two time periods service the trades ASNA and NAOC. When the demand on these trades is decreased, the need for these vessels is not as high, and it is more profitable to purchase vessels of type LCTC 1, which service the trades EUNA 2 and NAEU, trades that both have an increased demand.

For the medium test instance similar results are found, and the fleet decisions can be seen in Table 5.28. The lack of charter in vessels in the case of demand shift indicates, as in the full instance, that the total demand for capacity is decreased. The vessels purchased are also smaller, yet not fewer, than in the case of original demand. As discussed above, this is due

to the trades on which the demand is increased, and the corresponding need for vessels to service these.

When demand is shifted the number of vessels retrofitted is increased with two and one, for the full and medium test instances, respectively. When the demand is shifted towards the Atlantic Ocean a larger part of the time is spent within an ECA and it becomes more profitable to retrofit vessels. This also strengthens the theory that the total demand for capacity is reduced. When vessels are being retrofitted they are taken out of service for 30 days, and the fact that no vessels are chartered in indicates that the remaining fleet is capable of servicing all trades. The vessels retrofitted can be seen in Appendix E.

Table 5.27: Fleet decisions, original vs. changed demand, full

Original demand

t	Purchased	Chartered in	Chartered out
1	None	None	1 x PCTC 2 1 x PCTC 11
2	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11

Changed demand

t	Purchased	Chartered in	Chartered out
1	None	None	1 x PCTC 2 1 x PCTC 11
2	None	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
4	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
5	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 3

Table 5.28: Fleet decisions, original vs. changed demand, medium

Original demand

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant	2 x PCTC 2
2	2 x Ro-Ro 3 Compliant	None	2 x PCTC 2
3	2 x Ro-Ro 3 Compliant	1 x PCTC 8 Compliant	2 x PCTC 2
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	1 x PCTC 2 1 x PCTC 3

Changed demand

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	2 x PCTC 2
2	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	2 x PCTC 2
3	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 3
4	2 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 3
5	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 3

5.4.3 Sensitivity with regards to scrubber price

The future investment and installation cost for scrubbers are subject to uncertainty. As of today, these are high as there are few manufacturers and the yards do not have much experience with retrofitting vessels with scrubbers. When the stricter ECA regulations come into force in 2015, there is a possibility that more suppliers will approach the market, and that the scrubber technology could be further developed and improved. In addition, if retrofitting becomes more common, the efficiency of the yards and the costs related to retrofitting could decrease.(Balland, 2013)

In the following, the changes induced by reducing the scrubber investment and installation price by 30 % are discussed. There are only negligible changes, if any, to the fleet renewal decisions for all three test instances, and these can be found in Appendix E.

Table 5.29: Cost changes with decreased scrubber price

Type of cost	**Change**		
	Full	**Medium**	**Small**
Retrofit costs	215 %	215 %	N/A
Operational sailings costs	-1.143 %	-0.711 %	-8.677 %
Ballast sailings costs	-0.925 %	-1.149 %	-8.000 %
Time charter costs	0.145 %	-0.477 %	0 %
Total cost	-0.163 %	-0.174 %	-0.597 %

Table 5.30: Cost changes, decreased scrubber price, with vs. without ECAs

	Change, original scrubber price		
	Full	**Medium**	**Small**
Total cost	-0.602 %	-0.712 %	0 %
	Change, decreased scrubber price		
	Full	**Medium**	**Small**
Total cost	-1.107%	-1.480 %	-3.120 %

An increase in the number of retrofits, combined with small changes in fleet decisions, leads to a cost change as seen in Table 5.29. The changes are mostly small in magnitude, but despite the costs added for additional retrofitting the resulting decrease in sailings costs leads to a decrease in the total costs. The largest difference can be found in the small test instance, as a larger part of the fleet is retrofitted than in the other two instances. The small reduction in costs shows that a decrease in the scrubber price is less significant than a change in both fuel prices and in demand.

Table 5.30 shows the cost changes between the original and the ECA model, with original and decreased scrubber price. The savings of accounting for ECAs when making the fleet plan are higher in all three test instances when the scrubber price is decreased. As the costs of retrofitting decrease, the benefit of allowing these upgrades becomes higher accordingly. When more vessels are retrofitted, more fuel costs are saved and the benefit of taking ECAs into account increases.

As can be expected, the number of vessels retrofitted increases when the price of scrubbers are reduced. Tables 5.31–5.33 show that more vessels are retrofitted in each of the test instances. This denotes that the scrubber price is reduced to a level where it becomes more profitable to retrofit vessels than to perform fuel switches for these vessels.

Table 5.31: Number of retrofitted vessels, original vs. decreased scrubber price, full

Original scrubber price		
Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 3	4	2

Decreased scrubber price		
Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 3	4	3
PCTC 3	2	2
PCTC 8	2	1
PCTC 13	4	3

Table 5.32: Number of retrofitted vessels, original vs. decreased scrubber price, medium

Original scrubber price		
Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 3	4	2

Decreased scrubber price		
Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 3	4	3
PCTC 3	2	2
PCTC 8	2	1
PCTC 11	12	3

Table 5.33: Number of retrofitted vessels, original vs. decreased scrubber price, small

Original scrubber price		
Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 3	4	2

Decreased scrubber price		
Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 1	2	2
LCTC 2	4	4
LCTC 3	4	1
PCTC 1	2	1

Chapter 6

Conclusions and recommendations

In this thesis the effect of Emission Control Areas on the fleet renewal problem has been implemented and discussed. To the author's knowledge this is the only work considering the inclusion of ECAs when making a fleet plan, although several papers on each of the subjects are found in the literature. The fleet renewal problem is an important strategic planning problem in which the purpose in liner shipping is to find the best way to develop a fleet to minimize costs while servicing given trades.

A basic model formulation with fixed speeds for all vessels and an extended model including speed optimization are presented and the two solutions are compared. The results show fewer alterations to the fleet when optimizing speed, as the transportation capacity in the network is more flexible and increased speed in the extended model allows the current fleet to service all trades. The deployment costs for the two optimal fleets show that a cost decrease of 0.297 % and 0.330 %, for the full and medium test instances, respectively, is obtained by taking speed optimization into consideration when making the fleet plan. Even though these numbers are small one should keep in mind that the magnitude of the total costs are several billion dollars, and thus that this decrease corresponds to a significant amount of money. Based on these results the conclusion is drawn that including speed optimization is favorable when using a fleet renewal model to make fleet decisions.

If ECAs are not considered when making the fleet renewal plan, they must be when the deployment is planned. According to the results in this thesis taking ECAs into consideration in the fleet renewal plan could result in cost savings. For the full test instance the costs decrease by 0.602 % while for the medium instance the decrease is 0.712 %. The results indicate that the fleet is adjusted to be more suitable for the ECA regulations, and that ECAs should be accounted for when the future of the fleet is planned.

Analyses of possible future changes in the MGO price, demand situation, and scrubber price are performed. These suggest that if the price difference between HFO and MGO is to decrease, the benefit of retrofitting vessels disappear and the costs of not accounting for ECAs are decreased as fuel switch is less costly. When the price difference increases the opposite is the result; more vessels are retrofitted and the costs of not considering ECAs increase. Lower scrubber price and a shift in demand towards ECAs show the same trend. In all cases taking ECAs into account when making the fleet renewal plan results in reductions in total costs.

In the small test instance the fleet is sufficiently large to service all trades without changes throughout the five year period. This means that no savings occur when accounting for ECAs in the model with the original input values. When the MGO price increases and when scrubber price decreases vessels will however be retrofitted and costs can be saved.

In some of the analyses the fleet does not change in the first time period, but changes that occur in later time periods lead to a cost difference for the two models. In these cases the benefit of using the ECA extended model rather than the original model is absent, but using the former can nevertheless be beneficial as it indicates a long term plan that differ from the one resulting from the original model.

When estimates for the input values are made the ECA model is easy to use, and the solving time for the full WWL test instance is 11.9 seconds. All analyses performed in this thesis indicate that it is profitable to account for ECAs when planning the renewal of a fleet. The magnitude of the benefit varies with the input values tested, but is strictly positive. These facts suggest that there is great potential in using the ECA extended model for fleet renewal planning.

As the emission limits used in these models are not implemented until January of 2015, there has been no opportunity to compare the results from the ECA extended model to plans made manually in WWL. Therefore nothing can be said about possible improvements in this regard.

Should the subject of ECA extended fleet renewal models be further researched, looking into the uncertainty of the estimates made in this thesis is recommended. Extending the ECA model to include stochastic elements could help investigate the effect of possible changes to fuel prices, demand situations, and other important factors. The analyses performed in this thesis consider permanent changes to the input values, and allowing them to change gradually would provide insight to a more realistic future situation.

Other extensions could regard including other emission abatement measures, like switching to LNG when sailing in ECAs. This alternative has in this thesis been assumed too space consuming, inaccessible, and expensive for the current situation, but if the access to LNG bunkering is developed and the LNG price reduces, this could become an alternative.

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Appendix A

Model with speed optimization

Sets and indices

$\mathcal{V}$	Set of vessel types indexed by v
$\mathcal{T}$	Set of time periods indexed by t
$\mathcal{R}$	Set of regions indexed by r
$\mathcal{S}$	Set of sailing speeds that can be chosen for vessel v indexed by s
$\mathcal{I}$	Set of trades indexed by i. $\mathcal{I} = \mathcal{I}^O \cup \mathcal{I}^B$
$\mathcal{I}^O$	Set of operational trades. $\mathcal{I}^O \subseteq \mathcal{I}$
$\mathcal{I}^B$	Set of ballast trades/sailings. $\mathcal{I}^B \subseteq \mathcal{I}$
$\mathcal{I}_v$	Set of trades to which vessel type v is compatible
$\mathcal{I}_r^S$	Set of trades starting in region r
$\mathcal{I}_r^L$	Set of trades ending in region r
$\mathcal{V}_i$	Set of vessel types that are compatible with trade i

Parameters

F^O_{it}	Required minimum frequency of voyages on operational trade i in time period t
D_{it}	Total volume requirement for operational trade i in time period t
Q_v	Total capacity of vessel v
T_{vis}	Sailing time (in days) on operational or ballast trade i for vessel v sailing at speed s
T^A_{vt}	Number of available vessel days for one vessel of type v in time period t
N_{vt}	Number of vessels of type v in fleet plan in time period t
$\overline{N}_t$	Maximum number of vessels that may be purchased in time period t
$\overline{I}_t$	Maximum number of vessels that may be chartered in in time period t
C_{vits}	Total fuel and port/canal costs of sailing vessel type v on trade i in time period t at speed s
C^{TC}_{vt}	Time charter cost for using vessel type v in the fleet in time period t
C^{IN}_{vt}	The cost of chartering in a vessel of type v in time period t

Variables

x_{vits}	The number of times vessels of type v sail operational trade i in time period t at speed s
x^B_{vits}	The number of times vessels of type v sail ballast trade i in time period t at speed s
y_{vt}	The number of vessels of type v that are used in time period t
w_{vt}	The number of vessels of type v that are chartered in in time period t
p_{vt}	The number of vessels of type v that are purchased in time period t

Objective function

$$\min \sum_{v\in\mathcal{V}}\sum_{i\in\mathcal{I}^O}\sum_{t\in\mathcal{T}}\sum_{s\in\mathcal{S}_v} C_{vits}x_{vits} + \sum_{v\in\mathcal{V}}\sum_{i\in\mathcal{I}^B}\sum_{t\in\mathcal{T}}\sum_{s\in\mathcal{S}_v} C_{vits}x^B_{vits} + \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} C^{TC}_{vt}y_{vt} + \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} C^{IN}_{vt}w_{vt} \tag{A.1}$$

The objective function (A.1) minimizes the total costs, consisting of sailing costs for operational and ballast trades, time charter costs, and costs for vessels chartered in.

Constraints

$$\sum_{v \in \mathcal{V}_i} \sum_{s \in \mathcal{S}_v} x_{vits} \geq F^O_{it}, \qquad t \in \mathcal{T}, i \in \mathcal{I}^O, \tag{A.2}$$

$$\sum_{v \in \mathcal{V}_i} \sum_{s \in \mathcal{S}_v} Q_v x_{vits} \geq D_{it}, \qquad t \in \mathcal{T}, i \in \mathcal{I}^O \tag{A.3}$$

Constraints (A.2) and (A.3) make sure that the frequency and volume demand requirements are met for all trades.

$$\sum_{i \in \mathcal{I}^S_r \cap \mathcal{I}^O \cap \mathcal{I}_v} \sum_{s \in \mathcal{S}_v} x_{vits} + \sum_{i \in \mathcal{I}^S_r \cap \mathcal{I}^B \cap \mathcal{I}_v} \sum_{s \in \mathcal{S}_v} x^B_{vits} = \sum_{i \in \mathcal{I}^L_r \cap \mathcal{I}^O \cap \mathcal{I}_v} \sum_{s \in \mathcal{S}_v} x_{vits} + \sum_{i \in \mathcal{I}^L_r \cap \mathcal{I}^B \cap \mathcal{I}_v} \sum_{s \in \mathcal{S}_v} x^B_{vits}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, r \in \mathcal{R} \tag{A.4}$$

Constraints (A.4) ensure flow conservation by stating that for each vessel type and time period, the number of vessels ending in a region must be equal to the number of vessels starting in the same region.

$$\sum_{i \in \mathcal{I}^B \cap \mathcal{I}_v} T_{vi} \sum_{s \in \mathcal{S}_v} x^B_{vits} + \sum_{i \in \mathcal{I}^O \cap \mathcal{I}_v} \sum_{s \in \mathcal{S}_v} T_{vis} x_{vits} \leq T^A_{vt}(y_{vt} + w_{vt}), \qquad v \in \mathcal{V}, t \in \mathcal{T}, \tag{A.5}$$

Constraints (A.5) state that the sailing time for both operational and ballast trades cannot exceed the available time for each vessel type.

$$y_{vt} = N_{vt} + \sum_{t'=1}^{t} p_{vt'}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, \tag{A.6}$$

$$\sum_{v \in \mathcal{V}} p_{vt} \leq \overline{N}_t, \qquad t \in \mathcal{T}, \tag{A.7}$$

$$\sum_{v \in \mathcal{V}} w_{vt} \leq \overline{I}_t, \qquad t \in \mathcal{T}, \tag{A.8}$$

Constraints (A.6) define the number of vessels in the fleet, while constraints (A.7) and (A.8) make sure that the number of vessels that are purchased and chartered in cannot exceed the maximum number of vessels available for purchasing and chartering in.

$$x_{vits} \geq 0, \text{(and integer)}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, i \in \mathcal{I}^O \cap \mathcal{I}_v, s \in \mathcal{S}_v, \tag{A.9}$$

$$x^B_{vits} \geq 0, \text{(and integer)}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, i \in \mathcal{I}^B \cap \mathcal{I}_v, s \in \mathcal{S}_v, \tag{A.10}$$

$$y_{vt}, w_{vt}, p_{vt} \geq 0, \text{and integer}, \qquad v \in \mathcal{V}, t \in \mathcal{T}, \tag{A.11}$$

The last constraints, (A.9), (A.10), and (A.11), are non-negativity and integer constraints for all variables.

Appendix B

Complete initial fleets

The complete initial fleets can be seen on the next page.

Table B.1: Initial fleets, all three test instances

Vessel type	**# of vessels in fleet**		
	Full	**Medium**	**Small**
LCTC 1	3	4	2
LCTC 2	4	4	4
LCTC 3	4	4	4
LCTC 4	2	0	0
PCTC 1	2	2	2
PCTC 2	3	3	0
PCTC 3	2	2	0
PCTC 4	4	4	0
PCTC 5	1	2	0
PCTC 6	0	0	0
PCTC 7	0	0	0
PCTC 8	2	2	0
PCTC 9	1	1	1
PCTC 10	0	0	0
PCTC 11	1	0	0
PCTC 12	12	12	0
PCTC 13	4	0	0
Ro-Ro 1	3	3	1
Ro-Ro 2	1	1	0
Ro-Ro 3	4	4	0
Ro-Ro 4	4	0	0

Appendix C

Additional results, speed extended model

Table C.1: Average speed, fixed vs. optimized speed, medium

t	**Fixed speed**	**Optimized speed**
1	17.55	18.67
2	17.59	18.29
3	17.66	18.90
4	17.72	19.04
5	17.78	19.06

Table C.2: Difference in speed, fixed vs. optimized, medium

Vessel type	Fixed speed	Optimized speed
LCTC 1	18	19
LCTC 2	19	17/18
LCTC 3	18	19/20
PCTC 1	17	15/16
PCTC 2	16	18.8
PCTC 3	16	19
PCTC 4	16	17/18
PCTC 5	17	16/17
PCTC 8	18	20
PCTC 9	18	20.5
PCTC 12	17	18/19/19.2
Ro-Ro 1	18	16.5
Ro-Ro 2	18	17
Ro-Ro 3	19	20/21

Table C.3: Fleet decisions, fixed vs. optimized speed, small

Fixed speed

t	Purchased	Chartered in	Chartered out
1	None	None	2 x PCTC 1
2	None	None	2 x LCTC 3
3	None	None	2 x PCTC 1
4	None	None	1 x LCTC 3 1 x PCTC 1
5	None	None	1 x LCTC 3 1 x PCTC 1

Optimized speed

t	Purchased	Chartered in	Chartered out
1	None	None	2 x LCTC 3
2	None	None	2 x LCTC 3
3	None	None	2 x LCTC 3
4	None	None	2 x LCTC 3
5	None	None	2 x LCTC 3

Appendix D

Additional results, ECA extended model

Table D.1: Example: Trades serviced by retrofitted vessels, medium

LCTC 3	**# of vessels in fleet: 4**	**# of vessels retrofitted: 2**
Trades serviced	**Trade percent in ECA**	**Type of vessel used**
ASNA	12	Non-compliant
EUNA 2	32	Both types
NAEU	32	Retrofit
NAOC	17	Non-compliant

Table D.2: Fleet decisions, with and without ECAs, small

Original model

t	Purchased	Chartered in	Chartered out
1	None	None	2 x LCTC 3
2	None	None	2 x LCTC 3
3	None	None	2 x LCTC 3
4	None	None	2 x LCTC 3
5	None	None	2 x LCTC 3

ECA extended model

t	Purchased	Chartered in	Chartered out
1	None	None	2 x LCTC 3
2	None	None	2 x LCTC 3
3	None	None	2 x LCTC 3
4	None	None	2 x LCTC 3
5	None	None	2 x LCTC 3

Appendix E

Additional results, sensitivity analyses

Table E.1: Fleet decisions, original vs. 20 % decreased MGO prices, small

Original MGO prices

t	Purchased	Chartered in	Chartered out
1	None	None	2 x LCTC 3
2	None	None	2 x LCTC 3
3	None	None	2 x LCTC 3
4	None	None	2 x LCTC 3
5	None	None	2 x LCTC 3

20 % decreased MGO prices

t	Purchased	Chartered in	Chartered out
1	None	None	2 x LCTC 3
2	None	None	2 x LCTC 3
3	None	None	2 x LCTC 3
4	None	None	2 x LCTC 3
5	None	None	2 x LCTC 3

Table E.2: Fleet decisions, original vs. 20 % decreased MGO prices, full

Original MGO prices

t	Purchased	Chartered in	Chartered out
1	None	None	1 x PCTC 2 1 x PCTC 11
2	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11

20 % decreased MGO prices

t	Purchased	Chartered in	Chartered out
1	None	None	1 x PCTC 2 1 x PCTC 11
2	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
4	2 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 3

Table E.3: Fleet decisions, original vs. 20 % increased MGO prices, full

Original MGO prices

t	Purchased	Chartered in	Chartered out
1	None	None	1 x PCTC 2 1 x PCTC 11
2	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11

20 % increased MGO prices

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
2	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
4	2 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 3

Table E.4: Fleet decisions, original vs. 20 % increased MGO prices, small

Original MGO prices

t	Purchased	Chartered in	Chartered out
1	None	None	2 x LCTC 3
2	None	None	2 x LCTC 3
3	None	None	2 x LCTC 3
4	None	None	2 x LCTC 3
5	None	None	2 x LCTC 3

20 % increased MGO prices

t	Purchased	Chartered in	Chartered out
1	None	None	1 x LCTC 3 1 x PCTC 9
2	None	None	1 x LCTC 3 1 x PCTC 1
3	None	None	2 x LCTC 3
4	None	None	2 x LCTC 3
5	None	None	2 x LCTC 3

Table E.5: Fleet decisions, original vs. 50 % increased MGO prices, full

Original MGO prices

t	Purchased	Chartered in	Chartered out
1	None	None	1 x PCTC 2 1 x PCTC 11
2	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11

50 % increased MGO prices

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
2	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
4	2 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 3

Table E.6: Fleet decisions, original vs. 50 % increased MGO prices, medium

Original MGO prices

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant	2 x PCTC 2
2	2 x Ro-Ro 3 Compliant	None	2 x PCTC 2
3	2 x Ro-Ro 3 Compliant	1 x PCTC 8 Compliant	2 x PCTC 2
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	1 x PCTC 2 1 x PCTC 3

50 % increased MGO prices

t	Purchased	Chartered in	Chartered out
1	2 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2
2	2 x Ro-Ro 3 Compliant	None	2 x PCTC 2
3	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 3 Compliant	2 x PCTC 2
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2

Table E.7: Fleet decisions, original vs. 50 % increased MGO prices, small

Original MGO prices

t	Purchased	Chartered in	Chartered out
1	None	None	2 x LCTC 3
2	None	None	2 x LCTC 3
3	None	None	2 x LCTC 3
4	None	None	2 x LCTC 3
5	None	None	2 x LCTC 3

50 % increased MGO prices

t	Purchased	Chartered in	Chartered out
1	None	None	2 x LCTC 3
2	None	None	2 x LCTC 3
3	None	None	2 x LCTC 3
4	None	None	2 x LCTC 3
5	None	None	2 x LCTC 3

Table E.8: Number of retrofitted vessels, original vs. 50 % increased MGO price, full

Vessel type	Number of vessels in fleet	Number of retrofitted vessels
LCTC 3	4	3
LCTC 4	2	2
PCTC 3	2	2
PCTC 8	2	1
PCTC 12	12	1
PCTC 13	4	3
Ro-Ro 3	4	4
Ro-Ro 4	4	4

Table E.9: Number of retrofitted vessels, original vs. 50 % increased MGO price, medium

Vessel type	Number of vessels in fleet	Number of retrofitted vessels
LCTC 1	4	1
LCTC 3	4	4
PCTC 3	2	2
PCTC 8	2	2
PCTC 11	12	3
Ro-Ro 3	4	4

Table E.10: Number of retrofitted vessels, original vs. 50 % increased MGO price, small

Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 1	2	2
LCTC 2	4	4
LCTC 3	4	1
PCTC 1	2	2

Table E.11: Number of retrofitted vessels, changed demand, full

Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 1	3	1
LCTC 3	4	3

Table E.12: Number of retrofitted vessels, changed demand, medium

Vessel type	**Number of vessels in fleet**	**Number of retrofitted vessels**
LCTC 3	4	3

Table E.13: Fleet decisions, original vs. decreased scrubber price, full

Original scrubber price

t	Purchased	Chartered in	Chartered out
1	None	None	1 x PCTC 2 1 x PCTC 11
2	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11

Decreased scrubber price

t	Purchased	Chartered in	Chartered out
1	None	None	1 x PCTC 2 1 x PCTC 11
2	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
3	2 x LCTC 1 Compliant	None	1 x PCTC 2 1 x PCTC 11
4	2 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	None	1 x PCTC 2 1 x PCTC 11

Table E.14: Fleet decisions, original vs. decreased scrubber price, medium

Original scrubber price

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant	2 x PCTC 2
2	2 x Ro-Ro 3 Compliant	None	2 x PCTC 2
3	2 x RoRo 3 Compliant	1 x PCTC 8 Compliant	2 x PCTC 2
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2
5	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	1 x PCTC 2 1 x PCTC 3

Decreased scrubber price

t	Purchased	Chartered in	Chartered out
1	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 3 Compliant	2 x PCTC 2
2	2 x Ro-Ro 3 Compliant	None	2 x PCTC 2
3	2 x Ro-Ro 3 Compliant	1 x PCTC 8 Compliant	2 x PCTC 2
4	1 x LCTC 1 Compliant 1 x Ro-Ro 3 Compliant	1 x LCTC 3 Compliant	2 x PCTC 2
5	1 x LCTC 1 Compliant 1 X Ro-Ro 3 Compliant	1 x LCTC 1 Compliant 1 x LCTC 3 Compliant	2 x PCTC 2

Table E.15: Fleet decisions, original vs. decreased scrubber price, small

Original scrubber price

t	Purchased	Chartered in	Chartered out
1	None	None	2 x LCTC 3
2	None	None	2 x LCTC 3
3	None	None	2 x LCTC 3
4	None	None	2 x LCTC 3
5	None	None	2 x LCTC 3

Decreased scrubber price

t	Purchased	Chartered in	Chartered out
1	None	None	2 x LCTC 3
2	None	None	2 x LCTC 3
3	None	None	2 x LCTC 3
4	None	None	2 x LCTC 3
5	None	None	2 x LCTC 3