NTNU – Trondheim
Norwegian University of
Science and Technology

Optimal ship speed and routing when considering ECA regulations

Nora Therese Gausel

Industrial Economics and Technology Management
Submission date: June 2014
Supervisor: Kjetil Fagerholt, IØT
Co-supervisor: Jørgen Glomvik Rakke, IMT

Norwegian University of Science and Technology
Department of Industrial Economics and Technology Management

NTNU
Det skapende universitet

MASTERKONTRAKT

- uttak av masteroppgave

1. Studentens personalia

Etternavn, fornavn **Gausel, Nora Therese**	Fødselsdato **02. okt 1989**
E-post **norather@stud.ntnu.no**	Telefon **92848166**

2. Studieopplysninger

Fakultet **Fakultet for samfunnsvitenskap og teknologiledelse**	
Institutt **Institutt for industriell økonomi og teknologiledelse**	
Studieprogram **Industriell økonomi og teknologiledelse**	Hovedprofil **Anvendt økonomi og optimering**

3. Masteroppgave

Oppstartsdato **15. jan 2014**	Innleveringsfrist **11. jun 2014**
Oppgavens (foreløpige) tittel **Optimal ship speed and routing when considering ECA regulations**	
Oppgavetekst/Problembeskrivelse The purpose of this thesis is to develop mathematical models to illuminate how shipping companies might adapt to the regulations of emissions from ships in Emission Control Areas (ECA). The models will consider costs of different fuel options combined with sailing route and speed decisions for ships operating in these areas. Analyses will be conducted based on these models, to evaluate the overall outcome of the regulations' effectiveness in reducing emissions both in ECA zones and globally, and their economic impacts for the ship operators. The thesis includes a problem description, literature research for related problems and analyses of the problem using the developed models.	
Hovedveileder ved institutt **Professor Kjetil Fagerholt**	Medveileder(e) ved institutt **Jørgen Glomvik Rakke**
Merknader **1 uke ekstra p.g.a påske.**	

4. Underskrift

Student: Jeg erklærer herved at jeg har satt meg inn i gjeldende bestemmelser for mastergradsstudiet og at jeg oppfyller kravene for adgang til å påbegynne oppgaven, herunder eventuelle praksiskrav.

Partene er gjort kjent med avtalens vilkår, samt kapitlene i studiehåndboken om generelle regler og aktuell studieplan for masterstudiet.

14.05.2014
Sted og dato

Nora Gaustad
Student

Kjetil Fagerholt
Hovedveileder

Originalen lagres i NTNUs elektroniske arkiv. Kopi av avtalen sendes til instituttet og studenten.

Preface

This Master's thesis is written as an integrated part of the Master of Science in Industrial Economics and Technology Management with specialisation within Managerial Economics and Operations Research at the Norwegian University of Science and Technology (NTNU). The thesis is an independent paper and the work has been carried out during the spring term going from January to June 2014.

The thesis examines ship speed and routing considering Emission Control Area (ECA) regulations implemented by the International Maritime Organization (IMO), with associated environmental consequences.

I would like to thank my supervisors Professor Kjetil Fagerholt and Postdoctoral Fellow Jørgen Glomvik Rakke for all their valuable guidance and feedback during the past months, and also for arranging and accompanying me on the visit to the Technical University of Denmark (DTU). To that regard, I would like to thank Professor Harilaos Psaraftis and Assistant Professor Christos Kontovas for meeting with us and contributing with useful opinions and insights.

Trondheim, June 6th 2014

Nora Gausel

Abstract

Annex VI of the MARPOL convention under the International Maritime Organization (IMO) considers air pollution from ships and defines four Emission Control Areas (ECAs) with more stringent control of sulphur emissions. In 2015, the restrictions will tighten resulting in a sulphur limit of 0.1% within ECAs, whereas it is 3.5% outside ECAs. This thesis evaluates how the imposed regulations affect ship operations concerning speed and routing, and the associated consequences for the global environment.

In order to comply with ECA regulations, ships are assumed to apply fuel switching, where marine gas oil (MGO) with 0.1% sulphur content is consumed within ECAs and heavy fuel oil (HFO) is used elsewhere. MGO is more expensive than HFO, and the price differential induces the potential change in ship operations. Future fuel prices are uncertain, and the differential might increase due to higher demand for MGO when the ECA regulations tighten. A standard scenario is defined representing the current market situation, with MGO and HFO prices of USD 920 and 590 per tonne, respectively.

General optimisation models are developed for speed and routing decisions from a shipping company's point of view. The objective function minimises fuel costs, given as the product of fuel consumption and price for each of the fuels. Fuel consumption depends largely on speed, and it is often approximated as a cubic relation. Linear models are implemented using real data with discrete speed alternatives for which the fuel consumption for a given ship is known. Four different sub problems are studied, and speed is an important decision variable in all the corresponding models. The most emphasised problem includes alternative sailing leg options, where different legs are proposed between two ports so as to avoid stretches within ECA where the fuel is more expensive.

Findings show that ships would benefit from reducing speed within ECAs and compensate for the longer sailing time by speeding up on stretches outside ECAs. This leads to increased total fuel consumption compared to sailing at constant speed throughout the route, but the consumption of MGO is reduced from this strategy and so are total fuel costs. For the problem with fixed routes and sequences, the total fuel consumption is found to increase by 0.1-1% when ECAs are enforced. A greater increase appears for the variable leg problems, as total sailing distances increase in order to avoid ECA stretches. Speed consequently also increases to meet the generated time constraints. For this type of problem, the total fuel consumption is increased by around 3-7% for all the implemented cases.

The ECA regulations are intended to reduce sulphur emissions within the defined areas and protect coastal life from these harmful substances. Sulphur oxides (SO_X) emissions are calculated for all the problems in this thesis, and a great reduction is expected to follow the tighter sulphur limits, both in total and especially within ECAs. CO_2 emissions on the other hand are proportional to the total fuel consumption, and as such increase by the same relative amount of 0.1-1% for the fixed leg cases and 3-7% with variable legs. This increase is significant, and constitutes the downside of the predicted ECA implications. CO_2 is an important greenhouse gas contributing to global warming. Costs of the different emissions are not estimated or compared, but the general findings are of great importance for the evaluation of ECA impacts on the global environment.

Sammendrag

Annex VI til MARPOL-konvensjonen under den Internasjonale Sjøfartsorganisasjonen (IMO) tar for seg luftforurensning fra skip og definerer fire utslippskontrollområder (ECA) med strengere kontroll av svovelutslipp. I 2015 vil restriksjonene strammes inn og resultere i en svovelgrense på 0,1% innenfor ECA. Denne avhandlingen vurderer hvordan de pålagte forskriftene påvirker skipsoperasjoner med hensyn til fartsvalg og ruting, og de følgende konsekvensene for miljøet på regionalt og globalt nivå.

For å overholde ECA-forskriftene, antas det at skip anvender fuel switching, der marin gassolje (MGO) med 0,1 % svovelinnhold er brukt som drivstoff innen ECA og tungolje (HFO) brukes alle andre steder. MGO er dyrere enn HFO, og prisforskjellen gir incentiv til å endre gjeldende skipsoperasjoner. Fremtidige drivstoffpriser er usikre, og prisforskjellen kan øke på grunn av økt etterspørsel etter MGO når ECA-regelverket blir strengere. Et standard scenario er definert for å representere den nåværende markedssituasjonen, med MGO og HFO priser på henholdsvis USD 920 og 590 per tonn.

Generelle optimeringsmodeller er utviklet for fart- og rutingsbeslutninger fra et rederis standpunkt. Målfunksjonen minimerer drivstoffkostnader, gitt som produktet av drivstofforbruket og prisen for hvert av drivstoffene. Drivstofforbruk avhenger i stor grad av fart, og det blir ofte tilnærmet som en kubisk relasjon. Lineære modeller er implementert ved hjelp av virkelige data med diskrete fartsalternativer hvor forbruket for et gitt skip er kjent. Fire forskjellige underproblemer er studert, og fart er en viktig beslutningsvariabel i alle de tilhørende modellene. Det mest fremhevede problemet involverer alternative seilingsruter, der flere ulike løsninger er foreslått mellom to havner for å unngå lengre strekninger innenfor ECA, hvor drivstoffet er dyrere.

Funn viser at skipene vil ha nytte av å redusere farten innenfor ECA og kompensere for lengre seilingstid ved å seile raskere på strekninger utenfor ECA. Dette fører til en økning i det totale drivstofforbruket sammenlignet med å seile med konstant fart gjennom hele ruten, men forbruket av MGO blir redusert med denne strategien, og likeså de totale kostnadene. For problemet med fastsatte ruter og sekvenser, er det totale drivstofforbruket anslått å øke med 0,1-1 % når ECA blir håndhevet. En større økning oppstår for problemene som involverer variable seilingsruter, ettersom totale seilingsavstander blir lengre for å unngå strekninger innenfor ECA. Farten øker dermed også for å overholde de genererte tidsrestriksjonene. For denne typen problemer øker det totale drivstofforbruket med rundt 3-7% for alle de implementerte casene.

ECA regelverket har som formål å redusere svovelutslippene innenfor de definerte områdene og beskytte kystlivet fra disse skadelige partiklene. Utslipp av svoveloksider (SO_X) er beregnet for alle problemene i denne avhandlingen, og det forventes en stor reduksjon som følge av strengere svovelrestriksjoner, både totalt og spesielt innenfor ECA. CO_2-utslipp er derimot proporsjonal med totalt drivstofforbruk, og øker som sådan like mye, med 0.1-1% for fastsatte seilingsruter og 3-7% for variable. Denne økningen er betydelig, og utgjør nedsiden av de forventede ECA-implikasjonene. CO_2 er en viktig drivhusgass som bidrar til global oppvarming. Kostnadene av de ulike utslippene er ikke beregnet eller sammenlignet, men de generelle funnene er av stor betydning for evalueringen av ECA-reglenes påvirkning på det globale miljøet.

Contents

List of figures

List of tables

List of abbreviations

CO_2	Carbon dioxide
DWT	Deadweight Tonnes
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EUR	Euro
GT	Gross Tonnes
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MAC	Marginal Abatement Cost
MARPOL	International convention for the prevention of pollution from ships
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
nmi	Nautical miles
NO_X	Nitrogen oxides
NPV	Net Present Value
PM	Particulate matters
Ro-ro	Roll-on-Roll-off
SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Area
SO_X	Sulphur oxides
USD	US Dollars
VRP	Vehicle Routing Problem

1. Introduction

Shipping is a very international industry, serving more than 90 per cent of global trade (IMO, 2014) World shipping is environmentally efficient considering its productive value, but there are still significant emissions associated with the operations. Sulphur oxides (SO_X) emissions pollute the atmosphere and may cause acidification and deterioration of ecology and human health (Sørgård, 2013). Ship transportation leads to substantial SO_X emissions due to the high sulphur content of the commonly used marine fuels. Since ships move between different jurisdictions, there is a need for international regulations. The International Maritime Organization (IMO) is responsible for safety and security of shipping and the prevention of maritime pollution by ships. MARPOL is the main international convention concerning prevention of pollution of the marine environment by ships. Annex VI of MARPOL more specifically considers air pollution from ships and establishes four Emission Control Areas (ECAs) with more stringent control of sulphur emissions. Figure 1.1 shows the current ECAs in the world.

Figure 1.1 Map over current Emission Control Areas (Sørgård, 2013)

The sulphur restrictions will tighten in 2015, with a maximum sulphur content of 0.1% in the fuels used within ECAs compared to 1.0% today. Outside these areas the limit is 3.5% and expected to remain unchanged at least until 2020. Shipping companies can comply with the regulations in different ways, such as fuel switching to low-sulphur fuel within ECAs, installing cleaning systems or using Liquefied Natural Gas (LNG) as fuel. Fuel switching is the method that will be considered for the analyses in this thesis.

Fuel costs have become an important cost item in shipping, accounting for more than 50 per cent of total operational costs (Lindstad et al., 2012). Low-sulphur fuel is more expensive than normal bunker fuel, and the new IMO regulations will impact international shipping in several ways. Speed is a key determinant of fuel costs, as fuel consumption is approximately proportional to the third power of speed (Psaraftis and Kontovas, 2013). Shipping companies that operate both within and outside ECAs are therefore facing different speed decisions in each area. A possible consequence of the restrictions is that ships sail at a lower speed within ECAs where fuel is more expensive and speed up outside to compensate for the longer sailing time. Besides speed, the regulations may also affect routing and scheduling of ships. Repositioning of sailing legs could lead to lower fuel costs if larger parts of the legs were moved outside ECAs, but there are several trade-offs to recognise due to the relations between distance, speed and costs. Key questions that this thesis sets out to answer are if and how optimal speed and routing decisions change when considering ECA regulations. Next, it is essential to evaluate the consequences of these decisions for the global environment.

The objective of this thesis is to develop optimisation models for the speed and routing decisions resulting from the ECA regulations and apply these models to different problems and analyse the impacts on fuel consumption and costs. Moreover, the aim is to consider the bigger picture and examine the implications for the society with regards to environmental effects. Comparisons of cases could allow informed predictions concerning regional and global outcomes of the sulphur restrictions.

The rest of this thesis is structured as follows: A more detailed background chapter about the ECA regulations and compliance methods succeeds the introduction. Next, the relevant problem is described followed by a comprehensive literature study, taking on different topics such as ship operations and emissions, speed optimisation in shipping, and routing problems. Chapter 6 describes the problems in-depth together with mathematical models representing each problem, based on assumptions given in chapter 5. Thereafter, a chapter is devoted to the analyses of the operational and environmental implications, and finally, conclusions are drawn with additional discussions.

2. Background

The shipping sector is rather complex and there are many issues that require attention. It is a very international industry, serving more than 90 per cent of global trade (IMO, 2014). Ships move between different jurisdictions and the management of them may involve many countries. There is consequently a need for international standards to regulate shipping. In this chapter, the development and structure of the main international legislations of the International Maritime Organization (IMO) is first explained with its growing focus on the environment. Next, a brief introduction is given to the MARPOL convention under which the specific regulations about Emission Control Areas (ECAs) are given. The information presented in this chapter is mainly gathered from IMO's own website. The main compliance methods are further explained along with a brief evaluation of their properties based on various literature.

2.1. The International Maritime Organization

The International Maritime Organization (IMO) is a specialised agency of the United Nations for maritime safety, responsible for safety and security of shipping and the prevention of maritime pollution by ships. The organisation was founded in 1948 to meet the need for international regulations arising in the 20th century. IMO has 170 member states and comprise several committees.

IMO's main task has been to develop and maintain a comprehensive regulatory framework for shipping. The meetings of the organisation are attended by maritime experts from member governments and interested parties from other organisations. Key treaties of the IMO are the SOLAS, MARPOL, STCW and SAR conventions, concerning safety of merchant ships, pollution, standards for training of seafarers, and maritime search and rescue, respectively.

There are five main committees of IMO in addition to Assembly and Council, of which the Marine Environment Protection Committee (MEPC) is one. It consists of all member states and is empowered to consider any matter within the scope of the organisation concerned with prevention and control of pollution from ships. MEPC is responsible for the adoption and revision of conventions and regulations. There are a number of sub-committees that assist the different IMO bodies. An organisational chart of the IMO structure is shown in Figure 2.1. The sub-committees under the Marine Environment Protection Committee also support the Marine Safety Committee.

The need for a new convention or amendments to existing conventions can be raised in any of the main bodies of IMO. The adoption of a convention is the first stage of a long process, as individual governments have to formally accept it before it comes into force. Amendments to conventions are necessary to keep up with new technology and requirements. The organisation itself has no powers to enforce conventions, this responsibility lies on the member governments.

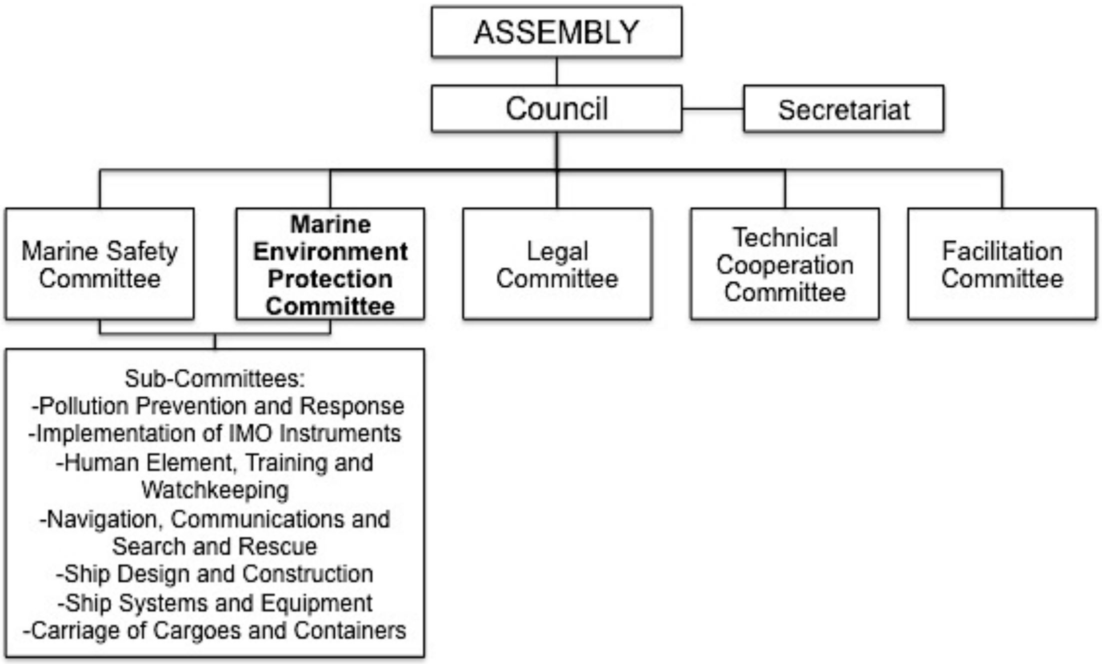

Figure 2.1 The structure of the IMO

2.2. MARPOL

Pollution emerged as a new focus for the IMO some decades back, and the early measures were designed to prevent tanker accidents and minimise their consequences. MARPOL, the international convention for the prevention of pollution from ships from 1973, also covers other types of spillage as well as air pollution. The convention entered into force in 1983. It now includes six technical annexes that regulate special areas of pollution. Amendments to the convention were added in 1997 when Annex VI was included, which was implemented in 2005. A list of the annexes is given below.

Annex I	Regulations for the prevention of pollution by oil (1983)
Annex II	Regulations for the control of pollution by Noxious liquid substances in bulk (1983)
Annex III	Prevention of pollution by harmful substances carried by sea in packaged form (1992)
Annex IV	Prevention of pollution by sewage from ships (2003)
Annex V	Prevention of pollution by garbage from ships (1988)
Annex VI	Prevention of air pollution from ships (2005)

Table 2-1 List of MARPOL Annexes

Annex I, II, IV and V define special areas where certain mandatory methods are required for the prevention of sea pollution. These areas are provided with a higher level of protection than other areas of the sea. Annex VI came into force in 2005 and seeks to minimise airborne emissions from ships and their contribution to local and global air pollution and environmental problems. The annex limits the main air pollutants contained in ships exhaust gas. Annex VI further established Emission Control Areas (ECA) with more stringent control on sulphur emissions particularly. There are 73 contracting states, representing 94.7 per cent of the world tonnage. MARPOL in general applies to 99 per cent of the world's merchant tonnage. A revised Annex VI was adopted in 2008, with stricter regulations for global emissions of sulphur oxides (SO_X), nitrogen oxides (NO_X) and particulate matters (PM), and the

ECAs were enforced to further reduce emissions in these defined areas of the sea. The protected special areas are selected based on the amount of sea traffic and the oceanographical and ecological conditions in the areas. Reduction of greenhouse gas emissions from ships is not considered by the current regulations, but is a key issue on the IMO agenda in the 2010s.

2.3. Emission Control Areas

The emission control areas (ECA) with sulphur limits are the Baltic Sea, the North Sea, North American areas and the United States Caribbean Sea, as indicated by the lines on the maps in Figure 2.2 and Figure 2.3. The latter two areas also have regulations for NO_X and PM. Table 2-2 lists the areas with respective dates of enforcement. A few amendments to Annex VI are planned for the coming years.

Established Emission Control Areas	In effect	Pollutants
Baltic Sea area	19 May 2006	SO_X only
North Sea area	22 Nov 2007	SO_X only
North American area	01 Aug 2012	SO_X, NO_X and PM
United States Caribbean Sea area	01 Jan 2014	SO_X, NO_X and PM

Table 2-2 Emission Control Areas with respective enforcement dates and targeted pollutants

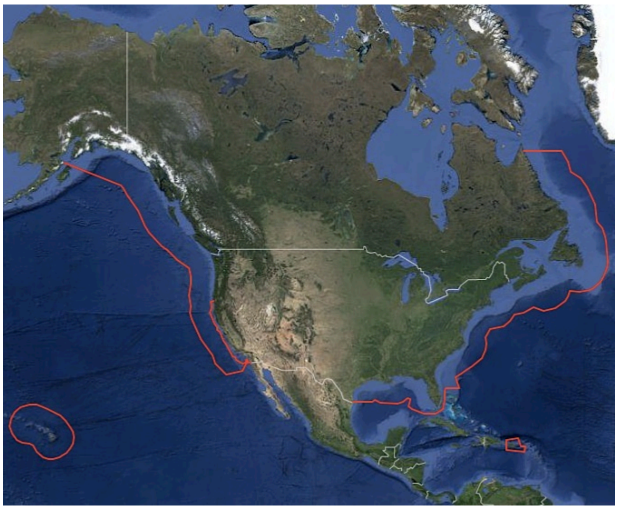

Figure 2.2 Map of North American ECAs

Figure 2.3 Map of European ECAs

Annex VI includes restrictions on sulphur emissions both at sea in general and within the ECAs. Shipboard incineration is also subject to the regulations. All four ECAs have the same sulphur limits, and Table 2-3 below gives the limits within and outside ECA. The restriction is considerably stricter within the ECAs than elsewhere, especially for the years between 2015 and 2020. The limits are expressed in terms of mass per cent (% m/m), corresponding to the sulphur content of the fuel. The limits will be lowered within ECAs from 2015, and the differences between the areas might be greatly reduced after 2020.

Outside ECA	Within ECA
4.50% m/m prior to 1 January 2012	1.50% m/m prior to 1 July 2010
3.50% m/m from 1 January 2012	1.00% m/m from 1 July 2010
0.50% m/m from 1 January 2020*	0.10% m/m from 1 January 2015

*Depending on the outcome of a review to be conducted in 2018, can be delayed

Table 2-3 Sulphur limits within and outside ECA set by MARPOL annex VI

A proposed IMO review will take place in 2018 to evaluate whether the global sulphur limits should be reduced to 0.5%, and if so, at what time. EU legislation encompasses both the IMO's global SO_X regulations and its ECA limits, and also includes slightly more stringent variations. Irrespective of the outcome of the 2018 review, the new limit of 0.5% will be implemented in the EU from 2020 (Cullinane and Bergqvist, 2014).

Progressive reductions in NO_X emissions from marine diesel engines installed on ships are also included in the revised Annex VI. Different tiers of control 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, and Tier II is valid outside these areas. The tiers are presented in Table 2-4, where *n* is the engine's rated speed (rpm). Total weighted cycle emission limit is given in grams per kilowatt-hours.

Tier	**Ship construction date on or after**	**Total weighted cycle emission limit**		
		$n \leq 130$	$130 \leq n \leq 1999$	$n \geq 2000$
I	1 January 2000	17.0	$45 \cdot n^{-0.2}$	9.8
II	1 January 2011	14.4	$44 \cdot n^{-0.23}$	7.7
III	1 January 2016	3.4	$9 \cdot n^{-0.2}$	2.0

Table 2-4 NO_X limits based on construction dates and engine speed set by MARPOL Annex VI

2.4. ECA compliance

There are several ways to achieve compliance with the ECA regulations. The most common type of fuel for ships is heavy fuel oil (HFO), but the sulphur content in this fuel does not meet the requirements within ECAs. Heavy fractions of crude oil contain the most sulphur, and HFO has on average 2.7% m/m (Endresen et al., 2005). For sulphur restrictions, fuel switching is a straightforward compliance alternative for ships that operate both within and outside ECAs, where a fuel with lower sulphur content is used within ECAs. Equivalent levels of SO_X emissions can also be obtained through different means, either by avoiding the formation of the pollutant or removing the pollutant after its formation and prior to discharge of the exhaust gas stream. For restrictions on NO_X, other technologies must be applied, such as water injection or selective catalytic reduction (SCR). The different sulphur compliance options are explained and discussed in the next sections, as regulations of sulphur is the main concern of this thesis.

There are three main methods for complying with the sulphur related regulations. The first is a switch to fuel with lower sulphur content such as marine gas oil (MGO). This fuel is more expensive, but the change is simple. The second option is to install a cleaning system to remove the sulphur from the exhaust, called scrubbers. The third alternative involves using liquefied natural gas (LNG) as fuel. This reduces emissions of sulphur and potentially many other substances such as nitrogen oxides.

2.4.1. Fuel switching

Most ships that operate both outside and within ECAs will operate on different fuel oils in order to comply with the respective limits (IMO, 2014). SO_X emission controls apply to all fuel oils, combustion equipment and devices on board and as such include both main and auxiliary engines and generators. These controls divide between those applicable within ECAs and those outside, and are primarily achieved by limiting the maximum sulphur content of the fuel oils as loaded, bunkered, and subsequently used on board.

Prior to entering an ECA, ships are required to have fully changed over to using the ECA compliant fuel oil and to have implemented written procedures on board as to how this is undertaken. At each change-over it is required that the quantities of the ECA compliant fuel oils on board are recorded together with the date, time and position of the ship when completing the switch. The first level of control is therefore on the actual sulphur content of the fuel oils as bunkered (IMO, 2014).

2.4.2. Scrubbers

Installing a scrubber is a secondary method, or an end of pipe abatement technique. Guidelines have been adopted for exhaust gas cleaning systems, which operate by water washing the exhaust gas stream prior to discharge. Scrubbers using seawater are called open loop scrubbers and the water is returned to the sea (Brynolf et al., 2013). Sulphur oxides are either absorbed in the water or react and become chemically bound to a solid substance. When scrubbers are used, there is no constraint on the sulphur content of the fuel oils as bunkered (IMO, 2014).

2.4.3. Liquefied Natural Gas

LNG contains almost no sulphur. The use of LNG as a marine fuel reduces several emissions, although it can lead to increases in pollution of methane, which is a harmful substance. LNG infrastructure is currently limited, and the use of this fuel may require conversion of vessels and space for LNG tanks. There were 30 LNG vessels in operation in mid 2012 and the same number of vessels on order.

2.5. Evaluation of ECA compliance methods in the literature

A special issue of the journal *Transportation Research* concerning emission control areas and their impacts on maritime transport was published in May 2014, with several articles touching upon the evaluation of different ECA compliance technologies. Future fuel prices is a recurrent topic, decisive for economic analysis of fuel switching compared to other compliance methods. A brief review of compliance method evaluation is included as a justification of the assumption in this thesis that fuel switching is used.

The switch to low-sulphur fuel oil is considered a smooth and easy way to comply with ECA regulations. Some issues are however related to this alternative as well, since such fuel is not envisaged in all machinery. Certain precautions should be taken with regards to diesel engines, boilers, fuel pump, change-over of fuel oils and compatibility of mixed fuels (ClassNK, 2010). The main disadvantage with fuel switching is nevertheless the high costs of low-sulphur fuel. The costs depend the price spread between MGO and HFO, assuming these are the two fuels consumed. Prices can be expected to increase when the new regulations are introduced and the demand for MGO becomes greater.

A conservative estimate of the performance of sea scrubbing technology is a reduction of sulphur dioxide (SO_2) by 82% or more (Wang and Corbett, 2007). Jiang et al. (2014) find that a sulphur scrubber can indeed reduce sulphur emissions by 98%, but the reliability of this technology has not been verified to the extent that safe future use and compatibility with other technologies are guaranteed. Scrubbers come with a high installation cost, approximated to USD 160 per kilowatt of installed power, and operating costs about 3% of capital costs.

LNG has low operating costs, but require large capital investments. Savings from using this fuel are largest for vessels that spend much time within ECAs and have high fuel consumption. For some vessels, LNG is economically viable, and the advantages may be of greater importance in the future, as new regulations probably will be introduced. The IMO is for instance considering regulations that address black carbon emissions, underwater noise and climate change, and LNG lead to improved performance for all these issues. The impact on climate change is positive when a low methane slip is introduced (Deal, 2013). LNG contains practically no sulphur and is more efficient as a fuel than fossil fuels. Some issues relate to LNG infrastructure, which is currently limited, conversion of vessels, barging fuel to vessels and loss of cargo space for larger LNG tanks.

The mentioned air emission controls have different reduction characteristics. The technologies and associated costs are somewhat uncertain. Several studies compare the methods against each other measuring both the economics of the alternatives and environmental implications. Table 2-5 gives a summary of some papers and their conclusions regarding optimal sulphur compliance options.

Paper	Findings
Balland et al., 2012	Fuel switching optimal from 2015 based on optimisation model considering control interactions
Balland et al., 2013	Fuel switching optimal based on deterministic model, scrubbers optimal based on stochastic model
Balland and Gundersen, 2013	Fuel switching optimal until 2018, then scrubber or LNG (for a specific vessel)
Jiang et al., 2014	Fuel switching optimal when price spread between HFO and MGO is less than EUR 231, otherwise scrubber
Yang et al., 2012	Fuel switching superior to scrubbers
Brynolf et al., 2013	Combined with NO_X reduction: Scrubber lowest NPV, fuel switching cheapest installation
Madsen and Olsson, 2012	Combined with NO_X reduction: Scrubbers optimal, fuel switching second choice

Table 2-5 Overview of conclusions regarding optimal compliance option in some research papers

Figure 2.4 below is an example of a financial comparison for the options for a small container vessel from Balland and Gundersen (2013). Technology investment, cost of fuel switch, and cost of reduced capacity due to installation of abatement technology on board can be considered the main cost components when evaluating ECA compliance options. In the short term, fuel switching is seemingly the best choice, but the other options are at the same time expected to outperform fuel switching going from around 2018. This result might change for different types of vessels, since costs depend on the relevant ship.

Jiang et al. (2014) similarly perform an economic analysis to compare scrubbers and fuel switching where emissions and externalities are included. This paper is included in the *Transportation Research* special issue mentioned. For a specific period, Jiang et al. find that fuel switching is more appealing, but the solutions are highly dependent on the fuel prices, which are uncertain. The price spread between MGO and HFO can be expected to increase when the new restrictions are enforced in 2015. Particularly, results from the analysis conclude that MGO is more attractive on a container vessel when the price spread is less than EUR 231 per tonne, a scenario that approximately reflects the current market situation.

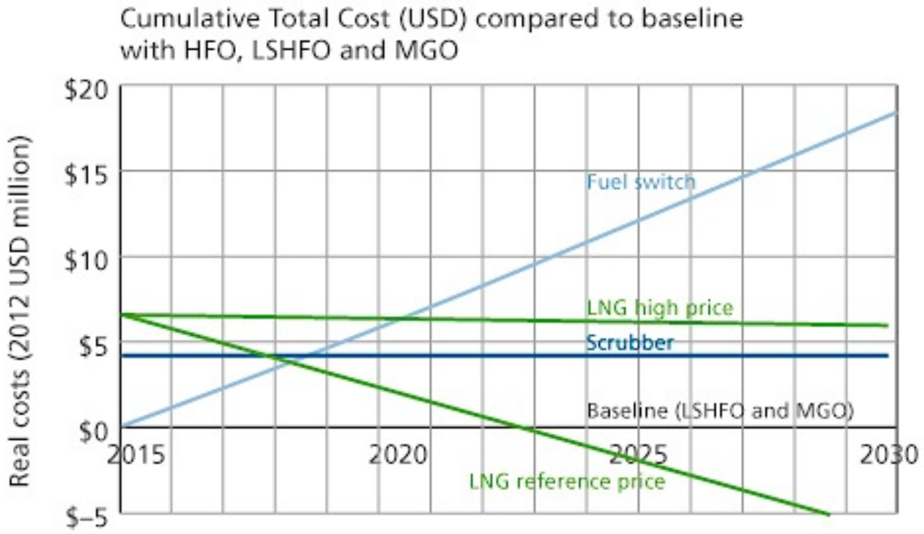

Figure 2.4 Economic comparison of compliance methods (Balland and Gundersen, 2013)

Rauta (2012) concludes that fuel switching is the easiest to apply but also expensive, although without capital expenditures. It leads to more than 5% fuel saving. LNG on the other hand can save more than 20% fuel, but comes with a high capital cost. Yang et al. (2012) assess the alternatives through identified criteria such as capital costs and operational costs, operational difficulty and maintenance requirement. Findings show that the fuel switching method is preferred for SO_X control, but scrubbers may become more important with stricter future limits.

In Brynolf et al. (2013) and Madsen and Olsson (2012) SO_X compliance is analysed in combination with NO_X abatement. Both studies find that sulphur reduction through scrubbers is cost effective when installed together with selective catalytic reduction for NO_X. Engines running on MGO is not considered cost-effective, as the price of this fuel is high and expected to increase. LNG is cost-effective and the most environmentally friendly, but comes with a high investment. Conclusions on costs depend largely on future development of fuel prices.

Hodne (2012) summarises advantages, disadvantages and uncertainties of the three main solutions going forward. Table 2-6 below aggregates some of the findings discussed in the foregoing paragraphs and Hodne’s presentation. His forecast is that global sulphur limits possibly enforced in 2020 will be a more important driver for new technology than the ECA limits. Based on the reviewed literature, it appears realistic to assume that fuel switching will be the main compliance method used by shipping companies between 2015 and 2020, which is the most relevant time period for the analysis of this thesis.

	Advantages	**Disadvantages**	**Uncertainties**
Fuel switching	Safe and proven Simple change Reduces SO_X and PM Available globally Limited investments	High fuel costs Risk of engine shut down during switch Does not reduce NO_X	Future fuel costs Quality
Scrubbers	Often cost-effective Efficient SO_X removal Well established Long track record Easier than LNG to retrofit	Space requirements, structure and stability Expensive integration Attention and maintenance required Does not reduce NO_X	Compatibility with NO_X abatement Manufacturer and installation capacity
LNG	Safe and proven Reduces CO_2, NO_X, SO_X and PM Suits fixed trading routes Can give supreme NPV Clean and vibration free	High capital costs Limited LNG infrastructure Tank space on board Little experience Crew training needed	Future LNG prices Space efficient tanks

Table 2-6 Summary of advantages, disadvantages and uncertainties of the three main sulphur compliance methods

3. Problem description

The new ECA regulations from the IMO influence international shipping on many levels. The final outcomes are uncertain because of the complexity of the industry and all the involved parties. Shipping companies have to decide on a compliance method, but the regulations also have impacts on their operations in several ways and encourage a careful review of previously made decisions and strategies. High costs are associated with the industry, with daily operating costs typically amounting to more than ten thousand dollars for one ship. Fuel costs have become a large share of total costs for ship owners or ship managers, often constituting over 50 per cent (Lindstad et al., 2012), partly due to a rapid increase in fuel prices over the past decades. Fuel consumption depends on ship characteristics, external conditions and speed, which means that speed and costs are closely related.

Figure 3.1 Picture of a typical transportation vessel (WWL, 2014)

Speed is an important decision variable for shipping companies as they seek to minimise costs or maximise profits. For voyages by ship where the route is completely unrestricted by ECAs, shipping companies would normally choose a constant speed for each sailing leg, as this leads to the least fuel consumption. Since costs increase with higher speed, the optimal speed may be relatively low if this is allowed and appropriate with regards to restrictions concerning time, service demand and market conditions. Fuel consumption, and consequently costs, may also vary due to the load on board the ship and the ship's corresponding weight, or weather conditions. The optimal speed need therefore not be the same for different trips along the same leg, even for the exact same ship. Different types of ships can lead to different speed choices depending on the ships' characteristics related to fuel consumption.

Shipping companies can adapt to the new regulations concerning ECA sulphur limits in several ways. The most straightforward alternative is to switch to approved low-sulphur fuel within ECAs and use normal and less expensive fuel elsewhere at sea. In this thesis, the analyses are conducted assuming the ship uses marine gas oil (MGO) within ECAs and heavy fuel oil (HFO) outside. As seen from the evaluation of compliance methods in various studies given by section 2.5, fuel switching is the easiest to implement and a likely choice in the short to medium term. Scrubbers would not affect ship operations to the same extent, and neither would the use of LNG as a fuel, which is still in the establishment phase. Both alternatives require high capital costs and ship adjustments, so different analyses would be fitting to examine their impacts.

There are several potential outcomes from the fuel switching compliance strategy. Firstly, a ship operating both within and outside ECAs faces two speed decisions, arising from the different fuel prices of the fuels used within each area. A possible consequence is that the ship sails at a lower speed within the ECA where the fuel is more expensive. Secondly, fuel switching may impact the choice of routes and schedules for the ships. This could occur if the route is relatively close to the border between the areas or involves a long distance within the ECA. An example of this particular problem is illustrated in Figure 3.2, where the dashed line represents an alternative sailing leg located partly outside the ECA. A shipping company might try to relocate as much of the leg as possible outside the ECA since this could lead to lower fuel costs, although the alternative leg would mean a longer sailing leg in total. For a fixed sailing time on the leg regardless of alternative paths, higher speed throughout the route would be required to compensate for increased distances. Hence, there are several trade-offs to consider as part of the shipping decisions based on speed, routing and costs, as all factors are closely interrelated.

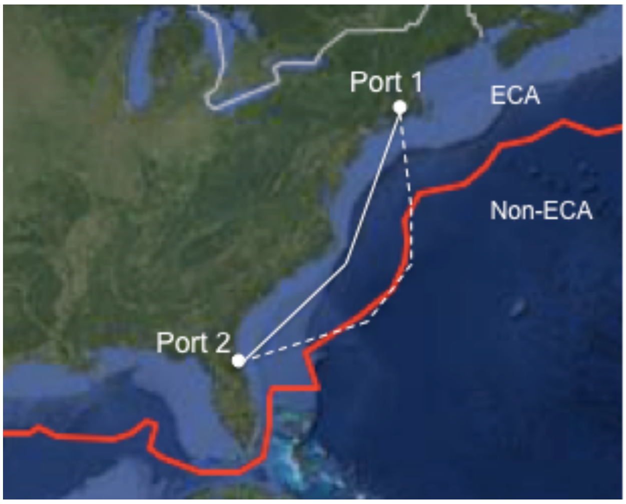

Figure 3.2 Illustration of a potential change in a sailing leg to avoid stretches within an ECA

The objective of this thesis is to develop optimisation models for the speed and route decisions associated with the ECA regulations that minimise the costs from a ship manager's point of view. Chapter 4 contains a review of relevant theory and research for similar topics, and this will form the basis for the modelling approach. After the development of the specific problems and mathematical formulations, the further aim of the thesis is to use the outputs from the implemented models to analyse the regulations' impacts on fuel consumption and moreover the implications for the society, considering effects on the environment.

4. Literature

This chapter provides a review of literature and theory relevant to the problems addressed in this thesis. The problems consist of different elements, where ship speed optimisation and routing are the central topics within operational research, and the environment is in focus through the consideration of ECA regulations. A great deal of literature exists for each of these issues, but to the author's knowledge, no studies have considered the combination of speed and routing in the ECA setting. In the following, papers addressing the various subjects are presented. First, relevant information about the shipping industry is given as a foundation to understand the principal operations that may be affected by ECAs. Next, research on ship speed optimisation is reviewed, followed by a section about ship routing and scheduling. Thereafter, environmental aspects of shipping are reviewed, examining emissions and their impacts, and the connection to speed and routing through fuel consumption. Finally, section 4.5 states potential implications of the ECA regulations.

4.1. The shipping industry and operations

A ship is associated with a major capital investment and high daily operating costs. The planning of fleets and their operations is therefore a key challenge faced by the industry, with large impacts on economic performance. Compared to other transportation modes, shipping is among the cheapest, able to move large volumes over long distances. Ships are also probably the least regulated mode of transportation because of the international aspects that require international treaties. The industry is highly fragmented, and the structure of a single vessel may involve multiple companies in different countries, due to for example tax or legal reasons (Christiansen et al., 2007).

Shipping is essential for international trade and facilitates the expansion of the global economy. During the first decade of the new millennium the cargo carrying capacity of oil tankers, dry bulk carriers and containerships grew by 60%, 65% and 164%, respectively. Seaborne international trade has simultaneously increased by 40% (Christiansen et al., 2013).

The size of a ship is measured by its weight and volume carrying capacities, given by Deadweight (DWT) in metric tonnes and Gross Tonnes (GT) in cubic feet respectively. There are many varieties of ships. Tankers are designed to carry liquids in bulk, bulk carriers carry dry bulk and container ships carry standardised metal containers with packaged goods. Roll-on-Roll-off (ro-ro) vessels have ramps for trucks and cars to drive on an off the vessel. These are just some of the vessel types. Oil tankers are the largest vessel type in the world fleet given in million DWT, followed closely by bulk carriers (Christiansen et al., 2007).

There are three basic modes of operation of commercial ships: liner, tramp and industrial. Liners follow a given schedule similar to a bus line. This mode is common for container ships and general cargo vessels. Tramp ships are comparable to taxis, carrying available cargo. They often engage in contracts of affreightment, specifying quantities of cargo and time frames for delivery. Industrial operators usually own the cargoes shipped and control the vessels through ownership or time chartering. It is possible to charter in vessels when demand exceeds capacity or charter out when there is excess capacity (Christiansen et al., 2007).

In tramp shipping, ship owners carry fuel costs if the ship is on spot charter. For time charters, fuel costs are borne by the charterer. Revenue is often assumed fixed in tramp problems, while ship owners usually try to maximise profits of liner services. Cost minimisation is the standard objective for industrial shipping (Psaraftis and Kontovas, 2012). Figure 4.1 below illustrates characteristics of the maritime transportation demand and supply, retrieved from Christiansen et al. (2007).

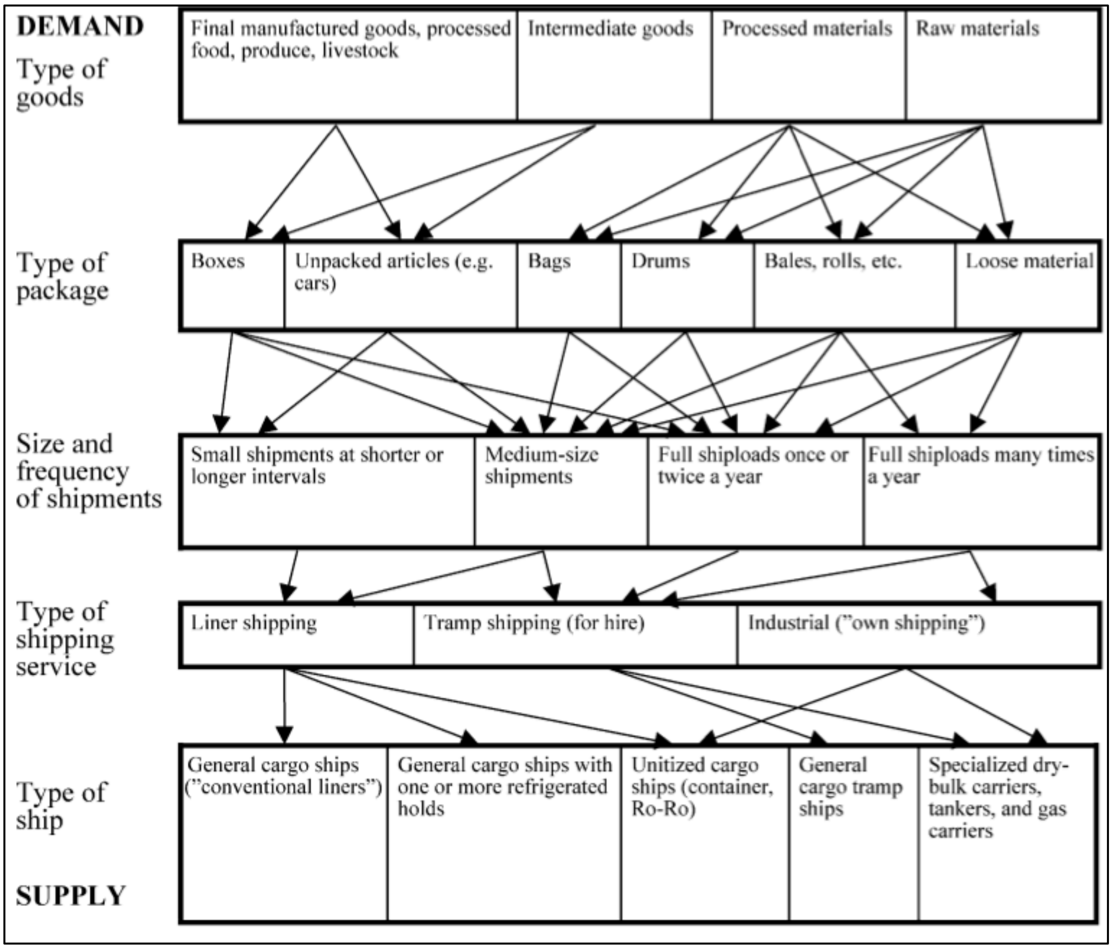

Figure 4.1 Characteristics of maritime transportation demand and supply in maritime transportation (Christiansen et al., 2007)

Maritime transportation planning problems can be classified as strategic, tactical and operational. Strategic problems are long term and include ship design and fleet size and mix decisions. Tactical problems can involve fleet deployment and ship routing and scheduling. On the operational level there are short-term problems such as speed selection, ship loading and environmental routing (Christiansen et al., 2007).

Shipping routes may be classified as deep-sea (between continents), short-sea (for shorter distances), coastal or inland waterways. Routing is the assignment of a sequence of ports to a vessel (Christiansen et al., 2007). Most containership routes take from a few weeks up to a few months to complete (Doudnikoff and Lacoste, 2014).

4.2. Speed optimisation in shipping

Speed is an important factor for ships for economic reasons, as it is a key determinant of fuel costs, which represents a significant part of the operating costs for ships. It is also important for the logistical chain of a shipping company, in the planning of all its operations. There may be large benefits from high speed considering faster delivery of goods, lower inventory costs and increased trade. At the same time, increasing fuel prices and depressed market conditions work in the opposite direction, lowering the optimal speed choice. A higher speed is better when fuel prices are low and the economy good (Psaraftis and Kontovas, 2013).

In this thesis, speed decisions are of great importance since the objective is to imitate the operational reactions of shipping companies to the ECA regulations, and they attempt to minimise costs. Fuel costs are in focus, and these depend directly on the chosen speed. Other costs and revenues are not emphasised since ECAs will not affect these items in the same direct way. Speed selection can also be an inherent part of routing and scheduling decisions. The next section presents different approaches to modelling the fuel consumption based on speed.

4.2.1. The fuel consumption function

Traditionally, seagoing vessels have been designed and optimised to operate at maximum economic speeds, standardised for vessels of similar type and size (Lindstad et al., 2011). The optimal speed for a vessel on a given sailing leg can be found through differentiating the speed dependant objective function. Its absolute value will vary based on many parameters and conditions. Different objective functions may consider profits, costs or emissions, but all potential variations rely in some way on the fuel consumption.

It is well established that fuel consumption is proportional to speed. Most papers assume that the fuel consumption is approximately a cubic function of speed (Psaraftis and Kontovas, 2013). This means that a change in the speed leads to a higher relative change in the fuel consumption, and hence speed selection is a determinant for fuel costs. Some of the considered elements in the fuel consumption function will be elaborated upon.

Wang and Meng (2012a) aim to verify the belief that the fuel consumption function is related to the third power of speed. They calibrate the fuel consumption using historical operating data from a global liner shipping company. A general form of the relation between consumption f and speed v is suggested as $f = A \cdot v^b$, equivalent to the logarithmic version $\ln f = \ln A + b \ln v$, where A is a given term. Regressions are done on the data, and all the datasets return values of the exponent b between 2.7 and 3.3 for the relevant significance interval. Therefore, their conclusion is that $b = 3$ is a good approximation for the actual relationship. Containerships are the most important exception, and an appropriate exponent for these vessels could be between 3.5 and 5 (Wang et al., 2013b; Psaraftis and Kontovas, 2013).

Cariou and Cheaitou (2012) also give a general formulation of the fuel consumption function with a variable exponent of the speed relation. Fuel consumption per time is given as $f = F^R \cdot (v_i/V_0)^b$, where V_0 is the vessel design speed and F^R is the design fuel consumption rate. F^R is the product of the specific fuel oil consumption K, the engine load L and the engine power Z: $F^R = (K \cdot L \cdot Z)$. The specific fuel oil consumption rate is optimal when a ship sails at its design speed. It is unchanged for small speed reductions, but increase for reductions above 10%, while the engine load decreases (Cariou, 2011). The value varies by engine type and can change under different conditions. Doudnikoff and Lacoste (2014) use the same fuel consumption function when considering speed decisions with ECAs. The fuel consumption for a certain trip given by weight is $f = F^R \cdot (v_i/V_0)^a \cdot s$, where s is the sailing time. The same equation applies to both fuel types MGO and HFO.

Doudnikoff and Lacoste (2014) include the fuel consumption of the main and auxiliary engines separately, and so do Corbett et al. (2009). The general cubic fuel consumption function becomes $f = \left[F^{R,main} \cdot (v_i/V_0)^3 + F^{R,aux}\right] \cdot s$. The fuel consumption of the auxiliary engine does not depend on sailing speed, only time in use, according to this approach.

The cubic approximation is not valid for sailing speeds below certain points. Otherwise, the fuel consumption for ships would always be reduced whenever the speed is reduced and reach zero when the ship is stationary, which is not the case. (Psaraftis and Kontovas, 2013). Illustrations of the fuel consumption curves for two given sailing distances are shown in Figure 4.2. The optimal speed is marked by the dashed line, below which the fuel consumption would increase. The approximation of the function is thus only appropriate for the relevant range of speed choices.

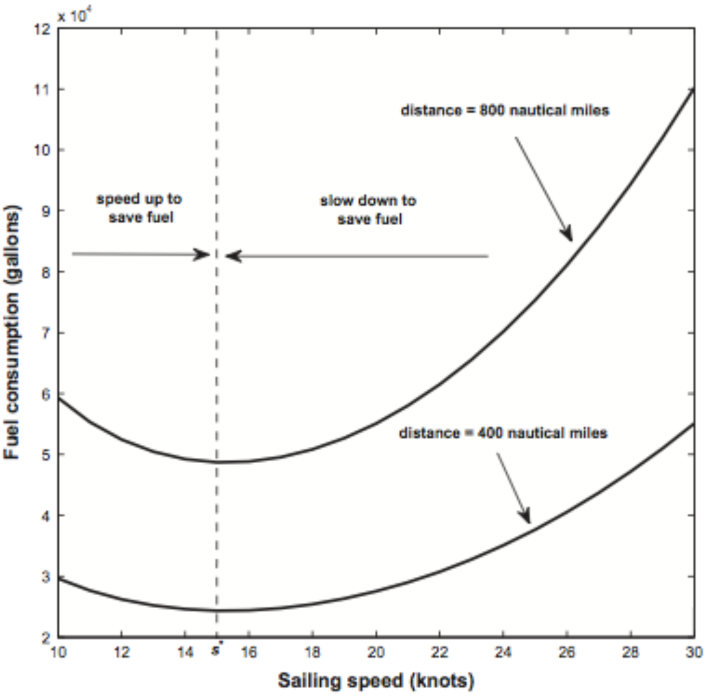

Figure 4.2 Fuel consumption for two sailings with given distances and optimal speed (Du et al., 2011)

An example of a fuel consumption function for a specific LNG carrier with a load capacity of 150,000 cubic metres and a speed range from 14 to 22 knots is given by Norstad et al. (2011) as: $f = 0.0036v^2 - 0.1015v + 0.8848$. The corresponding curve is shown in Figure 4.3 for the relevant speed interval.

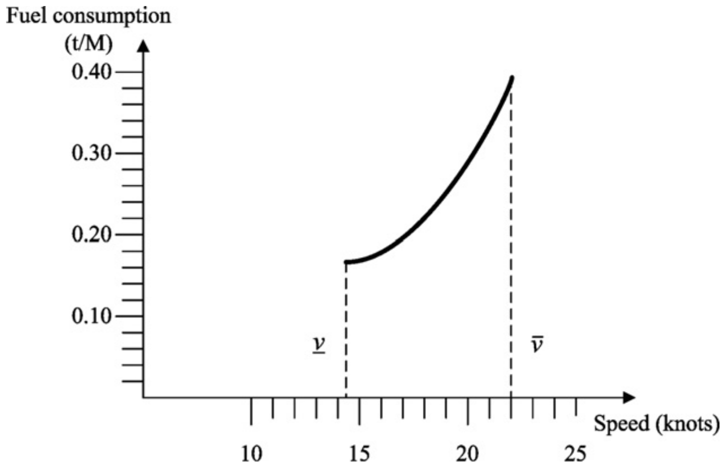

Figure 4.3 Fuel consumption per nautical mile with speed limits for an LNG carrier (Norstad et al., 2011)

The fuel consumption function could also be estimated by including other parameters representing the engine type and size, the geometry of the ship hull, propeller design and more (Psaraftis and Kontovas, 2013). Besides, the function is not static, as fuel consumption further depends on external conditions such as the weather and sea conditions (Wang and Meng, 2012a). When the main engines consequently operate at non-optimal points, the specific fuel oil consumption increases (Dedes et al., 2011). Lindstad et al. (2011; 2012a) derive the power term of the fuel consumption rate as a function of speed and sea conditions. For the main engine, the required power includes consideration of waves and wind and propeller efficiency.

Psaraftis and Kontovas (2013) discuss other considerations to the approximation of the fuel consumption. In addition to speed, they include payload between two ports as an important element. For a given speed, the fuel consumption can be assumed proportional to the sum of the payload and the weight of the ship to the power of two thirds, i.e. $(w + L)^{2/3}$, where w is the payload and L is the weight. Most papers in the literature approximate the fuel consumption as a cubic function of speed, but a combination of speed and payload is also possible. Optimal ballast speeds are typically higher than optimal laden speeds except if cargo inventory costs are accounted for. Ships consume fuel in port as well, where fuel consumption can be approximated to 5% of the main engine consumption at design speed (Cariou, 2011).

To sum up, a good approximation of the fuel consumption function is $f = F^R \cdot (v/V_0)^n \cdot s$, where the fuel consumption rate F^R is a given parameter depending on the specific vessel type, and the value of n is usually 3. The derived function is non-linear. For simple problem instances, optimal solutions may be found with a commercial solver, but a different method is required for more complex cases. The approximation is moreover uncertain and does not represent the fuel consumption truthfully.

4.2.2. Linearization of the fuel consumption

The approximation of the fuel consumption results in a non-linear function. This is not suitable in optimisation as it may be difficult to solve with a commercial solver. There are several ways to deal with the non-linearity. A linear regression of the fuel consumption can be adopted, but this is not precise enough for analyses on the operational level, according to Du et al. (2011).

A method used by Wang and Meng (2012a) and Wang et al. (2013b) involve using the reciprocals of sailing speed as decision variables. They argue that an outer approximation with a predetermined tolerance level is satisfactory since the function is convex and can be piecewise linearized. Du et al. (2011) cast a mixed integer second order cone programming model to handle nonlinearity, and Wang et al. (2013a) make a note to this and propose two quadratic outer approximation approaches, static and dynamic, that can handle fuel consumption rate functions more efficiently.

Norstad et al. (2011) and Fagerholt et al. (2010) instead discretise the arrival time at each node in a route and solve the problem as a shortest path problem on a directed acyclic graph to find the optimal arrival time at each port and the corresponding speed for each leg. Alternatively, speed can be discretised, which is perhaps more intuitive but there can be a trade-off following this option between solution time and quality for different problems. Doudnikoff and Lacoste (2014) discretise the speed and calculate the associated costs when considering a given arrival time.

4.2.3. Linear fuel consumption based on discrete speed alternatives

Andersson et al. (2014) likewise approximate the non-linear fuel consumption by discrete speed alternatives and linear combinations of these. Combinations will always involve neighbouring points since the fuel consumption is a convex function. Hence, a type 2 special ordered set is implicitly enforced to achieve piecewise linearization. The method leads to an overestimation of costs because of the curve's convexity. Determined weights for speed alternatives are used to calculate corresponding sailing times with known distances. Figure 4.4 illustrates how the interpolation between neighbouring points will give the lowest cost option. Three speed alternatives are used, and this is found to give a good approximation. It is evident that any combination of the "Low" and "High" speeds in the figure would give higher costs than combinations with the "Medium" option.

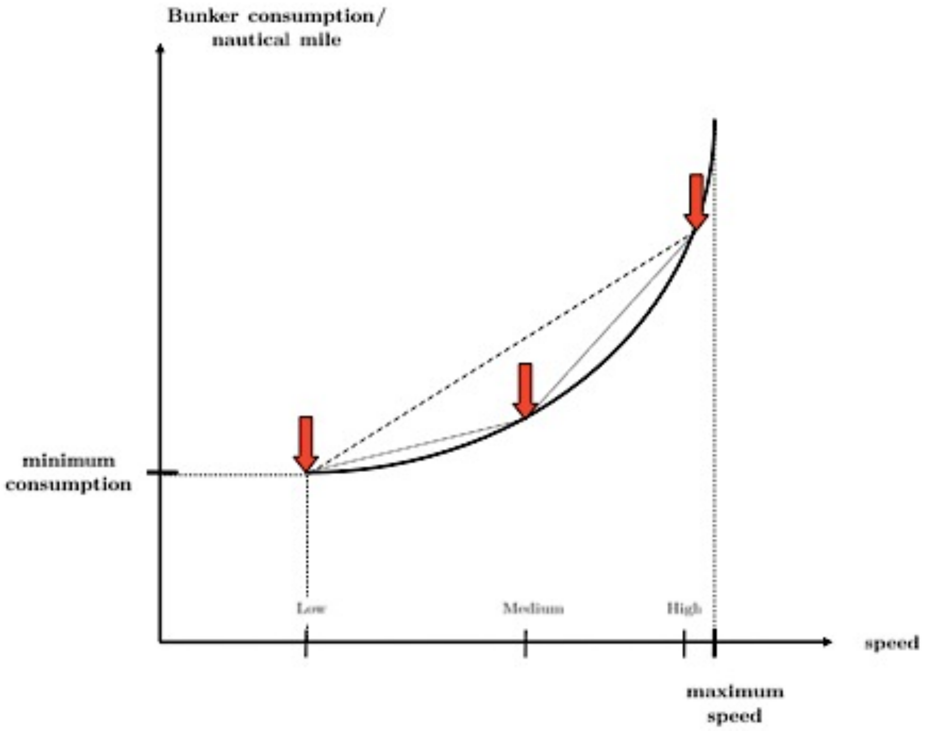

Figure 4.4 Piecewise linearization of the convex fuel consumption function (Andersson et al., 2014)

An additional overestimation is associated with the fuel consumption because of the non-linear relationship between time and speed. The weights of the speed alternatives are used for calculating corresponding sailing time, which yields a minor overestimation as illustrated in Figure 4.5. Andersson et al. (2014) present an example to show the overestimation. If the weight of a speed alternative of 17 knots is 0.3 and 0.7 for 19 knots, the speed becomes 18.40 knots. A distance of 1,000 nautical miles at 18.40 knots would take 54.35 hours to sail. At 17 and 19 knots, the same distance takes 58.82 and 52.63 hours respectively. Interpolation of these sailing times yields 54.49 hours, which is more than the result of 54.35 when interpolating the speeds. The overestimation is not substantial, and it is exaggerated in the figure. The magnitude of the errors depends on the number of discretisation points used. The authors find that the errors will not dominate over inaccuracies in parameter values, such as in fuel consumption functions and sailing distances.

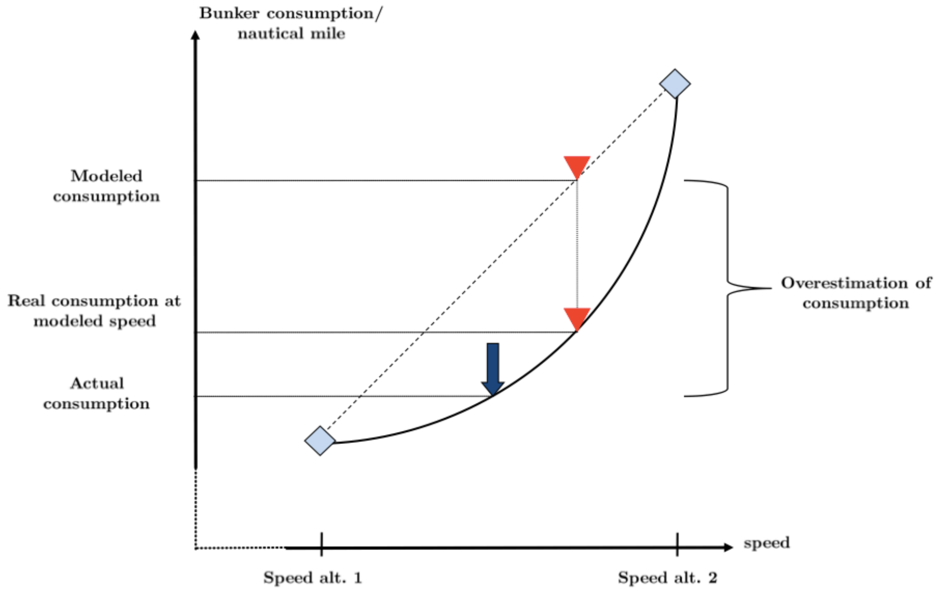

Figure 4.5 Overestimation of fuel consumption due to speed and time relation (Andersson et al., 2014)

Instead of approximating the fuel consumption function in order to get a linear objective function, it is possible to use real life data to estimate fuel consumption directly. Such data include actual measures of the consumption at different speed points, given for specific vessels. With a set of discrete speed alternatives and corresponding fuel consumption, all the necessary elements are known, and the decision involves finding the speed that minimises fuel costs. The gathered data points give a more truthful representation than the derived approximation of the fuel consumption function above.

Instead of a decision variable representing speed as used in section 4.2.1, a new variable x_v is introduced as the weight of speed alternative v. The discussed interpolation between two neighbouring points is achieved through setting the sum of the speed weight variables equal to one, i.e. $\sum_{v \in V} x_v = 1$. In some cases, an exact speed point v is chosen and the related weight for the point becomes 1. Otherwise, the weights of two speed points are numbers between 0 and 1. Fuel consumption for each speed alternative is given as a parameter F_v for a specific ship. The fuel consumption f for each stretch is the product of F_v and x_v summed over all the speed alternatives: $f = \sum_{v \in V} F_v \cdot x_v$.

It may be difficult to obtain sufficient data to use the chosen method, in which case the approximated fuel consumption function can be used to calculate the data points instead. Sailing time and fuel consumption would be pre-calculated parameters based on chosen speed alternatives, so the fuel consumption F_v for a given speed point along a stretch with a known distance is: $F_v = F^R \cdot (v/V_0)^n \cdot S_v$. This would involve a linear approximation of the already uncertain function, but the linearization is not likely to affect the error of the approximation to a large extent.

The linear approaches discussed involve a small degree of uncertainty due to the interpolation between speed alternatives. The approach based on the approximated fuel consumption function has additional uncertainty related to the estimated input parameters, and should only be used if there is not sufficient real data available.

4.2.4. Other elements of speed optimisation models

The literature concerning speed models is scarce since speed is often assumed fixed. The literature can be evaluated based on certain parameters such as the optimisation criterion, the market context, logistical context and various assumptions and considerations (Psaraftis and Kontovas, 2013).

Typical speed optimisation models include time windows. In Norstad et al. (2011) a speed optimisation problem occurs as a sub problem in the tramp ship routing and scheduling problem. The time windows are formulated as $\underline{t_i} \leq t_i \leq \overline{t_i}$, where the start of a service at a node t_i is given as $t_i \geq t_{i-1} + D_{i-1,i}/v_{i-1,i}$. Time restrictions can also apply to delay. In Du et al. (2011) the objective is to minimise fuel consumption while meeting the departure delay constraints. More on time windows is given when routing problems are discussed.

Fleet size and service frequency are other elements that naturally appear in speed models, since changes in speed imply a different number of deliveries to ports within a given time period unless additional ships are added to serve the route (Corbett et al., 2009). Another way to maintain service is to reduce the time spent at port, but this is not always possible (Kontovas and Psaraftis, 2011). This introduces another trade-off, as higher costs follow increased fleet size. Speed decisions also affect the effective capacity of the fleet for a shipping company (Christiansen et al., 2007).

4.3. Routing and scheduling

Routing and scheduling are important parts of the planning of any transportation system. Greater uncertainty is associated with routing at sea than on land, but the same principles apply to the models. Routing is the assignment of sequences of nodes to a vehicle or vessel, while scheduling is assignment of times to these and other events on the route. The different vessels are assigned to routes, referred to as deployment (Christiansen and Fagerholt, 2002).

Some well known problems will be presented briefly in this section. One of the objectives of this thesis is to study whether ECA regulations may lead to changed sailing legs or routes due to increased fuel prices within ECAs. Basic insight into routing and scheduling literature is therefore relevant.

4.3.1. Vehicle routing problems

Vehicle routing problems in general are problems seeking to find optimal routes from one or several depots to a number of destinations, such as cities or customers. Different constraints may apply for variations of the problem. The models are central in planning of physical distribution and logistics (Laporte, 1992). When there are time window constraints, service at a customer must begin within the time window (Desrosiers et al., 1995). The vehicle routing problem is an expansion of simpler models like the shortest path problem and the travelling salesman problem.

The shortest path problem consists of finding the least cost route between two specified nodes in a graph. It is a relaxation of the travelling salesman problem, relaxing the requirement that each node must be visited (Desrosiers et al., 1995). Figure 4.6 is an illustration of the shortest path problem, where the objective is to find the cost minimising path between node 1 and node 7, while each arc in the graph has an assigned cost.

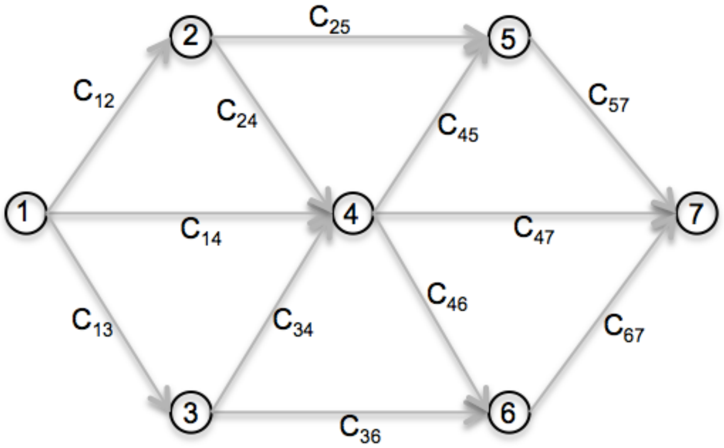

Figure 4.6 Illustration of the shortest path problem with directed arcs of specific arc costs between node 1 and node 7

The fixed schedule problem considers a set of tasks or trips characterised by an origin, a destination, duration and a fixed starting time. The problem to be solved consists of forming a schedule, i.e. sequences of tasks where each task is performed exactly once. These sequences are sometimes called routes. In transportation, the trips are described by legs, where a leg must start where the previous leg ended (Desrosiers et al., 1995).

These routing problems are to some extent related to the problems concerning ECAs. The choice of sailing leg between a pair of ports could be seen as a shortest path problem where the alternative legs are constructed based on a set of nodes resulting in different costs when considering distance and time. Also, when the sequence is variable, the decisions concern both the design of the route sequence and the legs included in the route. For this case, the sequencing corresponds to the vehicle routing planning where all ports must be visited, and each leg has similarities to the shortest path problem. Time is essential in the planning, and speed is therefore an integrated part of the problem.

Inclusion of time windows is a common extension to the routing and scheduling problem. There is a distinction between hard time windows, where service must begin within a given interval, and soft time windows that allow violation of this interval. A violation leads to a penalty or inconvenience cost, representing for example lost sales or goodwill. The increased flexibility may contribute to reduced costs (Fagerholt, 2001).

4.3.2. Ship routing and scheduling

Shipping in general refers to moving cargoes by ships. In ship routing problems, the routes may either be open paths or terminating at the origin port (Coccola and Mendez, 2013). Problems usually relate to one of the modes of operation, namely liner, tramp or industrial shipping. Elements that can be present in routing and scheduling problems for ships include loading and discharge times, number of commodities, types of vessels, demands, speed and sea route constraints. Sailing speed and shipment sizes can be included as decision variables to describe a problem more realistically (Christiansen et al., 2013). In this thesis, a general model will be developed for one single vessel operating in any mode. Loading time and cargo capacity are for instance not as relevant, since additional assumptions would be needed and the model would lose some of its generality.

The routing problem is concerned with sequencing port calls and the scheduling problem is concerned with sequencing and fixing the time of each port call. When the sequence is given, the problem can be referred to as a timetabling problem. A voyage refers to one traversal of the route (Kjeldsen, 2012). A simple formulation of the ECA problems could be referred to as a timetabling problem, if the sequence is given and the decisions only concern speed in each area on each leg.

Yan et al. (2009) consider the timetabling of two a priori planned routes. All possible voyage legs, representing a ship moving between two ports, are installed into a network with available time slots at corresponding ports. Each voyage leg arc contains information about departure time and port, arrival time and port, and the operating cost. The most suitable voyage leg in each arc band is chosen after optimisation. This approach is of relevance, as various sailing legs between two ports restricted by ECAs could similarly be pre-generated and optimised comparing the associated times and costs.

It is common to plan ship routes assuming a given service speed and include the speed decision at a later stage based on time windows for the fixed route. Andersson et al. (2013) consider a fleet deployment problem and develop an integrated approach to deal with routing and speed with a rolling horizon solution method. The proposed method can also be used for other integrated routing and speed optimisation problems in maritime transportation. The study seeks to determine ship routes, sailing speeds, start times for voyages and coupling of ships and voyages, with time window and demand restrictions.

For longer voyages, conditions at sea may influence the fuel consumption and hence the choice of route (Christiansen and Fagerholt, 2002). The cost of bunker fuel is a major component in the operating expenses of a ship. Fuel consumption for a merchant ship is approximately related to the third power of the speed. There is a trade-off between fuel savings and loss of revenues due to increased travelling time. When fuel costs in different areas at sea are different due to ECA requirements of low-sulphur fuel use, the trade-off becomes more complicated. The total fuel costs are no longer directly connected to the total fuel consumption, so longer routes may potentially give reduced costs even though total fuel consumption could increase.

The shortest path problem occurs in Fagerholt et al. (2000), where it is used to determine estimated arrival times at destination ports when there are obstacles on the route hindering a straight sailing. Instead of generating a complete graph, the arcs are constructed during the solution process, and the calculation of distances between the ship and the ports is a shortest path problem.

In Fagerholt (2001), a ship scheduling problem with soft time windows is studied, where a number of candidate schedules are generated a priori together with their operating and inconvenience costs. Then, the scheduling problem is formulated and solved as a set partitioning problem, where one schedule should be chosen. The operating cost is not completely determined by the route, since fuel consumption depends on speed and the timing of the route. Fagerholt discretises the possible times for start of service, and the nodes in the sequence are duplicated, leading to a structured acyclic network. The problem can be solved as a shortest path problem. The proposed solution approach brings the possibility to determine optimal speeds on the sailing legs in the schedule.

4.3.3. Model formulations

An example of a routing model formulation is taken from Karlaftis et al. (2009). The presentation here is a simplification, only considering one ship and not the loads. The decision variable x_{ij} is a binary variable, taking the value 1 if the ship uses arc (i,j) and 0 otherwise. In this model, the costs of travelling along all arcs are minimised in (1), when each node in the set J must be visited exactly once given by constraints (2) and (3) and the ship must exit the same node as it entered, formulated in constraints (4).

$$min \sum_{i \in J} \sum_{j \in J} C_{ij} x_{ij} \tag{1}$$

$$\sum_{i \in J} x_{ij} = 1, \qquad j \in J \tag{2}$$

$$\sum_{j \in J} x_{ij} = 1, \qquad i \in J \tag{3}$$

$$\sum_{i \in J} x_{ip} = \sum_{j \in J} x_{pj}, \qquad p \in J \tag{4}$$

A different formulation implies a pre-generation of the routes, where x_r takes the value 1 if a given route r is chosen and 0 otherwise. The following is a simplification and modification of Christiansen et al., (2013). The objective function (5) minimises the cost of the chosen routes, while the constraint (6) allows exactly one route to be chosen.

$$\min \sum_{r \in R} C_r x_r \tag{5}$$

$$\sum_{r \in R} x_r = 1 \tag{6}$$

The arrival time t_j at a port j must be at least the sum of the arrival time at the previous port i and the sailing time between the ports s_{ij}. This is given by constraints (7) below, where the constraints are relevant when the ship travels on the arc between the ports, given by x_{ij}. Since all the terms are variables, the constraint is non-linear, which is not practical in a model formulation. The constraints are linearized in (8), where a new term M_{ij} is introduced, taking the largest value possible of the left hand side. When the arc is used, the constraint becomes binding, while it is redundant when the arc is not in the solution. This linearization method referred to as the “Big M” method is common, used among others by Christiansen (1999).

$$x_{ij}\left(t_j + s_{ij} - t_i\right) \geq 0, \qquad i \in J, j \in J \tag{7}$$

$$t_j + s_{ij} - t_i \geq M_{ij}(x_{ij} - 1), \qquad i \in J, j \in J \tag{8}$$

4.4. Ship emissions

Shipping is statistically the least environmentally damaging mode of transport when its productive value is taken into consideration. In 2007 international shipping was estimated to have contributed to about 2.7% of global emissions of CO_2. It is still a comparatively minor contributor to marine pollution from human activities (Psaraftis and Kontovas, 2013). Vessel-sourced pollution has a great potential for improvements considering its wide reach. The diagram in Figure 4.7 shows the sources of global CO_2 emissions.

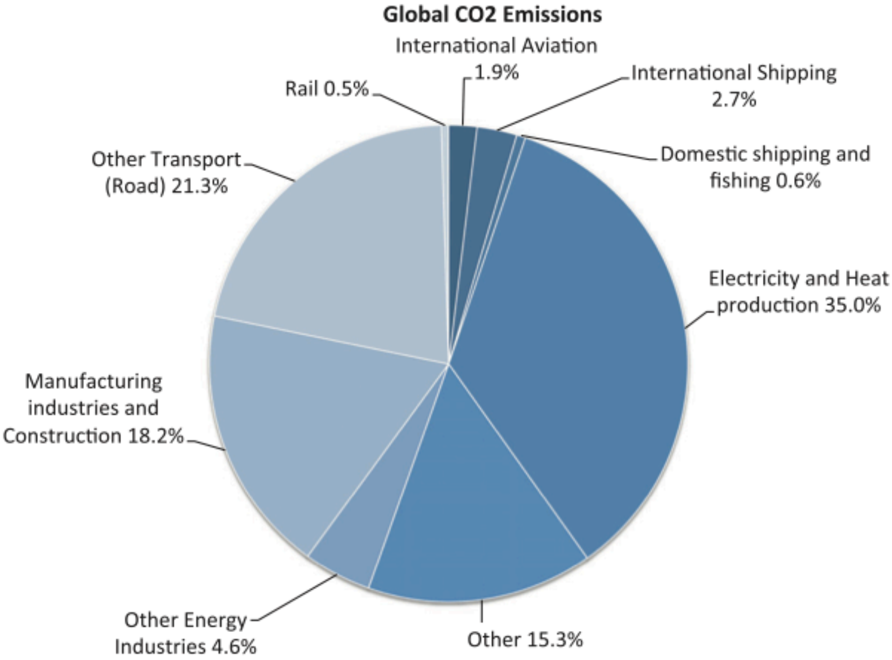

Figure 4.7 Global CO_2 emissions by industries in 2007 (Psaraftis and Kontovas, 2013)

The vast majority (95%) of the world fleet runs on diesel, but the diesel used in ships, referred to as bunker oil, has lower quality than that used in road vehicles. Because of the lower quality, emissions per power output are higher for marine engines than on-road diesel engines. A great range of pollutants is of concern in relation to the shipping industry, and CO_2 is not the most immediate (Cullinane and Bergqvist, 2014).

4.4.1. Emissions and impacts

There are several categories of gas emissions from ships. Greenhouse gases include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). During combustion of fuels in marine engines, significant amounts of black smoke, particulate matter, nitrogen and sulphur oxides, unburned hydrocarbons and carbon monoxide and dioxide are also produced (Lin and Lin, 2006).

Sulphur oxides (SO_X) emissions pollute the atmosphere and may cause acidification and deterioration of ecology and human health. Sulphur oxides have a high water-solubility and humans 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 (Sørgård, 2013). Emissions of sulphur, in the quantities emitted from shipping, are not known to have any significant negative effects on the sea itself or on the marine life (Kågeson, 2005). Nitrogen oxides (NO_X) are mainly composed of NO and NO_2 and can cause acid rain, destruction of the ozone layer and adverse health effects. NO_X emissions contribute to an environmental problem called hypertrophication (Psaraftis and Kontovas, 2012).

Nearly 70% of ship emissions occur within 400 kilometres of coastlines, causing air quality problems. Some particles can travel hundreds of kilometres, leading to damages further inland as well. Emissions from vessels in port may have a disproportionate impact on the local environment considering the vessel is stationary and has low fuel consumption, due to the closeness to the nature and people (Eyring et al., 2010). Fuel consumption can be distributed to locations proportional to ship traffic intensity, and emissions estimated correspondingly.

4.4.2. Calculation of emissions

In this thesis, the aim is to use results from analyses of models and draw conclusions about the implications of the ECA regulations for the society as a whole. It is very difficult to measure the emissions from a particular ship. Vessel emissions can roughly be calculated by the fuel consumption multiplied with an emission factor, but there are different approaches to the estimations and different levels of details depending on the known elements (Du et al., 2011).

A common emission factor for CO_2 is 3.17, meaning that 3.17 tonnes of CO_2 is produced per tonne of fuel, a number found from multiplying the carbon fraction (0.864) and a converting factor (44/12) (Corbett et al., 2009). According to Psaraftis and Kontovas (2009), the actual emission factors are slightly lower, with values 3.082 for MGO and 3.021 for HFO, but 3.17 has been used for both fuels in the majority of literature. Total emissions are simply found by multiplying the emission factor with the fuel consumption.

Emissions of SO_X depend on the sulphur content in the respective fuel. The percentage content is multiplied by the fuel consumption and a factor of 0.02 to compute the emissions. There are rather large regional variations in sulphur contents of heavy fuels, from 1.9% in South America to 3.07% in Asia, and a weighted average is given as 2.68% (Endresen et al., 2005). NO_X emissions depend on the engine, and the ratio to fuel consumed can be between 0.057 and 0.087 (Psaraftis and Kontovas, 2012). NO_X will not be considered in this thesis, since only the SO_X restrictions of the ECAs are in focus.

When fuel consumption is unknown, other methods of estimation must be used. De Meyer et al. (2008) for instance develop a formula to calculate emissions, where the amount is given as the product of the activity time, the engine power, the load factor divided by a correction factor, and a specific emission factor given. This model performs reasonably well compared to proven figures.

Different vessels have different fuel consumption and corresponding emissions depending on characteristics such as the ship size and engines. Containerships are the top CO_2 emitters in the world fleet, representing 4% of the fleet and 22% of the fleet's CO_2 emissions from international shipping (Corbett et al., 2009). Fuel consumption also depends on the current ship operations. Under ballast, the overall emissions are taken to be 9-20% lower compared to at maximum utilisation (Faber et al., 2010). Fuel is moreover consumed in port, and Streets et al. (1997) find port emissions comprise 4.5% of the total emissions.

4.4.3. Emissions and speed

Since emissions are directly proportional to the fuel consumed, speed is connected with the environmental dimension of shipping, and it has become a greater focus as a measure toward greener operations. There is a non-linear relationship between speed and fuel consumption, so a reduction in speed can consequently have a large impact on air emissions (Psaraftis and Kontovas, 2013). A minimisation of CO_2 emissions is equivalent to minimising the fuel consumption, and when only one fuel is considered it would also lead to minimised fuel costs.

Lindstad et al. (2011) compare cases of cost minimisation and emission minimisation. Minimisation of emissions gave large speed reductions but higher costs. A cost minimisation approach also caused reduced emissions from speed reduction, but not to the same extent.

Speed can be reduced either through building ships with reduced installed power or by going slower than design speed. The latter is known as slow steaming, and it was pioneered by Maersk Line (Psaraftis and Kontovas, 2012). Speed reduction is expected to be a key mechanism to reduce fuel consumption in the future. The Danish EPA (2012) estimates the expected average speed reduction to 7 % for the North Sea fleet.

Slow steaming involves reducing speed to save costs and reduce emissions. Speed reduction is restricted by demand service constraints, the supply of ships, the maximum capacity utilisation and the engine characteristics (Faber et al., 2010). Slow steaming has the potential to reduce emissions significantly without requiring new technology. Cariou (2011) considers costs of adding vessels to a service and inventory costs as these will be affected by reduced speed. A speed reduction may require a higher number of ships serving the route to maintain service frequency, but lower speeds still provide CO_2 reduction on most routes.

4.4.4. Routing and the environment

Green logistics explicitly consider external factors associated with the environment. The vehicle routing problem (VRP) is widely researched, and Eguia et al. (2013) includes external costs in the objective function of the mixed integer linear programming model. Selection of eco-efficient routes can help to reduce emissions without losing competitiveness in transport companies. The external effects of transport can be internalised through taxation.

The majority of literature on the subject focuses on the economic aspects of routing problems, minimising costs in objective functions. Sbihi and Eglese (2007) provide a brief overview of vehicle routing involving emissions. By reducing the total distance, reduction in fuel consumption is also achieved. When ECAs are considered however, different fuels are used, and emissions do not only depend on the total fuel consumption, but on the consumption of each particular fuel with corresponding emissions.

Lin et al. (2014) provide a survey of green vehicle routing problems. Green-VRP is optimisation of energy consumption of transportation. Fuel costs are a significant part of the total cost, and the aim is to reduce greenhouse gases by reducing the consumption of petroleum based fuel. When emissions and fuel consumption are minimised, the amount of greenhouse gases is a function of speed and distance. It is difficult to estimate social, health and environmental costs of emissions accurately (Figliozzi, 2010).

Lai et al. (2010) examine the environmental awareness and measures taken in the shipping industry. Much research has focused on the environmental and financial impacts of different shipping technologies, but not considered the institutional forces from different stakeholders that shape the environmental responses of the industry. There has been an increasing trend for firms to engage in activities to promote sustainability and the environment, but the commitment has not been convincing due to the lack of strong incentives for adopting green practices. ECA regulations might complicate the decisions of shipping companies, since certain substances are restricted while the cost levels rise significantly. Efforts to reduce costs may not necessarily coincide with a reduction of emissions.

4.4.5. Emission reduction measures

The ECA regulations prohibit SO_X emissions above a certain level in the designated control areas. This is a direct measure toward reducing sulphur based emissions. This final section of the literature concerning emissions will briefly review some alternative measures to reduce ship emissions. The different measures could allow comparisons of the effects of ECAs versus the recommended actions towards greenhouse gas emissions.

A fuel tax policy is considered in Cariou and Cheaitou (2012) where a tax is added to the bunker price. This is compared to a second policy involving a speed limit. The latter leads to a regional decrease in speed and emissions, but may generate more emissions globally as the intercontinental speed has to increase to meet required service frequency. It is found to be suboptimal compared to the bunker levy. The cost for CO_2 will also be higher than the society is willing to pay, so the conclusion in the paper is that a preferable policy is for polluters to pay for the marginal damage they cause. A fuel tax would incentivise ships to reduce speed.

Psaraftis and Kontovas (2010) look at different policies for reducing maritime emissions and how they might lead to trade-offs between environmental and economic performance. They discuss three main ways to reduce greenhouse gas emissions: technical measures involving ship design, market based measures such as emissions trading and carbon levy schemes, and operational options including speed optimisation. When the marginal abatement cost, which is the change in profit divided by the avoided CO_2 emissions, is negative, ship owners would have an economic incentive to implement the respective measure (Psaraftis, 2012). The ECA regulations do not concern greenhouse gases, but may still have an impact on these emissions.

Lindstad et al (2012b) suggest rewarding ships exploiting economies of scale, since larger vessels can improve costs and emissions. Kågeson (2005) explores the feasibility of introducing a charge for maritime transport related to distance travelled at sea. The idea is to internalise the social costs in a similar way to what has been proposed for road transport. Other measures include a cap and trade scheme or funding of pollutant abatement technologies.

Through the ECAs, the IMO imposes higher costs on ships, since a costly compliance method must be chosen when a ship operates within ECAs. Fuel switching to a more expensive low-sulphur fuel is similar to the idea of a tax within the area, except that the premium price depends on fuel consumption. This may have different implications for the ship operations, as shipping companies want to minimise fuel consumption of the expensive fuel.

4.5. Potential ECA implications

The measures taken by the IMO through the adopted regulations for air pollution from ships will undoubtedly have different implications for both the environment and for shipping operations. According to the International Petroleum Industry Environmental Conservation Association (IPIECA, 2007), the expected consequences of the SECAs include a reduction of SO_X in the designated areas without any negative environmental effects. Fuel supply availability is the only mentioned concern. This section will go through some of the other relevant issues, considering potential changes in ship operations, the corresponding environmental outcomes, and the possible reactions in the markets.

A special issue of the *Transportation Research* journal dedicated to emission control areas and their impact on maritime transport was published in May 2014. Ten articles consider relevant topics such as evaluation of ECA compliance technology, speed reduction and modal shifts. In the editorial by Cullinane and Bergqvist (2014), a summary of the issue is given, and they conclude that there are large socio-economic benefits of the ECA regulations and that it is important to designate more regions as ECAs, especially considering densely populated areas like the Mediterranean and Asia. Some of the contributors to the issue also highlight the need for different policies and regulatory measures.

4.5.1. Speed reductions within ECAs

Speed is an important factor for ships being a key determinant of fuel costs (Psaraftis and Kontovas, 2012). A ship can reduce its operating cost by operating at a speed slower than its design speed. Speed reduction within ECAs is a likely consequence of the ECA regulations because the costs of operating in these areas will be higher with more expensive fuel, assuming that low-sulphur fuel is used to comply. Lower speed within ECAs may be compensated by higher speed outside where the fuel is more harmful to the environment.

Doudnikoff and Lacoste (2014) examines this exact event in a paper that is included in the mentioned special issue of *Transportation Research*, and set out to answer if speed reduction in SECA can help mitigate the higher fuel costs and what the consequences of such a behaviour are for the speed outside SECA and the emissions of the entire cycle. The authors assume that fuel switching is applied, with MGO used as the low-sulphur fuel within SECAs and HFO elsewhere. The fuel consumption function studied is cubic and equal for both fuels. Their findings are that shipping companies' costs will be lower if the ships choose a lower speed within the SECA and compensate with a higher speed outside. Emissions on the other hand increase when ships follow this strategy, compared to a case where they maintain a constant speed throughout the entire route. Doudnikoff and Lacoste observe that the cost saving from different speeds may not be large enough to induce companies to change their decisions unless the fuel price differential increases.

4.5.2. New sailing legs and rerouting

Development of new routes may be relevant when it is possible to avoid ECA-restricted parts of the route. The European Marine Safety Agency predicts that fuel will become more expensive and some short-sea routes might be affected (Schinar and Stefanakos, 2012). With a small control area, ships may deviate from the shortest shipping lanes to lanes outside the area when this route is less expensive (Wang and Corbett, 2007). For the North Sea, this is relevant for routes passing through the English Channel.

Rerouting could also occur in the sense that the ports in the route are changed. This decision will depend on costs of ECA operations and also the cost of using alternative ports. There are greater potential benefits from an alternative route when a large part of a journey is originally within the ECA. It is therefore more likely on routes for example from UK to Spain and Ireland to France than for routes from Europe to other continents (Danish EPA et al., 2012).

4.5.3. Modal shift

Various trade-offs are at stake in the goal for reduced ship emissions and may impact the cost-effectiveness of the maritime logistics chain. Low-sulphur fuel is expensive compared to other marine fuels, and the required use of this in certain areas may lead to a shift to land based transportation if this option becomes cheaper and more efficient (Psaraftis and Kontovas, 2009). Speed reduction due to the increased prices may also lead to unwanted side effects, as shippers may be induced to use land-based transport alternatives instead (Psaraftis and Kontovas, 2012).

Rowland and Wright (2013) did a study of the SECA impacts for shipping between UK and the continent, and ferry services from Scotland in particular. The new regulations were found likely to damage economics of longer distance ro-ro services that help removing traffic from the UK road networks. The authors use the three common sulphur compliance methods to evaluate the implications. The commercial and economic impacts on individual ro-ro services depend upon the age of the vessel deployed and the length of the crossing, as longer distances mean higher fuel costs. Results from the analysis imply that some traffic would switch to the shorter crossings of the Dover Straits, leading to increased land transportation and hence increased emissions on land. SECA regulations will reduce emissions from shipping, but in this case lead to significant increases in use of the road network. A different analysis done by Psaraftis and Kontovas (2009) on a given sea route also concludes that trucks may be a cheaper alternative and thus emissions on land may be higher than those saved at sea.

Modal shift related to SECA regulations is further considered by Holmgren et al. (2014) in the special May 2014 issue of *Transportation Research*. They state that higher costs in ECAs will likely lead to an increase in freight rates as shipping companies have difficulty absorbing the cost increase, and this may cause a shift in transport modes. Yet, the main findings suggest that a modal backshift to road transport is unlikely for the studied types and routes of transport. ECA regulations may pose a risk in terms of reverse environmental effects, but the effect is expected to be short-lived, as companies and the market adapt to the new operating conditions.

Panagakos et al. (2014) contribute with another of the articles in the special ECA issue in which they study the implications of a designation of the Mediterranean Sea as a SECA through a specific case of transporting cargoes from Greece to Germany. The first transportation alternative involves a combination of ferry and truck, and this is compared to the alternative of a road-only option. The results predict that the designation of this SECA would lead to a modal shift to the road-only route by more than 5%, up to 17% considering uncertainties. In this case, emission levels are also improved because the route distance of the road alternative is shorter and the vessels perform poorly due to the need to maintain a relatively high speed.

Modal shift effects resulting from the ECA regulations appear to be rather limited, according to Cullinane and Bergqvist (2014). More stringent sulphur limits and greater geographical applicability will make shipping companies focus on efficiency, and new operating measures may enable them to better absorb the price changes arising from the ECA regulations.

4.5.4. Market development

There has been a strong correlation between the prices of marine fuels and crude oil. The future prices are very uncertain, but demand for MGO is expected to increase, and a prediction is a USD 500 per tonne differential between MGO and HFO for 2020 (Panagakos et al., 2014), which is around 50% more than today. This may lead to higher freight rates and cancelling of certain ship routes (Psaraftis and Kontovas, 2009).

Hodne (2012) predicts that the ECAs alone will not drive mass uptake of LNG or scrubbers, but that the global sulphur limits from the IMO will be a major driver for new technology uptake. Therefore, the full effect will come closer to 2020 and may change the shipping industry. The supply volume of low-sulphur fuel is an important concern for the future. The refining industry is however willing to participate in a process at IMO to analyse the need and justification for a lower SECA sulphur limit and the impacts on supply and emissions, including CO_2 (IPIECA, 2007).

Besides the mentioned issues, there may be other indirect effects arising from the increased costs incurred by shipping companies. These effects could potentially involve changes in the supply and demand for shipping services, possibly leading to changed international trade patterns, unemployment or pressured economies. Such issues are outside the scope of this thesis and will not be considered.

To sum up, there are ambiguous implications of ECA regulations. Several possible indirect effects work in the opposite direction of what is intentional concerning the environment. Higher fuel costs inside the ECA may lead to a shift in transportation mode, rerouting or sailing a longer distance outside the zone, and increased fuel consumption due to different speed decisions. The regulations may also affect the market itself, with even higher fuel prices and freight rates, different demand and supply and a changed economic environment.

5. Model introduction

In this section, the background for the model formulations is explained. Common terms and notation used in all the models are presented, and important model assumptions are introduced and justified. Lastly, an overview is given to compare the features of the studied problems.

5.1. Definition of terms

A common vocabulary is developed to fit the different models, and the terms are defined and explained in this section with illustrative figures. *Route* refers to the complete course between the port of origin and the final destination, including all the ports that are visited, but not necessarily in a given order. The term *leg* is used to describe the path between two ports. There may be several specific ways to move along a leg referred to as alternative *leg options*. A *stretch* is defined as a part of a leg. A stretch ends when the leg enters a new zone, that is, enters or leaves an ECA, or when the ship arrives at a port. *Sequencing* means determining the order in which the different ports should be visited. Figures 5.1, 5.2 and 5.3 below illustrate some of these terms for a set of ports.

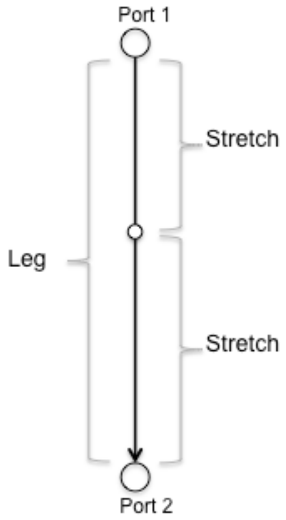

Figure 5.1 Leg and stretches

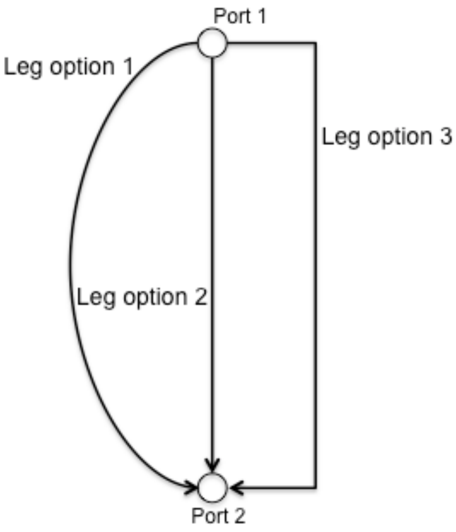

Figure 5.2 Alternative leg options

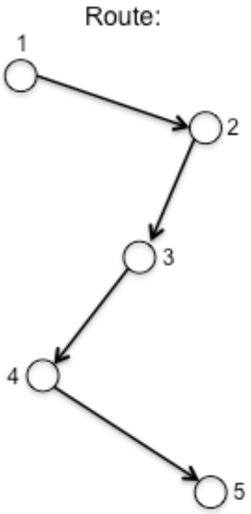

Figure 5.3 Sequenced route

There can be up to three stretches within a leg, occurring if the ship leaves a port within an ECA, sails out of it and returns to an ECA zone to arrive at the next port in the route. In principle, the number of stretches in a leg can be higher than three, although one such leg is unlikely to appear in actual route plans. When two consecutive ports are both outside an ECA, the leg will usually not cross through any ECAs, due to their outlines and positions. Finally, a leg between ports on either side of an ECA consists of two stretches. These claims do not apply to the case where alternative leg options are generated through combining a number of artificial stretches between different points at sea.

5.2. Model assumptions

For all the models, only one vessel is considered. This single vessel has to travel to all the defined ports in the case route. It is assumed that the ships comply with the ECA regulations through fuel switching, by using MGO as fuel within ECAs and HFO elsewhere. Some time is required to perform the switch of fuels, but since the time is less than one hour it is disregarded. Assumptions regarding the modelling of the problems are given in the following paragraphs.

5.2.1. Speed and fuel consumption

Specific properties for the ship in question are given as inputs to the model, and these parameters are unchanged for all problems. The properties include fuel consumption data for different speed points, and it is assumed that linear combinations of these points give a sufficiently precise representation of the consumption for the speed in between. This linear approach was discussed in section 4.2.3. The models are general, so different vessel types can be considered. The fuel consumption data are average numbers and do not include information about specific legs, engines or external conditions. These factors are therefore not explicitly considered, but it is reasonable to suppose that average data account for different situations and would be accurate when several sailings are aggregated. It is further assumed that the fuel consumption is the same for different fuels, so an equal amount of fuel is consumed of MGO and HFO at the same speed point. Fuel consumed in ports is disregarded since it is independent of speed decisions.

The vessel has a lower speed limit, below which the engine might stall (Psaraftis and Kontovas, 2013) or the fuel consumption becomes non-optimal, and an upper speed limit depending on the vessel's capabilities. The optimal speed for a vessel changes for different conditions including time restrictions. The optimal speed along stretches in a route may consequently be different for each stretch. As seen from previous research on the topic (e.g. Wang et al., 2013b; Doudnikoff and Lacoste, 2014), the speed in any single stretch will be constant. This can be shown through the fuel consumption curve characteristics.

5.2.2. Time flexibility

All the models include time windows for the start of the sailing out from each port in the route, and these can be adjusted to represent different situations. Service time in ports is not considered since it is independent of other factors and decisions in the model, and the time windows are correspondingly given based on this assumption. There may however be some waiting time at a port, occurring if the lower limit of the time window starts later than the arrival time at the respective port.

5.2.3. Objective function

The objective of all the problems is to minimise fuel costs. This allows a clean and general formulation of the models that can apply to different types of ship operations. Other costs could be considered, but many additional assumptions about the shipping mode and market conditions would be required in that case to justify the chosen cost elements. By only considering fuel costs, the analysis becomes comprehensible and with as little noise as possible. Some ship operations are optimised based on profits or revenues as well, but this is disregarded here for the same reasons. The different shipping modes and objectives were explained in a separate section of the literature review. Further discussions of costs and objectives will be given in a concluding section (6.5) of next chapter, along with possible model extensions including the modification of certain assumptions.

6. Problems and mathematical formulations

The general problem was described in chapter 3. Four sub problems are defined considering different variations and simplifications of the problem. Each problem is explained in separate sections (6.1-6.4) with related model formulations. Two alternative models are given for some of the problems. The models differ in their input characteristics and consequently the desired output. The very first problem considers fixed routes, where both the sequence of the ports and the legs sailed between them are predetermined. The only decisions in this situation concern the speed. Next, routing aspects are included, related to the options of different sailing legs between ports and/or the visiting sequence. Speed is a key decision variable for all the models as the objective is to minimise the strongly speed-dependent fuel costs. The mathematical formulations are given in general terms, hence the models can easily be adapted to different cases, for instance with different number of ports and locations.

Table 6-1 gives an overview of the variations that are included in the different sub problems. Each row corresponds to a problem in the following sections. Three main elements are considered, namely the sequence, sailing legs and the speed. For each model, F is used to indicate that the respective component is fixed, while V implies that it is variable and is part of the decisions. With a fixed sequence, the ports have to be visited according to a specified list. Fixed legs mean that a ship can only sail in one specified way between two ports. When the legs are variable, the ship can take different leg options consisting of different stretches.

Problem	Sequence	Legs	Speed
P1	F	F	V
P2	F	V	V
P3	V	F	V
P4	V	V	V

Table 6-1 Overview of the fixed (F) and variable (V) elements in the different problems

The sub problems are named P1 – P4 as shown in Table 6-1. In problem P1, both sequence and sailing legs are fixed, and the decisions concern speed. P2 aims to decide the sailing legs between ports as well as the speed. In P3, there is one fixed leg between each pair of ports, but the sequence between them is not given. The final problem, P4, seeks to determine all the elements based on sets of alternative legs.

The models in the next sections are given the same name as the relevant problem, since a model is merely another way of describing the problem in mathematical terms. When two models are developed for one problem, they are numbered. For instance, the models developed for P1 are called P1-1 and P1-2. The next sections are dedicated to each of the four problems with corresponding models. The last section in this chapter (6.5) gives a discussion on possible extensions to the models or modifications of the assumptions.

In all the models, variables and indices are given as lower case letters while parameters and sets are capital letters. Sets, parameters and variables are defined first, and then the models are formulated with an objective function and relevant constraints. The given parameters are present in all models, but with different definitions depending on the defined sets and the problem structure.

6.1. Problem P1: Speed optimisation with fixed routes

In this problem, the complete route is fixed, with known distances of all stretches. For each leg that lies on either sides of an ECA, there will be two speed variables. The ship retains constant speed in each of the areas, but the two speeds may be different.

This instance can be identified for any route restricted partly by an ECA. In Europe, the ECAs of the North Sea and the Baltic Sea cover the entire basin between Northern Europe, the United Kingdom and the mainland of Europe, as shown in Figure 6.1. Figure 6.2 shows the map of the North American ECAs, where they lie around 200 nautical miles outside the coasts of the United States and Canada.

Figure 6.1 European ECAs

Figure 6.2 American ECAs

The four ECAs pose the same challenges to shipping companies with regards to sulphur limits, fuels and speed choices, but the different geographic outlines substantiate slightly different problems because of the different route characteristics on the two continents. Sea transport within and between Canada and the US is for example likely to happen on routes that lie entirely within an ECA. Transport to other countries or for greater distances however may involve different areas, for example routes going from the southern states to Mexico or Latin America, or intercontinental routes. In Europe, routes between ports in Northern Europe will similarly often lie completely within ECAs, while transport from Southern Europe or other continents to Northern Europe must cross through both areas.

A simple example of the current problem is illustrated in Figure 6.3. The example involves a fixed route between three ports, where Port A and Port C lie within an ECA and Port B outside. This route corresponds to two legs with four different stretches in total. The illustration does not represent any particular ECA or geographic location.

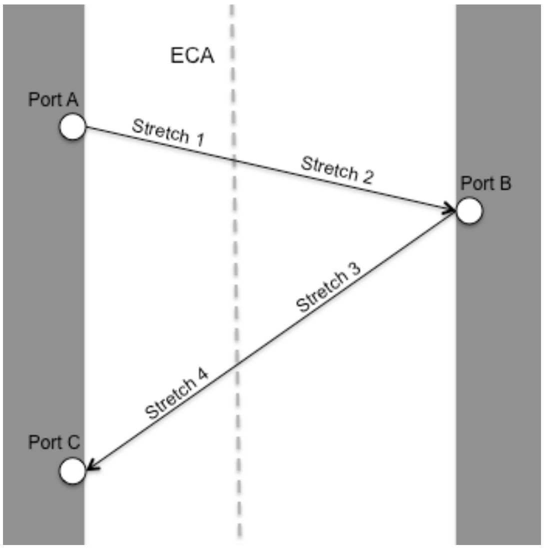

Figure 6.3 P1: Example of fixed route between three ports with two legs and four stretches

General model formulations are given in the next sections, based on either a set of stretches or a set of legs. These can be used for any route, for instance a route comprising many ports on different continents or a route going from one port to a second one only. One ship is deployed, and this ship has to follow the predetermined route. The aim of the model is to decide the sailing speed on each stretch of the route in a way that minimises the fuel costs.

6.1.1. Model P1-1: Non-linear formulation with a set of stretches

First, the sets and parameters are defined. There is a set of fuels, which could contain different fuels, but the following models and analyses mainly consider the two types MGO and HFO, used within ECAs and outside, respectively. A set of stretches is introduced, and a subset of these consists of the stretches that start from ports. One of the fuels is used on each stretch.

The parameters giving vessel speeds and fuel consumption rate concern ship characteristics and depend on the chosen type of vessel for the case studies. Fuel prices will be given as input based on current markets, but as they are uncertain in the future, different prices can be used to analyse the sensitivity of the results to fuel prices. The parameters are constant and given inputs to the model, and will appear in similar terms for the more complex problems as well. There is a given distance for each stretch and time limits for the start of a sailing out from the ports.

The variables are grouped in two, where the auxiliary variables are all directly related to the main decision variable, which is the speed v_k for each stretch k. This model formulation is non-linear, appropriate for the use of approximated fuel consumption functions as described in section 4.2.1. As discussed, it is not suitable to implement such non-linear models in commercial software, but they are developed for P1 to illustrate the approach.

Sets

B	Set of fuels
K	Set of sequenced stretches, stretches in K_b uses fuel $b \in B$
K^P	Subset of stretches going out from ports

Parameters

P_b	Fuel price of fuel b, for $b \in B$
V_0	Vessel design speed
V^{MIN}, V^{MAX}	Lower and upper speed limits
F^R	Fuel consumption rate for ship at design speed
D_k	Sailing distance of stretch k, for $k \in K$
T_k^{MIN}, T_k^{MAX}	Lower and upper time limits for starting stretch k going out from a port, for $k \in K^P$

Auxiliary variables

c	Total costs
f_b	Fuel consumption of each fuel, for $b \in B$
s_k	Sailing time on stretch k, for $k \in K$
t_k	Start time on stretch k, for $k \in K$

Decision variables

v_k	Speed on stretch k, for $k \in k$

Model

$$\min c = \sum_{b \in B} P_b \cdot f_b \tag{1.1}$$

$$f_b = \sum_{k \in K_b} F^R \left(\frac{v_k}{V_0}\right)^n \cdot s_k \qquad b \in B \tag{1.2}$$

$$V^{MIN} \leq v_k \leq V^{MAX} \qquad k \in K \tag{1.3}$$

$$T_k^{MIN} \leq t_k \leq T_k^{MAX} \qquad k \in K^P \tag{1.4}$$

$$s_k = \frac{D_k}{v_k} \qquad k \in K \tag{1.5}$$

$$t_k - t_{k-1} - s_{k-1} = 0 \qquad k \in K \mid k \notin K^P \tag{1.6}$$

$$t_k - t_{k-1} - s_{k-1} \geq 0 \qquad k \in K^P \tag{1.7}$$

The model equations are numbered with the problem number as prefix. The objective function (1.1) minimises the total fuel costs, summing the product of the fuel prices and the fuel consumption of the respective fuels. Constraints (1.2) give the fuel consumption for each of the fuels, as described in section 4.2.1. It corresponds to the non-linear approach, and will not be used for analyses since sufficient real fuel consumption data are gathered. Constraints (1.3) give the lower and upper speed limits for all the stretches. Constraints (1.4) are the time windows for starting the stretch going out from each of the ports in the route. Equations (1.5) define the sailing time variables for each stretch as the distance of it divided by the speed. Constraints (1.6) give the start time on each stretch as the sum of the start time and sailing time on the previous stretch in the route, for all stretches not originating in a port. The inequality sign in constraints (1.7) allows waiting time at ports, needed if the vessel is ready to start on a stretch before the earliest time limit associated with it, relevant for the stretches going out from ports.

6.1.1.1. *Model formulation of a simple example*

The model above is reformulated to apply to the introductory example to the section illustrated in Figure 6.3, to show how it can be applied to a situation with three ports where two lie within an ECA and the last one outside. There are consequently four stretches, and the first and fourth are within the ECA.

$$\min c = P_{MGO} \cdot f_{MGO} + P_{HFO} \cdot f_{HFO} \tag{1.8}$$

$$f_{MGO} = F^R \cdot (\frac{v_1}{V_0})^3 \cdot s_1 + F^R \cdot (\frac{v_4}{V_0})^3 \cdot s_4 \tag{1.9}$$

$$f_{HFO} = F^R \cdot (\frac{v_2}{V_0})^3 \cdot s_2 + F^R \cdot (\frac{v_3}{V_0})^3 \cdot s_3 \tag{1.10}$$

$$V^{MIN} \leq v_1, v_2, v_3, v_4 \leq V^{MAX} \tag{1.11}$$

$$T_3^{MIN} \leq t_3 \leq T_3^{MAX} \tag{1.12}$$

$$s_1 = \frac{D_1}{v_1}, s_2 = \frac{D_2}{v_2}, s_3 = \frac{D_3}{v_3}, s_4 = \frac{D_4}{v_4} \tag{1.13}$$

$$t_1 = 0 \tag{1.14}$$

$$t_2 = t_1 + s_1 \tag{1.15}$$

$$t_3 \geq t_2 + s_2 \tag{1.16}$$

$$t_4 = t_3 + s_3 \tag{1.17}$$

The objective function (1.8) minimises fuel costs. Fuel consumption of MGO and HFO is given in constraints (1.9) and (1.10), respectively. The constraints for speed limits (1.11), start times (1.14)–(1.17) and sailing times (1.13) are given for all stretches. The time window in constraint (1.12) is only given for the stretch going out from Port B, number three in the sequence, since there is no stretch exiting Port C and the start time of the route from Port A is given. A fifth artificial stretch should be added going out from Port C, to allow time windows for the completion of the route.

6.1.2. Model P1-1: Linear formulation with a set of stretches

The present model is reformulated to a linear model based on the principles described in section 4.2.3. A set of speed alternatives is introduced, which can contain three or more different speeds for a given ship including the minimum and maximum speed. The lower and upper speed limits are therefore not relevant as constraints anymore. A new parameter is defined for the sailing time on each stretch with a given speed alternative. Each parameter is associated with one of the speed alternatives and the fixed distance of the stretch. The fuel consumption for each stretch and speed alternative is also given as a parameter. Instead of a speed decision variable, there are now variables x_{kv} corresponding to the weight of a speed alternative v for the sailing stretch k.

Sets

B	Set of fuels
K	Set of sequenced stretches, stretches in K_b uses fuel $b \in B$
K^P	Subset of stretches going out from ports
V	Set of speed alternatives

Parameters

P_b	Fuel price of fuel b, for $b \in B$
D_k	Sailing distance of stretch k, for $k \in K$
T_k^{MIN}, T_k^{MAX}	Lower and upper time limits for starting stretch k, for $k \in K^P$
S_{kv}	Sailing time on stretch k with speed alternative v, for $k \in K$ and $v \in V$
F_{kv}	Fuel consumption on stretch k with speed alternative v, for $k \in K$ and $v \in V$

Auxiliary variables

c	Total costs
f_b	Fuel consumption of each fuel b, for $b \in B$
t_k	Start time on stretch k, for $k \in K$

Decision variables

x_{kv}	Weight of speed alternative v on stretch k, for $k \in K$ and $v \in V$

Model

$$\min c = \sum_{b \in B} P_b \cdot f_b \tag{1.18}$$

$$f_b = \sum_{k \in K_b} \sum_{v \in V} F_{kv} \cdot x_{kv} \qquad b \in B \tag{1.19}$$

$$T_k^{MIN} \leq t_k \leq T_k^{MAX} \qquad k \in K^P \tag{1.20}$$

$$t_k - t_{k-1} - \sum_{v \in V} S_{k-1,v} \cdot x_{k-1,v} = 0 \qquad k \in K \mid k \notin K^P \tag{1.21}$$

$$t_k - t_{k-1} - \sum_{v \in V} S_{k-1,v} \cdot x_{k-1,v} \geq 0 \qquad k \in K^P \tag{1.22}$$

$$\sum_{v \in V} x_{kv} = 1 \qquad k \in K \tag{1.23}$$

$$x_{kv} \geq 0 \qquad k \in K, v \in V \tag{1.24}$$

The objective function (1.18) minimises fuel costs. Equations (1.19) give the fuel consumption of each fuel as the weighted fuel consumption of each stretch with the corresponding sailing speed. The formulation of the start time windows (1.20) remains unchanged. Constraints (1.21) and (1.22) give the start time on each stretch as the sum of the start time and sailing time on the previous stretch, interpolating between the sailing times associated with the different speed alternatives. With sailing times as given parameters, there is no need for a sailing time variable. Finally, constraints (1.23) force the sum of the speed weights to equal one for each stretch. From this, one of the speed alternatives may for instance be weighted by 0.8 and a neighbouring point by 0.2. Constraints (1.24) ensure that the weight variables are non-negative.

6.1.3. Model P1-2: Non-linear formulation with a set of legs

An alternative formulation of the problem is given, also in general terms but somewhat more explicit. Instead of a set of stretches, there is a set of legs between the ports in the route. Each leg begins and ends up in a port.

There is a given distance for each stretch of the legs, where the distances are accumulated for the stretches within ECA if the leg includes two such stretches in addition to a third stretch outside ECA. Other defined parameters are the lower and upper time limits for the start of sailing a leg. The speed related variables are given for each of the areas in each leg. The model is non-linear and equivalent to the model in section 6.1.1, giving the exact same results only with different presentation.

Sets

B	Set of fuels
J	Set of sequenced legs, legs in J^b are parts using fuel $b \in B$

Parameters

P_b	Fuel price of fuel b, for $b \in B$
D_j^{ECA}	Sailing distance within ECA along leg j, for $j \in J$
D_j^N	Sailing distance outside ECA along leg j, for $j \in J$
T_j^{MIN}, T_j^{MAX}	Lower and upper time limit for starting leg j, for $j \in J$

Auxiliary variables

c	Total costs
f_b	Fuel consumption of each fuel, for $b \in B$
s_j^{ECA}	Sailing time on stretch within ECA along leg j, for $j \in J$
s_j^N	Sailing time on stretch outside ECA along leg j, for $j \in J$
t_j	Start time on leg j, for $j \in J$

Decision variables

v_j^{ECA}	Speed on the stretch within ECA along leg j, for $j \in J$
v_j^N	Speed on the stretch outside ECA along leg j, for $j \in J$

Model

$$\min c = \sum_{b \in B} P_b \cdot f_b \tag{1.25}$$

$$f_b = \sum_{j \in J^b} F^R \cdot (\frac{v_j^b}{V_0})^n \cdot s_j^b \qquad b \in B \tag{1.26}$$

$$V^{MIN} \leq v_j^{ECA} \leq V^{MAX} \qquad j \in J \tag{1.27}$$

$$V^{MIN} \leq v_j^N \leq V^{MAX} \qquad j \in J \tag{1.28}$$

$$T_j^{MIN} \leq t_j \leq T_j^{MAX} \qquad j \in J \tag{1.29}$$

$$s_j^{ECA} = \frac{D_j^{ECA}}{v_j^{ECA}} \qquad j \in J \tag{1.30}$$

$$s_j^N = \frac{D_j^N}{v_j^N} \qquad j \in J \tag{1.31}$$

$$t_j - t_{j-1} - (s_{j-1}^{ECA} + s_{j-1}^N) \geq 0 \qquad j \in J \tag{1.32}$$

The model equations above are similar to those in model P1-1 with the exception of the doubling of sailing time variables and speed variables to account for the different sailing areas with related decisions. All legs start in ports, so all start time relations are given by constraints (1.32). This formulation is equivalent to P1-1, but it is more explicit. For the same problem, fewer variables are needed in P1-2 than in P1-1, as the start times are only given for the ports and the stretches within a leg are aggregated into one representative stretch when there is more than one stretch in each area. However, there is not a large difference in the complexity of the two models. The formulation of P1-2 will be used in the remaining models because it gives the differences between the variables within ECAs and outside explicitly and it can therefore be easier to relate to.

6.1.4. Model P1-2: Linear formulation with a set of legs

Model P1-2 is also reformulated into a linear model in the same way as P1-1. Now, the new parameters and variables are doubled to account for the different areas that require different fuels. The principles applied in the linearization are explained earlier.

Sets

B	Set of fuels
J	Set of legs, legs in J^b are parts using fuel $b \in B$
V	Set of speed alternatives

Parameters

P_b	Fuel price of fuel b, for $b \in B$
D_j^{ECA}	Sailing distance within ECA along leg j, for $j \in J$
D_j^N	Sailing distance outside ECA along leg j, for $j \in J$
T_j^{MIN}, T_j^{MAX}	Lower and upper time limit for starting leg j, for $j \in J$
S_{jv}^{ECA}	Sailing time with speed alternative v within ECA along leg j, for $j \in J$ and $v \in V$
S_{jv}^N	Sailing time with speed alternative v outside ECA along leg j, for $j \in J$ and $v \in V$
F_{jv}^{ECA}	Fuel consumption within ECA on leg j with speed alternative v, for $j \in J$ and $v \in V$
F_{jv}^N	Fuel consumption outside ECA on leg j with speed alternative v, for $j \in J$ and $v \in V$

Auxiliary variables

c	Total costs
f_b	Fuel consumption of fuel b, for $b \in B$
t_j	Start time on leg j, for $j \in J$

Decision variables

x_{jv}^{ECA}	Weight of speed alternative v within ECA along leg j, for $j \in J$
x_{jv}^N	Weight of speed alternative v outside ECA along leg j, for $j \in J$

Model

$$\min c = \sum_{b \in B} P_b \cdot f_b \qquad (1.33)$$

$$f_b = \sum_{j \in J^b} \sum_{v \in V} F_{jv} \cdot x_{jv} \qquad b \in B \qquad (1.34)$$

$$T_j^{MIN} \le t_j \le T_j^{MAX} \qquad j \in J \qquad (1.35)$$

$$t_j - t_{j-1} - \sum_{v \in V} (S_{j-1,v}^{ECA} \cdot x_{j-1,v}^{ECA} + S_{j-1,v}^N \cdot x_{j-1,v}^N) \ge 0 \qquad j \in J \qquad (1.36)$$

$$\sum_{v \in V} x_{jv}^{ECA} = 1 \qquad j \in J \qquad (1.37)$$

$$\sum_{v \in V} x_{jv}^N = 1 \qquad j \in J \qquad (1.38)$$

$$x_{jv}^{ECA}, x_{jv}^N \ge 0 \qquad j \in J, v \in V \qquad (1.39)$$

The fuel costs are minimised. Constraints (1.35) give the time windows for the start on each leg, constraints (1.36) give the start time variables, and the interpolation between speed points is imposed by constraints (1.37) and (1.38).

6.2. Problem P2: Fixed sequence and alternative leg options

This problem includes a routing aspect as well as the speed decisions. The sequence of the ports is still fixed, but there may be several ways to undertake the leg between two consecutive ports. When the shortest leg lies entirely outside ECAs, no alternative legs will be proposed. For legs with a long distance within an ECA however, or where a leg is positioned within an ECA but close to its fringe, alternative leg options can potentially lower the fuel costs considering the less expensive fuel used outside ECAs. The total distance will be longer, but the expensive fuel is used for a smaller part of the leg.

Examples of alternative leg options are illustrated in Figure 6.4, where the shortest feasible leg between two ports is represented as a continuous line, and the dashed line suggests an alternative leg where the ECA is avoided for a significant part of the leg. The proposed new leg is longer than the original leg. The key question is whether such a solution is profitable or not, considering the possible requirements for higher speeds to compensate for the increased distance.

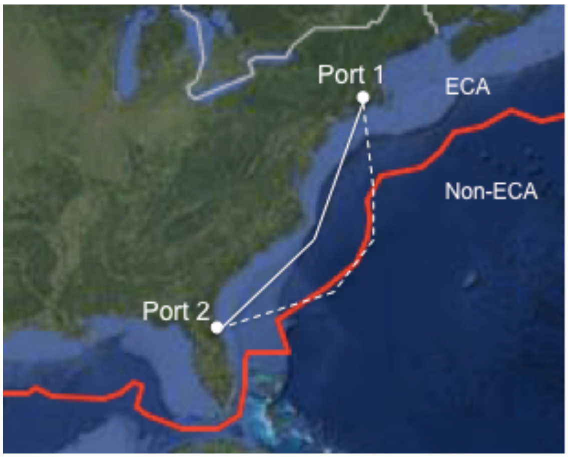

Figure 6.4 Example of alternative leg options between two ports

The problem is more likely to occur in the North American ECAs because of the shapes of the areas that may easily allow leg repositioning. In Europe, legs between north and south could be changed, for instance if the shortest leg includes the North Sea and the English Channel, as it is possible to sail around the UK instead.

Two different models will be presented for this problem. In the first model, a number of nodes are given with possible stretches between node pairs, and the alternative leg options are found through the combination of several such stretches. This approach can be seen as an introduction to the next model, in which the alternative legs are generated beforehand based on the most promising combinations of stretches.

6.2.1. Model P2-1: Formulation with alternative leg stretches

In P2-1, the problem will be formulated using given nodes representing the possible breaks of stretches that form a leg between two ports. Figure 6.5 below is an illustration of a simple example for this model. In the figure there are several nodes between two ports, and the dashed lines represent stretches going between certain node pairs. From Port A, stretches are defined to nodes a, b and B, but the stretch from Port A to Node c is not defined and cannot be in the solution. A solution to the problem includes an uninterrupted sailing leg between the ports that gives minimised costs.

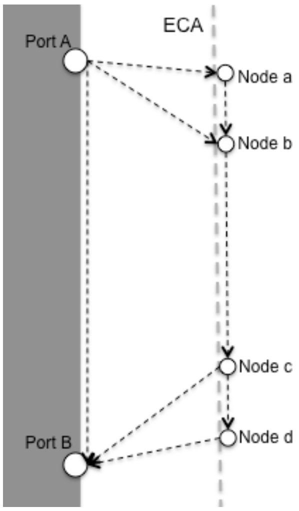

Figure 6.5 P2-1: Illustration of alternative leg stretches between two ports

The sequence of ports is fixed, and there is a set of nodes representing different points at sea between two ports. A number of these nodes correspond to ports. A set of arcs is given between certain nodes, equivalent to the feasible stretches in the legs. The set of arcs is divided in two, with the arcs that lie within ECAs in one set and the remaining arcs in the other. No arc crosses the area boundaries. The binary variables z_{ij} say whether the arc from node i to j is a part of the solution or not, i.e. if the given stretch is used. For P2 and the remaining problems, only the linear models are given. The linearization is done using the same methods as for the models in P1.

Sets

B	Set of fuels
I	Set of nodes, including all ports and artificial nodes
I^P	Subset of nodes containing the sequenced port nodes
A	Set of arcs, arcs in A^b use fuel $b \in B$
A^{ECA}, A^N	Subsets of arcs within and outside ECAs
V	Set of speed alternatives

Parameters

P_b	Fuel price of fuel b, for $b \in B$
D_{ij}	Sailing distance along arc (i,j), for $(i,j) \in A$
T_i^{MIN}, T_i^{MAX}	Lower and upper time limit for leaving port i, for $i \in I^P$
S_{ijv}	Sailing time on arc (i,j) with speed alternative v, for $(i,j) \in A$ and $v \in V$
F_{ijv}	Fuel consumption on arc (i,j) with speed alternative v, for $(i,j) \in A$ and $v \in V$
M_{ij}	Constant term to support the linearization, for $(i,j) \in A$

Auxiliary variables

c	Total costs
f_b	Fuel consumption of each fuel, for $b \in B$
t_{ij}	Start time from node i on arc (i,j), for $(i,j) \in A$

Decision variables

z_{ij}	Binary variable, taking the value 1 if a ship sails on arc (i,j) and 0 otherwise, for $(i,j) \in A$
x_{ijv}	Weight of speed alternative v on arc (i,j), for $(i,j) \in A$ and $v \in V$

Model

$$\min c = \sum_{b \in B} P_b \cdot f_b \tag{2.1}$$

$$f_b = \sum_{(i,j)\in A^b} \sum_{v \in V} F_{ijv} \cdot x_{ijv} \qquad b \in B \tag{2.2}$$

$$T_i^{MIN} \cdot z_{ij} \leq t_{ij} \leq T_i^{MAX} \cdot z_{ij} \qquad (i,j) \in A \mid i \in I^P \tag{2.3}$$

$$t_{ij} - \sum_{k \in I | (k,i) \in A} \Big(t_{ki} + \sum_{v \in V} S_{kiv} \cdot x_{kiv}\Big) \geq M_{ij} \cdot (z_{ij} - 1) \qquad (i,j) \in A \tag{2.4}$$

$$\sum_{v \in V} x_{ijv} = z_{ij} \qquad (i,j) \in A \tag{2.5}$$

$$\sum_{i \in I \,|(i,j) \in A} z_{ij} = 1 \qquad j \in I^P \tag{2.6}$$

$$\sum_{i \in I | (i,j) \in A} z_{ij} = \sum_{k \in I | (j,k) \in A} z_{jk} \qquad j \in I \mid j \leq (|I| - 1) \tag{2.7}$$

$$z_{ij} \in \{0,1\} \qquad (i,j) \in A \tag{2.8}$$

$$x_{ijv} \geq 0 \qquad (i,j) \in A, v \in V \tag{2.9}$$

$$t_{ij} \geq 0 \qquad (i,j) \in A \tag{2.10}$$

The objective function (2.1) minimises the fuel costs and equations (2.2) give the fuel consumptions. Constraints (2.3) are time windows for starting any stretch going out from a port. If the arc is used, the time windows apply, and otherwise the start time on the arc is zero. Constraints (2.4) give the start time on any arc as the sum of the start time on the arc leading into the current node and the sailing time on that arc. Here, the “Big M” method is used to linearize the constraints, presented in section 4.3.3 in the literature chapter. When the sequence is such that node j is visited directly after node i, $z_{ij} = 1$ and the right hand side of the inequality becomes zero. When the two nodes are not consecutive, $z_{ij} = 0$ and the right hand side reads $-M_{ij}$. The size of M_{ij} should be the largest possible value that the sum on the left hand side can take, to give $t_{ij} \geq 0$. For each arc, the corresponding value is:

$$M_{ij} = \max_{(k,i)\in A} \left\{ t_{ki} + \sum_{v \in V} S_{kiv} \cdot x_{kiv} \right\}$$

This formulation of the start time constraints allows waiting time at any node, not only at ports, so there might be several symmetric solutions. It could be avoided by duplicating the constraint and let one apply to port nodes and the other to all other nodes.

Constraints (2.5) say that the sum of speed weights for any arc must equal the binary flow variable for that arc. If the arc is not used, there should not be any other variables greater than zero related to the arc. Constraints (2.6) state that each port node must be entered along one arc. Any node that is entered must also be exited, as given in constraints (2.7). This does not apply to the very last port in the route, marked as the last element in the set of nodes. Finally, constraints (2.8), (2.9) and (2.10) define the binary arc flow variables, the non-negative speed weight variables and the start time variables, respectively.

6.2.2. Model P2-2: Formulation with alternative leg options

For the formulation with a set of alternative complete sailing legs, only certain promising combinations of the possible stretches are generated. Figure 6.6 illustrates a simple example where there is one leg and two alternative options for sailing that leg. Model P2-2 has a simpler structure and solution than P2-1, but with a possibly higher number of variables depending on the number of legs generated.

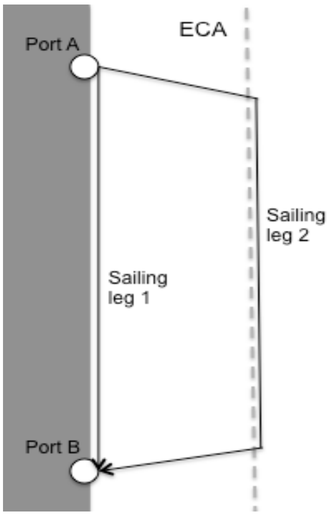

Figure 6.6 P2-2: Illustration of two alternative leg options between two ports

There is a set of sequenced legs between the ports. For each of these legs, there is a set of alternative leg options, defining the possible ways to undertake the respective leg. For each alternative, there is a distance to be travelled within ECA and a distance outside. Because of this, there are also two speed variables to be determined for each leg between two ports, one speed for each of the areas. Lower and upper time limits are given for the start time of each leg going out from a port. The different inputs to the linear model are listed below.

Sets

B	Set of fuels
J	Set of sequenced legs, legs in J^b are parts using fuel $b \in B$
R_j	Set of alternative leg options for each of the legs $j \in J$
V	Set of speed alternatives

Parameters

P_b	Fuel price of fuel b, for $b \in B$
D_{jr}^{ECA}	Sailing distance within ECA on a chosen leg option r on leg j, for $j \in J$ and $r \in R_j$
D_{jr}^{N}	Sailing distance outside ECA on a chosen leg option r on leg j, for $j \in J$ and $r \in R_j$
T_j^{MIN}, T_j^{MAX}	Lower and upper time limit for starting leg j, for $j \in J$
S_{jrv}^{ECA}	Sailing time within ECA along leg option r on leg j with speed alternative v, for $v \in V$, $j \in J$ and $r \in R_j$
S_{jrv}^{N}	Sailing time outside ECA along leg option r on leg j with speed alternative v, for $v \in V$, $j \in J$ and $r \in R_j$
F_{jrv}^{ECA}	Fuel consumption within ECA along leg option r on leg j with speed alternative v, for $v \in V$, $j \in J$ and $r \in R_j$
F_{jrv}^{N}	Fuel consumption outside ECA along leg option r on leg j with speed alternative v, for $v \in V$, $j \in J$ and $r \in R_j$

Auxiliary variables

c	Total costs
f_b	Fuel consumption of fuel b, for $b \in B$
t_j	Start time on leg j, $j \in J$
z_{jr}	Binary variable, takes the value 1 if leg option r is chosen for leg j, and 0 otherwise, for $j \in J$ and $r \in R_j$

Decision variables

x_{jrv}^{ECA}	Weight of speed alternative v within ECA on leg j with option r, for $v \in V$, $j \in J$ and $r \in R_j$
x_{jrv}^{N}	Weight of speed alternative v outside ECA on leg j with option r, for $v \in V$, $j \in J$ and $r \in R_j$

Model

$$\min c = \sum_{b \in B} P_b \cdot f_b \tag{2.11}$$

$$f_b = \sum_{j \in J^b} \sum_{r \in R_j} \sum_{v \in V} F_{jrv} \cdot x_{jrv} \qquad b \in B \tag{2.12}$$

$$T_j^{MIN} \leq t_j \leq T_j^{MAX} \qquad j \in J \tag{2.13}$$

$$t_j - t_{j-1} - \sum_{v \in V} \sum_{r \in R_j} (S_{jrv}^{ECA} \cdot x_{jrv}^{ECA} + S_{jrv}^{N} \cdot x_{jrv}^{N}) \geq 0 \qquad j \in J \tag{2.14}$$

$$\sum_{v \in V} x_{jrv}^{ECA} = z_{jr} \qquad j \in J, r \in R_j \tag{2.15}$$

$$\sum_{v \in V} x_{jrv}^{N} = z_{jr} \qquad j \in J, r \in R_j \tag{2.16}$$

$$\sum_{r \in R_j} z_{jr} = 1 \qquad j \in J \tag{2.17}$$

$$z_{jr} \in \{0,1\} \qquad j \in J, r \in R_j \tag{2.18}$$

$$x_{jrv}^{ECA}, x_{jrv}^{N} \geq 0 \qquad j \in J, r \in R_j, v \in V \tag{2.19}$$

The objective function (2.11) minimises fuel costs, and equations (2.12) give the fuel consumption of each fuel. Time windows are given by constraints (2.13) for the start on each leg. Constraints (2.14) give the start time for each leg as the sum of the start time on the previous leg and the sailing time along the chosen leg option and speed alternatives for that leg. Constraints (2.15) and (2.16) say that the sum of the speed weight variables for each leg option should equal the binary variable reflecting whether this leg option is used. Constraints (2.17) force exactly one leg option to be chosen for each of the legs in the route. Lastly, the binary variables and the speed weight variables are defined in constraints (2.18) and (2.19), respectively.

6.3. Problem P3: Sequencing problem with fixed legs

Problem P3 involves sequencing of the ports as well as determining the speed on all stretches. It is assumed that the sailing legs between all pairs of ports in the route are given and fixed. A number of ports have to be visited once. Figure 6.7 is an illustration of such a problem. The start and end points of the route are given. From Start, the ship can travel to either Port A or Port B. Next, it has to visit the other one, before going to the final destination. The chosen sequence depends on the distances and time windows. P3 is an introduction to sequencing, and a simplification of the more complex problem P4.

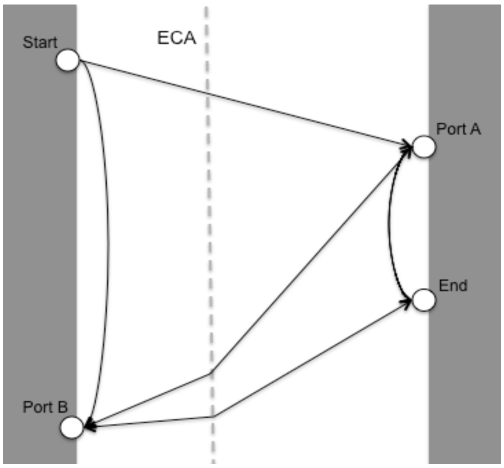

Figure 6.7 P3: Illustration of sequencing problem with fixed sailing legs between four ports

6.3.1. Model P3: Formulation with fixed sailing legs

There is a set of ports. One sailing leg can be chosen between each pair of ports, and the distances within and outside ECAs are given for each leg. The variables w_{ij} state the sequence of the port, where a variable takes the value 1 if port j is visited directly after port i.

Sets

B	Set of fuels
J	Set of ports
A	Set of arcs between ports, arcs in A^b use fuel $b \in B$
V	Set of speed alternatives

Parameters

P_b	Fuel price of fuel b, for $b \in B$
D_{ij}^{ECA}	Sailing distance within ECA between port i and j, for $(i,j) \in A$
D_{ij}^{N}	Sailing distance outside ECA between port i and j, for$(i,j) \in A$
T_j^{MIN}, T_j^{MAX}	Lower and upper time limit for leaving port j, for $j \in J$
S_{ijv}^{ECA}	Sailing time within ECA between port i and j for speed alternative v, for $(i,j) \in A$ and $v \in V$
S_{ijv}^{N}	Sailing time outside ECA between port i and j for speed alternative v, for $(i,j) \in A$ and $v \in V$
F_{ijv}^{ECA}	Fuel consumption within ECA between port i and j for speed alternative v, for $(i,j) \in A$ and $v \in V$
F_{ijv}^{N}	Fuel consumption outside ECA between port i and j for speed alternative v, for $(i,j) \in A$ and $v \in V$
M_{ij}	Constant term to support the linearization, for $(i,j) \in A$

Auxiliary variables

c	Total costs
f_b	Fuel consumption of fuel b, for $b \in B$
w_{ij}	Binary variable, 1 if a ship sails directly from port i to j and 0 otherwise, for $(i,j) \in A$
t_{ij}	Start time on arc (i,j) going out from port i, for $(i,j) \in A$

Decision variables

x_{ijv}^{ECA}	Weight of speed alternative v within ECA between port i and j, for $(i,j) \in A$and $v \in V$
x_{ijv}^{N}	Weight of speed alternative v outside ECA between port i and j, for $(i,j) \in A$ and $v \in V$

Model

$$\min c = \sum_{b \in B} P_b \cdot f_b \tag{3.1}$$

$$f_b = \sum_{(i,j) \in A^b} \sum_{v \in V} F_{ijv} \cdot x_{ijv} \tag{3.2}$$

$$T_i^{MIN} \cdot w_{ij} \leq t_{ij} \leq T_i^{MAX} \cdot w_{ij} \qquad (i,j) \in A \tag{3.3}$$

$$t_{ij} - \sum_{k \in I | (k,i) \in A} \left(t_{ki} + \sum_{v \in V} (S_{kiv}^{ECA} \cdot x_{kiv}^{ECA} + S_{kiv}^{N} \cdot x_{kiv}^{N})\right) \geq M_{ij}(w_{ij} - 1) \qquad (i,j) \in A \tag{3.4}$$

$$\sum_{v \in V} x_{ijv}^{ECA} = w_{ij} \qquad (i,j) \in A \tag{3.5}$$

$$\sum_{v \in V} x_{ijv}^{N} = w_{ij} \qquad (i,j) \in A \tag{3.6}$$

$$\sum_{i \in J} w_{ij} = 1 \qquad j \in J \mid j \geq 2 \tag{3.7}$$

$$\sum_{k \in J} w_{jk} = 1 \qquad j \in J \mid j \leq (|J| - 1) \tag{3.8}$$

$$w_{ij} \in \{0,1\} \qquad (i,j) \in A \tag{3.9}$$

$$x_{ijv}^{ECA}, x_{ijv}^{N} \geq 0 \qquad (i,j) \in A, v \in V \tag{3.10}$$

The objective function (3.1) minimises fuel costs, and fuel consumption is given by equation (3.2). Constraints (3.3) are time windows for leaving a port along any arc. The start time on an arc is given by constraints (3.4), where the “Big M” method is used in the same way as for model P2-1, where the approach was explained. Constraints (3.5) and (3.6) say that the sum of the speed weight variables for an arc must equal the value of the binary flow variable for that arc. All ports should be entered and exited once, given by constraints (3.7) and (3.8), except the first and the last ports of the route. The decision variables are defined in constraints (3.9) and (3.10).

6.4. Problem P4: Sequencing problem with alternative leg options

This final problem instance is the most complex of the problems so far. Here, neither sequence nor sailing legs are fixed. Sailing speeds on all chosen stretches must also be determined. Figure 6.8 below is an illustration of a simple problem of this kind. From Start, the ship can travel to Port A or Port B. There are two alternative ways to sail the leg from Start to Port B, and also between Port A and Port B. The route concludes in the final destination, End.

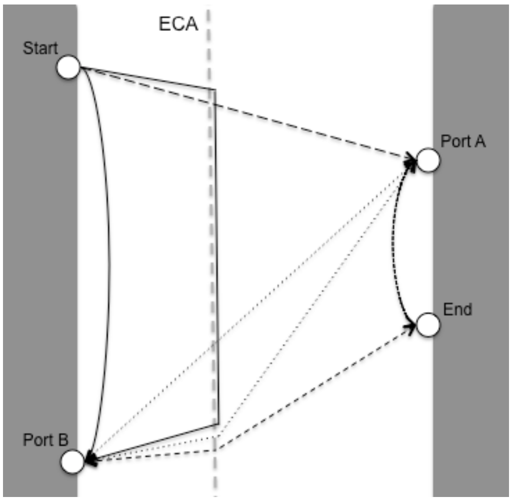

Figure 6.8 P4: Illustration of sequencing problem with alternative leg options between four ports

6.4.1. Model P4: Formulation with alternative leg options

There is a set of ports and a set of arcs between the ports, corresponding to the possible legs in the route. Another set consists of the sailing leg options given for each leg. There are two speeds to decide for each leg along the chosen route, as the speed may be different in the two different areas. The binary variables w_{ijr} are specific combinations where port j is visited directly after port i along sailing leg r.

Sets

B	Set of fuels
J	Set of ports
A	Set of arcs, arcs in A^b use fuel $b \in B$
R_{ij}	Set of alternative sailing legs for each leg $(i,j) \in A$
V	Set of speed alternatives

Parameters

P_b	Fuel price of fuel b, for $b \in B$
D_{ijr}^{ECA}	Sailing distance within ECA between port i and j on sailing leg r, for $(i,j) \in A$ and $r \in R_{ij}$
D_{ijr}^{N}	Sailing distance outside ECA between port i and j on sailing leg r, for $(i,j) \in A$ and $r \in R_{ij}$
T_j^{MIN}, T_j^{MAX}	Lower and upper time limits for leaving port j, for $j \in J$
S_{ijrv}^{ECA}	Sailing time within ECA with speed alternative v between port i and j on sailing leg r, for $(i,j) \in A$, $v \in V$ and $r \in R_{ij}$
S_{ijrv}^{N}	Sailing time outside ECA with speed alternative v between port i and j on sailing leg r, for $(i,j) \in A$, $v \in V$ and $r \in R_{ij}$
F_{ijrv}^{ECA}	Fuel consumption within ECA with speed alternative v between port i and j on sailing leg r, for $(i,j) \in A$, $v \in V$ and $r \in R_{ij}$

F_{ijrv}^{N}	Fuel consumption outside ECA with speed alternative v between port i and j on sailing leg r, for $(i,j) \in A$, $v \in V$ and $r \in R_{ij}$
M_{ijr}	Constant term to support the linearization of the time constraints, for $(i,j) \in A$ and $r \in R_{ij}$

Auxiliary variables

c	Total costs
f_b	Fuel consumption of each fuel, for $b \in B$
t_{ijr}	Start time on arc (i,j) going out from port i on sailing leg r, for $(i,j) \in A$ and $r \in R_{ij}$
w_{ijr}	Binary variable, 1 if a ship travels directly from port i to j along sailing leg r, and 0 otherwise, for $(i,j) \in A$ and $r \in R_{ij}$

Decision variables

x_{ijrv}^{ECA}	Weight of speed alternative v within ECA between port i and j on sailing leg r, for $(i,j) \in A$, $r \in R_{ij}$ and $v \in V$
x_{ijrv}^{N}	Weight of speed alternative v outside ECA between port i and j on sailing leg r, for $(i,j) \in A$, $r \in R_{ij}$ and $v \in V$

Model

$$\min c = \sum_{b \in B} P_b \cdot f_b \tag{4.1}$$

$$f_b = \sum_{(i,j) \in A^b} \sum_{r \in R_{ij}} \sum_{v \in V} F_{ijrv} \cdot x_{ijrv} \qquad b \in B \tag{4.2}$$

$$T_i^{MIN} \cdot w_{ijr} \leq t_{ijr} \leq T_i^{MAX} \cdot w_{ijr} \qquad (i,j) \in A, r \in R_{ij} \tag{4.3}$$

$$\begin{aligned} t_{ijr} - \sum_{k \in I \mid (k,i) \in A} \sum_{s \in R_{ki}} \Big(t_{kis} & \\ + \sum_{v \in V} S_{kirv}^{ECA} \cdot x_{kirv}^{ECA} + S_{kirv}^{N} \cdot x_{kirv}^{N}\Big) & \\ \geq M_{ijr}\Big(\sum_{r \in R_{ij}} w_{ijr} - 1\Big) & \end{aligned} \qquad (i,j) \in A, r \in R_{ij} \tag{4.4}$$

$$\sum_{v \in V} x_{ijrv}^{ECA} = w_{ijr} \qquad (i,j) \in A,\ r \in R_{ij} \tag{4.5}$$

$$\sum_{v \in V} x_{ijrv}^{N} = w_{ijr} \qquad (i,j) \in A,\ r \in R_{ij} \tag{4.6}$$

$$\sum_{r \in R_{ij}} w_{ijr} \leq 1 \qquad (i,j) \in A \tag{4.7}$$

$$\sum_{i \in J} \sum_{r \in R_{ij}} w_{ijr} = 1 \qquad j \in J \mid j \geq 2 \tag{4.8}$$

$$\sum_{k \in J} \sum_{r \in R_{ij}} w_{jkr} = 1 \qquad j \in J \mid j \leq (|J| - 1) \tag{4.9}$$

$$w_{ijr} \in \{0,1\} \qquad (i,j) \in A,\ r \in R_{ij} \tag{4.10}$$

$$x_{ijrv}^{ECA}, x_{ijrv}^{N} \geq 0 \qquad (i,j) \in A,\ r \in R_{ij}, v \in V \tag{4.11}$$

The objective function (4.1) minimises fuel costs, and equations (4.2) give the fuel consumption of each fuel. Constraints (4.3) are the time windows for leaving a port along any arc. The start time on an arc is given by constraints (4.4) using the same linearization method as in Model P3. Constraints (4.5) and (4.6) say that the sum of the speed weight variables on a leg alternative should equal the binary flow variable for that leg option. At most one sailing leg can be chosen between two ports, given by constraints (4.7). Constraints (4.8) and (4.9) force all ports to be entered and exited once with the exception of the start port and the final port. Decision variables are defined in constraints (4.10) and (4.11).

6.5. Model extensions and alternative considerations

There are many possible extensions to this model, and also several levels of details that can be included. The fuel consumption function used in the non-linear models of P1 could be improved by considering other elements. For instance, Lindstad et al. (2012a) splits the engine power into terms of power needed for normal operations, wind and waves, and several previously developed models also account for the main engine and the auxiliary engines separately, such as Corbett et al. (2009) and Doudnikoff and Lacoste (2014). Here, the non-linear models will not be used in the further analyses, so it is not sensible to develop the approximation of the fuel consumption function.

More important, other costs could be considered. One alternative is to include the operating cost rate given per time unit, as it is costly to operate and maintain the ship. However, these costs are not significantly higher for a ship at sea than for a ship at port, so it may not be a good estimate. A different option is to include an opportunity cost, that is, the value of the vessel at its next best use for the time spent sailing. A natural approximation of this value is the charter rate for a similar vessel, as this is the price the ship owner would get from deploying the ship differently. Some conditions follow such an assumption as well, since the charter rate is uncertain and also depending on the market state. In a depressed market, there may not be any demand for chartering ships. These considerations also depend on the shipping mode applicable for the current operations. Due to these mentioned ambiguities and other factors, operating costs are perhaps best left out. Another alternative is to include an additional cost term in the objective functions of the models to account for the delay from the earliest time window at the final port of the route. The objective function for any of the problems, where t_J is the potential start time out from the final port in the route and T_J^{MIN} is the associated lower time limit, becomes:

$$\min c = \sum_{b \in B} P_b \cdot f_b + C \cdot (t_J - T_J^{MIN})$$

This formulation of the objective function is more appropriate if it is assumed that the ship could be of value through other uses once the current route is finished. The model now considers a single voyage, not paying attention to the operations beyond the model horizon.

Besides the extensions and considerations already mentioned, the model could be reformulated to include several vessels instead of just one. For the one route, it would be sensible to consider several voyages, so that the service frequency at each port becomes essential. Such an adjustment could moreover change the implications of time windows, and there might be a trade-off between the speed and the addition of more vessels to meet the requirements. Other possibilities for the model, but on a different matter, could involve other fuel types or compliance means with respect to the ECA regulations.

For the purpose of this thesis, it is optimal to keep the models as clean and general as possible. Any additional assumption adds uncertainty and it is conceivably better to use the simplest models with the highest relevance to the central issue of this thesis, namely speed optimisation and routing considering the ECA regulations.

7. Data input and implementation

In this chapter, the implementation of the developed models is described. First, the software used is briefly presented. Next, values of the input parameters are given, related to market prices of fuel and fuel consumption for the chosen ship type. Thereafter, the background for the cases is explained with generation of time windows and routes, and a summary of all the case routes is given.

7.1. Software

All the models have been implemented in the commercial optimisation software Xpress, in the Mosel programming language using the Xpress-MP system. This system utilises the simplex and Branch and Bound algorithms to solve problems. A model is saved in a .mos file that is compiled into a .bim file and read and executed by Mosel. The module mmxpres connects Mosel to the Xpress-Optimizer. Xpress-Optimizer is designed for solving linear, mixed integer and quadratic problems. The models in this thesis are simple and linear, with a straightforward solution procedure returning the optimal values in minimal time (<0.01s) on any standard PC. Therefore, no further discussions about solution methods or the software/hardware will be included.

The complete codes for the problems are given in the electronic appendix.

7.2. Fuel prices

The fuel prices vary from port to port and change constantly. For HFO, recent historical prices from have been rather stable around USD 575-605 per tonne in April 2014, while prices of MGO range from USD 870 to 1,000 per tonne. The fuel prices chosen as inputs to the models are based on a combination of the prices in Rotterdam in Europe and Houston in the US, since a ship operating within any ECA is likely to bunker from ports on these continents. The absolute fuel prices may change, but the relationship between the fuel prices for fuels allowed within and outside ECAs is the decisive factor.

Each case is tested for several prices of MGO, referred to as different scenarios, reflecting possible developments of the fuel price ratios in the future. The actual input price of HFO is set to USD 590 for all cases and scenarios. A *standard scenario* analysed for all cases is based on an MGO price of USD 920 per tonne. The *benchmark scenario* represents the situation prior to the implementation of ECAs, where only HFO costing USD 590 per tonne is used everywhere. The two key scenarios are summarised in Table 7-1.

Scenario name	**Fuel price**	
	ECA	*Non-ECA*
Benchmark scenario	590	590
Standard scenario	920	590

Table 7-1 Main fuel price scenarios

7.3. Fuel consumption

There are large differences in the fuel consumption of different ships as well. The models are general and can apply to any type of vessel. Two ships with the fuel consumption data in Table 7-2 have been chosen. Both vessels are ro-ro ships, but Ship 2 is a new and more efficient type than Ship 1. Speed is given in knots, which is equivalent to nautical miles per hour. The conversion of fuel consumption to tonnes per hour is appropriate, although it is more common to deal with daily consumption in the industry. Both hours and days are used as time units in the analyses. The fuel consumption is given for speeds up to 23 knots for Ship 1 and 21 knots for Ship 2.

Speed	**Fuel consumption Ship 1**		**Fuel consumption Ship 2**	
[knots]	*[Tonnes/day]*	*[Tonnes/hour]*	*[Tonnes/day]*	*[Tonnes/hour]*
15	52.997	2.208	46.289	1.929
16	59.147	2.464	50.648	2.110
17	66.116	2.755	55.418	2.309
18	73.955	3.081	60.637	2.527
19	82.715	3.446	66.348	2.765
20	92.448	3.852	72.596	3.025
21	103.205	4.300	79.432	3.310
22	115.036	4.793	-	-
23	127.993	5.333	-	-

Table 7-2 Fuel consumption per speed points for given ships

The fuel consumption for both ships in tonnes is plotted for a specific sailing with a fixed distance of 500 nautical miles in Figure 7.1. This representation gives a precise picture of the properties of the fuel consumption curve, and it is apparent that it is a non-decreasing and convex curve. The dashed lines drawn between the data points represent the linear combinations where new points can be found through interpolation. The speed axis stops at 21 knots to make the curves comparable. The upper curve represents Ship 1 and this is higher than the lower curve for Ship 2, reflecting differences in size and/or efficiency. Furthermore, the upper curve is steeper, implying that it will be more costly for Ship 1 to adjust its speed when changing fuels than for Ship 2.

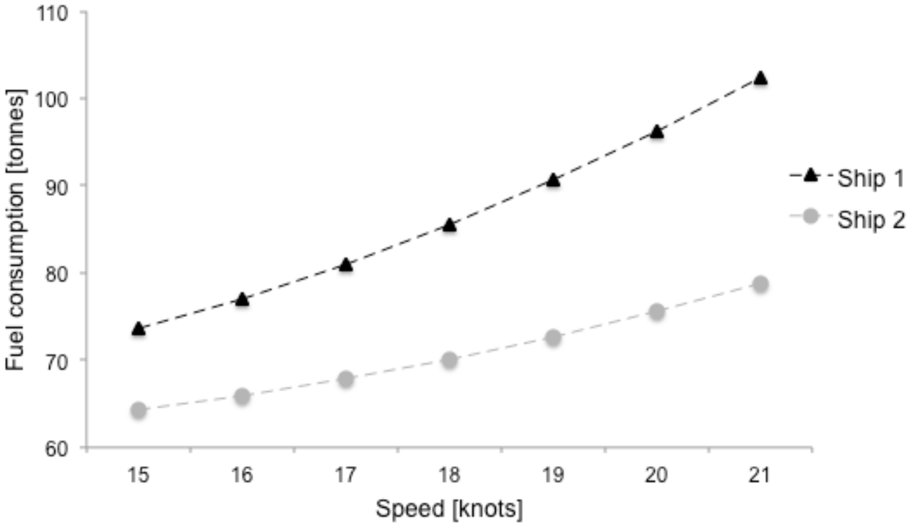

Figure 7.1 Fuel consumption per speed for two ships sailing a given distance of 500 nautical miles

7.4. Generation of time windows

The time constraints for each port in a route are generated methodically using the algorithm in Table 7-3. For each leg, a speed point is randomly drawn from a narrow range of speed points for the vessel given as inputs. For both chosen vessels, the sample range is between 17 and 19 knots. The reference start time at each port is based on the sailing time on previous legs at the reference speeds while sailing the shortest legs, and this time is the mean value of the generated time window. The lower and upper time limits are set to a certain number of days before and after this point. An additional set of time constraints are implemented, where the only restriction concerns the finishing time of the route. In this setting, the maximum sailing time is equal to the upper limit of the time window for the last port in the route.

Algorithm 1: Generation of time constraints

```
Start with a set of legs: J

forall legs j in the set J do
    Draw reference speed $V_j^{REF}$ for leg randomly from given speed interval
    Calculate reference sailing time $S_j^{REF}$ on leg using reference speed and the distance
    of the shortest leg option

    if leg number 1 then
        Set time window for start on leg 1 to $[0,\ 0]$
    else
        if Time window setting then
            Set lower time limit on leg j to the sum of reference sailing times on
            previous legs minus time range of window:
            $T_j^{MIN} = \sum_{i=1}^{j} S_i^{REF} - TimeRange$

            Set upper time limit on leg j to the sum of reference sailing times on
            previous legs plus time range of window:
            $T_j^{MAX} = \sum_{i=1}^{j} S_i^{REF} + TimeRange$

            Time window for leg j: $[T_j^{MIN}, T_j^{MAX}]$
        else Time limit setting
            Set lower time limit on leg j to zero: $T_j^{MIN} = 0$

            Set upper time limit on leg j to the sum of reference sailing times on all
            legs in the set plus time range of window:
            $T_j^{MAX} = \sum_{i=1}^{J} S_i^{REF} + TimeRange$

            Time window for leg j: $[T_j^{MIN}, T_j^{MAX}]$
    end of conditions
end of loop

Generation of time constraints for case situation is complete
```

Table 7-3 Algorithm to generate reference speeds and time constraints

This approach does not represent how the shipping companies actually plan their schedules, but such data have not been accessed in the work on this thesis. The chosen approach is a reasonable way of finding realistic times since the reference speeds are common sailing speeds for the ship. Alternatively, the reference arrival times could be calculated using the same speed for all the legs in the route, potentially leading to less variation in the resulting speed decisions. Since the objective functions of the models only consider fuel costs for one single voyage, the speed can always be lowered to save fuel compared to the generated reference speed, unless longer legs are taken instead. The time constraints would be of even greater significance if the objective function depended on time through including several trips or other aspects of costs or revenue.

Five different feasible time windows and corresponding maximum time limits are generated for each case scenario on average to evaluate the impact on the chosen speeds and legs. With the time limit setting, the speed decisions should be equal for all stretches in similar areas. It is a typical example of industrial shipping, where the planning process is internal and more flexible.

7.5. Overview of ports

The routes in the cases have been generated using a free tool, Google Earth, which is a virtual globe, map and geographical information program where navigation coordinates can be plotted. The coordinates of the ECAs are given by the IMO, so the distances can be found for each area and stretch based on the specified points at sea. Table 7-4 is a list of all the ports that are included in the various routes generated for the different cases, with their geographic locations. The ports in Europe and North America are numbered and plotted on the maps in Figure 7.2 and Figure 7.3.

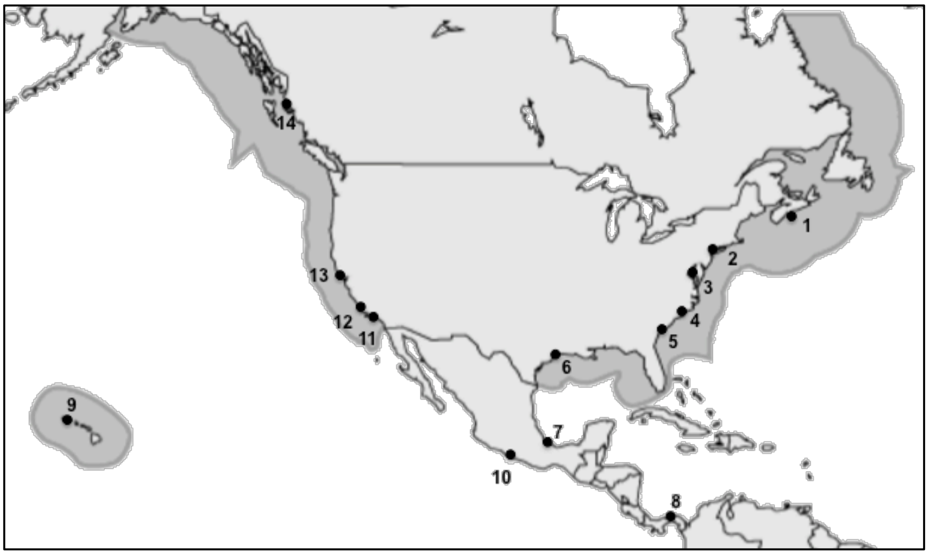

Figure 7.2 Map of numbered ports in North America

Figure 7.3 Map of numbered ports in Europe

Port	No	Location	ECA	Latitude	Longitude
North America East					
Halifax, Canada	1	Atlantic Ocean	Yes	44.6370	-3.5681
New York, New York, US	2	Atlantic Ocean	Yes	40.6683	-74.0456
Baltimore, Maryland, US	3	Atlantic Ocean	Yes	39.2750	-76.5845
Charleston, S. Carolina, US	4	Atlantic Ocean	Yes	32.7846	-79.9240
Brunswick, Georgia, US	5	Atlantic Ocean	Yes	31.1477	-1.4974
Galveston, Texas, US	6	Gulf of Mexico	Yes	29.3167	-94.7833
Vera Cruz, Mexico	7	Gulf of Mexico	No	19.1903	-96.1533
Manzanillo, Panama	8	Caribbean Sea	No	9.3684	-79.8824
North America West					
Honolulu, Hawaii, US	9	Pacific Ocean	Yes	21.2964	-157.8685
Lazaro Cardenas, Mexico	10	Pacific Ocean	No	17.9269	-102.1689
Long Beach, California, US	11	Pacific Ocean	Yes	33.7542	-118.2165
Hueneme, California, US	12	Pacific Ocean	Yes	34.1603	-119.1944
San Francisco, California, US	13	Pacific Ocean	Yes	37.7946	-122.3978
Prince Rupert, Canada	14	Pacific Ocean	Yes	54.3187	-130.3205
Europe					
Livorno, Italy	15	Mediterranean	No	43.5622	10.2950
Santander, Spain	16	Atlantic Ocean	No	43.4589	-3.8066
Southampton, UK	17	English Channel	Yes	50.8965	-1.3968
Le Havre, France	18	English Channel	Yes	49.4900	0.1000
Antwerp, Belgium	19	North Sea	Yes	51.2700	4.3367
Bremerhaven, Germany	20	North Sea	Yes	53.5500	8.5833
Gothenburg, Sweden	21	Baltic Sea	Yes	57.7000	11.9333
Kristiansand, Norway	22	North Sea	Yes	58.1450	7.9990
Flekkefjord, Norway	23	North Sea	Yes	58.2661	6.6498
Stavanger, Norway	24	North Sea	Yes	58.9719	5.7365
Bergen, Norway	25	North Sea	Yes	60.3943	5.3142
Florø, Norway	26	North Sea	Yes	61.5999	5.0337
Asia/Oceania					
Yokohama, Japan	27	Pacific Ocean	No	35.4500	139.6461
Singapore, Singapore	28	Indian Ocean	No	1.2657	103.8422
Cilacap, Australia	29	Indian Ocean	No	-7.7457	109.0183
Dampier, Indonesia	30	Indian Ocean	No	-20.6370	116.7177

Table 7-4 Overview of ports included in case routes including country, location and geographical coordinates

Latitude and longitude are coordinates specifying the position of a point on the Earth's surface. Latitude is a positive number when the location is on the northern hemisphere, and negative on the southern hemisphere. The Equator lies at zero degrees. Longitude describes the east-west position, where east is a positive number and west is negative. The decimal numbers corresponds to degrees, and can be converted into degrees, minutes and seconds.

7.6. Case route generation

The cases are specific routes that relate to one of the problems P1-P4. The most promising cases with regards to making new and original discoveries involve the alternative leg options since several previous studies have examined speed optimisation within shipping, and Doudnikoff and Lacoste (2014) moreover related speed to the issues of ECA. However, to the author's knowledge, no studies consider speed combined with ECAs using a linear model based on real fuel consumption data, so speed decisions are still relevant from this angle. Two simple cases are developed for P1 to illustrate the speed decisions. Greatest emphasis is placed on

P2, where complete sailing leg options are constructed prior to the analyses. The sequencing problems P3 and P4 are not as relevant for the current ECAs, but one case is analysed to illustrate the purpose of the implemented models and study potential impacts on sequencing, in combination with alternative legs options for P4.

Several of the cases are based on real routes used by the shipping company Wallenius Wilhelmsen Logistics (WWL) as presented in their online route maps. What is important in the case generation is to find routes that are fitting for the planned analyses, especially with regards to demonstrating new sailing legs as a potential consequence of the ECAs. At the same time, the routes should be realistic.

7.7. Summary of cases

Each case is named based on the relevant problem (1-4) and a case number, as there might be several cases for each problem. Table 7-5 below gives an overview of all the cases for the four problems, defined by the route. For P3 and P4 the routes are made up by sets of ports, as the sequence is variable.

Problem	Case	Route
P1	C1.1	Gothenburg – Le Havre – Santander – Livorno
	C1.2	San Francisco – Hueneme – Honolulu
P2	C2.1	Bremerhaven – Antwerp – Halifax – Brunswick
	C2.2	Yokohama – Prince Rupert – Long Beach – Lazaro Cardenas
	C2.3a	Kristiansand – Santander
	C2.3b	Flekkefjord – Santander
	C2.3c	Stavanger – Santander
	C2.3d	Bergen – Santander
	C2.3e	Florø – Santander
	C2.4a	Singapore – Southampton
	C2.4b	Cilacap – Southampton
	C2.4c	Dampier – Southampton
P3	C3	Baltimore, Galveston, Vera Cruz, Manzanillo
P4	C4	Baltimore, Galveston, Vera Cruz, Manzanillo

Table 7-5 Overview of case routes for all problems

Each case is analysed for several different fuel prices, referred to as different scenarios. A scenario takes the name after the case and the MGO price. In addition, several time constraints are generated for each such scenario. The resulting combination of data input is referred to as a case situation. These situations are named after the scenario and the type and width of the time constraints on the form *C.ProblemNo.CaseNo._MGOPrice_TimeConstraint_Width. MGOPrice* is the price of the fuel that must be used within ECAs (MGO). *TimeConstraint* can either be of the type time windows (TW) or maximum time limit (TL). *Width* is the deviation in days of the time window limits on either side of the mean time calculated from the reference speeds. If for example a ship spends five days sailing one leg at reference speed and the width is one, the time window for the second leg would read [4, 6], adding one day on either side of the mean. The whole time window interval is actually two days wide.

As mentioned in section 7.2, a standard scenario is developed for an MGO price of USD 920 per tonne. HFO has a constant price of USD 590 in all scenarios. For the special benchmark scenario, the fuel price within ECAs is also USD 590 since it is assumed that there are no ECA regulations and HFO can be used everywhere at sea. This scenario is included for comparison purposes, to evaluate the effect of enforced ECA regulations. The benchmark scenario of for example case C1.1 is named C1.1_590, while the standard scenario is named C1.1_920.

Table 7-6 below is a summary of all case situations analysed for case C1.1, as an example to illustrate the coverage of the cases. A total number of 40 situations is considered. The first situation is C1.1_590_TW_0.25, representing the benchmark scenario using time windows with a deviation of 0.25 days, or six hours, on either side of the mean. For all the cases and scenarios, the problems are implemented for both Ship 1 and Ship 2.

Price	**# Situations**			**Width**	
scenario	*TW*	*TL*	*Total*	*Min*	*Max*
590	4	4	8	0.25	1
920	4	4	8	0.25	1
960	4	4	8	0.25	1
1 020	4	4	8	0.25	1
1 200	4	4	8	0.25	1
	20	20	40		

Table 7-6 Overview of case situations for C1.1

8. Computational study

In this chapter, the specific cases are presented along with the results of the analyses. A case includes a route or a set of ports that must be visited and time windows for the visits. Also, different scenarios are considered with varying MGO prices. The HFO price is assumed constant, but the ratio between the two fuel prices is the essential measure. For each case, the most important outputs from the implemented models are given and discussed. The cases are based on actual routes and distances with realistic time constraint generation as explained in the previous chapter.

Only the most important findings are reported for each case. The remaining and supporting outputs can be found in Appendix A. The models and analyses are general, and the specific results depend largely on the constructed inputs. The time constraint intervals differ for the different cases as well as for some of the scenarios within one case, so the absolute or average numbers cannot always be compared directly. The focus of the analyses is the relationships between certain parameters and variables, studied through qualified comparisons. Concluding remarks will be given for each problem separately, and the final section of the chapter includes a summary of all the analyses.

Some of the terms used frequently in this chapter are repeated in Table 8-1 with a short explanation.

Term	Meaning
Problem	Problem variations P1-P4, with variable or fixed speed, legs and sequence
Case	Specific route or set of ports used in the analyses of a problem
Scenario	Reflects given MGO price. Several price scenarios within each case
Situation	Reflects given time constraint. Several time situations for each scenario
Leg	Path between two ports
Leg option	One of several pre-generated paths between two ports

Table 8-1 Explanation of common terms used in the computational study

Outputs and comparisons of different scenarios and situations will be given in tables for each case. The term *Difference* used in a table means a scenario or situation compared with the benchmark, unless otherwise stated. When the benchmark scenario is considered, assuming ECAs are not implemented, emissions are calculated based on a 2.7% sulphur content in all the fuel consumed. *Ratio* is used to compare a measure, most often speed, outside ECA with the value within ECA.

8.1. Case analysis P1: Fixed routes and sequences

In P1, the routes and sequence are fixed, and the only decision concerns speed. The cases describe routes between a number of ports, with known distances within and outside ECAs. P1 is relatively uncomplicated, and valuable results can be obtained from simple cases. The main point is to facilitate the analysis of different speed decisions within and outside ECAs and the associated fuel consumption and environmental consequences. Two cases are analysed for P1, given in Table 8-2.

Case	**Route**
C1.1	Gothenburg – Le Havre – Santander – Livorno
C1.2	San Francisco – Port Hueneme – Honolulu

Table 8-2 Cases analysed for P1

8.1.1. C1.1: Case analysis

Table 8-3 below shows the legs in the first case used for the analyses of problem P1. The distances are given in nautical miles (nmi) for each stretch separately, i.e. within and outside ECA. The route starts in Gothenburg in Sweden and goes through the North Sea and the English Channel and finally around Spain and to Livorno in Italy. Figure 8.1 shows a map of the route. The circles represent the ports in Sweden, France, Spain and Italy. The total distance of the route is 2,973 nautical miles, and with a normal speed of for example 17 knots, the trip would take approximately seven days and seven hours. Time spent in port is disregarded in all the cases, along with the fuel consumed during those periods.

Leg	**Distance**		
	ECA	*Non-ECA*	*Total*
Gothenburg – Le Havre	680	0	680
Le Havre – Santander	210	345	555
Santander – Livorno	0	1,738	1,738
Total distance	890	2,083	2,973

Table 8-3 C1.1: Distances of route legs in nautical miles

Figure 8.1 C1.1: Map of route

Without time restrictions, the lowest speed of 15 knots would be chosen on all legs when minimising fuel costs, leading to a total sailing time of eight days and six hours. Time constraints are generated based on a random reference speed and different values of the intervals. These intervals might not reflect the reality accurately, but it is more important to study the overall effects of the variations than the actual tightness.

Table 8-4 below shows the time constraint situations for C1.1. For each leg, a reference speed is found, and these are used to generate the time constraints. The reference speeds are fixed for all scenarios and situations. *Sailing time* shows the time it would take to sail the respective leg while maintaining reference speed. *Mean time* refers to the start time on the leg if sailing at the reference speed on all legs. There is no need to account for waiting time in any situation. The expected start time on leg 2 is 1.52 days, corresponding to the sailing time on the previous leg. For leg 3, the expected start time is 2.83, corresponding to the sum of the sailing times on leg 1 and leg 2 (1.52 + 1.31), and so on. The constructed time limits are a certain number of days, given by the situation name, before and after the mean time.

	Generated time constraints			
Input/leg	1	2	3	Finish
Distance	680	555	1,738	-
Reference speed	18.67	17.69	17.32	-
Sailing time	1.52	1.31	4.18	-
Mean time	0	1.52	2.83	7.01
Time situation				
TW_0.25	[0, 0]	[1.27, 1.77]	[2.57, 3.07]	[6.76, 7.26]
TW_0.5	[0, 0]	[1.02, 2.02]	[2.32, 3.32]	[6.51, 7.51]
TW_0.75	[0, 0]	[0.77, 2.27]	[2.07, 3.57]	[6.26, 7.76]
TW_1	[0, 0]	[0.52, 2.52]	[1.82, 3.82]	[6.01, 8.01]
TL_0.25	[0, 0]	[0, 7.26]	[0, 7.26]	[0, 7.26]
TL_0.5	[0, 0]	[0, 7.51]	[0, 7.51]	[0, 7.51]
TL_0.75	[0, 0]	[0, 7.76]	[0, 7.76]	[0, 7.76]
TL_1	[0, 0]	[0, 8.01]	[0, 8.01]	[0, 8.01]

Table 8-4 C1.1: Generated time situations based on reference speed and times

Four different time window intervals are implemented, given in number of days counting from zero, which is the start time of the route. The tightest one allows the ship to start 0.25 days, or six hours, before or after the mean value when sailing at reference speed, while the widest interval has a range of one day on either side. The total width consequently varies between 12 and 48 hours in this case. The time window for *Finish* is the time interval within which a ship must be ready to leave the final port, equal to the arrival time at the port. In addition to the four time window (TW) situations, an equivalent set of time limit (TL) situations is analysed. Here, only the upper time limit for the last port in the route acts as a constraint.

The ship characteristics data input in the following analysis belongs to Ship 1, which is the ship considered in all the tables and analyses unless otherwise stated. Analyses based on the data for Ship 2 give very similar results. The main difference is that the fuel consumption is lower, leading to lower costs and in general lower-scaled results compared to Ship 1. Complete outputs from both ships can be found in Appendix A.1.

The output for the standard scenario with an MGO price of USD 920 per tonne is given in Table 8-5. The numbers correspond to one single set of time constraints, shown in the previous table, with a fixed random generator. *Time* gives the start times on each leg in number of days. The time at finish is equal to the upper time limit for the last port, while start times on previous legs are often earlier than the respective limits. This holds for all situations because the objective is to minimise costs and this is done through sailing at the lowest speed possible and thus using the longest total time allowed. *Speed* is given in knots and found for each area separately. Legs 1 and 3 lie entirely within one single area, so the speed for the opposite area is not reported. The resulting fuel consumption is given in tonnes. Fuel consumed within ECAs is MGO while HFO is consumed outside.

Case situation	Leg	Time	Speed		Fuel consumption	
			ECA	*Non-ECA*	*ECA*	*Non-ECA*
C1.1_920_TW_0.25	1	0	16.4	N/A	106.9	N/A
	2	1.73	16.0	18.0	32.3	59.1
	3	3.07	N/A	17.3	N/A	286.9
	Total	**7.26**			**139.2**	**346.0**
C1.1_920_TW_0.5	1	0	15.6	N/A	102.9	N/A
	2	1.82	15.0	17.0	30.9	55.9
	3	3.25	N/A	17.0	N/A	281.7
	Total	**7.51**			**133.8**	**337.6**
C1.1_920_TW_0.75	1	0	15.0	N/A	100.1	N/A
	2	1.89	15.0	17.0	30.9	55.9
	3	3.32	N/A	16.3	N/A	272.3
	Total	**7.76**			**131.0**	**328.2**
C1.1_920_TW_1	1	0	15.0	N/A	100.1	N/A
	2	1.89	15.0	15.0	30.9	50.8
	3	3.43	N/A	15.8	N/A	265.7
	Total	**8.01**			**131.0**	**316.5**
C1.1_920_TL_0.25	1	0	16.0	N/A	104.7	N/A
	2	1.77	16.0	17.6	32.3	57.8
	3	3.14	N/A	17.6	N/A	291.0
	Total	**7.26**			**137.1**	**348.7**
C1.1_920_TL_0.5	1	0	15.5	N/A	102.2	N/A
	2	1.83	15.5	17.0	31.6	55.9
	3	3.25	N/A	17.0	N/A	281.7
	Total	**7.51**			**133.8**	**337.6**
C1.1_920_TL_0.75	1	0	15.0	N/A	100.1	N/A
	2	1.89	15.0	16.4	30.9	54.4
	3	3.35	N/A	16.4	N/A	273.8
	Total	**7.76**			**131.0**	**328.2**
C1.1_920_TL_1	1	0	15.0	N/A	100.1	N/A
	2	1.89	15.0	15.7	30.9	52.4
	3	3.39	N/A	15.7	N/A	264.1
	Total	**8.01**			**131.0**	**316.5**

Table 8-5 C1.1: Speed decisions and fuel consumption in each area for different situations of the standard scenario

Some clear connections regarding the speed decisions are found in all situations. First, the speed is in general higher with tighter time windows in order to meet the constraints, and second, the speed outside ECAs is always higher than the speed within ECAs on the same leg, or equal if the lowest speed is chosen. The fuel consumption is correspondingly higher for tight time constraints, and so are fuel costs. The speed is below the reference speed in both areas for all situations. This is expected since the reference speed is drawn from an interval between 17 and 19 knots while the minimal ship speed is 15 knots. What is important is the difference between the speed within ECAs and outside, and this distinction is significant.

The difference between the situations with time windows (TW) and an upper time limit (TL) is that the speed is constant within each area throughout the route for the latter. The higher flexibility may lead to lower costs since the speed decisions can be made for all legs as one. This can for instance be seen when the tightest time windows are imposed, where additional flexibility has the highest value. For the standard scenario, total fuel costs equal USD 331,857 with constant speeds (TL_0.25), and USD 332,227 with time windows (TW_0.25). The difference is only 0.1%, but it shows the potential value of flexibility in time planning.

The output, including the data in Table 8-4, will not be presented with the same level of details for the other scenarios and cases, but the tables are included in this first case to give the reader an understanding of the type of information that the models return. All other model output can be found in Appendix A.

The output data are aggregated into average numbers for the different price scenarios. First, the average speed is found for each situation. This is a weighted average based on the distance travelled at the given speed. This method leads to a minor overestimation due to the previously discussed non-linearity of time versus speed, with reference to chapter 4.2.3. For this particular example, the error is less than two minutes, or 0.016%, for the entire route. An alternative and accurate calculation of the average speed involves transforming speed into sailing times and back again after calculating the times, but since the ratio between the speed within and outside ECAs is nevertheless precise and more important, the first calculation will be used going forward.

Next, the average of all values for the eight different case situations in the price scenario is found. Table 8-6 shows the resulting average speeds in knots and fuel consumption in tonnes within each area. Case scenario C1.1_590 is the benchmark where the ECA regulations are not enforced and only HFO is used. For this scenario the speed is equal in both areas, although possibly with different speed on different legs in the presence of time windows. In addition to the standard scenario with an MGO price of USD 920 per tonne, three other prices are analysed. These prices are chosen at points when there are significant changes in the speed, found through trials, and they stay constant for a certain price range at each point. *Ratio* compares the speed outside and within the ECAs. For the standard scenario, the speed outside ECAs is 8.18% higher than within the ECA. As expected, the ratio increases with the fuel price, since it becomes more expensive to maintain a higher speed within ECAs. The total sailing time is the same for all scenarios. *Difference* compares the total fuel consumption of each price scenario with the benchmark.

Scenario	**Average speed**			**Average fuel consumption**			
	ECA	*Non-ECA*	*Ratio*	*ECA*	*Non-ECA*	*Total*	*Difference*
C1.1_590	16.26	16.26	0.00%	138.2	326.5	464.7	-
C1.1_920	15.40	16.66	8.18%	133.5	332.4	465.9	0.25%
C1.1_960	15.37	16.68	8.55%	133.2	332.8	466.0	0.28%
C1.1_1020	15.16	16.80	10.81%	132.0	335.0	466.9	0.48%
C1.1_1200	15.12	16.82	11.19%	131.8	335.4	467.2	0.53%

Table 8-6 C1.1: Average speed and fuel consumption in each area with ratio of non-ECA and ECA speed and comparison of total fuel consumption for each scenario with the benchmark

The essential take-away from this case is that shipping companies and ship operators indeed make different speed decisions when the ECA regulations are implemented. The consequences involve different fuel consumption and costs. For each increase in the price of MGO, the consumption of fuel within ECAs decreases slightly while the consumption outside increases. The increase is larger than the decrease, leading to an increase in the total fuel consumption. This difference between the standard scenario and the benchmark is 0.25%, and increasing for higher MGO prices. It corresponds to 1.16 to 2.45 tonnes of fuel. The numbers are small, but possibly still significant since these calculations represent one single trip along the route for one ship only. The difference between the various scenarios and the benchmark is less pronounced for Ship 2, ranging from 0.15% to 0.30%.

The costs naturally also increase when the MGO price increases. However, changes in speed decisions lead to lower costs than keeping a constant speed when the

ECAs are enforced. Table 8-7 shows the fuel costs for the four price scenarios resulting from the optimised speed decisions presented above, next to the estimated fuel costs based on the benchmark speed decisions. The estimated costs within ECAs are calculated using the ECA fuel consumption as given for the benchmark scenario in Table 8-6 multiplied with the MGO prices in the different scenarios. The fuel consumption within ECAs is 138.2 tonnes for C1.1_590, so the estimated ECA costs for example for C1.1_920 are 138.2*920 = 127,173. This is USD 4,358 higher than the fuel costs within ECAs based on the optimised decisions. Outside ECAs however, the costs are USD 3,481 lower. The loss is smaller than the gain, so there is a combined saving of USD 876, or 0.27%, from making adjusted speed decisions when the MGO price changes to the standard scenario. There are greater savings from the higher price scenarios, as seen in the table. This is a small share of the total costs, but can amount to great sums over time.

Scenario	**Optimised fuel costs**			**Benchmark fuel costs**			**Saving**
	ECA	*Non-ECA*	*Total*	*ECA*	*Non-ECA*	*Total*	
C1.1_920	122,816	196,119	318,935	127,173	192,637	319,811	876
C1.1_960	127,913	196,356	324,269	132,703	192,637	325,340	1,071
C1.1_1020	134,611	197,637	332,248	140,997	192,637	333,634	1,386
C1.1_1200	158,120	197,895	356,015	165,878	192,637	358,516	2,501

Table 8-7 C1.1: Average fuel costs based on optimised speed decisions and based on benchmark decisions, and the cost saving arising from the optimisation

So far, it has been shown that the optimal speed decisions change, leading to slightly higher total fuel consumption. The final effect to examine is the impact on the environment. The amount of SO_X emissions depends on the sulphur content of the respective fuels. Emissions of SO_X will thus decrease a great deal within ECAs when using MGO instead of HFO, although there will be somewhat higher emissions outside ECAs than before due to the increased HFO consumption. It is assumed that HFO has an average sulphur content of 2.7% while MGO complies with the ECA limits of *2015* at 0.1%. The upper limit is actually 3.5% outside ECAs, but the average bunker oil currently has a lower concentration. Calculation of emissions was discussed in chapter 4.4.2. CO_2 is calculated with an emission factor of 3.17. Combustion of MGO and HFO produces approximately the same amount of CO_2. These numbers will be used in the environmental analyses for all cases in this thesis.

Table 8-8 shows the average total emissions of the two pollutants and the difference between each price scenario and the benchmark. Since CO_2 emissions are equal for each fuel, these emissions consequently increase at the same rate as the total fuel consumption. There is a significant decrease in SO_X emissions, as the large reduction within ECAs outweighs the minor increase outside considerably. The SO_X emissions are found to decrease by around 27% for all scenarios. The ECA regulations are successful in this case with regards to protecting the coastlines from SO_X. However, there are different consequences for emissions of CO_2 and potentially other pollutants that have not been included in the analysis. There will be more CO_2 emissions following the ECA regulations, which is harmful for the global environment.

Scenario	**CO_2 emissions**		**SO_X emissions**	
	Tonnes	*Difference*	*Kilograms*	*Difference*
C1.1_590	1 473.2	-	251.0	-
C1.1_920	1 476.9	0.25%	182.2	-27.41%
C1.1_960	1 477.4	0.28%	182.4	-27.33%
C1.1_1020	1 480.2	0.48%	183.5	-26.87%
C1.1_1200	1 481.0	0.53%	183.5	-26.87%

Table 8-8 C1.1: Average total emissions of CO_2 and SO_X and comparisons with benchmark

8.1.2. C1.2: Case analysis

Case C1.2 is a route from San Francisco to Port Hueneme, both in California, and further to Honolulu in Hawaii. All ports lie within an ECA, but the leg between Port Hueneme and Honolulu includes a long stretch in the Pacific Ocean outside the ECA. The distances are given in nautical miles by Table 8-9, and a map of the route is shown in Figure 8.2. The inner line along the coast of California indicates another environmental zone, but this becomes irrelevant for the issue of sulphur restrictions when the new ECA sulphur limits enter into force in 2015.

Leg	**Distance**		
	ECA	*Non-ECA*	*Total*
San Francisco – Port Hueneme	308	0	308
Port Hueneme – Honolulu	529	1,661	2,190
Total distance	837	1,661	2,498

Table 8-9 C1.2: Distances of route legs in nautical miles

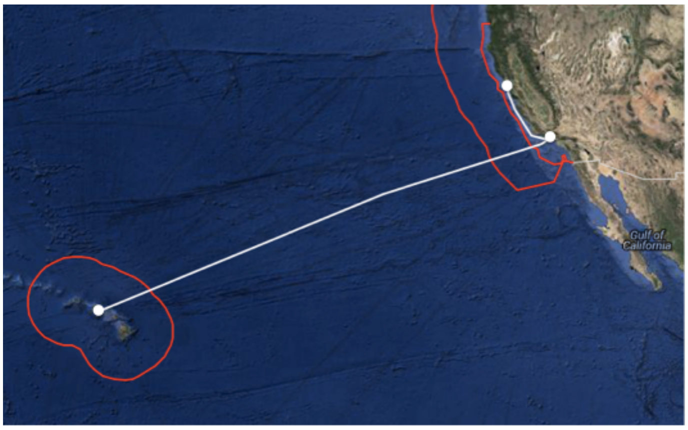

Figure 8.2 C1.2: Map of route

All the output presented for case C1.2 is related to Ship 1, but the findings from the two ships are in general the same. The aggregated output from case C1.2 for both ships is given in Appendix A.2. Here, the main findings are presented.

The average speeds are calculated the same way as in C1.1, and the results are shown in Table 8-10 along with the corresponding average fuel consumption in each area. The price scenarios are chosen at points when the decisions change significantly, and are therefore not the same for the different cases with the exception of the benchmark and the standard scenario. The speed outside ECAs is approximately 8% higher than within for the standard scenario, and the ratio increases for the higher MGO price scenarios.

Scenario	**Average speed**			**Average fuel consumption**			
	ECA	*Non-ECA*	*Ratio*	*ECA*	*Non-ECA*	*Total*	*Difference*
C1.2_590	16.1	16.1	0.00%	129.9	258.1	388.1	-
C1.2_920	15.3	16.6	7.95%	125.1	263.9	389.0	0.25%
C1.2_1020	15.1	16.7	10.33%	123.9	265.9	389.9	0.46%
C1.2_1280	15.0	16.8	11.89%	123.2	267.5	390.7	0.68%

Table 8-10 C1.2: Average speed and fuel consumption in each area with ratio of non-ECA and ECA speed and comparison of total fuel consumption for each scenario with the benchmark

The patterns discovered in C1.1 are evident for this case as well, as anticipated. Less MGO is consumed at higher MGO prices, compensated by a slightly larger increase in HFO consumption. The difference in total fuel consumption between the various scenarios and the benchmark ranges from 0.25% to 0.68% for the given prices. The total fuel costs are given in Table 8-11 for the solved problems and estimated for the benchmark decisions as in C1.1. The rightmost column shows the saving in costs arising from the new and optimal speed decisions compared to maintaining a constant speed equal to that in the benchmark scenario. The savings constitute a larger share of total costs for the higher price scenarios. However, the saving is less than 1% for all scenarios, but considering the large scale it might still be enough to induce shipping companies to reassess their speed decisions.

Scenario	**Optimised fuel costs**			**Benchmark fuel costs**			**Saving**
	ECA	*Non-ECA*	*Total*	*ECA*	*Non-ECA*	*Total*	
C1.2_920	115,116	155,704	270,821	119,550	152,294	271,844	1,023
C1.2_1020	126,416	156,903	283,319	132,545	152,294	284,839	1,520
C1.2_1280	157,704	157,824	315,528	166,331	152,294	318,625	3,096

Table 8-11 C1.2: Average fuel costs based on optimised speed decisions and based on benchmark decisions, and the cost saving arising from the optimisation

The average emissions of each pollutant are given in Table 8-12 along with the difference from the benchmark scenario given in per cent. There is a substantial reduction in SO_X emissions of around 30%, which is as expected. Emissions of CO_2 increase due to the higher total fuel consumption. For the standard scenario, 3.05 tonnes more CO_2 is emitted during one trip along the route, and 64.6 kg less SO_X. The findings concur with case C1.1 results. Some concluding remarks for both cases are given in the next paragraphs.

Scenario	**CO_2 emissions**		**SO_X emissions**	
	Tonnes	*Difference*	*Kilograms*	*Difference*
C1.2_590	1,230.2	-	209.6	-
C1.2_920	1,233.2	0.25%	145.0	-30.80%
C1.2_1020	1,235.9	0.46%	146.1	-30.29%
C1.2_1280	1,238.5	0.68%	146.9	-29.89%

Table 8-12 C1.2: Average total emissions of CO_2 and SO_X and comparisons with benchmark

8.1.3. Concluding remarks for the analysis of P1

The main objective of the case analysis for problem P1 has been to analyse the effect of the ECA regulations on speed decisions made by shipping companies, and the consequences these decisions have for the parties involved and the environment. Findings lead to the conclusion that the speed is reduced within ECAs compared to the benchmark with constant speed, and this reduction is compensated by a speed increase outside ECAs. Doudnikoff and Lacoste (2014) executed a similar analysis with the same result. They also found that reduced speed within ECAs could give around 0.3% lower costs compared to maintaining a constant speed. Here, this number lies between 0.2% and 1%, based on the calculations of the cost savings from optimal decisions compared to benchmark decisions.

The speed ratio of the two areas depends on the fuel price ratio between MGO and HFO, as well as the distances sailed and characteristics of the time constraints allowing more or less flexibility. The least fuel is consumed when a ship sails at constant speed throughout each leg, therefore sailing at different speeds leads to higher total fuel consumption. The fuel consumption is reduced within ECAs where the fuel is more expensive.

Emissions of CO_2 are directly related to the total fuel consumption, since MGO produces as much CO_2 as HFO when burned. Hence, the CO_2 emissions are expected to increase slightly with the enforced ECA regulations when ships optimise speed and sail fixed routes. Findings by Doudnikoff and Lacoste (2014) support this general prediction. There will be a reduction of CO_2 emission within ECAs, but damages caused by CO_2 do not depend on discharge site and are moreover harmful for the global environment. Emissions of SO_X are greatly reduced as a consequence of the ECAs both within these areas and in total. The slight increase outside ECAs is supposedly rather unimportant since SO_X has worse impacts when emitted close to land. SO_X is not a greenhouse gas, and does not contribute to global warming like CO_2.

8.2. Case analysis for P2: Fixed routes and alternative leg options

Problem P2 considers alternative sailing legs between ports. The cases involve routes between ports in a fixed sequence, but with a number of different ways to sail certain legs. Complete sailing legs are generated prior to the implementation and the distances of stretches in similar areas are aggregated for each leg.

The relevant cases for P2 are routes restricted by ECAs where it is possible to move larger parts of the leg outside the ECA. In Europe, the ECAs cover an enclosed sea basin, and routes within Northern Europe would not benefit from modifications of the legs. Routes between north and south where the shortest leg is through the North Sea and the English Channel are more likely influenced. Depending on the location of the northern port within the North Sea, it may be profitable to sail around the UK instead. For North America, the ECAs extend along the coasts and it is easier to imagine beneficial repositioning of legs between ports. The cases for P2 are given in Table 8-13 below, to some extent based on actual routes used by shipping companies and their relevance to the problem.

Case	**Route**
C2.1	Bremerhaven – Antwerp – Halifax – Brunswick
C2.2	Yokohama – Prince Rupert – Long Beach – Lazaro Cardenas
C2.3a	Kristiansand – Santander
C2.3b	Flekkefjord – Santander
C2.3c	Stavanger – Santander
C2.3d	Bergen – Santander
C2.3e	Florø – Santander
C2.4a	Singapore – Southampton
C2.4b	Cilacap – Southampton
C2.4c	Dampier – Southampton

Table 8-13 Cases analysed for P2

8.2.1. C2.1: Case analysis

Case C2.1 considers a route starting in Bremerhaven in Germany, crossing the Atlantic Ocean after visiting Antwerp and then sailing south along the North American east coast from Halifax to Brunswick. The shortest leg between the two latter ports involves a long distance within the ECA. It is therefore appropriate to examine impacts of longer alternatives for this leg. Table 8-14 below gives specific distances for each stretch of the leg options in the route, given in nautical miles. The numbers are aggregated for all the stretches within the same area on a given leg. Only a few promising leg options are suggested.

Leg	**Leg option**	**Distance**		
		ECA	*Non-ECA*	*Total*
Bremerhaven – Antwerp	-	306	0	306
Antwerp – Halifax	-	772	2,101	2,873
Halifax – Brunswick	1	1,186	0	1,186
	2	514	831	1,345
	3	476	890	1,366
	4	445	987	1,432
	5	879	352	1,231

Table 8-14 C2.1: Distances of route leg options in nautical miles

Common shipping routes sometimes include one or two stops on the leg between Halifax and Brunswick, for instance in New York and Charleston. A few tests were done for such routes as well. The shortest leg between Halifax and New York is 548 nautical miles (nmi) within the ECA. Moving parts of the leg outside the ECA could lead to a reduction in the ECA stretches of around 15%, but the total distance would at the same time have to increase by more than 50%. It is evident that this is not a realistic consideration. Tests similarly show that an alternative leg between New York and Charleston would only be considered for very high and improbable MGO prices, where MGO is almost six times as expensive as HFO. Since this ratio is currently around 1.5, this is disregarded as an irrelevant case. When instead the ship travels directly from New York to Brunswick where the shortest leg is 748 nmi within the ECA, up to 40% of the ECA distances could be avoided with a compensation of approximately 41% longer total distance. The analysis shows that a comparable option would be chosen for MGO prices of around USD 1,500 per tonne. Predictions for the future do not deem this scenario likely either. However, considering that the demand for MGO might rise significantly from 2015, it is not completely unthinkable.

The sailing legs between Halifax and Brunswick for case C2.1 are shown in Figure 8.3. Leg option 1 is the shortest leg, going in nearly a straight line between the ports, entirely within the ECA. Leg option 4 is the leg with the minimal ECA distance, but also the longest in total. The total distance travelled when following the shortest legs for the entire route is 4,365 nmi, of which 2,264 nmi are within ECAs. Based on the leg options presented in Table 8-14, the minimum ECA distance possible is 1,523 nmi, corresponding to a reduction in ECA stretches of 32.7%. This option leads to a total sailing distance of 4,611 nmi, which is an increase of 5.6% in the total distance. The leg crossing the Atlantic Ocean involves a long stretch outside ECAs in any case. Several combinations can be chosen, so these figures are merely the maximum and minimum distances, but they give an idea of the potential for this case.

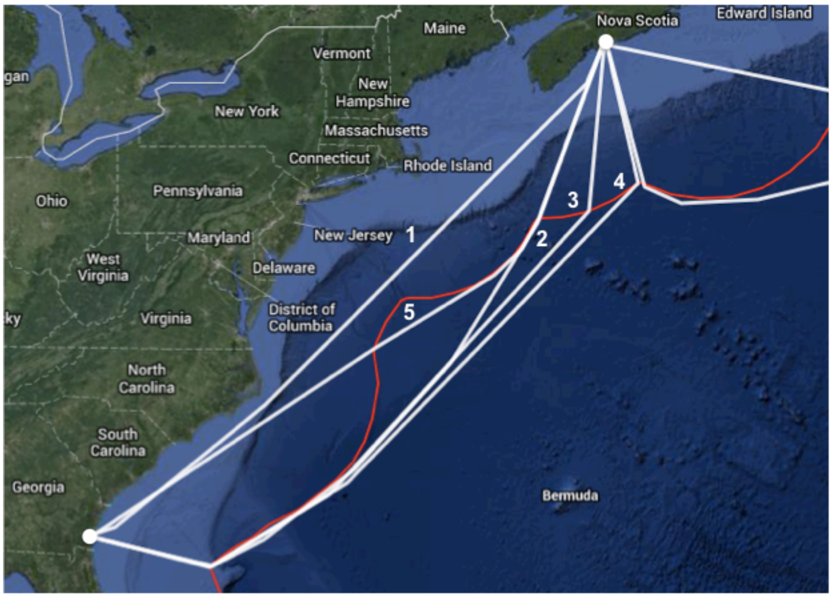

Figure 8.3 C2.1: Map of alternative leg options between Halifax and Brunswick

Case C2.1 has been tested for total time window widths between one and five days and corresponding upper time limits of up to 2.5 days above the mean expected sailing time. A number of different MGO prices ranging from USD 720 to USD 2,000 per tonne have been analysed in addition to the benchmark where only HFO costing USD 590 is used. The results from the standard scenario with an MGO price of USD 920 are shown in Table 8-15 with five different time windows. The equivalent set of time constraints based on upper time limits gives identical total results, and is not presented separately, but the numbers are included in the calculations of averages.

The presented data relate to Ship 1. Complete output for all price scenarios and both ships can be found in Appendix A.3.

Situation	**Leg**	**Chosen leg option**	**Distance** *ECA*	*Non-ECA*	*Total*	**Speed** *ECA*	*Non-ECA*
C2.1_920_TW_0.5	1	-	306	0	306	16.0	N/A
	2	-	772	2,101	2,873	16.0	18.0
	3	5	879	352	1,231	16.0	17.4
	Total		**1,957**	**2,453**	**4,410**		
C2.1_920_TW_1	1	-	306	0	306	15.0	N/A
	2	-	772	2,101	2,873	15.0	17.0
	3	5	879	352	1,231	16.0	17.0
	Total		**1,957**	**2,453**	**4,410**		
C2.1_920_TW_1.5	1	-	306	0	306	15.0	N/A
	2	-	772	2,101	2,873	15.0	16.1
	3	5	879	352	1,231	15.0	16.0
	Total		**1,957**	**2,453**	**4,410**		
C2.1_920_TW_2	1	-	306	0	306	15.0	N/A
	2	-	772	2,101	2,873	15.0	15.7
	3	2	514	831	1,345	15.0	15.0
	Total		**1,592**	**2,932**	**4,524**		
C2.1_920_TW_2.5	1	-	306	0	306	15.0	N/A
	2	-	772	2,101	2,873	15.0	15.0
	3	3	476	890	1,366	15.0	15.0
	Total		**1,554**	**2,991**	**4,545**		

Table 8-15 C2.1: Chosen leg option with corresponding distances and speed decisions in each area for different time window situations for the standard scenario

For the three tightest time windows, leg option 5 is chosen between Halifax and Brunswick, with a resulting total distance of 1,957 nmi within ECAs and 2,453 nmi outside. When the time window range reaches two days, the second option is taken, and for the most flexible situation, the distance within ECAs is further decreased by 41 nmi with option 3. Option 4 is the leg with the shortest ECA distance between Halifax and Brunswick, but this leg is only chosen for very high and unrealistic MGO prices above USD 3,000 per tonne. The additional sailing distance is too long relative to the saving in ECA stretches.

The more efficient test ship, Ship 2, gives slightly different results for this case. Since its fuel consumption curve is flatter, it takes a little less to change the decisions for this ship. For the standard scenario, leg option 2 and 3 are chosen for all the time situations. The costs are lower due to the lower fuel consumption. For Ship 1, the leg decision starts deviating from the benchmark when the MGO price reaches USD 760 and the time range is 1.5 days, while the change occurs at USD 720 for Ship 2. Leg option 2 is the most commonly used in all the most likely scenarios for both ships, which is not unexpected based on visual estimates from Figure 8.3.

The average speed within each area for Ship 1 is presented in Table 8-16 for the various implemented price scenarios next to the speed ratio between the non-ECA speed and the ECA speed. As seen from the table, the speed outside ECAs is approximately 6.6% higher than the speed within ECAs for the MGO prices near the standard scenario. This difference is significant, and leads to changed fuel consumption as seen from previous cases. However, it is not straightforward to analyse the speed impacts when studying this problem, since the average distances sailed are different for the various scenarios due to the possibility of sailing alternative leg options. The distances are also given in Table 8-16, and the ratio gives the non-ECA distance divided by the ECA distance. For each price ascent, the ratio increases, and so does the total distance. For the standard scenario, the ECA stretches are reduced by over 20% compared to the benchmark, while the non-ECA stretches become over 26% longer. The total distance increases by 2.17%. The ratio correspondingly changes from the non-ECA distance being 7% shorter to it instead being 47% longer.

Scenario	**Average speed**			**Average distances**			
	ECA	*Non-ECA*	*Ratio*	*ECA*	*Non-ECA*	*Total*	*Ratio*
C2.1_590	15.7	15.7	0.00%	2,264	2,101	4,365	-7.20%
C2.1_760	15.6	15.8	1.85%	2,080	2,312	4,392	11.17%
C2.1_900	15.3	16.3	6.62%	1,811	2,645	4,456	46.03%
C2.1_920	15.3	16.3	6.62%	1,803	2,656	4,460	47.30%
C2.1_970	15.4	16.4	6.59%	1,657	2,848	4,505	71.84%
C2.1_1020	15.2	16.6	9.50%	1,584	2,944	4,528	85.80%
C2.1_1200	15.2	16.7	9.63%	1,577	2,956	4,532	87.44%
C2.1_2000	15.0	17.2	14.75%	1,504	3,115	4,619	107.05%

Table 8-16 C2.1: Average speed and distances, and ratio between non-ECA and ECA measures

Average numbers for the fuel consumption are given for the same scenarios in Table 8-17 along with comparisons between each scenario and the benchmark. There is a clear trend for all the results, where ECA consumption falls compensated by increases outside. For the standard scenario, the consumption within ECAs is reduced by 21.75% compared to the benchmark, with an associated increase in non-ECA consumption of 30.01%. The relatively larger increase results in 3.17% higher total fuel consumption. This is a substantial difference, equal to 21 tonnes of fuel for one trip along the route.

Scenario	**Average fuel consumption**					
	ECA	*Difference*	*Non-ECA*	*Difference*	*Total*	*Difference*
C2.1_590	344.1	-	319.5	-	663.6	-
C2.1_760	315.0	-8.45%	353.5	10.65%	668.5	0.75%
C2.1_900	270.4	-21.42%	413.6	29.47%	684.0	3.08%
C2.1_920	269.3	-21.75%	415.3	30.01%	684.6	3.17%
C2.1_970	248.8	-27.69%	448.5	40.38%	697.3	5.08%
C2.1_1020	235.4	-31.59%	471.1	47.47%	706.5	6.47%
C2.1_1200	234.3	-31.92%	473.3	48.16%	707.6	6.63%
C2.1_2000	221.4	-35.65%	512.9	60.55%	734.3	10.66%

Table 8-17 C2.1: Average fuel consumption in each area and comparison of each scenario with the benchmark

The fuel consumption in the scenarios for MGO prices between USD 590 and 1,200 are plotted together in Figure 8.4. The dashed lines are trendlines estimated by Excel, showing the average slope of the fuel consumption per MGO price. The curves do not fit a linear approximation very well, since new decisions occur at different price points and the jumps in the graph are uneven and steeper in some places than others. However, the changes for each measure always move in the same direction, decreasing for the MGO curve and increasing for the other two curves.

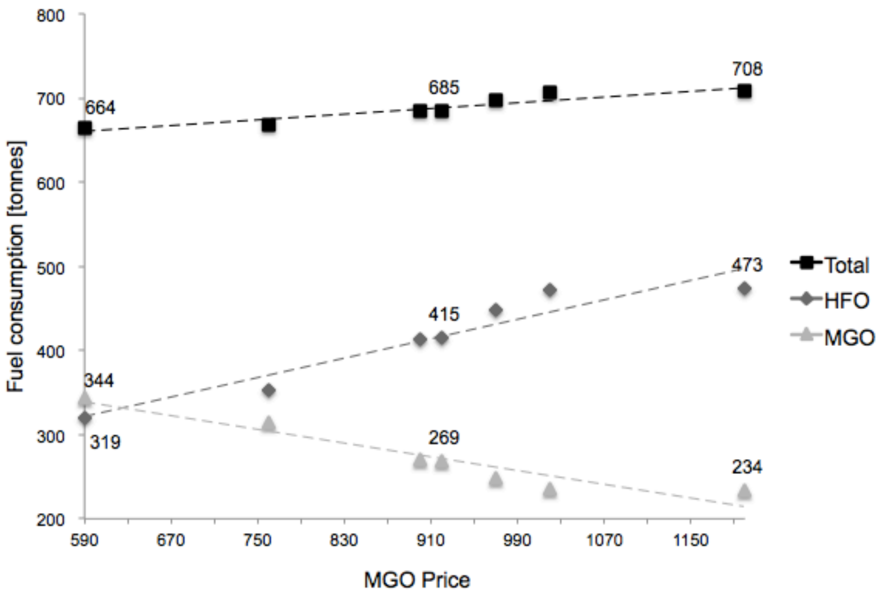

Figure 8.4 C2.1: Average fuel consumption within ECA (MGO), outside ECA (HFO) and in total with estimated trendlines for different price scenarios

Table 8-18 shows the optimised fuel costs for each price scenario based on the new leg and speed decisions, and the fuel costs based on benchmark decisions for the corresponding MGO prices. Now, more than USD 12,000 are saved from making new and optimal decisions for the standard scenario compared to maintaining the benchmark operations when ECAs are enforced. The numbers are large, comprising 2.5% of the total costs for the standard scenario, and more than 7% for C2.1_1200, which is a higher but still thinkable MGO price. If a shipping company for example controlled five similar vessels sailing this route once a month each, the total annual saving for the standard scenario would equal USD 736,560, and USD 1,284,000 for C2.1_1020. These numbers signify the great cost impacts.

Scenario	**Optimised fuel costs**			**Benchmark fuel costs**			**Saving**
	ECA	*Non-ECA*	*Total*	*ECA*	*Non-ECA*	*Total*	
C2.1_760	239,421	208,549	447,970	261,507	188,480	449,988	2,018
C2.1_900	243,344	244,018	487,362	309,679	188,480	498,160	10,797
C2.1_920	247,723	245,043	492,766	316,561	188,480	505,042	12,276
C2.1_970	241,332	264,590	505,922	333,766	188,480	522,246	16,324
C2.1_1020	240,097	277,954	518,051	350,970	188,480	539,450	21,400
C2.1_1200	281,124	279,248	560,373	412,906	188,480	601,386	41,014
C2.1_2000	442,876	302,596	745,472	688,176	188,480	876,657	131,185

Table 8-18 C2.1: Average fuel costs based on optimised speed and leg decisions and based on benchmark decisions, and the cost saving arising from the optimisation

The results have shown that the ECA regulations lead to increased HFO and total fuel consumption when different speed and leg choices are made. Impacts of speed decisions were analysed in the analysis section for problem P1. It is therefore interesting to examine the specific effects arising from the possibility to sail different legs isolated from speed decision impacts. Table 8-19 shows different solutions of the standard scenario. First, the benchmark decisions are used where the speed is constant and the shortest legs are sailed, and the fuel costs are found by multiplying the benchmark ECA consumption with the new MGO price of USD 920 as above. Next, the problem is solved for variable speed and fixed legs like the model in P1, where only the shortest legs are used. Finally, the new and optimal decisions found for P2 are presented, with optimal sailing legs and speed.

Decisions	**Fuel consumption**			**Fuel costs**		
	ECA	*Non-ECA*	*Total*	*USD*	*Difference*	*Saving*
Benchmark	344.1	319.5	663.5	505,042	-	-
P1 Optimised	337.4	327.5	664.9	503,653	-0.27%	1,389
P2 Optimised	269.3	415.3	684.6	492,766	-2.43%	12,276

Table 8-19 C2.1: Average fuel consumption and costs with fixed speed and legs (Benchmark), optimised speed and fixed legs (P1), and optimised speed and legs (P2), with comparisons

The fuel consumption within ECAs is 344.1 tonnes for the benchmark scenario, and this is reduced by 2% for the standard scenario with fixed legs (P1). This leads to a rather small increase of 0.21% in the total fuel consumption. With alternative legs however, the difference is many times larger. The ECA consumption is reduced by 21.75% for the standard scenario with different leg alternatives, corresponding to 3.17% more total fuel. Table 8-19 shows that the fuel costs are reduced by 0.27% when the speed can be altered compared to the benchmark, and an additional 2.16% resulting in 2.43% less costs when legs are also variable. This is a significant decrease, and the costs are actually reduced by USD 10,887 *more* when optimal decisions are made compared to the P1 decisions. These findings are of great importance, as they show clearly how decisions concerning sailing legs have a considerably higher impact on fuel consumption and costs than speed decisions alone. Speed is nevertheless a determinant, since different leg distances require changed speed.

The average total emissions of CO_2 and SO_X are given in Table 8-20 paired with the difference between each scenario and the benchmark. These numbers represent one trip along the given route with the chosen leg options, and for one such voyage with the standard scenario, more than 66 tonnes of additional CO_2 is produced when ECA regulations are enforced, corresponding to 3.17%. For relatively small MGO price increases to USD 970 and USD 1,020 per tonne, 5.08% and 6.47% more CO_2 is emitted, respectively. The percentage increase in CO_2 emissions is equal to that of the total fuel consumption.

Scenario	**CO_2 emissions**		**SO_X emissions**	
	Tonnes	*Difference*	*Kilograms*	*Difference*
C2.1_590	2,103.4	-	358.3	-
C2.1_760	2,119.2	0.75%	197.2	-44.97%
C2.1_900	2,168.2	3.08%	228.7	-36.16%
C2.1_920	2,170.2	3.17%	229.7	-35.91%
C2.1_970	2,210.3	5.08%	247.1	-31.03%
C2.1_1020	2,239.6	6.47%	259.1	-27.69%
C2.1_1200	2,243.0	6.63%	260.3	-27.36%
C2.1_2000	2,327.8	10.66%	281.4	-21.47%

Table 8-20 C2.1: Average total emissions of CO_2 and SO_X and comparisons with benchmark

The magnitude of SO_X emissions is different with lower absolute values, but the damage caused by SO_X can regardless be severe. The sulphur limits within ECAs combined with lower speed and shorter distances lead to a reduction in SO_X in these areas of 70%. Outside ECAs however, the emissions increase by around 30% for the most relevant prices. The overall consequence is a reduction of around 35%. Since SO_X is considered more damaging in coastal areas due to the close presence of humans and living species, the regulations are undoubtedly successful in their attempt to provide cleaner air in those regions. The effects of lower speed and new sailing legs work in the same direction as the direct reduction effects within ECAs.

Environmental calculations are also done for the case with fixed sailing legs as in P1 for the standard scenario. Emissions and comparisons of CO_2 and SO_X are given in Table 8-21. It has already been discovered through analyses of the total fuel consumption that the CO_2 emissions would increase by 0.21% when legs are fixed (P1 Optimised) and 3.17% when both speed and legs are variable (P2 Optimised). Here, benchmark decisions lead to the lowest total SO_X emissions of 241.3 kilograms but the highest within ECAs. Variable speed reduces ECA emissions by 2%, while variable legs result in a 22% reduction. The total amount of SO_X emissions increases by 1.25% and 15.25%. However, these comparisons do not reflect actual situations. Without ECA regulations, it was shown that SO_X emissions would be 358 kg, of which 186 kg within ECAs. The analysis in this paragraph merely shows the additional effects created by the ECAs when speed and legs are optimised. Within ECAs, the objectives of the regulations are strengthened. Assuming the local factor is considerably more important than global for SO_X, the overall effect is beneficial, although not for CO_2.

Decisions	**CO_2 emissions**		**SO_X emissions**			
	Total	*Difference*	*ECA*	*Non-ECA*	*Total*	*Difference*
Benchmark	2,103.3	-	68.8	172.5	241.3	-
P1 Optimised	2,107.7	0.21%	67.5	176.9	244.3	1.25%
P2 Optimised	2,170.2	3.17%	53.9	224.3	278.1	15.25%

Table 8-21 C2.1: Average total emissions of CO_2 and SO_X with fixed speed and legs (Benchmark), optimised speed and fixed legs (P1), and optimised speed and legs (P2), with comparisons

In this case, it has been shown that shipping companies will benefit from a change in their speed decisions, lowering speed where the fuel is more expensive. This was also the conclusion from the analyses of problem P1. It may also be profitable to sail longer distances if ECA stretches can be avoided. These two findings both lead to increased total fuel consumption, most influenced by the variable legs. SO_X emissions are greatly reduced through the change to low-sulphur fuel, especially within ECAs. Finally, the increase in total fuel consumption results in increased CO_2 emissions, with a substantial increase in this case.

8.2.2. C2.2: Case analysis

C2.2 is a route going from Japan across the Pacific Sea to Prince Rupert in Canada, south to Long Beach in California and ending up in Mexico. The shortest leg from Prince Rupert to Long Beach involves a long distance within the ECA, and five alternatives are proposed to move parts of the leg outside. The other two legs are not restricted by ECAs in the same way, so these legs are fixed. The distances are given in Table 8-22 below.

Leg	**Leg option**	**Distance**		
		ECA	*Non-ECA*	*Total*
Yokohoma – Prince Rupert	-	320	3,528	3,848
Prince Rupert – Long Beach	1	1,486	0	1,486
	2	799	840	1,639
	3	714	1,008	1,722
	4	656	1,159	1,806
	5	458	1,509	1,967
Long Beach – Lazaro Cardenas	-	72	1,291	1,363

Table 8-22 C2.2: Distances of route leg options in nautical miles

Because of the very long leg crossing the Pacific Ocean, this route usually takes at least two weeks to sail. The time ranges are accordingly set between one and four days, resulting in complete time window widths of two to eight days. The different leg options between Prince Rupert and Long Beach are shown in Figure 8.5.

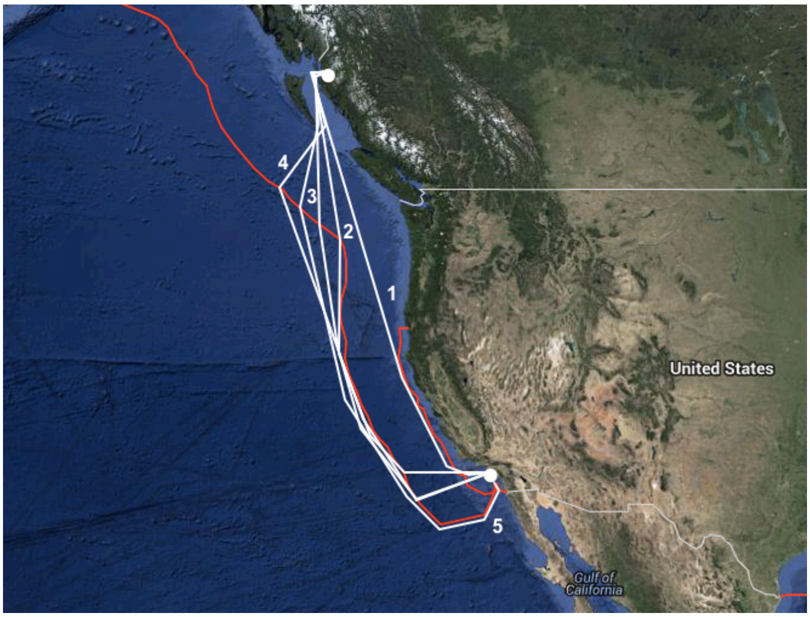

Figure 8.5 C2.2: Map of alternative leg options between Prince Rupert and Long Beach

Both Ship 1 and Ship 2 have been analysed for C2.2, but only data for Ship 1 will be presented. Complete output tables can be found in Appendix A.4.

The average speed in each area for the various implemented scenarios are given in Table 8-23 alongside the ratio between the non-ECA and ECA speed. Also, the distances within each area are found based on the average distances sailed with the chosen legs for each situation within a scenario. The rightmost column compares the distance outside ECA with the distance within ECA. Because of the long non-ECA stretch from Yokohoma to Prince Rupert, the majority of the route lies outside ECAs, but it is nevertheless evident that the ECA distances are reduced significantly when looking at the differences in the ratio for the scenarios. For C2.2_920, leg option 2 is chosen for any time constraint. This is the second shortest leg, where the ECA stretch is reduced by 46.2% between Prince Rupert and Long Beach compared to the shortest leg. The total distance of the route increases by 2.3%.

Scenario	Average speed			Average distances			
	ECA	*Non-ECA*	*Ratio*	*ECA*	*Non-ECA*	*Total*	*Ratio*
C2.2_590	15.83	15.83	0.00%	1,878	4,819	6,697	256.6%
C2.2_840	15.25	16.18	6.05%	1,535	5,239	6,774	351.1%
C2.2_920	15.25	16.31	6.88%	1,191	5,659	6,850	475.1%

Table 8-23 C2.2: Average speed and distances, and ratio between non-ECA and ECA measures

For Ship 2, changes in leg decisions occur at lower MGO prices than for Ship 1, similar to the finding in case C2.1. The average distances change at around USD 840 for Ship 1 and USD 800 for Ship 2. At higher prices such as for the standard scenario, the outputs coincide for the two ships. No leg alternative besides option 2 is taken for any MGO price within a realistic range, that is, below USD 1,200 – 1,300.

The new speed and leg decisions for the price scenarios result in different fuel consumption within each area and in total compared to the benchmark, as shown in Table 8-24 for Ship 1. The fuel consumption within ECAs is greatly reduced when the regulations are considered. There is an associated increase in the fuel consumption outside ECAs, and because of the longer distances and higher speed, the total fuel consumption is also increased. This increase is almost 4% for the standard scenario, corresponding to 40.4 tonnes of fuel for one trip. The fuel consumption is in general lower for Ship 2 than for Ship 1, and the total difference between the standard scenario and the benchmark becomes somewhat smaller.

Scenario	Average fuel consumption					
	ECA	*Difference*	*Non-ECA*	*Difference*	*Total*	*Difference*
C2.2_590	288.4	-	737.7	-	1,026.1	-
C2.2_840	229.1	-20.57%	814.6	10.42%	1,043.7	1.71%
C2.2_920	177.3	-38.51%	889.1	20.53%	1,066.5	3.93%

Table 8-24 C2.2: Average fuel consumption in each area and comparison of each scenario with the benchmark

Table 8-25 below shows the average fuel costs in each area for the two implemented price scenarios, based on the optimal decisions and the benchmark decisions. The saving for the standard scenario from changing speed and leg decisions is USD 12,833, which is almost 2% of the total optimised costs. Even for an improbable low MGO price of 840, the saving of USD 4,482 is significant, comprising 0.7% of the total costs.

Scenario	Optimised fuel costs			Benchmark fuel costs			Saving
	ECA	*Non-ECA*	*Total*	*ECA*	*Non-ECA*	*Total*	
C2.2_840	192,420	480,604	673,023	242,259	435,246	677,505	4,482
C2.2_920	163,153	524,591	687,744	265,331	435,246	700,577	12,833

Table 8-25 C2.2: Average fuel costs based on optimised speed and leg decisions and based on benchmark decisions, and the cost saving arising from the optimisation

As in C2.1, calculations have been done to compare the impacts from new speed decisions and changed legs. The average fuel consumption for the benchmark scenario, the corresponding P1 solution, and the optimised decisions of P2 are given in Table 8-26. Similar to C2.1, it is clear that the changed legs is the major contributor to different costs, as USD 11,192 additional can be saved from altering leg decisions compared to only adjusting the speed in each area. Considering a fleet of five ships sailing one trip per month each, the annual saving amounts to USD 769,980 when legs are optimised, which shows the incentive for shipping companies to make new operating decisions.

Decisions	**Fuel consumption**			**Fuel costs**		
	ECA	*Non-ECA*	*Total*	*USD*	*Difference*	*Saving*
Benchmark	288.4	737.7	1 026.1	700,577	-	-
P1 Optimised	279.6	748.6	1 028.2	698,936	-0.23%	1,641
P2 Optimised	177.3	889.1	1 066.5	687,744	-1.83%	12,833

Table 8-26 C2.2: Average fuel consumption and costs with fixed speed and legs (Benchmark), optimised speed and fixed legs (P1), and optimised speed and legs (P2), with comparisons

It has been shown that the total fuel consumption is expected to increase. The estimated emissions are given in Table 8-27 below. As seen before, the CO_2 emissions change by the same percentage as the total fuel consumption. For the standard scenario, the increase is almost 4%, which is significant and negative for the environment. SO_X emissions are reduced when ECAs are enforced, by approximately 13% for the standard scenario. Longer distances and correspondingly higher speed increase emissions outside ECAs, but will however further decrease emissions within the ECAs, which is the most essential measure of SO_X.

Scenario	**CO_2 emissions**		**SO_X emissions**	
	Tonnes	*Difference*	*Kilograms*	*Difference*
C2.2_590	3,252.8	-	554.1	-
C2.2_840	3,308.4	1.71%	444.5	-19.79%
C2.2_920	3,380.7	3.93%	483.7	-12.71%

Table 8-27 C2.2: Average total emissions of CO_2 and SO_X and comparisons with benchmark

Additional calculations are done to find the emissions for the standard scenario based on benchmark fuel consumption and P1 optimisation. The results are given in Table 8-28. Emissions of SO_X within the ECA are reduced when optimising compared to the benchmark, although the absolute value is not large in any case because of the low sulphur content of MGO. The emissions outside ECAs increase by a great deal, leading to an increase of 19.7% in total SO_X emissions when speed *and* legs are optimised (P2), whereas only resulting in a 1.41% increase with fixed legs (P1). Still, the benchmark numbers in the previous table (C2.2_590) showed the actual emissions based on a setting without ECAs, and the situation is greatly improved with the regulations regardless of the potential new decisions. Low-sulphur fuel, speed reductions and shorter distances all improve the emissions within ECAs.

Decisions	**CO_2 emissions**		**SO_X emissions**			
	Total	*Difference*	*ECA*	*Non-ECA*	*Total*	*Difference*
Benchmark	3,252.8	-	5.8	398.4	404.1	-
P1 Optimised	3,259.5	0.21%	5.6	404.2	409.8	1.41%
P2 Optimised	3,380.7	3.93%	3.5	480.1	483.7	19.70%

Table 8-28 C2.2: Average total emissions of CO_2 and SO_X with fixed speed and legs (Benchmark), optimised speed and fixed legs (P1), and optimised speed and legs (P2), with comparisons

CO_2 emissions increase by the same percentage as the total fuel consumption. The increase is only slight for the optimised speed decisions alone (P1), so the major contribution comes from the changed legs. This is the same outcome as found previously, and all the conclusions from the analysis of case C2.2 are similar to those of C2.1.

8.2.3. C2.3: Case analysis

Case C2.3 examines south-going routes from different ports in Norway to expose at which point it is profitable to sail around the UK instead of sailing through the North Sea and the English Channel. Five ports are considered, located in the south and west of Norway. The distances are given in nautical miles in Table 8-29. From Kristiansand to Santander there are two leg options, where the longer option involves sailing out of the ECA at the western border just north of Scotland. For the other four cases this is an alternative as well, but an additional leg involves exiting the ECA at the northern border outside the county of Sogn og Fjordane.

Case	**Leg**	**Leg option**	**Distance**		
			ECA	*Non-ECA*	*Total*
2.3a	Kristiansand – Santander	1	761	360	1,121
		2	395	1,025	1,420
2.3b	Flekkefjord – Santander	1	760	361	1,121
		2	340	1,030	1,370
		3	275	1,400	1,675
2.3c	Stavanger – Santander	1	790	362	1,152
		2	310	1,065	1,375
		3	230	1,430	1,660
2.3d	Bergen – Santander	1	872	365	1,237
		2	277	1,020	1,297
		3	120	1,420	1,540
2.3e	Florø – Santander	1	927	365	1,292
		2	307	1,022	1,329
		3	34	1,425	1,459

Table 8-29 C2.3: Distances of route leg options in nautical miles

All the different legs are illustrated in Figure 8.6 below, with the points along the coast representing the Norwegian ports. Visual estimates predict that it will seldom be advantageous to sail to the northern ECA border, but that the choice may easily fall on the leg option 2 at least from Bergen. Florø is located very close to the northern border, so in this case the choice is probably between option 2 and 3.

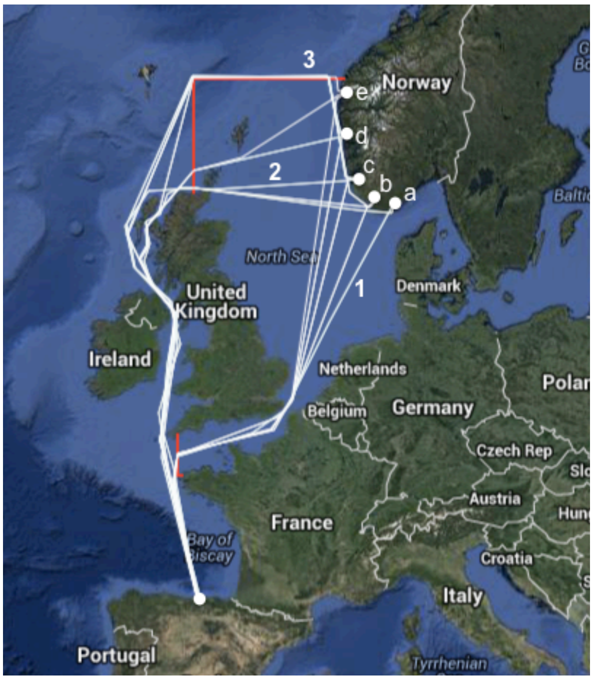

Figure 8.6 C2.3: Map of alternative leg options between different Norwegian ports and Santander

The various cases have been tested for time limits between 6 and 36 hours above the mean time. Since there is only one leg in this route, it is not necessary to study both time limits and time windows, as the outputs would be exactly the same. The route should take a couple of days to sail.

The shortest leg is chosen between Kristiansand and Santander for all MGO prices below USD 1,600 per tonne, which is a higher price scenario than what is probable. The same holds for the leg starting in Flekkefjord, where the MGO price must reach USD 1,420 before a change to leg option 2 occurs. These two case variations will therefore not be analysed further, but complete output can be found in Appendix A.5.

Some changes occur on the leg going from Stavanger (C2.3c). The standard scenario for C2.3c is presented in Table 8-30, with distances of the chosen leg and the speed in each area. When the time limit is high enough to allow nearly the lowest speed on both stretches, the second leg option is chosen. These time limits are perhaps wider than realistic planning assumptions. At an MGO price of USD 1,120, leg option 2 is also chosen for 12 hours tighter time constraints. The change leads to a reduction in ECA distances of 60%, and an increase in the total distance of 20%. The third option involving going north to the ECA border is never profitable from Stavanger.

Situation	**Chosen leg option**	**Distance**			**Speed**	
		ECA	*Non-ECA*	*Total*	*ECA*	*Non-ECA*
C2.3c_920_TL_0.25	1	783	363	1,146	16.6	18.0
C2.3c_920_TL_0.5	1	783	363	1,146	15.1	17.0
C2.3c_920_TL_0.75	1	783	363	1,146	15.0	15.0
C2.3c_920_TL_1	1	783	363	1,146	15.0	15.0
C2.3c_920_TL_1.25	2	310	1,065	1,375	15.0	15.1
C2.3c_920_TL_1.5	2	310	1,065	1,375	15.0	15.0

Table 8-30 C2.3c (Stavanger): Chosen leg option with corresponding distances and speed decisions in each area for different time window situations for the standard scenario

Meanwhile, it is always beneficial to go around the UK using the second leg option when travelling from Bergen (C2.3d). That is, already for MGO prices of USD 680, leg option 2 is chosen for most of the time situations. Leg option 3 is however not a good choice for this case either. For the leg going from Florø (C2.3e), leg option 2 is chosen for even lower price scenarios, since only 37 nmi differentiate it from the shortest leg. For the standard scenario, the third leg option is taken for the two highest time limits, and more often for increased prices.

The distance and speed within each area are given for the legs from Stavanger (C2.3c), Bergen (C2.3d) and Florø (C2.3e) in Table 8-31 for the benchmark and standard scenarios, along with the ratios between the non-ECA and ECA measures. The figures are average numbers of the different time constraints. The speed is 3.6-3.8% higher outside ECAs than within in all cases. The largest increase in total distance, of 6.6%, appears for the leg from Stavanger, even though the longer option is only chosen for two out of six time situations. This is because there is a larger difference between the total distances of the leg options than for the other two cases. The ratio on the other hand changes by much more for the other two cases.

Scenario	Average speed			Average distances			
	ECA	*Non-ECA*	*Ratio*	*ECA*	*Non-ECA*	*Total*	*Ratio*
C2.3c_590	15.44	15.44	0.00%	783	363	1,146	46.36%
C2.3c_920	15.27	15.84	3.64%	625	597	1,222	95.52%
C2.3d_590	15.49	15.49	0.00%	872	365	1,237	41.86%
C2.3d_920	15.36	15.96	3.79%	277	1,020	1,297	368.23%
C2.3e_590	15.52	15.52	0.00%	927	365	1,292	39.37%
C2.3e_920	15.28	15.86	3.73%	216	1,156	1,372	535.19%

Table 8-31 C2.3: Average speed and distances, and ratio between non-ECA and ECA measures for Stavanger (c), Bergen (d) and Florø (e)

The average fuel consumed when sailing the given legs is presented in Table 8-32 for the same three case variations and scenarios. The leg from Florø is the longest and at the same time the most suited for changes. For the standard scenario, this case consequently gives the largest reduction in ECA consumption, but also the largest increase outside and in total. The difference in total consumption compared to the benchmarks is around 7% for all cases. This increase is substantial, here corresponding to 12 to 15 tonnes.

Scenario	Average fuel consumption					
	ECA	*Difference*	*Non-ECA*	*Difference*	*Total*	*Difference*
C2.3c_590	117.8	-	54.6	-	172.4	-
C2.3c_920	93.6	-20.51%	90.3	65.40%	183.9	6.70%
C2.3d_590	131.5	-	55.0	-	186.5	-
C2.3d_920	41.5	-68.43%	157.8	186.62%	199.3	6.83%
C2.3e_590	140.0	-	55.1	-	195.1	-
C2.3e_920	32.4	-76.84%	177.0	221.11%	209.4	7.33%

Table 8-32 C2.3: Average fuel consumption in each area and comparison of each scenario with the benchmark for Stavanger (c), Bergen (d) and Florø (e)

Fuel costs are calculated for the optimised decisions given above and for the benchmark solutions with new fuel costs, given for the standard scenarios in Table 8-33. In this case, the majority of the savings from new decisions originate in the changed sailing legs. This is known because altering the speed alone would not have the potential to change the overall outcome by much considering the ECA distance is longer than the non-ECA distance for the shortest legs. From Stavanger (C2.3c), the fuel costs decrease by 0.82% with the new decisions, corresponding to a saving of USD 1,156. This is noteworthy, but not nearly as high as the other cases since the longer leg is only chosen for certain time situations from Stavanger. The impact of the changed legs is extensive for the legs from Bergen and Florø. For Bergen (C2.3d), the fuel costs become 14.45% lower when the new leg is sailed at the changed speeds. This equals a cost saving of USD 22,175 compared to keeping the constant benchmark speed going the shortest leg. Similarly for Florø (C2.3e), the reduction totals 16.77% and a cost saving of USD 27,052. These numbers are of great importance, as this is a large share of the total costs for the route and also a significant amount of money in itself regardless of relativeness. If a ship travelled 50 such trips along this route during a year, the cost difference would be more than USD 1 million even for just one single ship, which is remarkable.

Scenario	Optimised fuel costs			Benchmark fuel costs			Saving
	ECA	*Non-ECA*	*Total*	*ECA*	*Non-ECA*	*Total*	
C2.3c_920	86,120	53,279	139,399	108,343	32,211	140,555	1,156
C2.3d_920	38,195	92,073	131,267	120,970	32,473	153,442	22,175
C2.3e_920	29,826	104,416	134,242	128,777	32,517	161,295	27,052

Table 8-33 C2.3: Average fuel costs based on optimised speed and leg decisions and based on benchmark decisions, and the cost saving arising from the optimisation

The CO_2 emissions increase by the same percentage as the total fuel consumption, with a relatively large increase of around 7% for all cases. The average emissions and comparisons to the benchmark are given in Table 8-34. The absolute values of CO_2 emissions range from 546 to 618 tonnes for the benchmarks and 583 and 663 tonnes for the standard scenarios. Emissions of SO_X are reduced substantially within the ECA, but increase even more outside for most cases. From Stavanger, where the shortest leg is taken for several standard scenario situations, the overall reduction is large and positive, although there will be a lot more emissions outside the ECA. For the other two cases, the total reduction is not equally large, 14.6% from Bergen and 8.7% from Florø.

Scenario	**CO_2 emissions**		**SO_X emissions**	
	Tonnes	*Difference*	*Kilograms*	*Difference*
C2.3c_590	546.4	-	93.1	-
C2.3c_920	583.0	6.70%	50.6	-45.60%
C2.3d_590	591.3	-	100.7	-
C2.3d_920	631.7	6.83%	86.0	-14.60%
C2.3e_590	618.4	-	105.3	-
C2.3e_920	663.8	7.33%	96.2	-8.67%

Table 8-34 C2.3: Average total emissions of CO_2 and SO_X and comparisons with benchmark

When the MGO price reaches USD 1,120 for C2.3e, the *total SO_X* emissions actually *increase* as a consequence of the ECAs and the new decisions. It is reduced within the ECA, but increased elsewhere. Here, this outcome is perhaps of greater importance than for the considered North American routes, since this repositioning of the legs still imply travelling close to the coast, only in the UK and not mainland Europe.

The ECA regulations have ambiguous effects in case C2.3. Speed decisions change, and certain leg choices likewise, leading to increased total fuel consumption. The consequences are sensitive to increases in the fuel price ratio, since the change in SO_X emissions may shift to the negative side at points relatively close to the standard scenario. However, the routes considered in C2.3 are not very common, and the positive impacts on the rest of northern Europe will most likely outweigh the costs of these few legs close to the ECA fringe.

8.2.4. C2.4: Case analysis

The final case analysed for P2 is similar to the previous one, as one leg with two options is considered from different geographical points. C2.4 assumes that the Mediterranean Sea is a designated ECA with the same properties as the other SECAs, which has been up for discussion in the IMO. This means that the low-sulphur fuel must be used in the entire area enclosed by northern Africa and southern Europe. Many shipping companies currently sail from Southeast Asia to Europe through the Mediterranean Sea. Three cases are analysed where the route starts in different places located in Asia and Oceania and ends up in Southampton, UK. The alternative legs go around Africa in the south instead of crossing through the Mediterranean Sea. The distances for the legs are given in Table 8-35 in nautical miles.

Case	**Leg**	**Leg option**	**Distance**		
			ECA	*Non-ECA*	*Total*
2.4a	Singapore – Southampton	1	2,140	6,051	8,191
		2	180	11,454	11,634
2.4b	Cilacap – Southampton	1	2,140	6,429	8,569
		2	180	11,045	11,225
2.4c	Dampier – Southampton	1	2,140	7,088	9,228
		2	180	10,983	11,163

Table 8-35 C2.4: Distances of route leg options in nautical miles

The difference in distances for the two proposed legs is substantial. Almost 2,000 nautical miles within the ECA can be avoided, but the increase outside is much larger, resulting in a considerably longer total distance. However, there is another aspect that should be taken into account for this problem. Ships have to pay a high fee to sail through the Suez Canal, equal to USD 457,000 for ships like Ship 2. The same cost is used for Ship 1, as the vessels are of the same general type and no other specific price is found. This fee is added to the objective function when any ship travels along leg option 1. Thus, the new objective function is expected to affect the decisions substantially.

Findings from the analysis based on Ship 1 indicate that it will never be profitable to travel around Africa from Singapore. This would imply an exceedingly longer sailing leg, and the fuel price ratio is highly unlikely to reach levels such that this would be considered. The shortest leg is chosen, and there is a difference in the speed within each area causing higher total fuel consumption and associated CO_2 emissions. SO_X will naturally be greatly reduced in the Mediterranean Sea if it is declared a SECA.

The other two ports are located further south, and it is therefore easier to imagine a potential leg around the African continent to get to Europe from there. All legs are illustrated in the map in Figure 8.7, where the northernmost point is in Singapore, the middle one is Cilacap in Indonesia and the last one is Dampier in Australia. It is clear that the sailings involve long distances, and consequently large impacts of deviating from the shortest legs.

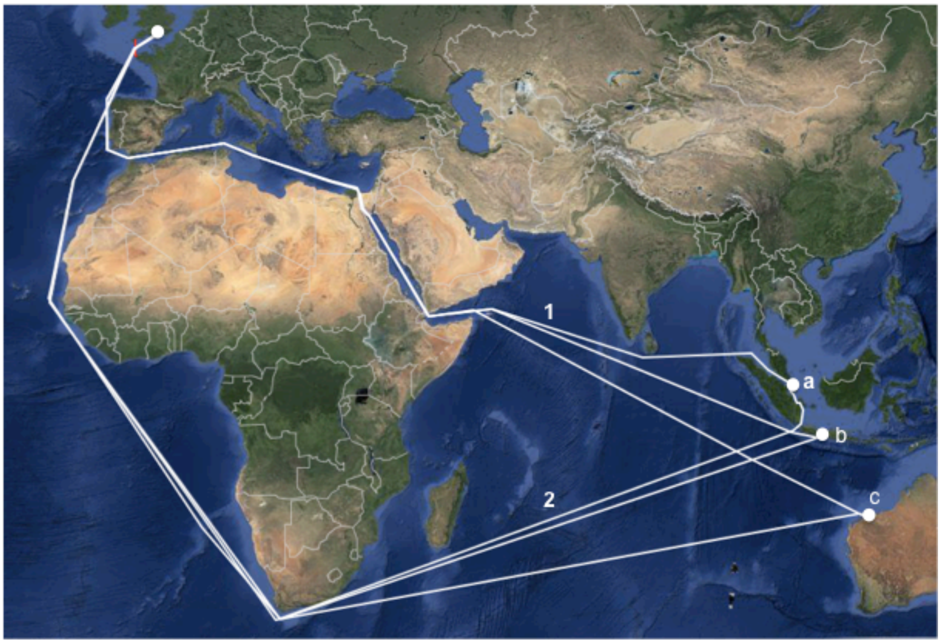

Figure 8.7 C2.4: Map of alternative leg options between Singapore (a) / Cilacap (b) / Dampier (c) and Southampton

Outputs from C2.4b (Cilacap) with Ship 1 show that the Mediterranean Sea would still often be crossed, but it depends largely on time flexibility. Table 8-36 gives the leg and speed decisions for three of the implemented time situations, where the second leg option is chosen for the widest time window, when the ship is allowed to sail for five days more than the sailing time at reference speed. Since only one leg is considered, upper time limits are appropriate. The speed is increased by 13.3% within ECAs and 26.6% outside when the time range increases from four to five days and the leg decision is altered. This is due to an increase in the total distance by almost 3,000 nmi, which has to be sailed using only slightly more time.

Situation	Chosen leg option	Distance			Speed	
		ECA	*Non-ECA*	*Total*	*ECA*	*Non-ECA*
C2.4b_920_TL_3	1	2,140	6,429	8,569	15.00	16.57
C2.4b_920_TL_4	1	2,140	6,429	8,569	15.00	15.61
C2.4b_920_TL_5	2	180	11,225	11,405	17.00	19.76

Table 8-36 C2.4b (Cilacap): Chosen leg option with corresponding distances and speed decisions in each area for different time window situations for the standard scenario

From Cilacap, the MGO price must reach almost USD 1,500 per tonne for a leg change to occur for tighter time windows. It is however more likely that wider time limits are used in the planning of this long route, as it is not even possible to sail the longer leg at time limit ranges of one day because of the large increase in total distance and the vessel's maximum speed.

Table 8-37 shows the difference in fuel consumption between the standard scenario and the benchmark for the three situations from Cilacap. The changes in fuel consumption arise from the different speed decisions when the same leg is sailed. The only large impact is found when different legs are chosen, for TL_5, as the total fuel consumption increases by 71.28%. This is an extreme increase, and it is due to the much longer distances at far higher speeds. It is profitable compared to the shorter leg option for the standard scenario because the Suez cost is avoided.

Situation	Fuel consumption					
	ECA	*Difference*	*Non-ECA*	*Difference*	*Total*	*Difference*
C2.4b_590_TL_3	332.1	-	997.5	-	1,329.6	-
C2.4b_590_TL_4	321.6	-	966.3	-	1,287.9	-
C2.4b_590_TL_5	315.0	-	946.3	-	1,261.4	-
C2.4b_920_TL_3	315.0	-5.13%	1,019.6	2.21%	1,334.6	0.38%
C2.4b_920_TL_4	315.0	-2.06%	972.9	0.69%	1,287.9	0.00%
C2.4b_920_TL_5	29.2	-90.74%	2,131.3	125.21%	2,160.5	71.28%

Table 8-37 C2.4b (Cilacap): Fuel consumption in each area for different time situations of the benchmark and standard scenarios with comparisons between the scenarios for each situation

Table 8-38 shows the fuel costs and total costs for the benchmark and the standard scenario with the difference between them. Total costs include both fuel costs and the Suez fee. For the two time situations where the leg option is the same for the standard scenario and the benchmark, the fuel costs are 13.6-13.7% higher and the total costs 8.5-8.6%. The leg option changes for the widest time limit TL_5, and in this situation the fuel costs increase by over 72% compared to the benchmark. Total costs on the other hand increase by 6.92%, which is less than the other cases without a leg change. This reflects the impact of the Suez cost, as it is a large share of total costs when incurred.

Situation	Costs			
	Fuel	*Difference*	*Total*	*Difference*
C2.4b_590_TL_3	784,463	-	1,241,463	-
C2.4b_590_TL_4	759,851	-	1,216,851	-
C2.4b_590_TL_5	744,201	-	1,201,201	-
C2.4b_920_TL_3	891,362	13.63%	1,348,362	8.61%
C2.4b_920_TL_4	863,803	13.68%	1,320,803	8.54%
C2.4b_920_TL_5	1,284,311	72.58%	1,284,311	6.92%

Table 8-38 C2.4b (Cilacap): Fuel costs and total costs for different time situations of the benchmark and standard scenarios with comparisons between the scenarios for each situation

As long as the leg decisions do not change from the benchmark decisions when ECAs are considered, the impact on the environment is straightforward. The CO_2 emissions change proportionately to the total fuel consumption, which in this case does not change much except for in TL_5 when a new leg is chosen. Table 8-39 shows the emissions of CO_2 and SO_X for the three situations for the benchmark and the standard scenario with comparisons. For the first two situations, SO_X emissions are reduced within ECAs by more than 96%, mostly due to the use of low-sulphur fuel, supported by the lower speed. There is an increase outside ECAs because of higher speed, but a reduction in total of 22-24%. The only major effect occurs for TL_5. Then, both total CO_2 and SO_X emissions increase by around 70%, which is not positive for the environment. The Mediterranean Sea coasts would benefit from the changed leg decisions, but the increase in CO_2 is so large that it probably outweighs the positive impacts.

Scenario	CO_2 emissions		SO_X emissions	
	Tonnes	*Difference*	*Kilograms*	*Difference*
C2.4b_590_TL_3	4,214.8	-	718.0	-
C2.4b_590_TL_4	4,082.6	-	695.5	-
C2.4b_590_TL_5	3,998.5	-	681.1	-
C2.4b_920_TL_3	4,230.7	0.38%	556.9	-22.44%
C2.4b_920_TL_4	4,082.6	0.00%	531.7	-23.55%
C2.4b_920_TL_5	6,848.7	71.28%	1,151.5	69.06%

Table 8-39 C2.4b (Cilacap): Total emissions of CO_2 and SO_X for different time situations of the benchmark and standard scenarios with comparisons between the scenarios for each situation

From Dampier in Australia (C2.4c), the longer leg option is always chosen, even for the benchmark case where the Mediterranean Sea is not considered an ECA, due to the high Suez cost. In this case, the introduction of the ECA does not lead to higher fuel consumption or significantly higher costs, since the ECA distance for leg option 2 is short (180 nmi) and a very small share of the total distance.

The results from the analyses of Ship 2 differ from those with Ship 1 for all the case variations in C2.4. Since fuel costs comprise a smaller share of the total sailing costs for this type of ship when adding the Suez cost, and it is moreover less expensive to increase speed, the choice falls on the longer leg for more situations. Also, the decisions remain unchanged between different scenarios, as the same leg is taken for the same situations in the benchmark, standard, and other tested scenarios. This shows that for Ship 2, the Suez cost and the time constraints are the important factors when optimising the sailing legs. The fuel costs are approximately 20% lower for Ship 2 than Ship 1 for the same distances and time constraints. Another difference between the ships is the maximum speed, which forces Ship 2 to sail the shorter leg in some situations because it is not able to speed up and meet the time constraint otherwise.

8.2.5. Concluding remarks for analysis of P2

The results of this problem's speed analyses concur with the findings from the previous problem. Speed decisions change, with a significantly lower speed within ECAs than outside, leading to higher total fuel consumption as shown both in P1 and P2.

More importantly, the sailing legs may change to leg options with a shorter distance within ECAs. This change is beneficial for ECAs, since they will experience less shipping traffic and less emissions. However, the reduction in ECA distances is compensated by a larger increase in the non-ECA stretches, resulting in a longer total sailing route. Fuel consumption and emissions consequently increase outside ECAs due to the increased distances intensified by the even higher speed to meet the same time constraints as before. The results depend on the fuel price ratio and the time limits as well as the geography of the routes and of the ECAs. Wider time constraints allow longer distances to be sailed at lower speeds, since the total sailing time on the route increases.

The regulations have a positive impact on life within ECAs. The major cause of the SO_X reduction is the required use of low-sulphur fuel within ECAs as a response to the IMO sulphur limit, and the combination of lower speed and shorter ECA sailings further contributes. SO_X emissions increase outside ECAs, but the total difference is positive for all the implemented cases with the exception of situations found in C2.4. However, the fee incurred when crossing the Suez Channel is the decisive factor in that case. Moreover, SO_X emissions are more important near the coasts.

Emissions of CO_2 on the other hand increase in total, and the change is substantial for some of the cases where longer distances are sailed. Changed legs have a significantly higher impact on fuel consumption and CO_2 emissions than speed optimisation alone. Therefore, the findings in this analysis are essential, since it is the first study to consider alternative legs as a consequence of ECAs. The overall environmental effect is ambiguous. It will be further discussed in the final section of this chapter.

8.3. Case analyses for P3 and P4: Sequencing problems

Problems P3 and P4 deal with sequencing of ports in a route. In P3, there is only one leg option between each pair of ports, while there are several alternatives in P4. The first and last ports in the route are given. The objective is to look at sequencing in light of ECA regulations, and the cases are developed bearing this in mind. There are not many regions among the current ECAs that are fitting to the problem, since there is a natural sequence in most routes either within the European ECA basin or along the coasts in North America. Otherwise time windows would be determining. One single case is implemented and used for both P3 and P4.

8.3.1. C3: Case analysis

First, case C3 is analysed for problem P3, where only the shortest legs between each pair of ports are offered. The distances are given in Table 8-40, split into ECA distances plus non-ECA distances. The starting point is Baltimore, and the route terminates in Manzanillo. The two possible sequences are referred to as sequence 1 and 2, given in Table 8-41 with corresponding total distances. Sequence 2 is approximately 4% longer than sequence 1, with an 18% reduction in ECA distances. Illustrations are shown in Figure 8.8.

	Baltimore	Galveston	Vera Cruz	Manzanillo
Baltimore	-	1,465 + 349 =1,814	953 + 942 = 1,895	-
Galveston	-	-	200 + 411 = 611	204 + 1,283 = 1,487
Vera Cruz	-	200 + 411 = 611	-	0 + 1,404 = 1,404
Manzanillo	-	-	-	-

Table 8-40 C3: Distances of route legs for problem P3 in nautical miles split into ECA distance + non-ECA distance

Sequence		**Distance**		
		ECA	*Non-ECA*	*Total*
1	Baltimore – Galveston – Vera Cruz – Manzanillo	1,665	2,164	3,829
2	Baltimore – Vera Cruz – Galveston – Manzanillo	1,357	2,636	3,993

Table 8-41 C3: Possible sequence solutions with resulting distances for P3

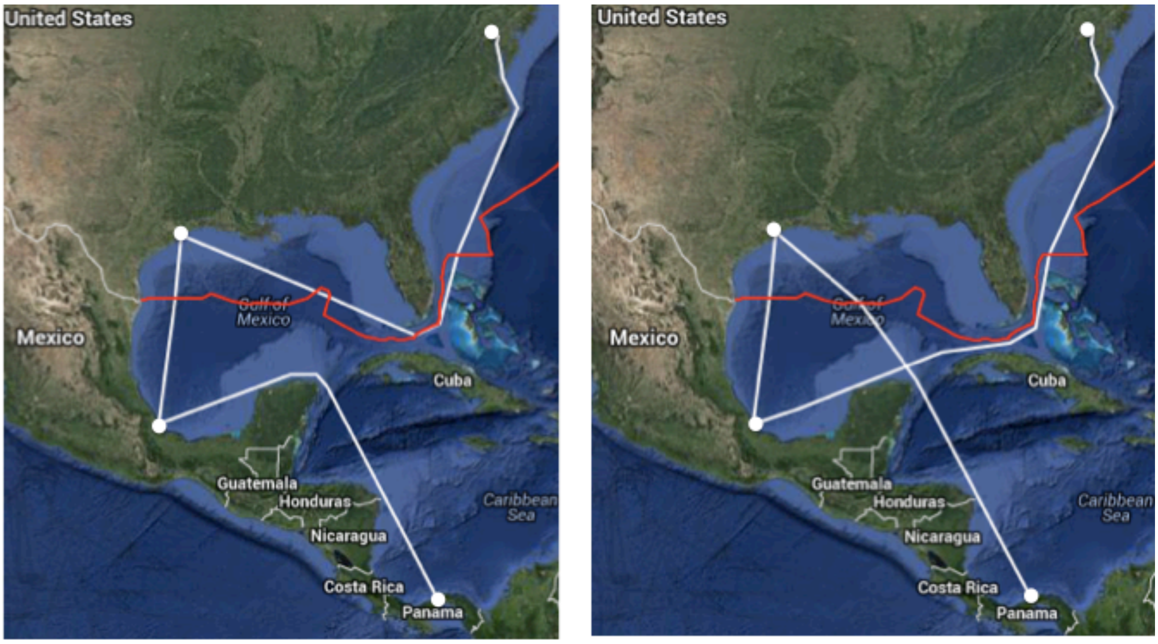

Figure 8.8 C3: Map of route for sequence 1 (left) and sequence 2 (right)

The scenarios are analysed using upper time limits only. Time windows with lower time limits would probably determine the sequence based on the possible start times. The maximum time limit allows any sequence, and also optimal speed adjustment since the entire route can be planned as one. The time limit ranges used in the case are between 12 and 60 hours, corresponding to 0.5 and 2.5 days after the mean reference times.

The lowest speed can be maintained throughout the route regardless of the sequence for the two slackest time limits. Sequence 1 is chosen for most situations within the standard scenario, except TL_2.5 where sequence 2 is instead selected. The outputs from the standard scenario are given in Table 8-42 below.

Situation	**Sequence**	**Distance**			**Speed**		
		ECA	*Non-ECA*	*Total*	*ECA*	*Non-ECA*	*Ratio*
C3_920_TL_0.5	1	1,665	2,164	3,829	16.83	18.00	6.96%
C3_920_TL_1	1	1,665	2,164	3,829	16.00	17.02	6.38%
C3_920_TL_1.5	1	1,665	2,164	3,829	15.00	16.38	9.21%
C3_920_TL_2	1	1,665	2,164	3,829	15.00	15.01	0.04%
C3_920_TL_2.5	2	1,357	2,636	3,993	15.00	15.00	0.00%

Table 8-42 Chosen sequence with corresponding distances and speed decisions in each area for different time window situations for the standard scenario

The average fuel consumption within each area for three price scenarios is given in Table 8-43. There is an increase in total fuel consumption for the standard scenario, but the average numbers do not show the whole picture. Case situation TL_2.5, where the sequence changes, leads to 4.28% higher fuel consumption compared to the corresponding benchmark situation. The consumption in the other situations changes only due to speed adjustments, and the increase ranges from 0% to 0.29%, which is a minor increase compared to the impact of the new sequence. With an MGO price of USD 1,200, sequence 1 is still chosen for three of the five time situations, and the average fuel consumption increases by 7.5% and 4.3% for the two situations with sequence 2.

Scenario	**Average fuel consumption**					
	ECA	*Difference*	*Non-ECA*	*Difference*	*Total*	*Difference*
C3_590	259.0		332.1		591.1	-
C3_920	242.8	-6.26%	353.6	6.48%	596.4	0.90%
C3_1200	229.2	-11.49%	378.5	13.97%	607.7	2.81%

Table 8-43 C3: Average fuel consumption in each area and comparison of each scenario with the benchmark

The presented numbers are obtained based on characteristics belonging to Ship 1. For Ship 2, the results change for higher price scenarios. At USD 1,080, the output for Ship 2 is similar to the output for Ship 1 at USD 1,200, with sequence 2 chosen in two situations and an increase in the average total fuel consumption of 2.4%. For USD 1,200, sequence 2 is always chosen when considering Ship 2, leading to 6.5% higher fuel consumption. The aggregated output can be found in Appendix A.7.

Average emissions for the three scenarios are given in Table 8-44 with comparisons of each scenario to the benchmark. As for the total fuel consumption, CO_2 emissions increase by 0.9%, but with large differences between the different case situations. The widest time limit results in a new sequence, which leads costs to decrease, but the change is not positive for the environment. 76 additional tonnes of CO_2 are produced when the sequence is altered, even though more sailing time is available. SO_X emissions are greatly reduced, especially within the ECA.

Scenario	**CO_2 emissions**		**SO_X emissions**	
	Tonnes	*Difference*	*Kilograms*	*Difference*
C3_590	1,873.7	-	319.2	-
C3_920	1,890.6	0.90%	195.8	-38.65%
C3_1200	1,926.4	2.81%	250.2	-21.60%

Table 8-44 C3: Average total emissions of CO_2 and SO_X and comparisons with benchmark

The findings from the analysis of P3 have similarities to the previous problems. When the sequence remains unchanged, it is equivalent to P1 where only speed is optimised within each area. A change in the sequence leads to different sailing legs resembling P2. Here, the distances change as a result of a different sequence instead of changes in specific legs. Speed is only a small contributor to variations in fuel consumption, while the changes in distances are of greater importance. Sequence 2 is chosen for more time situations when the MGO price rises, but the difference is minor for prices below USD 1,200 per tonne.

8.3.2. C4: Case analysis

The second analysis concerns problem P4, and the distances for all associated leg options of C4 are given in Table 8-45. Four leg options are suggested between Baltimore and Galveston and five between Baltimore and Vera Cruz. The last three potential legs have fixed distances. The leg between Galveston and Vera Cruz is identical for both directions. The possible sequences are the same as given in Table 8-41, but now there are options within each of these solutions as well, and the distances need not be the same.

Leg	**Leg option**	**Distance**		
		ECA	*Non-ECA*	*Total*
Baltimore – Galveston	1	1,465	349	1,814
	2	565	1,679	2,244
	3	913	1,010	1,923
	4	614	1,493	2,107
Baltimore – Vera Cruz	1	953	942	1,895
	2	363	1,919	2,282
	3	440	1,639	2,079
	4	716	1,210	1,926
	5	413	1,735	1,895
Galveston – Vera Cruz	1	200	411	611
Galveston – Manzanillo	1	204	1,283	1,487
Vera Cruz – Manzanillo	1	0	1,404	1,404

Table 8-45 C4: Distances of route leg options in nautical miles

A map of the various leg options is shown in Figure 8.9, where Baltimore is the northernmost port, located within the ECA. Both Galveston and Vera Cruz lie in the Gulf of Mexico, and Galveston is also within the ECA. Manzanillo is further south and not included in the illustration. The alternative legs exit and enter the ECA in different places.

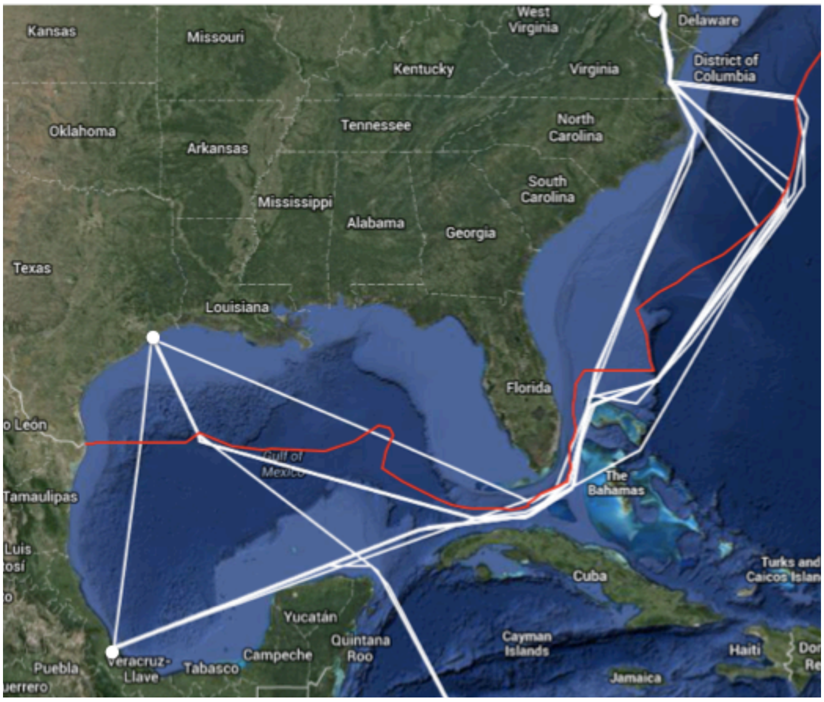

Figure 8.9 C4: Map of alternative leg options between Baltimore, Galveston and Vera Cruz

For C4, sequence 1 is always chosen, but different sailing legs are taken when the ECAs are enforced. This is because the new leg options give a greater decrease in ECA distances and a smaller increase in the total distance than changing the sequence. For the standard scenario, leg option 3 is chosen between Baltimore and Galveston for all time situations. This is the second shortest leg alternative. The total distances for the benchmark and standard scenarios are given in Table 8-46. For C4_1300, leg option 4 enters the solution for some of the time situations, so the distance given in the table represents an average. Average speed in each area and the ratio between them is also given for the price scenarios.

Situation	**Distance**			**Speed**		
	ECA	*Non-ECA*	*Total*	*ECA*	*Non-ECA*	*Ratio*
C4_590	1,665	2,164	3,829	15.77	15.77	-
C4_920	1,113	2,825	3,938	15.54	16.31	4.88%
C4_1300	993	3,018	4,012	15.00	16.80	12.02%

Table 8-46 C4: Average speed and distances, and ratio between non-ECA and ECA measures

The average fuel consumption for the same scenarios is given in Table 8-47. The increase in total fuel consumption for the standard scenario compared to the benchmark is 4.59%, a relatively large difference. There are variations within the scenarios, and the difference varies from 2.85% to 5.81%, with the highest increase for the tightest time limits. The distance is the same for all the time situations within the standard scenario, and speed consequently has to increase more when the time constraints are tighter.

Scenario	**Average fuel consumption**					
	ECA	*Difference*	*Non-ECA*	*Difference*	*Total*	*Difference*
C4_590	255.7	-	329.3	-	585.1	-
C4_920	168.1	-34.28%	443.9	34.78%	611.9	4.59%
C4_1300	146.2	-42.82%	485.2	47.33%	631.4	7.92%

Table 8-47 C4: rage fuel consumption in each area and comparison of each scenario with the benchmark

Table 8-48 gives the average total emissions of CO_2 and SO_X with comparisons to the benchmark. The ECA regulations lead to a rather large increase in CO_2 emissions following the increased fuel consumption. SO_X emissions are reduced by more than 97% within the ECA due to the low sulphur content in MGO, and the total consequence is also a significant reduction even though the emissions increase outside ECAs.

Scenario	**CO_2 emissions**		**SO_X emissions**	
	Tonnes	*Difference*	*Kilograms*	*Difference*
C4_590	1,854.7	-	315.9	-
C4_920	1,939.8	4.59%	243.0	-23.07%
C4_1300	2,001.6	7.92%	291.2	-7.81%

Table 8-48 C4: Average total emissions of CO_2 and SO_X and comparisons with benchmark

Finally, the cases for P3 and P4 are compared in Table 8-49. This shows that the option of alternative sailing legs has a much larger impact on fuel consumption and emissions than possible sequence alterations. Fuel consumption within ECAs comparably drop by 30.8% with the new leg options, there is an increase in total fuel consumption and CO_2 emissions of 2.6%, and total SO_X emissions become 24.1% higher when alternative leg options are chosen. SO_X within ECAs however are less for C4 than C3, since a larger part of the route is moved outside of the ECA. The fuel costs are lower for C4, and it is economically beneficial to change the legs. The environmental effect is ambiguous, with positive implications within ECAs but negative outside and in total.

Situation	**Fuel consumption**			**Emissions**		**Fuel costs**
	ECA	*Non-ECA*	*Total*	**CO_2**	**SO_X**	
C3_920	242.8	353.6	596.4	1,890.6	195.8	431,986
C4_920	168.1	443.9	611.9	1,939.8	243.0	416,502
Difference	-30.80%	25.5%	2.60%	2.60%	24.11%	-3.58%

Table 8-49 Average fuel consumption, emissions and fuel costs for the standard scenarios of C3 and C4, and the difference between the two cases

8.3.3. Concluding remarks for analyses of P3 and P4

The results from the analyses of C3 and C4 resemble the findings from the previous cases. Speed decisions change as a response to the ECA regulations, and legs are moved when it is possible and profitable. Total fuel consumption increases as a consequence.

Sequence is introduced as a new variable, but for the current ECAs it will not make a big difference, assuming that routes are logically constructed with regards to geographical locations. If for example the last ports in the routes were flexible, there might be more options to execute the route with alternative legs. However, for most routes the final destination is set, depending on the goods that are transported by the ships.

8.4. Summary of case analyses

Findings show that speed and routing decisions can be greatly affected by the ECA regulations. The changed decisions arise due to the increased costs incurred by shipping companies, since the ECA complying fuel MGO is more expensive than HFO. Speed is lowered within ECAs and increased outside for all scenarios and cases when ECA regulations are considered. This leads to less fuel consumption within the ECAs and more elsewhere. Since the least fuel is consumed when the speed is constant, the total fuel consumption also increases to some extent. When legs are variable, total fuel consumption could increase considerably more. The effects of speed and leg decisions work in the same direction, reducing ECA consumption while increasing the total. The different variables are highly interrelated, so specific effects cannot be completely attributed to one variable alone.

Table 8-50 gives the average outputs of total fuel consumption, emissions and costs for the benchmark and standard scenarios with comparisons for all cases. For fixed legs (P1), the increase in fuel consumption is relatively small, totalling less than 0.5%. In problems P2 and P4 with variable legs, total fuel consumption increases by 3.17% at the least and 7.33% at the most, excluding case C2.4 since the Suez cost precludes direct comparisons of the cases.

Problem	Scenario	Fuel consumption	Emissions		Fuel costs
			CO_2	SO_X	
P1	C1.1_590	464.7	1,473.2	251.0	274,173
	C1.1_920	465.9	1,476.9	182.2	318,935
	Difference	**0.26%**	**0.25%**	**-27.41%**	**16.33%**
	C1.2_590	388.1	1,230.2	209.6	228,979
	C1.2_920	389.0	1,233.2	145.0	270,793
	Difference	**0.23%**	**0.24%**	**-30.82%**	**18.26%**
P2	C2.1_590	663.6	2,103.4	358.3	391,524
	C2.1_920	684.6	2,170.2	229.7	492,783
	Difference	**3.17%**	**3.17%**	**-35.91%**	**25.86%**
	C2.2_590	1,026.1	3,252.8	554.1	605,399
	C2.2_920	1,066.5	3,380.7	483.7	687,685
	Difference	**3.93%**	**3.93%**	**-12.71%**	**13.59%**
	C2.3c_590	172.4	546.4	93.1	101,716
	C2.3c_920	183.9	583.0	50.6	139,389
	Difference	**6.70%**	**6.70%**	**-45.60%**	**37.04%**
	C2.3d_590	186.5	591.3	100.7	110,035
	C2.3d_920	199.3	631.7	86.0	131,282
	Difference	**6.83%**	**6.83%**	**-14.60%**	**19.31%**
	C2.3e_590	195.1	618.4	105.3	115,109
	C2.3e_920	209.4	663.8	96.2	134,238
	Difference	**7.33%**	**7.33%**	**-8.67%**	**16.62%**
	C2.4b_590	1,292.9	4,098.6	698.2	1,219,838*
	C2.4b_920	1,594.3	5,054.0	746.7	1,317,826*
	Difference	**23.31%**	**23.31%**	**6.94%**	**8.03%**
P3	C3_590	591.1	1,873.7	319.2	348,738
	C3_920	596.4	1,890.6	195.8	431,986
	Difference	**0.90%**	**0.90%**	**-38.65%**	**23.87%**
P4	C4_590	585.1	1,854.7	315.9	345,192
	C4_920	611.9	1,939.8	243.0	416,502
	Difference	**4.59%**	**4.59%**	**-23.07%**	**20.66%**

* Including Suez costs. Fuel costs increase by 12.85%.

Table 8-50 Summary of average output for benchmark and standard scenarios for all cases

CO_2 emissions are proportional to the total fuel consumption, and therefore increase as a result of the speed and routing decisions when considering ECA regulations. The increase is substantial for the problems with alternative leg options. SO_X emissions are greatly reduced through the use of MGO fuel with low sulphur content. The reduced speed and avoided distances further decrease emissions within ECAs, while there is an increase outside ECAs.

8.5. Dependencies and limitations of the case studies

Doudnikoff and Lacoste (2014) recently did a study on speed optimisation considering ECA regulations in which they also estimated consequences for the environment. However, their model was specific to one type of ship and operations, and they moreover used an approximation of the fuel consumption function in the objective function. Several papers agree that fuel consumption is proportional to approximately the third power of speed. The models in this thesis are instead based on real data including actual fuel consumption for different speed points. The approach led to linear model formulations using a set of discrete speed alternatives. Characteristics of the fuel consumption allowed interpolation between neighbouring speed points to find exact speeds that minimised fuel costs.

It should be noted that the magnitude of the changes in speed and route decisions depends on the planning flexibility. Time is an important factor in which variations have large impacts on speed and routing. The analysed cases only consider one trip along one route with a single ship, and time would perhaps play a more important role if other aspects were included. The case analysis outputs are not completely realistic, but the cases have been developed in a careful manner.

The ratio between the fuel prices is essential, as larger premiums imply greater incentives for shipping companies. Future fuel prices are uncertain, and there might be more room for unprecedented changes in the ratio based on the industry's reaction to the ECA regulations. Assuming fuel switching becomes the main compliance method for the years following 2015, the demand for low-sulphur fuel like MGO will probably rise, and this may affect the market situation with supply and demand conditions, potentially influencing the prices of some fuels more than others. The correlation between various fuel prices might be less distinct in the future.

The analyses in this thesis are based on the IMO sulphur limits of 2015, with a maximum content of 0.1% within ECAs. NO_X abatement is not considered, and the inclusion of these restrictions could affect the assumptions about SO_X compliance methods and calculations of emissions, depending on the chosen technology. Moreover, the IMO is currently planning new measures towards reducing greenhouse gases, and an implementation of international regulations could make findings in this thesis obsolete. In a relatively short term perspective, the analyses are regardless valid.

9. Discussion

Potential impacts of the ECA regulations on ship speed and routing and the associated consequences for the environment were analysed in the computational study for specific cases. In this chapter, the results will be applied in a broader perspective. General and global ECA implications are discussed.

9.1. Environmental ECA implications

Different emissions have different impacts, and it is not straightforward to compare the costs and the importance of them. Environmental costs have not been estimated or considered in this thesis, and it is unwise to draw final conclusions about the overall impacts of the ECAs without more specific measures. However, it is apparent that the regulations are successful with respect to their target pollutant, as SO_X emissions undoubtedly will be reduced enormously within ECAs. The associated negative effects of CO_2 are however also significant. Emissions of other substances have not been included, so several additional calculations and considerations might be necessary to evaluate the total outcomes. Since NO_X restrictions have been ignored in this thesis, NO_X emissions cannot be assessed accurately based on the presented outputs.

9.1.1. Global environmental impacts

A rough estimate of the change in global CO_2 emissions as a result of ECAs will be derived in the following. The estimation is uncertain and should not be dwelt upon further. The purpose is to show potential global impacts of the ECAs.

First, it is useful to know the total fuel consumption of the world fleet. According to UNCTAD (2013), there are around 87,000 vessels above 100 GT in the world fleet, and it is thus very complicated to estimate accurate fuel consumption figures. Psaraftis and Kontovas (2009) compare assessments of the annual fuel consumption for the early 2000s by different researchers. 300 million tonnes globally is an acceptable approximation and will be used in this macro evaluation.

Approximately 5% of the consumption occurs in ports (Cariou et al., 2011), and this consumption is independent of ECA regulations, meaning that 285 million tonnes are relevant and consumed at sea. Fuel consumption in ECAs is about 10-15% of the total consumption for the world fleet (Hodne, 2012), rounded to 40 million tonnes out of the 285. Ships that only operate within ECAs are assumed to consume 50%, or 20 million tonnes, of the total fuel consumption in these areas. This amount of HFO would be replaced by MGO if all ships comply with the regulations using fuel switching, but no other operational effect from ECA regulations is expected.

It is assumed that the remaining 20 million tonnes consumed within ECAs are consumed on inter-area routes, i.e. routes that involve sailing stretches both within and outside ECAs. 245 million tonnes are consumed outside ECAs. A large share is probably consumed on routes that are completely unrestricted by ECAs, although northern Europe and North America are involved in a great deal of international shipping. Countries bordering ECAs own approximately 25% of the world fleet given in DWT (UNCTAD, 2013). This is not representative of the actual operations, but for lack of better data 25% of the fuel consumption outside ECAs is assumed to occur on inter-area routes. In total, around 80 million tonnes are now assumed partly subject to ECA regulations.

All the inter-area routes face potential new speed decisions, and it is assumed that 10% could also benefit from changes in sailing legs. In the analyses of this thesis, it was found that speed optimisation on fixed routes could lead to around 0.5% more total fuel consumption, while optimised legs have the potential of increasing fuel consumption by 3-7%, also accounting for the speed alteration. Hence, 72 million tonnes of fuel (90% of inter-area consumption) could be expected to increase by 360,000 tonnes (0.5%), and the remaining 8 million by 400,000 tonnes (5%). In total, this amounts to 760,000 additional tonnes of fuel annually. Since the routes in the analysis have been developed to highlight a particular issue, this is probably an overestimation. A fairer figure could for example be 300,000 tonnes in total.

Without ECAs, CO_2 emissions produced at sea can be calculated from the fuel consumption of 285 million tonnes to equal 903.5 million tonnes. An increase in the total world fleet consumption to 285.3 million tonnes corresponds to almost 0.1%. CO_2 emission would increase by the same amount, with resulting CO_2 emissions totalling 904.4 million tonnes.

The derived numbers are relatively small, but still significant. Similar calculations have not been done with respect to SO_X emissions, as it is certain that they will decrease substantially, and especially within ECAs which is the objective of the given IMO regulations.

The final verdict on environmental consequences is left open, but the findings from the current analyses are essential regardless of further research and conclusions. Policy makers should be made aware of the consequences associated with speed and routing decisions arising from the ECA regulations in order to evaluate their importance to the desired outcomes.

9.2. Economic ECA implications

Based on the assumptions made in chapter 9.1.1, 285 million tonnes of fuel are consumed at sea annually, of which 40 million tonnes within ECA. Disregarding potential effects of changes in speed and legs, cost impacts can be roughly assessed. The fuel costs of 285 million tonnes of HFO with a price of USD 590 per tonne are USD 168.15 billion. With ECAs, 40 million tonnes of the fuel must instead be low-sulphur MGO costing USD 920 per tonne, a price differential of USD 330. The additional cost is therefore USD 13.2 billion, leading total global fuel costs to increase by 7.85% to USD 181.35 billion. Even if this number is uncertain, the ECA regulations will undoubtedly increase costs for ships operating in these areas significantly, and this may be unfortunate in several ways. Possible consequences include modal shifts to more land based transportation, which could be negative for the environment. A common proxy of fuel consumption for trucks is 0.8kg per kilometre, and this can be used to estimate costs in specific cases where it is possible to move the route from sea to land.

Increased costs in the industry could also lead to depressed markets, possibly hurting countries and people through unemployment and difficult economic conditions, and different international trade patterns. On the other hand, the increased costs could foster competition and drive development of more efficient technology and environmentally friendly solutions. Such indirect effects can be of importance, but are outside the scope of this thesis.

9.3. Future research

This thesis is an independent piece of work that raises questions about the impacts of the ECA regulations on ship operations and the environment. The objectives have been fulfilled with regards to developing optimisation models and analysing the given issues. The developed models are general and could easily be adapted to fit any type of ship operation. Therefore, shipping companies could benefit from using a similar tool in operational planning for decision support. The solution time of the implemented models is negligible, and the given output can be of value in daily planning. However, several courses could be taken to improve the work done here or apply the models and findings in different contexts.

Firstly, the models are very general, and it could be useful to make modifications and apply them to more specific problems. For instance, the different modes of ship operations involve different types of routes and objectives. Possible extensions involve consideration of load, weather and sea conditions, realistic time constraints and service times in ports. Furthermore, the objective function would in reality consist of several elements besides fuel costs, where other types of operational costs and time dependent costs might be added, and revenues play a role in some operations as well. Also, the models cover one trip along one route for a single ship, and a natural extension is to integrate a larger fleet and several voyages, perhaps leading to a better incorporation of the time aspect.

Secondly, the underlying assumptions regarding the ECA regulations and the compliance methods could be challenged. Scrubbers and LNG could be included as alternatives to fuel switching, and NO_X restrictions and compliance likewise. Environmental analyses might also be improved if several substances were included.

Besides the mentioned possible future research areas, the optimisation process could be given more attention. Alternatives include the integration of compliance choice in the models or stochastic fuel prices.

10. Conclusion

The purpose of this thesis has been to study impacts of the ECA regulations on ship operations regarding speed and routing decisions, and to further evaluate the associated environmental consequences.

To answer the key questions of this thesis, a background study was first undertaken in order to fully understand the requirements and objectives of the ECA regulations. Fuel switching was found to be an easily implemented compliance method and a probable choice for shipping companies in the next few years. It implies the use of low-sulphur fuel such as MGO when sailing within ECAs.

Findings showed that the ECA regulations could have a great impact on speed and routing decisions. When minimising fuel costs, ships would benefit from speed reductions within ECAs and increased speed outside to compensate for the longer sailing time. This result was found in all the tested cases and scenarios. Fuel consumption is minimised when a ship sails at constant speed, therefore the new speed decisions led to higher total fuel consumption. For the problem with fixed routes and sequences, the total fuel consumption increased by 0.1-1%. A greater difference materialised when legs were variable, as total sailing distances increased in order to avoid long stretches within ECAs. Speed consequently also had to increase to meet the time constraints. The total fuel consumption increased by around 3-7% for the implemented cases, including routes both in Europe and in North America. Finally, sequencing of routes was studied with and without alternative leg options. The results concurred with the previous findings. To summarise, it is economically beneficial for ships to reconsider speed and leg decisions when ECAs are enforced compared to maintaining constant speed and sailing the shortest legs.

The next main purpose of this thesis involved an environmental analysis. Based on the fuel consumption within and outside ECAs as found from the model outputs, emissions of CO_2 and SO_X were calculated. SO_X emissions were greatly reduced following the ECA regulations. Within ECAs, the reduction originated from the switch to low-sulphur fuel combined with a lower speed and shorter distances sailed within these areas. The emissions of SO_X increased outside ECAs because of the longer distances and higher speed, but the overall outcome was a large improvement in the pollution of this substance. MGO and HFO supposedly produce the same amount of CO_2 when burned as a marine fuel, proportional to the fuel consumption. Therefore, since it was discovered that total fuel consumption increased due to the new and cost-optimal decisions, emissions of CO_2 also increased. This increase was substantial, especially for the cases with alternative leg options, and consequently harmful for the global environment. CO_2 is an important greenhouse gas contributing to global warming, while SO_X influence ecology and human health. It is complicated to compare the costs and benefits of the two with regards to overall environmental outcomes, and further conclusions are not asserted in this thesis. It is nevertheless important to be aware of all the effects that could arise.

Lastly, a brief discussion part has been included in the thesis to account for general implications of the ECAs and of potential future research. Future fuel prices are uncertain, and so is the direction of the shipping industry developments. Regardless, all indications are that the environment will be in focus and gain greater attention within the shipping segment going forward. This thesis has provided analyses highlighting some of the current issues on the agenda.

11. References

Andersson, H., Fagerholt, K. and Hobbesland, K., 2014. Integrated maritime fleet deployment and speed optimization: Case study from RoRo shipping. *Working paper*, NTNU, 2014.

Armstrong, V., 2013. Vessel optimisation for low carbon shipping. *Ocean Engineering*, Vol. 73 (2013), pp. 195–207.

Balland, O. and Gundersen, H., 2013. Efficiency through technology choices. Available from: <http://www.dnv.com/industry/maritime/publications/archive/maritime_update/2013/1_2013/Efficiency_through_technology_choices.asp>. [30.05.2014].

Balland, O., Erikstad, S. and Fagerholt, K., 2012. Optimized selection of air emission controls for vessels. *Maritime Policy & Management*, Vol. 39, No. 4 (July 2012), pp. 387-400.

Balland, O., Erikstad, S., Fagerholt, K. and Wallace, S., 2013. Planning vessel air emission regulations compliance under uncertainty. *Journal of Marine Science and Technology*, Vol. 18, No. 3 (2013), pp. 349–357.

Brynolf, S., Magnusson, M., Fridell, E. and Andersson, K., 2014. Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. *Transportation Research Part D: Transport and Environment*, Vol. 28 (May 2014), pp. 6-18.

Cariou, P., 2011. Is slow steaming a sustainable means of reducing CO2 emissions from container shipping? *Transportation Research Part D*, Vol. 16, No. 3 (2011), pp. 260–264.

Cariou, P. and Cheaitou, A., 2012. The effectiveness of a European speed limit versus an international bunker-levy to reduce CO2 emissions from container shipping. *Transportation Research Part D*, Vol. 17, No. 2 (2012), pp. 116–123.

Catalani, M., 2009. Ship scheduling and routing optimization. An application to Western Mediterranean area. *European Transport*, No. 42 (2009), pp. 67-82.

Christiansen, M., 1999. Decomposition of a Combined Inventory and Time Constrained Ship Routing Problem. *Transportation Science*, Vol. 33, No. 1 (Feb 1999), pp. 3-16.

Christiansen, M., Fagerholt, K. and Ronen, D., 2004. Ship Routing and Scheduling: Status and Perspectives. *Transportation Science*, Vol. 38, No. 1 (Feb 2004), pp. 1-18.

Christiansen, M., Fagerholt, K., Nygreen, B. and Ronen, D., 2007. Maritime Transportation. In Handbook in OR & MS (Barnhart and Laporte), Vol. 14, Chapter 4, pp. 189-284.

Christiansen, M., Fagerholt, K., Nygreen, B. and Ronen, D., 2013. Ship routing and scheduling in the new millennium. *European Journal of Operational Research*, Vol. 228, No. 3 (2013), pp. 467–483.

ClassNK, 2010. Issues and measures for use of low-sulfur fuel oil. Available from: <http://www.classnk.com/hp/pdf/reseach/seminar/2010_05e.pdf>. [30.05.2014].

Coccola, M. and Mendez, C., 2013. Logistics Management in Maritime Transportation Systems. *Chemical Engineering Transactions*, Vol. 32 (2013), pp. 1291-1296.

Corbett, J., Wang, H. and Winebrake, J., 2009. The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D*, Vol. 14, No. 8 (2009), pp. 593–598.

Cullinane, K. and Bergqvist, R., 2014. Emission control areas and their impact on maritime transport. *Transportation Research Part D: Transport and Environment*, Vol. 28 (May 2014), pp. 1-5.

Danish EPA, Danish Incentive Partners and Litehauz, 2012. Economic Impact Assessment of a NOX Emission Control Area in the North Sea. *Environmental Project* no. 1427, 2012. The Danish Environmental Protection Agency.

De Meyer, P., Maes, F. and Volckaert, A., 2008. Emissions from international shipping in the Belgian part of the North Sea and the Belgian seaports. *Atmospheric Environment*, Vol. 42, No. 1 (2008), pp. 196–206

Deal, A., 2013. Liquefied Natural Gas as a Marine Fuel. A Closer Look at TOTE's Containership Projects. *Working Paper*, NEPI.

Dedes, E., Hudson, D. and Turnock, S., 2012. Assessing the potential of hybrid energy technology to reduce exhaust emissions from global shipping. *Energy Policy*, Vol. 40 (2012), pp. 204–218.

Desrosiers, J., Dumas, Y., Solomon, M. and Soumis, F., 1995. Time constrained routing and scheduling. In: Handbooks in Operations Research and Management Science, Vol. 8, Network Routing, Chapter 2, pp. 35-139.

Dore, A., Vieno, M., Tang, Y., Dragosits, U., Dosio, A., Weston, K. and Sutton, M., 2007. Modelling the atmospheric transport and deposition of sulphur and nitrogen over the United Kingdom and assessment of the influence of SO2 emissions from international shipping. *Atmospheric Environment*, Vol. 41 (2007), pp. 2355–2367.

Doudnikoff, M. and Lacoste, R., 2014. Effect of a speed reduction of containerships in response to higher energy costs in Sulphur Emission Control Areas. *Transportation Research Part D*, Vol. 27 (2014), pp. 19–29.

Du, Y., Chen, Q., Quan, X., Long, L. and Fung, R., 2011. Berth allocation considering fuel consumption and vessel emissions. *Transportation Research Part E*, Vol. 47 (2011), pp. 1021–1037

Eguia, I., Racero, J., Molina, J. and Guerrero, F., 2013. Environmental Issues in Vehicle Routing Problems, In: Sustainability Appraisal: Quantitative Methods and Mathematical Techniques for Environmental Performance Evaluation (M. G. Erechtchoukova et al., 2013), pp. 215-243.

Endresen, Ø., Bakke, J., Sørgård, E., Berglen, T. and Holmvang, P., 2005. Improved modelling of ship SO2 emissions—a fuel-based approach. *Atmospheric Environment*, Vol. 39, No. 20 (2005), pp. 3621–3628.

Eyring, V., Isaksen, I., Berntsen, T., Collins, W., Corbett, J., Endresen, Ø., Grainger, R., Moldanova, J., Schlager, H. and Stevenson, D., 2010. Transport impacts on atmosphere and climate: Shipping. *Atmospheric Environment*, Vol. 44, No. 37 (2010), pp. 4735–4771.

Faber, J., Freund, M., Köpke, M. and Nelissen, D., 2010. Going Slow to Reduce Emissions. Can the current surplus of maritime transport capacity be turned into an opportunity to reduce GHG emissions? *Seas at risk*, 2010.

Fagerholt, K., 2001. Ship scheduling with soft time windows: An optimisation based approach. *European Journal of Operational Research*, Vol. 131, No. 3 (2001), pp. 559-571

Fagerholt, K., Heimdal, S. and Loktu, A., 2000. Shortest path in the presence of obstacles: An application to ocean shipping. *Journal of the Operational Research Society*, Vol. 51, No. 6 (2000), pp. 683-688.

Fagerholt, K., Christiansen, M., Hvattum, L., Johnsen, T. and Vabø, T, 2009. A decision support methodology for strategic planning in maritime transportation. *Omega*, Vol. 38, No. 6 (2010), pp. 465–474.

Fagerholt, K., Laporte, G. and Norstad, I., 2010. Reducing fuel emissions by optimizing speed on shipping routes. *Journal of the Operational Research Society*, Vol. 61, No. 3 (2010), pp. 523-529.

Figliozzi, M., 2010. Vehicle Routing Problem for Emissions Minimization. *Journal of the Transportation Research Board*, No. 2197 (2010), pp. 1–7.

Gilbert, P., 2014. From reductionism to systems thinking: How the shipping sector can address sulphur regulation and tackle climate change. *Marine Policy*, Vol. 43 (2014), pp. 376–378.

Han, C., 2010. Strategies to Reduce Air Pollution in Shipping Industry. *The Asian Journal of Shipping and Logistics*, Vol. 26, No. 1 (June 2010), pp. 7-30.

Harrison, D., Radov, D. and Patchett, J., 2004. Evaluation of the Feasibility of Alternative Market-Based Mechanisms To Promote Low-Emission Shipping In European Union Sea Areas. A Report for the European Commission, Directorate-General Environment, NERA Economic Consulting.

Hodne, T., 2012. SOx ECA requirements 2015 Challenges and solutions. DNV, Conference GMEC 2012.

Holmgren, J., Nikopoulou, Z., Ramstedt, L. and Woxenius, J., 2014. Modelling modal choice effects of regulation on low-sulphur marine fuels in Northern Europe. *Transportation Research Part D: Transport and Environment*, Vol. 28 (May 2014), pp. 62-73.

IMO, 2014. International Maritime Organization websites. Available from: <http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx>. [30.03.2014].

IPIECA, 2007. Maritime air emissions and MARPOL Annex VI: Strategies and consequence. Available from: <http://www.world-petroleum.org/docs/docs/socialres/marpol.pdf>. [30.05.2014].

Jiang, L., Kronbak, J. and Christensen, L., 2014. The costs and benefits of sulphur reduction measures: Sulphur scrubbers versus marine gas oil. *Transportation Research Part D: Transport and Environment*, Vol. 28 (May 2014), pp. 19-27.

Kågeson, P., 2005. Reducing Emissions from Ships in the Baltic Sea Area. The feasibility of introducing a distance-related en-route charge. Conference 'Greening Motorways of the Sea'.

Karlaftis, M., Kepaptsoglou, K. and Sambracos, E., 2009. Containership routing with time deadlines and simultaneous deliveries and pick-ups. *Transportation Research Part E*, Vol. 45 (2009), pp. 210–221.

Kjeldsen, K., 2012. Routing and Scheduling in Liner Shipping. *PhD Thesis*, Department of economics and business, Aarhus University.

Kontovas, C. and Psaraftis, H., 2011. Reduction of emissions along the maritime intermodal container chain: operational models and policies. *Maritime Policy & Management*, Vol. 38, No. 4 (July 2011), pp. 451-469.

Lagring, R., Degraer, S., de Montpellier, G., Jacques, T., Van Roy, W. and Schallier, R., 2012. Twenty years of Belgian North Sea aerial surveillance: A quantitative analysis of results confirms effectiveness of international oil pollution legislation. *Marine Pollution Bulletin*, Vol. 64, No. 3 (2012), pp. 644–652.

Lai, K., Lun, V., Wong, C. and Cheng, T., 2010. Green shipping practices in the shipping industry: Conceptualization, adoption, and implications. *Resources, Conservation and Recycling*, Vol. 55, No. 6 (2011), pp. 631–638.

Lin, B. and Lin, C., 2006. Compliance with international emission regulations: Reducing the air pollution from merchant vessels. *Marine Policy*, Vol. 30, No. 3 (2006), pp. 220–225

Lin, D. and Liu, H., 2011. Combined ship allocation, routing and freight assignment in tramp shipping. *Transportation Research Part E*, Vol. 47, No. 4 (2011), pp. 414–431.

Lin, Y., Fang, M. and Yeung, R., 2013. The optimization of ship weather-routing algorithm based on the composite influence of multi-dynamic elements. *Applied Ocean Research*, Vol. 43 (2013), pp. 184–194.

Lin, C., Choy, K., Ho, G., Chung, S. and Lam, H., 2014. Survey of Green Vehicle Routing Problem: Past and future trends. *Expert Systems with Applications Part 1*, Vol. 41, No. 4 (2014), pp. 1118–1138.

Lindstad, H., Asbjørnslett, B. and Strømman, A., 2011. Reductions in greenhouse gas emissions and cost by shipping at lower speeds. *Energy Policy*, Vol. 39, No. 6 (2011), pp. 3456–3464.

Lindstad, H., Asbjørnslett, B. and Jullumstrø, E., 2012(a). Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market. *Transportation Research Part D*, Vol. 19 (2013), pp. 5–12.

Lindstad, H., Asbjørnslett, B. and Strømman, A., 2012(b). The importance of economies of scale for reductions in greenhouse gas emissions from shipping. *Energy Policy*, Vol. 46 (2012), pp. 386–398.

Madsen, S. and Olsson, T., 2012. Cost efficient Emission Control Area Compliancy. *Master thesis in marine technology*, NTNU, 2012.

Matthias, V., Bewersdorff, I., Aulinger, A. and Quante, M., 2010. The contribution of ship emissions to air pollution in the North Sea regions. *Environmental Pollution*, Vol. 158, No. 6 (2010), pp. 2241-2250.

Norstad, I., Fagerholt, K. and Laporte, G., 2011. Tramp ship routing and scheduling with speed optimization. *Transportation Research Part C*, Vol. 19, No. 5 (2011), pp. 853–865.

Panagakos, G., Stamatopoulou, E. and Psaraftis, H., 2014. The Possible Designation of the Mediterranean Sea as a SECA: a Case Study. *Transportation Research D: Transport and Environment*, Vol. 28 (May 2014), pp. 74-90.

Psaraftis, H., 2012. Market-based measures for greenhouse gas emissions from ships: a review. *WMU Journal of Maritime Affairs*, Vol. 11, No. 2 (2012), pp. 211–232.

Psaraftis, H. and Kontovas, C., 2009. Ship emissions: Logistics and other tradeoffs. Available from: <http://www.researchgate.net/publication/228501943_Ship_Emissions_Logistics_and_Other_Tradeoffs/file/9fcfd5141d1ed0d431.pdf+&cd=1&hl=en&ct=clnk&client=safari>. [30.05.2014].

Psaraftis, H. and Kontocas, C., 2009. CO_2 Emission Statistics for the World Commercial Fleet. *WMU Journal of Maritime Affairs*, Vol. 8 (2009), No. 1, pp. 1-25.

Psaraftis, H. and Kontovas, C., 2010. Balancing the economic and environmental performance of maritime transportation. *Transportation Research Part D*, Vol. 15, No. 8 (2010), pp. 458–462.

Psaraftis, H. and Kontovas, C., 2013. Speed models for energy-efficient maritime transportation: A taxonomy and survey. *Transportation Research Part C*, Vol. 26 (2013), pp. 331–351.

Rauta, D., 2012. Compliance with ECA in 2015. Are there alternative options for ship owners? Intertanko, Conference: Building for the future 2012.

Ronen, D., 1982. The effect of Oil Price on the Optimal Speed of Ships. *The Journal of the Operational Research Society*, Vol. 33, No. 11 (Nov 1982), pp. 1035-1040.

Ronen, D., 1983. Cargo ships routing and scheduling: Survey of models and problems. *European Journal of Operational Research*, Vol. 12, No. 2 (1983), pp. 119-126.

Rowland, C. and Wright, C., 2013. The Impact of Sulphur Emission Control Area on the Scotland-Continent Ferry Service. MDS Transmodal, Scottish Transport Applications & Research (STAR) conference in Glasgow 2013.

Sbihi, A. and Eglese, R., 2007. Combinatorial optimization and Green Logistics. *Annals of Operations Research*, Vol. 175, No. 1 (2007), pp. 159-175.

Schinas, O. and Stefanakos, C., 2012. Cost assessment of environmental regulation and options for marine operators. *Transportation Research Part C*, Vol. 25 (2012), pp. 81–99.

Sørgård, E., 2013. Emission Control Areas: Effect on the fleet size and mix problem. *Project thesis in Maritime Technology*, NTNU, 2013.

UNCTAD, 2013. Review of Maritime Transport. *UNCTAD/RMT/2013*.

Wang, C. and Corbett, J., 2007. The costs and benefits of reducing SO2 emissions from ships in the US West Coastal waters. *Transportation Research Part D*, Vol. 12, No. 8 (2007), pp. 577–588.

Wang, S. and Meng, Q., 2012(a). Sailing speed optimization for container ships in a liner shipping network. *Transportation Research Part E*, Vol. 48, No. 3 (2012), pp. 701–714.

Wang, S. and Meng, Q., 2012(b). Liner ship route schedule design with sea contingency time and port time uncertainty. *Transportation Research Part B*, Vol. 46, No. 5 (2012), pp. 615–633.

Wang, S. and Meng, Q., 2012(c). Robust schedule design for liner shipping services. *Transportation Research Part E*, Vol. 48, No. 6 (2012), pp. 1093–1106.

Wang, S., Meng, Q. and Liu, Z., 2013(a). A note on ‘‘Berth allocation considering fuel consumption and vessel emissions’’. *Transportation Research Part E*, Vol. 49, No. 1 (2013), pp. 48–54.

Wang, S., Meng, Q. and Liu, Z., 2013(b). Bunker consumption optimization methods in shipping: A critical review and extensions. *Transportation Research Part E*, Vol. 53 (2013), pp. 49–62.

WWL, 2014. Wallenius Wilhelmsen Logistics. Available from: <http://www.2wglobal.com/www/productsServices/routeMaps/index.jsp>. [30.03.2014].

Yang, Z., Zhang, D., Caglayan, O., Jankinson, I., Bonsall, S., Wang, J., Huang, M. and Yan, X., 2012. Selection of techniques for reducing shipping NOx and SOx emissions. *Transportation Research Part D*, Vol. 17, No. 6 (2012), pp. 478–486.

Appendix A: Case outputs

Appendix A.1: Case outputs C1.1

Situation	**Leg**	**Reference speed**	**Time limits**		**Situation**	**Time limits**	
			Lower	Upper		Lower	Upper
TW_0.25	1	18.67	-	-	TL_0.5	-	-
	2	17.69	1.27	1.77		-	7.26
	3	17.32	2.58	3.08		-	7.26
	Finish		6.76	7.26		-	7.26
TW_0.5	1	18.67	-	-	TL_1	-	-
	2	17.69	1.02	2.02		-	7.51
	3	17.32	2.33	3.33		-	7.51
	Finish		6.51	7.51		-	7.51
TW_0.75	1	18.67	-	-	TL_1.5	-	-
	2	17.69	0.77	2.27		-	7.76
	3	17.32	2.08	3.58		-	7.76
	Finish		6.26	7.76		-	7.76
TW_1	1	18.67	-	-	TL_2	-	-
	2	17.69	0.52	2.52		-	8.01
	3	17.32	1.83	3.83		-	8.01
	Finish		6.01	8.01		-	8.01

Leg	**Distance**	
	ECA	*Non-ECA*
1	680	0
2	210	345
3	0	1,738

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_590_TW_0.25	1	-	17.00		110.2	-	110.2	65,018
	2	40.00	17.00	17.00	34.0	55.9	89.9	53,066
	3	72.65		17.13	-	283.7	283.7	167,394
	Finish	174.14			144.2	339.6	483.9	285,478
C1.1_590_TW_0.5	1	-	16.00		104.7	-	104.7	61,785
	2	42.50	16.00	16.00	32.3	53.1	85.5	50,427
	3	77.19		16.89	-	280.1	280.1	165,247
	Finish	180.14			137.1	333.2	470.3	277,459
C1.1_590_TW_0.75	1	-	16.00		104.7	-	104.7	61,785
	2	42.50	16.00	16.00	32.3	53.1	85.5	50,427
	3	77.19		15.95	-	267.1	267.1	157,596
	Finish	186.14			137.1	320.2	457.3	269,809
C1.1_590_TW_1	1	-	15.00		100.1	-	100.1	59,057
	2	45.33	15.00	15.00	30.9	50.8	81.7	48,201
	3	82.33		15.84	-	265.7	265.7	156,774
	Finish	192.14			131.0	316.5	447.5	264,031
C1.1_590_TL_0.25	1	-	17.08		110.7	-	110.7	65,296
	2	39.83	17.08	17.08	34.2	56.1	90.3	53,293
	3	72.34		17.08	-	282.9	282.9	166,889
	Finish	174.14			144.8	339.0	483.9	285,478
C1.1_590_TL_0.5	1	-	16.52		107.6	-	107.6	63,462
	2	41.20	16.52	16.52	33.2	54.6	87.8	51,796
	3	74.83		16.52	-	274.9	274.9	162,201
	Finish	180.14			140.8	329.5	470.3	277,459
C1.1_590_TL_0.75	1	-	15.97		104.6	-	104.6	61,712
	2	42.58	15.97	15.97	32.3	53.1	85.4	50,368
	3	77.32		15.97	-	267.3	267.3	157,729
	Finish	186.14			136.9	320.4	457.3	269,809
C1.1_590_TL_1	1	-	15.49		102.4	-	102.4	60,391
	2	43.95	15.49	15.49	31.6	51.9	83.5	49,289
	3	79.82		15.49	-	261.6	261.6	154,351
	Finish	192.14			134.0	313.5	447.5	264,031

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_920_TW_0.25	1	-	16.4		106.9	-	106.9	98,349
	2	41.50	16.0	18.0	32.3	59.1	91.4	64,594
	3	73.80		17.3	-	286.9	286.9	169,284
	Finish	174.14			139.2	346.0	485.2	332,227
C1.1_920_TW_0.5	1	-	15.6		102.9	-	102.9	94,670
	2	43.61	15.0	17.0	30.9	55.9	86.8	61,426
	3	77.91		17.0	-	281.7	281.7	166,178
	Finish	180.14			133.8	337.6	471.4	322,275
C1.1_920_TW_0.75	1	-	15.0		100.1	-	100.1	92,088
	2	45.33	15.0	17.0	30.9	55.9	86.8	61,426
	3	79.63		16.3	-	272.3	272.3	160,643
	Finish	186.14			131.0	328.2	459.2	314,157
C1.1_920_TW_1	1	-	15.0		100.1	-	100.1	92,088
	2	45.33	15.0	15.0	30.9	50.8	81.7	58,402
	3	82.33		15.8	-	265.7	265.7	156,774
	Finish	192.14			131.0	316.5	447.5	307,264
C1.1_920_TL_0.25	1	-	16.0		104.7	-	104.7	96,342
	2	42.50	16.0	17.6	32.3	57.8	90.1	63,832
	3	75.25		17.6	-	291.0	291.0	171,682
	Finish	174.14			137.1	348.7	485.8	331,857
C1.1_920_TL_0.5	1	-	15.5		102.2	-	102.2	94,061
	2	44.02	15.5	17.0	31.6	55.9	87.5	62,035
	3	77.91		17.0	-	281.7	281.7	166,178
	Finish	180.14			133.8	337.6	471.4	322,275
C1.1_920_TL_0.75	1	-	15.0		100.1	-	100.1	92,088
	2	45.33	15.0	16.4	30.9	54.4	85.3	60,509
	3	80.34		16.4	-	273.8	273.8	161,560
	Finish	186.14			131.0	328.2	459.2	314,157
C1.1_920_TL_1	1	-	15.0		100.1	-	100.1	92,088
	2	45.33	15.0	15.7	30.9	52.4	83.3	59,368
	3	81.33		15.7	-	264.1	264.1	155,808
	Finish	192.14			131.0	316.5	447.5	307,264

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_960_TW_0.25	1	-	16.03		104.9	-	104.9	100,688
	2	42.43	16.00	18.91	32.3	62.3	94.6	67,782
	3	73.80		17.33	-	286.9	286.9	169,284
	Finish	174.14			137.2	349.2	486.4	337,755
C1.1_960_TW_0.5	1	-	15.61		102.9	-	102.9	98,787
	2	43.61	15.00	17.00	30.9	55.9	86.8	62,663
	3	77.91		17.00	-	281.7	281.7	166,178
	Finish	180.14			133.8	337.6	471.4	327,628
C1.1_960_TW_0.75	1	-	15.00		100.1	-	100.1	96,092
	2	45.33	15.00	17.00	30.9	55.9	86.8	62,663
	3	79.63		16.33	-	272.3	272.3	160,643
	Finish	186.14			131.0	328.2	459.2	319,398
C1.1_960_TW_1	1	-	15.00		100.1	-	100.1	96,092
	2	45.33	15.00	15.00	30.9	50.8	81.7	59,638
	3	82.33		15.84	-	265.7	265.7	156,774
	Finish	192.14			131.0	316.5	447.5	312,504
C1.1_960_TL_0.25	1	-	16.00		104.7	-	104.7	100,531
	2	42.50	16.00	17.59	32.3	57.8	90.1	65,126
	3	75.25		17.59	-	291.0	291.0	171,682
	Finish	174.14			137.1	348.7	485.8	337,339
C1.1_960_TL_0.5	1	-	15.46		102.2	-	102.2	98,151
	2	44.02	15.46	17.00	31.6	55.9	87.5	63,298
	3	77.91		17.00	-	281.7	281.7	166,178
	Finish	180.14			133.8	337.6	471.4	327,628
C1.1_960_TL_0.75	1	-	15.00		100.1	-	100.1	96,092
	2	45.33	15.00	16.44	30.9	54.4	85.3	61,746
	3	80.34		16.44	-	273.8	273.8	161,560
	Finish	186.14			131.0	328.2	459.2	319,398
C1.1_960_TL_1	1	-	15.00		100.1	-	100.1	96,092
	2	45.33	15.00	15.70	30.9	52.4	83.3	60,604
	3	81.33		15.70	-	264.1	264.1	155,808
	Finish	192.14			131.0	316.5	447.5	312,504

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_1020_TW_0.25	1	-	16.03		104.9	-	104.9	106,981
	2	42.43	16.00	18.91	32.3	62.3	94.6	69,723
	3	73.80		17.33	-	286.9	286.9	169,284
	Finish	174.14			137.2	349.2	486.4	345,988
C1.1_1020_TW_0.5	1	-	15.00		100.1	-	100.1	102,098
	2	45.33	15.00	17.00	30.9	55.9	86.8	64,517
	3	79.63		17.30	-	286.5	286.5	169,006
	Finish	180.14			131.0	342.4	473.4	335,621
C1.1_1020_TW_0.75	1	-	15.00		100.1	-	100.1	102,098
	2	45.33	15.00	17.00	30.9	55.9	86.8	64,517
	3	79.63		16.33	-	272.3	272.3	160,643
	Finish	186.14			131.0	328.2	459.2	327,258
C1.1_1020_TW_1	1	-	15.00		100.1	-	100.1	102,098
	2	45.33	15.00	15.00	30.9	50.8	81.7	61,493
	3	82.33		15.84	-	265.7	265.7	156,774
	Finish	192.14			131.0	316.5	447.5	320,365
C1.1_1020_TL_0.25	1	-	15.25		101.2	-	101.2	103,259
	2	44.64	15.25	18.00	31.3	59.1	90.3	66,730
	3	77.59		18.00	-	297.5	297.5	175,518
	Finish	174.14			132.5	356.5	489.0	345,506
C1.1_1020_TL_0.5	1	-	15.00		100.1	-	100.1	102,098
	2	45.33	15.00	17.25	30.9	56.7	87.6	64,986
	3	79.34		17.25	-	285.7	285.7	168,538
	Finish	180.14			131.0	342.4	473.4	335,621
C1.1_1020_TL_0.75	1	-	15.00		100.1	-	100.1	102,098
	2	45.33	15.00	16.44	30.9	54.4	85.3	63,600
	3	80.34		16.44	-	273.8	273.8	161,560
	Finish	186.14			131.0	328.2	459.2	327,258
C1.1_1020_TL_1	1	-	15.00		100.1	-	100.1	102,098
	2	45.33	15.00	15.70	30.9	52.4	83.3	62,459
	3	81.33		15.70	-	264.1	264.1	155,808
	Finish	192.14			131.0	316.5	447.5	320,365

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_1200_TW_0.25	1	-	16.03		104.9	-	104.9	157,325
	2	42.43	15.90	19.00	32.2	62.6	94.8	85,212
	3	73.80		17.33	-	286.9	286.9	169,284
	Finish	174.14			137.1	349.5	486.6	411,821
C1.1_1200_TW_0.5	1	-	15.00		100.1	-	100.1	150,144
	2	45.33	15.00	17.00	30.9	55.9	86.8	79,355
	3	79.63		17.30	-	286.5	286.5	169,006
	Finish	180.14			131.0	342.4	473.4	398,505
C1.1_1200_TW_0.75	1	-	15.00		100.1	-	100.1	150,144
	2	45.33	15.00	17.00	30.9	55.9	86.8	79,355
	3	79.63		16.33	-	272.3	272.3	160,643
	Finish	186.14			131.0	328.2	459.2	390,142
C1.1_1200_TW_1	1	-	15.00		100.1	-	100.1	150,144
	2	45.33	15.00	15.00	30.9	50.8	81.7	76,331
	3	82.33		15.84	-	265.7	265.7	156,774
	Finish	192.14			131.0	316.5	447.5	383,249
C1.1_1200_TL_0.25	1	-	15.00		100.1	-	100.1	150,144
	2	45.33	15.00	18.15	30.9	59.6	90.5	81,520
	3	78.35		18.15	-	300.1	300.1	177,085
	Finish	174.14			131.0	359.7	490.7	408,749
C1.1_1200_TL_0.5	1	-	15.00		100.1	-	100.1	150,144
	2	45.33	15.00	17.25	30.9	56.7	87.6	79,823
	3	79.34		17.25	-	285.7	285.7	168,538
	Finish	180.14			131.0	342.4	473.4	398,505
C1.1_1200_TL_0.75	1	-	15.00		100.1	-	100.1	150,144
	2	45.33	15.00	16.44	30.9	54.4	85.3	78,438
	3	80.34		16.44	-	273.8	273.8	161,560
	Finish	186.14			131.0	328.2	459.2	390,142
C1.1_1200_TL_1	1	-	15.00		100.1	-	100.1	150,144
	2	45.33	15.00	15.70	30.9	52.4	83.3	77,297
	3	81.33		15.70	-	264.1	264.1	155,808
	Finish	192.14			131.0	316.5	447.5	383,249

Scenario	**Average speed**		**Average fuel consumption**			**Costs**
SHIP 1	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_590_TW_0.25	17.08	17.08	144.2	339.6	483.9	285,478
C1.1_590_TW_0.5	16.52	16.52	137.1	333.2	470.3	277,459
C1.1_590_TW_0.75	15.97	15.97	137.1	320.2	457.3	269,809
C1.1_590_TW_1	15.49	15.49	131.0	316.5	447.5	264,031
C1.1_590_TL_0.25	17.08	17.08	144.8	339.0	483.9	285,478
C1.1_590_TL_0.5	16.52	16.52	140.8	329.5	470.3	277,459
C1.1_590_TL_0.75	15.97	15.97	136.9	320.4	457.3	269,809
C1.1_590_TL_1	15.49	15.49	134.0	313.5	447.5	264,031
C1.1_920_TW_0.25	16.30	17.44	139.2	346.0	485.2	332,227
C1.1_920_TW_0.5	15.46	17.00	133.8	337.6	471.4	322,275
C1.1_920_TW_0.75	15.00	16.44	131.0	328.2	459.2	314,157
C1.1_920_TW_1	15.00	15.70	131.0	316.5	447.5	307,264
C1.1_920_TL_0.25	16.00	17.59	137.1	348.7	485.8	331,857
C1.1_920_TL_0.5	15.46	17.00	133.8	337.6	471.4	322,275
C1.1_920_TL_0.75	15.00	16.44	131.0	328.2	459.2	314,157
C1.1_920_TL_1	15.00	15.70	131.0	316.5	447.5	307,264
C1.1_960_TW_0.25	16.02	17.59	137.2	349.2	486.4	337,755
C1.1_960_TW_0.5	15.46	17.00	133.8	337.6	471.4	327,628
C1.1_960_TW_0.75	15.00	16.44	131.0	328.2	459.2	319,398
C1.1_960_TW_1	15.00	15.70	131.0	316.5	447.5	312,504
C1.1_960_TL_0.25	16.00	17.59	137.1	348.7	485.8	337,339
C1.1_960_TL_0.5	15.46	17.00	133.8	337.6	471.4	327,628
C1.1_960_TL_0.75	15.00	16.44	131.0	328.2	459.2	319,398
C1.1_960_TL_1	15.00	15.70	131.0	316.5	447.5	312,504
C1.1_1020_TW_0.25	16.02	17.59	137.2	349.2	486.4	345,988
C1.1_1020_TW_0.5	15.00	17.25	131.0	342.4	473.4	335,621
C1.1_1020_TW_0.75	15.00	16.44	131.0	328.2	459.2	327,258
C1.1_1020_TW_1	15.00	15.70	131.0	316.5	447.5	320,365
C1.1_1020_TL_0.25	15.25	18.00	132.5	356.5	489.0	345,506
C1.1_1020_TL_0.5	15.00	17.25	131.0	342.4	473.4	335,621
C1.1_1020_TL_0.75	15.00	16.44	131.0	328.2	459.2	327,258
C1.1_1020_TL_1	15.00	15.70	131.0	316.5	447.5	320,365
C1.1_1200_TW_0.25	16.00	17.61	137.1	349.5	486.6	411,821
C1.1_1200_TW_0.5	15.00	17.25	131.0	342.4	473.4	398,505
C1.1_1200_TW_0.75	15.00	16.44	131.0	328.2	459.2	390,142
C1.1_1200_TW_1	15.00	15.70	131.0	316.5	447.5	383,249
C1.1_1200_TL_0.25	15.00	18.15	131.0	359.7	490.7	408,749
C1.1_1200_TL_0.5	15.00	17.25	131.0	342.4	473.4	398,505
C1.1_1200_TL_0.75	15.00	16.44	131.0	328.2	459.2	390,142
C1.1_1200_TL_1	15.00	15.70	131.0	316.5	447.5	383,249

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_590_TW_0.25	1	-	17.00		92.4	-	92.4	54,492
	2	40.00	17.00	17.00	28.5	46.9	75.4	44,475
	3	72.65		17.13	-	237.1	237.1	139,886
	Finish	174.14			120.9	284.0	404.8	238,853
C1.1_590_TW_0.5	1	-	16.00		89.7	-	89.7	52,908
	2	42.50	16.00	16.00	27.7	45.5	73.2	43,182
	3	77.19		16.89	-	235.3	235.3	138,820
	Finish	180.14			117.4	280.8	398.2	234,911
C1.1_590_TW_0.75	1	-	16.00		89.7	-	89.7	52,908
	2	42.50	16.00	16.00	27.7	45.5	73.2	43,182
	3	77.19		15.95	-	228.9	228.9	135,074
	Finish	186.14			117.4	274.4	391.8	231,165
C1.1_590_TW_1	1	-	15.00		87.4	-	87.4	51,594
	2	45.33	15.00	15.00	27.0	44.4	71.4	42,110
	3	82.33		15.84	-	228.3	228.3	134,678
	Finish	192.14			114.5	272.6	387.1	228,382
C1.1_590_TL_0.25	1	-	17.08		92.6	-	92.6	54,632
	2	39.83	17.08	17.08	28.6	47.0	75.6	44,589
	3	72.34		17.08	-	236.7	236.7	139,632
	Finish	174.14			121.2	283.6	404.8	238,853
C1.1_590_TL_0.5	1	-	16.52		91.1	-	91.1	53,730
	2	41.20	16.52	16.52	28.1	46.2	74.3	43,853
	3	74.83		16.52	-	232.8	232.8	137,327
	Finish	180.14			119.2	279.0	398.2	234,911
C1.1_590_TL_0.75	1	-	15.97		89.6	-	89.6	52,873
	2	42.58	15.97	15.97	27.7	45.5	73.1	43,154
	3	77.32		15.97	-	229.0	229.0	135,138
	Finish	186.14			117.3	274.5	391.8	231,165
C1.1_590_TL_1	1	-	15.49		88.5	-	88.5	52,237
	2	43.95	15.49	15.49	27.3	44.9	72.3	42,634
	3	79.82		15.49	-	226.3	226.3	133,511
	Finish	192.14			115.9	271.2	387.1	228,382

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_920_TW_0.25	1	-	16.40	-	90.7	-	90.7	83,484
	2	41.50	16.00	18.00	27.7	48.4	76.1	54,054
	3	73.80	-	17.33	-	238.7	238.7	140,833
	Finish	174.14			118.4	287.1	405.6	278,372
C1.1_920_TW_0.5	1	-	15.61	-	88.8	-	88.8	81,696
	2	43.61	15.00	17.00	27.0	46.9	73.9	52,492
	3	77.91	-	17.00	-	236.1	236.1	139,276
	Finish	180.14			115.8	282.9	398.7	273,464
C1.1_920_TW_0.75	1	-	15.00	-	87.4	-	87.4	80,452
	2	45.33	15.00	17.00	27.0	46.9	73.9	52,492
	3	79.63	-	16.33	-	231.5	231.5	136,564
	Finish	186.14			114.5	278.3	392.8	269,509
C1.1_920_TW_1	1	-	15.00	-	87.4	-	87.4	80,452
	2	45.33	15.00	15.00	27.0	44.4	71.4	51,022
	3	82.33	-	15.84	-	228.3	228.3	134,678
	Finish	192.14			114.5	272.6	387.1	266,152
C1.1_920_TL_0.25	1	-	16.00	-	89.7	-	89.7	82,501
	2	42.50	16.00	17.59	27.7	47.8	75.5	53,673
	3	75.25	-	17.59	-	240.7	240.7	142,035
	Finish	174.14			117.4	288.5	405.9	278,209
C1.1_920_TL_0.5	1	-	15.46	-	88.5	-	88.5	81,402
	2	44.02	15.46	17.00	27.3	46.9	74.2	52,786
	3	77.91	-	17.00	-	236.1	236.1	139,276
	Finish	180.14			115.8	282.9	398.7	273,464
C1.1_920_TL_0.75	1	-	15.00	-	87.4	-	87.4	80,452
	2	45.33	15.00	16.44	27.0	46.1	73.1	52,043
	3	80.34	-	16.44	-	232.2	232.2	137,013
	Finish	186.14			114.5	278.3	392.8	269,509
C1.1_920_TL_1	1	-	15.00	-	87.4	-	87.4	80,452
	2	45.33	15.00	15.70	27.0	45.2	72.2	51,487
	3	81.33	-	15.70	-	227.5	227.5	134,213
	Finish	192.14			114.5	272.6	387.1	266,152

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_960_TW_0.25	1	-	16.40	-	90.7	-	90.7	87,114
	2	41.50	16.00	18.00	27.7	48.4	76.1	55,162
	3	73.80	-	17.33	-	238.7	238.7	140,833
	Finish	174.14			118.4	287.1	405.6	283,109
C1.1_960_TW_0.5	1	-	15.61	-	88.8	-	88.8	85,248
	2	43.61	15.00	17.00	27.0	46.9	73.9	53,573
	3	77.91	-	17.00	-	236.1	236.1	139,276
	Finish	180.14			115.8	282.9	398.7	278,097
C1.1_960_TW_0.75	1	-	15.00	-	87.4	-	87.4	83,950
	2	45.33	15.00	17.00	27.0	46.9	73.9	53,573
	3	79.63	-	16.33	-	231.5	231.5	136,564
	Finish	186.14			114.5	278.3	392.8	274,087
C1.1_960_TW_1	1	-	15.00	-	87.4	-	87.4	83,950
	2	45.33	15.00	15.00	27.0	44.4	71.4	52,102
	3	82.33	-	15.84	-	228.3	228.3	134,678
	Finish	192.14			114.5	272.6	387.1	270,730
C1.1_960_TL_0.25	1	-	16.00	-	89.7	-	89.7	86,088
	2	42.50	16.00	17.59	27.7	47.8	75.5	54,781
	3	75.25	-	17.59	-	240.7	240.7	142,035
	Finish	174.14			117.4	288.5	405.9	282,903
C1.1_960_TL_0.5	1	-	15.46	-	88.5	-	88.5	84,942
	2	44.02	15.46	17.00	27.3	46.9	74.2	53,879
	3	77.91	-	17.00	-	236.1	236.1	139,276
	Finish	180.14			115.8	282.9	398.7	278,097
C1.1_960_TL_0.75	1	-	15.00	-	87.4	-	87.4	83,950
	2	45.33	15.00	16.44	27.0	46.1	73.1	53,123
	3	80.34	-	16.44	-	232.2	232.2	137,013
	Finish	186.14			114.5	278.3	392.8	274,087
C1.1_960_TL_1	1	-	15.00	-	87.4	-	87.4	83,950
	2	45.33	15.00	15.70	27.0	45.2	72.2	52,568
	3	81.33	-	15.70	-	227.5	227.5	134,213
	Finish	192.14			114.5	272.6	387.1	270,730

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_1020_TW_0.25	1	-	16.03	-	89.8	-	89.8	91,550
	2	42.43	16.00	18.91	27.7	50.1	77.7	57,778
	3	73.80	-	17.33	-	238.7	238.7	140,833
	Finish	174.14			117.4	288.8	406.2	290,161
C1.1_1020_TW_0.5	1	-	15.61	-	88.8	-	88.8	90,576
	2	43.61	15.00	17.00	27.0	46.9	73.9	55,193
	3	77.91	-	17.00	-	236.1	236.1	139,276
	Finish	180.14			115.8	282.9	398.7	285,045
C1.1_1020_TW_0.75	1	-	15.00	-	87.4	-	87.4	89,197
	2	45.33	15.00	17.00	27.0	46.9	73.9	55,193
	3	79.63	-	16.33	-	231.5	231.5	136,564
	Finish	186.14			114.5	278.3	392.8	280,954
C1.1_1020_TW_1	1	-	15.00	-	87.4	-	87.4	89,197
	2	45.33	15.00	15.00	27.0	44.4	71.4	53,723
	3	82.33	-	15.84	-	228.3	228.3	134,678
	Finish	192.14			114.5	272.6	387.1	277,598
C1.1_1020_TL_0.25	1	-	16.00	-	89.7	-	89.7	91,469
	2	42.50	16.00	17.59	27.7	47.8	75.5	56,442
	3	75.25	-	17.59	-	240.7	240.7	142,035
	Finish	174.14			117.4	288.5	405.9	289,946
C1.1_1020_TL_0.5	1	-	15.46	-	88.5	-	88.5	90,250
	2	44.02	15.46	17.00	27.3	46.9	74.2	55,518
	3	77.91	-	17.00	-	236.1	236.1	139,276
	Finish	180.14			115.8	282.9	398.7	285,045
C1.1_1020_TL_0.75	1	-	15.00	-	87.4	-	87.4	89,197
	2	45.33	15.00	16.44	27.0	46.1	73.1	54,744
	3	80.34	-	16.44	-	232.2	232.2	137,013
	Finish	186.14			114.5	278.3	392.8	280,954
C1.1_1020_TL_1	1	-	15.00	-	87.4	-	87.4	89,197
	2	45.33	15.00	15.70	27.0	45.2	72.2	54,188
	3	81.33	-	15.70	-	227.5	227.5	134,213
	Finish	192.14			114.5	272.6	387.1	277,598

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_1200_TW_0.25	1	-	16.03	-	89.8	-	89.8	107,706
	2	42.43	16.00	18.91	27.7	50.1	77.7	62,763
	3	73.80	-	17.33	-	238.7	238.7	140,833
	Finish	174.14			117.4	288.8	406.2	311,302
C1.1_1200_TW_0.5	1	-	15.00	-	87.4	-	87.4	104,938
	2	45.33	15.00	17.00	27.0	46.9	73.9	60,054
	3	79.63	-	17.30	-	238.5	238.5	140,694
	Finish	180.14			114.5	285.3	399.8	305,685
C1.1_1200_TW_0.75	1	-	15.00	-	87.4	-	87.4	104,938
	2	45.33	15.00	17.00	27.0	46.9	73.9	60,054
	3	79.63	-	16.33	-	231.5	231.5	136,564
	Finish	186.14			114.5	278.3	392.8	301,556
C1.1_1200_TW_1	1	-	15.00	-	87.4	-	87.4	104,938
	2	45.33	15.00	15.00	27.0	44.4	71.4	58,584
	3	82.33	-	15.84	-	228.3	228.3	134,678
	Finish	192.14			114.5	272.6	387.1	298,199
C1.1_1200_TL_0.25	1	-	15.25	-	88.0	-	88.0	105,595
	2	44.64	15.25	18.00	27.2	48.4	75.6	61,186
	3	77.59	-	18.00	-	244.0	244.0	143,958
	Finish	174.14			115.2	292.4	407.6	310,739
C1.1_1200_TL_0.5	1	-	15.00	-	87.4	-	87.4	104,938
	2	45.33	15.00	17.25	27.0	47.3	74.3	60,289
	3	79.34	-	17.25	-	238.1	238.1	140,459
	Finish	180.14			114.5	285.3	399.8	305,685
C1.1_1200_TL_0.75	1	-	15.00	-	87.4	-	87.4	104,938
	2	45.33	15.00	16.44	27.0	46.1	73.1	59,605
	3	80.34	-	16.44	-	232.2	232.2	137,013
	Finish	186.14			114.5	278.3	392.8	301,556
C1.1_1200_TL_1	1	-	15.00	-	87.4	-	87.4	104,938
	2	45.33	15.00	15.70	27.0	45.2	72.2	59,049
	3	81.33	-	15.70	-	227.5	227.5	134,213
	Finish	192.14			114.5	272.6	387.1	298,199

Scenario	**Average speed**		**Average fuel consumption**			**Costs**
SHIP 2	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.1_590_TW_0.25	17.08	17.08	120.88	283.95	404.84	238,853.41
C1.1_590_TW_0.5	16.52	16.52	117.37	280.78	398.15	234,910.55
C1.1_590_TW_0.75	15.97	15.97	117.37	274.44	391.80	231,164.74
C1.1_590_TW_1	15.49	15.49	114.45	272.63	387.09	228,382.30
C1.1_590_TL_0.25	17.08	17.08	121.19	283.64	404.84	238,853.41
C1.1_590_TL_0.5	16.52	16.52	119.19	278.96	398.15	234,910.55
C1.1_590_TL_0.75	15.97	15.97	117.29	274.51	391.80	231,164.74
C1.1_590_TL_1	15.49	15.49	115.88	271.21	387.09	228,382.30
C1.1_920_TW_0.25	16.30	17.44	118.44	287.13	405.57	278,371.72
C1.1_920_TW_0.5	15.46	17.00	115.81	282.92	398.73	273,464.34
C1.1_920_TW_0.75	15.00	16.44	114.45	278.32	392.78	269,508.53
C1.1_920_TW_1	15.00	15.70	114.45	272.63	387.09	266,152.12
C1.1_920_TL_0.25	16.00	17.59	117.37	288.52	405.89	278,208.66
C1.1_920_TL_0.5	15.46	17.00	115.81	282.92	398.73	273,464.34
C1.1_920_TL_0.75	15.00	16.44	114.45	278.32	392.78	269,508.53
C1.1_920_TL_1	15.00	15.70	114.45	272.63	387.09	266,152.12
C1.1_960_TW_0.25	16.30	17.44	118.44	287.13	405.57	283,109.23
C1.1_960_TW_0.5	15.46	17.00	115.81	282.92	398.73	278,096.57
C1.1_960_TW_0.75	15.00	16.44	114.45	278.32	392.78	274,086.69
C1.1_960_TW_1	15.00	15.70	114.45	272.63	387.09	270,730.28
C1.1_960_TL_0.25	16.00	17.59	117.37	288.52	405.89	282,903.41
C1.1_960_TL_0.5	15.46	17.00	115.81	282.92	398.73	278,096.57
C1.1_960_TL_0.75	15.00	16.44	114.45	278.32	392.78	274,086.69
C1.1_960_TL_1	15.00	15.70	114.45	272.63	387.09	270,730.28
C1.1_1020_TW_0.25	16.02	17.59	117.45	288.75	406.20	290,161.31
C1.1_1020_TW_0.5	15.46	17.00	115.81	282.92	398.73	285,044.91
C1.1_1020_TW_0.75	15.00	16.44	114.45	278.32	392.78	280,953.93
C1.1_1020_TW_1	15.00	15.70	114.45	272.63	387.09	277,597.52
C1.1_1020_TL_0.25	16.00	17.59	117.37	288.52	405.89	289,945.53
C1.1_1020_TL_0.5	15.46	17.00	115.81	282.92	398.73	285,044.91
C1.1_1020_TL_0.75	15.00	16.44	114.45	278.32	392.78	280,953.93
C1.1_1020_TL_1	15.00	15.70	114.45	272.63	387.09	277,597.52
C1.1_1200_TW_0.25	16.02	17.59	117.45	288.75	406.20	311,302.11
C1.1_1200_TW_0.5	15.00	17.25	114.45	285.32	399.78	305,685.35
C1.1_1200_TW_0.75	15.00	16.44	114.45	278.32	392.78	301,555.65
C1.1_1200_TW_1	15.00	15.70	114.45	272.63	387.09	298,199.24
C1.1_1200_TL_0.25	15.25	18.00	115.17	292.43	407.60	310,739.30
C1.1_1200_TL_0.5	15.00	17.25	114.45	285.32	399.78	305,685.35
C1.1_1200_TL_0.75	15.00	16.44	114.45	278.32	392.78	301,555.65
C1.1_1200_TL_1	15.00	15.70	114.45	272.63	387.09	298,199.24

Appendix A.2: Case outputs C1.2

Situation	**Leg**	**Reference speed**	**Time limits**		**Situation**	**Time limits**	
			Lower	Upper		Lower	Upper
TW_0.25	1	18.67	-	-	TL_0.5	-	-
	2	17.69	0.44	0.94		-	6.10
	Finish		5.60	6.10		-	6.10
TW_0.5	1	18.67	-	-	TL_1	-	-
	2	17.69	0.19	1.19		-	6.35
	Finish		5.35	6.35		-	6.35
TW_0.75	1	18.67	-	-	TL_1.5	-	-
	2	17.69	-0.06	1.44		-	6.60
	Finish		5.10	6.60		-	6.60
TW_1	1	18.67	-	-	TL_2	-	-
	2	17.69	-0.31	1.69		-	6.85
	Finish		4.85	6.85		-	6.85

Leg	**Distance**	
	ECA	*Non-ECA*
1	308	-
2	529	1,661

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.2_590_TW_0.25	1	-	17.00		49.9	-	49.9	29,449
	2	18.12	17.09	17.09	86.2	270.6	356.7	210,472
	Finish	146.29			136.1	270.6	406.6	239,921
C1.2_590_TW_0.5	1	-	17.00		49.9	-	49.9	29,449
	2	18.12	16.34	16.34	82.9	260.3	343.2	202,482
	Finish	152.29			132.8	260.3	393.1	231,932
C1.2_590_TW_0.75	1	-	15.00		45.3	-	45.3	26,749
	2	20.53	15.90	15.90	81.1	254.7	335.8	198,137
	Finish	158.29			126.5	254.7	381.2	224,886
C1.2_590_TW_1	1	-	15.00		45.3	-	45.3	26,749
	2	20.53	15.25	15.25	78.8	247.3	326.0	192,360
	Finish	164.29			124.1	247.3	371.4	219,109
C1.2_590_TL_0.25	1	-	17.08		50.1	-	50.1	29,582
	2	18.04	17.08	17.08	86.1	270.4	356.5	210,339
	Finish	146.29			136.3	270.4	406.6	239,921
C1.2_590_TL_0.5	1	-	16.42		48.5	-	48.5	28,597
	2	18.78	16.42	16.42	83.2	261.4	344.6	203,335
	Finish	152.29			131.7	261.4	393.1	231,932
C1.2_590_TL_0.75	1	-	15.79		47.0	-	47.0	27,728
	2	19.52	15.79	15.79	80.7	253.4	334.2	197,158
	Finish	158.29			127.7	253.4	381.2	224,886
C1.2_590_TL_1	1	-	15.22		45.8	-	45.8	27,016
	2	20.26	15.22	15.22	78.6	246.9	325.6	192,093
	Finish	164.29			124.4	246.9	371.4	219,109

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.2_920_TW_0.25	1	-	16.00		47.4	-	47.4	43,637
	2	19.25	16.00	17.69	81.5	279.6	361.0	239,900
	Finish	146.29			128.9	279.6	408.5	283,537
C1.2_920_TW_0.5	1	-	15.00		45.3	-	45.3	41,711
	2	20.53	15.55	17.00	79.9	269.2	349.0	232,285
	Finish	152.29			125.2	269.2	394.4	273,996
C1.2_920_TW_0.75	1	-	15.00		45.3	-	45.3	41,711
	2	20.53	15.00	16.22	77.9	258.7	336.6	224,272
	Finish	158.29			123.2	258.7	381.9	265,982
C1.2_920_TW_1	1	-	15.00		45.3	-	45.3	41,711
	2	20.53	15.00	15.32	77.9	248.2	326.0	218,057
	Finish	164.29			123.2	248.2	371.4	259,767
C1.2_920_TL_0.25	1	-	16.00		47.4	-	47.4	43,637
	2	19.25	16.00	17.69	81.5	279.6	361.0	239,900
	Finish	146.29			128.9	279.6	408.5	283,537
C1.2_920_TL_0.5	1	-	15.35		46.1	-	46.1	42,384
	2	20.08	15.35	17.00	79.1	269.2	348.3	231,612
	Finish	152.29			125.2	269.2	394.4	273,996
C1.2_920_TL_0.75	1	-	15.00		45.3	-	45.3	41,711
	2	20.53	15.00	16.22	77.9	258.7	336.6	224,272
	Finish	158.29			123.2	258.7	381.9	265,982
C1.2_920_TL_1	1	-	15.00		45.3	-	45.3	41,711
	2	20.53	15.00	15.32	77.9	248.2	326.0	218,057
	Finish	164.29			123.2	248.2	371.4	259,767

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.2_1020_TW_0.25	1	-	15.00		45.3	-	45.3	46,244
	2	20.53	15.81	18.00	80.8	284.3	365.1	250,148
	Finish	146.29			126.1	284.3	410.4	296,393
C1.2_1020_TW_0.5	1	-	15.00		45.3	-	45.3	46,244
	2	20.53	15.00	17.22	77.9	272.6	350.4	240,246
	Finish	152.29			123.2	272.6	395.8	286,490
C1.2_1020_TW_0.75	1	-	15.00		45.3	-	45.3	46,244
	2	20.53	15.00	16.22	77.9	258.7	336.6	232,059
	Finish	158.29			123.2	258.7	381.9	278,303
C1.2_1020_TW_1	1	-	15.00		45.3	-	45.3	46,244
	2	20.53	15.00	15.32	77.9	248.2	326.0	225,843
	Finish	164.29			123.2	248.2	371.4	272,088
C1.2_1020_TL_0.25	1	-	15.51		46.4	-	46.4	47,341
	2	19.87	15.51	18.00	79.7	284.3	364.0	249,052
	Finish	146.29			126.1	284.3	410.4	296,393
C1.2_1020_TL_0.5	1	-	15.00		45.3	-	45.3	46,244
	2	20.53	15.00	17.22	77.9	272.6	350.4	240,246
	Finish	152.29			123.2	272.6	395.8	286,490
C1.2_1020_TL_0.75	1	-	15.00		45.3	-	45.3	46,244
	2	20.53	15.00	16.22	77.9	258.7	336.6	232,059
	Finish	158.29			123.2	258.7	381.9	278,303
C1.2_1020_TL_1	1	-	15.00		45.3	-	45.3	46,244
	2	20.53	15.00	15.32	77.9	248.2	326.0	225,843
	Finish	164.29			123.2	248.2	371.4	272,088

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.2_1280_TW_0.25	1	-	15.00	-	45.3	-	45.3	58,032
	2	20.53	15.00	18.37	77.9	290.6	368.4	271,100
	Finish	146.29			123.2	290.6	413.8	329,132
C1.2_1280_TW_0.5	1	-	15.00	-	45.3	-	45.3	58,032
	2	20.53	15.00	17.22	77.9	272.6	350.4	260,492
	Finish	152.29			123.2	272.6	395.8	318,524
C1.2_1280_TW_0.75	1	-	15.00	-	45.3	-	45.3	58,032
	2	20.53	15.00	16.22	77.9	258.7	336.6	252,304
	Finish	158.29			123.2	258.7	381.9	310,337
C1.2_1280_TW_1	1	-	15.00	-	45.3	-	45.3	58,032
	2	20.53	15.00	15.32	77.9	248.2	326.0	246,089
	Finish	164.29			123.2	248.2	371.4	304,121
C1.2_1280_TL_0.25	1	-	15.00	-	45.3	-	45.3	58,032
	2	20.53	15.00	18.37	77.9	290.6	368.4	271,100
	Finish	146.29			123.2	290.6	413.8	329,132
C1.2_1280_TL_0.5	1	-	15.00	-	45.3	-	45.3	58,032
	2	20.53	15.00	17.22	77.9	272.6	350.4	260,492
	Finish	152.29			123.2	272.6	395.8	318,524
C1.2_1280_TL_0.75	1	-	15.00	-	45.3	-	45.3	58,032
	2	20.53	15.00	16.22	77.9	258.7	336.6	252,304
	Finish	158.29			123.2	258.7	381.9	310,337
C1.2_1280_TL_1	1	-	15.00	-	45.3	-	45.3	58,032
	2	20.53	15.00	15.32	77.9	248.2	326.0	246,089
	Finish	164.29			123.2	248.2	371.4	304,121

Scenario	**Average speed**		**Average fuel consumption**			**Average costs**
SHIP 1	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.2_590_TW_0.25	17.08	17.08	136.1	270.6	406.6	239,921
C1.2_590_TW_0.5	16.42	16.42	132.8	260.3	393.1	231,932
C1.2_590_TW_0.75	15.79	15.79	126.5	254.7	381.2	224,886
C1.2_590_TW_1	15.22	15.22	124.1	247.3	371.4	219,109
C1.2_590_TL_0.25	17.08	17.08	136.3	270.4	406.6	239,921
C1.2_590_TL_0.5	16.42	16.42	131.7	261.4	393.1	231,932
C1.2_590_TL_0.75	15.79	15.79	127.7	253.4	381.2	224,886
C1.2_590_TL_1	15.22	15.22	124.4	246.9	371.4	219,109
C1.2_920_TW_0.25	16.00	17.69	128.9	279.6	408.5	283,537
C1.2_920_TW_0.5	15.35	17.00	125.2	269.2	394.4	273,996
C1.2_920_TW_0.75	15.00	16.22	123.2	258.7	381.9	265,982
C1.2_920_TW_1	15.00	15.32	123.2	248.2	371.4	259,767
C1.2_920_TL_0.25	16.00	17.69	128.9	279.6	408.5	283,537
C1.2_920_TL_0.5	15.35	17.00	125.2	269.2	394.4	273,996
C1.2_920_TL_0.75	15.00	16.22	123.2	258.7	381.9	265,982
C1.2_920_TL_1	15.00	15.32	123.2	248.2	371.4	259,767
C1.2_1020_TW_0.25	15.51	18.00	126.1	284.3	410.4	296,393
C1.2_1020_TW_0.5	15.00	17.22	123.2	272.6	395.8	286,490
C1.2_1020_TW_0.75	15.00	16.22	123.2	258.7	381.9	278,303
C1.2_1020_TW_1	15.00	15.32	123.2	248.2	371.4	272,088
C1.2_1020_TL_0.25	15.51	18.00	126.1	284.3	410.4	296,393
C1.2_1020_TL_0.5	15.00	17.22	123.2	272.6	395.8	286,490
C1.2_1020_TL_0.75	15.00	16.22	123.2	258.7	381.9	278,303
C1.2_1020_TL_1	15.00	15.32	123.2	248.2	371.4	272,088
C1.2_1280_TW_0.25	15.00	18.37	123.2	290.6	413.8	329,132
C1.2_1280_TW_0.5	15.00	17.22	123.2	272.6	395.8	318,524
C1.2_1280_TW_0.75	15.00	16.22	123.2	258.7	381.9	310,337
C1.2_1280_TW_1	15.00	15.32	123.2	248.2	371.4	304,121
C1.2_1280_TL_0.25	15.00	18.37	123.2	290.6	413.8	329,132
C1.2_1280_TL_0.5	15.00	17.22	123.2	272.6	395.8	318,524
C1.2_1280_TL_0.75	15.00	16.22	123.2	258.7	381.9	310,337
C1.2_1280_TL_1	15.00	15.32	123.2	248.2	371.4	304,121

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.2_590_TW_0.25	1		17.00		41.8	-	41.8	24,682
	2	18.12	17.09	17.09	72.1	226.3	298.4	176,037
	Finish	146.29			113.9	226.3	340.2	200,718
C1.2_590_TW_0.5	1		17.00		41.8	-	41.8	24,682
	2	18.12	16.34	16.34	70.5	221.2	291.7	172,110
	Finish	152.29			112.3	221.2	333.5	196,792
C1.2_590_TW_0.75	1		15.00		39.6	-	39.6	23,369
	2	20.53	15.90	15.90	69.6	218.5	288.1	169,988
	Finish	158.29			109.2	218.5	327.7	193,357
C1.2_590_TW_1	1		15.00		39.6	-	39.6	23,369
	2	20.53	15.25	15.25	68.5	214.9	283.4	167,206
	Finish	164.29			108.1	214.9	323.0	190,575
C1.2_590_TL_0.25	1		17.08		41.9	-	41.9	24,748
	2	18.04	17.08	17.08	72.0	226.2	298.3	175,970
	Finish	146.29			114.0	226.2	340.2	200,718
C1.2_590_TL_0.5	1		16.42		41.1	-	41.1	24,264
	2	18.78	16.42	16.42	70.6	221.8	292.4	172,528
	Finish	152.29			111.8	221.8	333.5	196,792
C1.2_590_TL_0.75	1		15.79		40.4	-	40.4	23,841
	2	19.52	15.79	15.79	69.4	217.9	287.3	169,517
	Finish	158.29			109.8	217.9	327.7	193,357
C1.2_590_TL_1	1		15.22		39.8	-	39.8	23,498
	2	20.26	15.22	15.22	68.4	214.8	283.2	167,077
	Finish	164.29			108.2	214.8	323.0	190,575

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.2_920_TW_0.25	1	-	16.00	-	40.6	-	40.6	37,368
	2	19.25	16.00	17.69	69.8	230.8	300.6	200,362
	Finish	146.29			110.4	230.8	341.2	237,730
C1.2_920_TW_0.5	1	-	15.00	-	39.6	-	39.6	36,440
	2	20.53	15.55	17.00	69.0	225.6	294.6	196,574
	Finish	152.29			108.6	225.6	334.2	233,014
C1.2_920_TW_0.75	1	-	15.00	-	39.6	-	39.6	36,440
	2	20.53	15.00	16.22	68.0	220.5	288.5	192,663
	Finish	158.29			107.6	220.5	328.1	229,103
C1.2_920_TW_1	1	-	15.00	-	39.6	-	39.6	36,440
	2	20.53	15.00	15.32	68.0	215.4	283.4	189,655
	Finish	164.29			107.6	215.4	323.0	226,095
C1.2_920_TL_0.25	1	-	16.00	-	40.6	-	40.6	37,368
	2	19.25	16.00	17.69	69.8	230.8	300.6	200,362
	Finish	146.29			110.4	230.8	341.2	237,730
C1.2_920_TL_0.5	1	-	15.35	-	40.0	-	40.0	36,764
	2	20.08	15.35	17.00	68.6	225.6	294.2	196,250
	Finish	152.29			108.6	225.6	334.2	233,014
C1.2_920_TL_0.75	1	-	15.00	-	39.6	-	39.6	36,440
	2	20.53	15.00	16.22	68.0	220.5	288.5	192,663
	Finish	158.29			107.6	220.5	328.1	229,103
C1.2_920_TL_1	1	-	15.00	-	39.6	-	39.6	36,440
	2	20.53	15.00	15.32	68.0	215.4	283.4	189,655
	Finish	164.29			107.6	215.4	323.0	226,095

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.2_1020_TW_0.25	1	-	16.00	-	40.6	-	40.6	41,430
	2	19.25	16.00	17.69	69.8	230.8	300.6	207,338
	Finish	146.29			110.4	230.8	341.2	248,768
C1.2_1020_TW_0.5	1	-	15.00	-	39.6	-	39.6	40,401
	2	20.53	15.55	17.00	69.0	225.6	294.6	203,473
	Finish	152.29			108.6	225.6	334.2	243,874
C1.2_1020_TW_0.75	1	-	15.00	-	39.6	-	39.6	40,401
	2	20.53	15.00	16.22	68.0	220.5	288.5	199,466
	Finish	158.29			107.6	220.5	328.1	239,867
C1.2_1020_TW_1	1	-	15.00	-	39.6	-	39.6	40,401
	2	20.53	15.00	15.32	68.0	215.4	283.4	196,458
	Finish	164.29			107.6	215.4	323.0	236,859
C1.2_1020_TL_0.25	1	-	16.00	-	40.6	-	40.6	41,430
	2	19.25	16.00	17.69	69.8	230.8	300.6	207,338
	Finish	146.29			110.4	230.8	341.2	248,768
C1.2_1020_TL_0.5	1	-	15.35	-	40.0	-	40.0	40,761
	2	20.08	15.35	17.00	68.6	225.6	294.2	203,113
	Finish	152.29			108.6	225.6	334.2	243,874
C1.2_1020_TL_0.75	1	-	15.00	-	39.6	-	39.6	40,401
	2	20.53	15.00	16.22	68.0	220.5	288.5	199,466
	Finish	158.29			107.6	220.5	328.1	239,867
C1.2_1020_TL_1	1	-	15.00	-	39.6	-	39.6	40,401
	2	20.53	15.00	15.32	68.0	215.4	283.4	196,458
	Finish	164.29			107.6	215.4	323.0	236,859

Situation	**Leg**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2			*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.2_1280_TW_0.25	1	-	15.00	-	39.6	-	39.6	50,699
	2	20.53	15.81	18.00	69.4	233.2	302.6	226,459
	Finish	146.29			109.0	233.2	342.2	277,158
C1.2_1280_TW_0.5	1	-	15.00	-	39.6	-	39.6	50,699
	2	20.53	15.00	17.22	68.0	227.3	295.3	221,188
	Finish	152.29			107.6	227.3	334.9	271,887
C1.2_1280_TW_0.75	1	-	15.00	-	39.6	-	39.6	50,699
	2	20.53	15.00	16.22	68.0	220.5	288.5	217,154
	Finish	158.29			107.6	220.5	328.1	267,853
C1.2_1280_TW_1	1	-	15.00	-	39.6	-	39.6	50,699
	2	20.53	15.00	15.32	68.0	215.4	283.4	214,146
	Finish	164.29			107.6	215.4	323.0	264,845
C1.2_1280_TL_0.25	1	-	15.51	-	40.1	-	40.1	51,362
	2	19.87	15.51	18.00	68.9	233.2	302.1	225,796
	Finish	146.29			109.0	233.2	342.2	277,158
C1.2_1280_TL_0.5	1	-	15.00	-	39.6	-	39.6	50,699
	2	20.53	15.00	17.22	68.0	227.3	295.3	221,188
	Finish	152.29			107.6	227.3	334.9	271,887
C1.2_1280_TL_0.75	1	-	15.00	-	39.6	-	39.6	50,699
	2	20.53	15.00	16.22	68.0	220.5	288.5	217,154
	Finish	158.29			107.6	220.5	328.1	267,853
C1.2_1280_TL_1	1	-	15.00	-	39.6	-	39.6	50,699
	2	20.53	15.00	15.32	68.0	215.4	283.4	214,146
	Finish	164.29			107.6	215.4	323.0	264,845

Scenario	**Average speed**		**Average fuel consumption**			**Average costs**
SHIP 1	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C1.2_590_TW_0.25	17.08	17.08	113.9	226.3	340.2	200,718
C1.2_590_TW_0.5	16.42	16.42	112.3	221.2	333.5	196,792
C1.2_590_TW_0.75	15.79	15.79	109.2	218.5	327.7	193,357
C1.2_590_TW_1	15.22	15.22	108.1	214.9	323.0	190,575
C1.2_590_TL_0.25	17.08	17.08	114.0	226.2	340.2	200,718
C1.2_590_TL_0.5	16.42	16.42	111.8	221.8	333.5	196,792
C1.2_590_TL_0.75	15.79	15.79	109.8	217.9	327.7	193,357
C1.2_590_TL_1	15.22	15.22	108.2	214.8	323.0	190,575
C1.2_920_TW_0.25	16.00	17.69	110.4	230.8	341.2	237,730
C1.2_920_TW_0.5	15.35	17.00	108.6	225.6	334.2	233,014
C1.2_920_TW_0.75	15.00	16.22	107.6	220.5	328.1	229,103
C1.2_920_TW_1	15.00	15.32	107.6	215.4	323.0	226,095
C1.2_920_TL_0.25	16.00	17.69	110.4	230.8	341.2	237,730
C1.2_920_TL_0.5	15.35	17.00	108.6	225.6	334.2	233,014
C1.2_920_TL_0.75	15.00	16.22	107.6	220.5	328.1	229,103
C1.2_920_TL_1	15.00	15.32	107.6	215.4	323.0	226,095
C1.2_1020_TW_0.25	16.00	17.69	110.4	230.8	341.2	248,768
C1.2_1020_TW_0.5	15.35	17.00	108.6	225.6	334.2	243,874
C1.2_1020_TW_0.75	15.00	16.22	107.6	220.5	328.1	239,867
C1.2_1020_TW_1	15.00	15.32	107.6	215.4	323.0	236,859
C1.2_1020_TL_0.25	16.00	17.69	110.4	230.8	341.2	248,768
C1.2_1020_TL_0.5	15.35	17.00	108.6	225.6	334.2	243,874
C1.2_1020_TL_0.75	15.00	16.22	107.6	220.5	328.1	239,867
C1.2_1020_TL_1	15.00	15.32	107.6	215.4	323.0	236,859
C1.2_1280_TW_0.25	15.51	18.00	109.0	233.2	342.2	277,158
C1.2_1280_TW_0.5	15.00	17.22	107.6	227.3	334.9	271,887
C1.2_1280_TW_0.75	15.00	16.22	107.6	220.5	328.1	267,853
C1.2_1280_TW_1	15.00	15.32	107.6	215.4	323.0	264,845
C1.2_1280_TL_0.25	15.51	18.00	109.0	233.2	342.2	277,158
C1.2_1280_TL_0.5	15.00	17.22	107.6	227.3	334.9	271,887
C1.2_1280_TL_0.75	15.00	16.22	107.6	220.5	328.1	267,853
C1.2_1280_TL_1	15.00	15.32	107.6	215.4	323.0	264,845

Appendix A.3: Case outputs C2.1

Situation	**Leg**	**Number of leg options**	**Reference speed**	**Time limits**		**Situation**	**Time limits**	
				Lower	Upper		Lower	Upper
TW_0.5	1	1	18.67	-	-	TL_0.5	-	-
	2	1	17.69	0.18	1.18		-	10.80
	3	5	17.32	6.95	7.95		-	10.80
	Finish			9.80	10.80		-	10.80
TW_1	1	1	18.67	-	-	TL_1	-	-
	2	1	17.69	-0.32	1.68		-	11.30
	3	5	17.32	6.45	8.45		-	11.30
	Finish			9.30	11.30		-	11.30
TW_1.5	1	1	18.67	-	-	TL_1.5	-	-
	2	1	17.69	-0.82	2.18		-	11.80
	3	5	17.32	5.95	8.95		-	11.80
	Finish			8.80	11.80		-	11.80
TW_2	1	1	18.67	-	-	TL_2	-	-
	2	1	17.69	-1.32	2.68		-	12.30
	3	5	17.32	5.45	9.45		-	12.30
	Finish			8.30	12.30		-	12.30
TW_2.5	1	1	18.67	-	-	TL_2.5	-	-
	2	1	17.69	-1.82	3.18		-	12.80
	3	5	17.32	4.95	9.95		-	12.80
	Finish			7.80	12.80		-	12.80

Leg	**Leg option**	**Distance**	
		ECA	*Non-ECA*
1	-	306	0
2	-	772	2,101
3	1	1,186	0
	2	514	831
	3	476	890
	4	445	987
	5	879	352

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_590_TW_0.5	1	1	-	16.00	-	47.1	-	47.1	27,803
	2	1	19.13	17.00	17.00	125.1	340.5	465.6	274,701
	3	1	188.13	16.69	-	189.2	-	189.2	111,624
	Finish		259.26			361.4	340.5	701.9	414,128
C2.1_590_TW_1	1	1	-	16.00	-	47.1	-	47.1	27,803
	2	1	19.13	16.15	16.15	119.8	326.0	445.8	263,046
	3	1	197.14	16.00	-	182.6	-	182.6	107,760
	Finish		271.26			349.6	326.0	675.6	398,609
C2.1_590_TW_1.5	1	1	-	15.00	-	45.0	-	45.0	26,575
	2	1	20.40	15.23	15.23	114.9	312.6	427.5	252,207
	3	1	209.14	16.00	-	182.6	-	182.6	107,760
	Finish		283.26			342.6	312.6	655.2	386,542
C2.1_590_TW_2	1	1	-	15.00	-	45.0	-	45.0	26,575
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	249,514
	3	1	211.93	15.00	-	174.6	-	174.6	103,002
	Finish		291.00			333.3	309.3	642.5	379,092
C2.1_590_TW_2.5	1	1	-	15.00	-	45.0	-	45.0	26,575
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	249,514
	3	1	211.93	15.00	-	174.6	-	174.6	103,002
	Finish		291.00			333.3	309.3	642.5	379,092
C2.1_590_TL_0.5	1	1	-	16.84	-	49.2	-	49.2	29,032
	2	1	18.18	16.84	16.84	124.1	337.9	462.0	272,575
	3	1	188.82	16.84	-	190.7	-	190.7	112,521
	Finish		259.26			364.1	337.9	701.9	414,128
C2.1_590_TL_1	1	1	-	16.10	-	47.4	-	47.4	27,944
	2	1	19.02	16.10	16.10	119.5	325.2	444.7	262,361
	3	1	197.56	16.10	-	183.6	-	183.6	108,305
	Finish		271.26			350.4	325.2	675.6	398,609
C2.1_590_TL_1.5	1	1	-	15.43	-	45.9	-	45.9	27,098
	2	1	19.86	15.43	15.43	115.9	315.3	431.2	254,418
	3	1	206.30	15.43	-	178.0	-	178.0	105,026
	Finish		283.26			339.8	315.3	655.2	386,542
C2.1_590_TL_2	1	1	-	15.00	-	45.0	-	45.0	26,575
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	249,514
	3	1	211.93	15.00	-	174.6	-	174.6	103,002
	Finish		291.00			333.3	309.3	642.5	379,092
C2.1_590_TL_2.5	1	1	-	15.00	-	45.0	-	45.0	26,575
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	249,514
	3	1	211.93	15.00	-	174.6	-	174.6	103,002
	Finish		291.00			333.3	309.3	642.5	379,092

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_760_TW_0.5	1	1	-	16.00	-	47.1	-	47.1	35,343
	2	1	19.13	16.52	17.00	122.1	340.5	462.6	292,462
	3	1	189.50	17.00	-	192.2	-	192.2	144,151
	Finish		259.26			361.4	340.5	701.9	471,957
C2.1_760_TW_1	1	1	-	16.00	-	47.1	-	47.1	35,343
	2	1	19.13	16.00	16.20	118.9	327.0	445.8	282,068
	3	1	197.14	16.00	-	182.6	-	182.6	136,983
	Finish		271.26			348.7	327.0	675.6	454,394
C2.1_760_TW_1.5	1	1	-	15.00	-	45.0	-	45.0	33,782
	2	1	20.40	15.00	16.00	113.6	323.6	437.2	276,126
	3	5	203.18	15.14	16.00	130.2	54.2	184.4	129,657
	Finish		283.26			288.9	377.8	666.7	439,565
C2.1_760_TW_2	1	1	-	15.00	-	45.0	-	45.0	33,782
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	267,696
	3	5	211.93	15.00	15.00	129.4	51.8	181.2	127,612
	Finish		294.00			288.1	361.1	649.2	429,091
C2.1_760_TW_2.5	1	1	-	15.00	-	45.0	-	45.0	33,782
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	267,696
	3	5	211.93	15.00	15.00	129.4	51.8	181.2	127,612
	Finish		294.00			288.1	361.1	649.2	429,091
C2.1_760_TL_0.5	1	1	-	16.70	-	48.9	-	48.9	36,638
	2	1	18.34	16.70	17.00	123.2	340.5	463.7	293,319
	3	1	188.19	16.70	-	189.3	-	189.3	142,001
	Finish		259.26			361.4	340.5	701.9	471,957
C2.1_760_TL_1	1	1	-	16.00	-	47.1	-	47.1	35,343
	2	1	19.13	16.00	16.20	118.9	327.0	445.8	282,068
	3	1	197.14	16.00	-	182.6	-	182.6	136,983
	Finish		271.26			348.7	327.0	675.6	454,394
C2.1_760_TL_1.5	1	1	-	15.06	-	45.2	-	45.2	33,881
	2	1	20.32	15.06	16.00	114.0	323.6	437.5	276,375
	3	5	202.89	15.06	16.00	129.8	54.2	184.0	129,309
	Finish		283.26			288.9	377.8	666.7	439,565
C2.1_760_TL_2	1	1	-	15.00	-	45.0	-	45.0	33,782
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	267,696
	3	5	211.93	15.00	15.00	129.4	51.8	181.2	127,612
	Finish		294.00			288.1	361.1	649.2	429,091
C2.1_760_TL_2.5	1	1	-	15.00	-	45.0	-	45.0	33,782
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	267,696
	3	5	211.93	15.00	15.00	129.4	51.8	181.2	127,612
	Finish		294.00			288.1	361.1	649.2	429,091

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_900_TW_0.5	1	1	-	16.00	-	47.1	-	47.1	42,412
	2	1	19.13	16.00	18.00	118.9	359.6	478.5	319,176
	3	5	184.10	16.00	17.42	135.4	58.4	193.7	156,273
	Finish		259.26			301.4	418.0	719.4	517,860
C2.1_900_TW_1	1	1	-	15.00	-	45.0	-	45.0	40,539
	2	1	20.40	15.00	17.00	113.6	340.5	454.1	303,161
	3	5	195.45	15.96	17.00	135.1	57.0	192.1	155,245
	Finish		271.26			293.8	397.5	691.3	498,945
C2.1_900_TW_1.5	1	1	-	15.00	-	45.0	-	45.0	40,539
	2	1	20.40	15.00	16.07	113.6	324.7	438.3	293,840
	3	5	202.66	15.00	16.00	129.4	54.2	183.6	148,433
	Finish		283.26			288.1	378.9	667.0	482,812
C2.1_900_TW_2	1	1	-	15.00	-	45.0	-	45.0	40,539
	2	1	20.40	15.00	15.72	113.6	319.6	433.2	290,845
	3	2	205.60	15.00	15.00	75.7	122.3	198.0	140,265
	Finish		295.26			234.3	441.9	676.3	471,649
C2.1_900_TW_2.5	1	1	-	15.00	-	45.0	-	45.0	40,539
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	284,742
	3	2	211.93	15.00	15.00	75.7	122.3	198.0	140,265
	Finish		301.60			234.3	431.6	665.9	465,546
C2.1_900_TL_0.5	1	1	-	16.00	-	47.1	-	47.1	42,412
	2	1	19.13	16.00	17.92	118.9	358.0	476.9	318,229
	3	5	184.67	16.00	17.92	135.4	60.0	195.3	157,219
	Finish		259.26			301.4	418.0	719.4	517,860
C2.1_900_TL_1	1	1	-	15.43	-	45.9	-	45.9	41,342
	2	1	19.85	15.43	17.00	115.9	340.5	456.4	305,188
	3	5	193.53	15.43	17.00	132.0	57.0	189.0	152,414
	Finish		271.26			293.8	397.5	691.3	498,945
C2.1_900_TL_1.5	1	1	-	15.00	-	45.0	-	45.0	40,539
	2	1	20.40	15.00	16.06	113.6	324.5	438.2	293,744
	3	5	202.74	15.00	16.06	129.4	54.4	183.8	148,529
	Finish		283.26			288.1	378.9	667.0	482,812
C2.1_900_TL_2	1	1	-	15.00	-	45.0	-	45.0	40,539
	2	1	20.40	15.00	15.52	113.6	316.7	430.3	289,115
	3	2	207.39	15.00	15.52	75.7	125.3	200.9	141,995
	Finish		295.26			234.3	441.9	676.3	471,649
C2.1_900_TL_2.5	1	1	-	15.00	-	45.0	-	45.0	40,539
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	284,742
	3	2	211.93	15.00	15.00	75.7	122.3	198.0	140,265
	Finish		301.60			234.3	431.6	665.9	465,546

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_920_TW_0.5	1	1	-	16.00	-	47.1	-	47.1	43,354
	2	1	19.13	16.00	18.00	118.9	359.6	478.5	321,553
	3	5	184.10	16.00	17.42	135.4	58.4	193.7	158,980
	Finish		259.26			301.4	418.0	719.4	523,887
C2.1_920_TW_1	1	1	-	15.00	-	45.0	-	45.0	41,440
	2	1	20.40	15.00	17.00	113.6	340.5	454.1	305,434
	3	5	195.45	15.96	17.00	135.1	57.0	192.1	157,947
	Finish		271.26			293.8	397.5	691.3	504,821
C2.1_920_TW_1.5	1	1	-	15.00	-	45.0	-	45.0	41,440
	2	1	20.40	15.00	16.07	113.6	324.7	438.3	296,113
	3	5	202.66	15.00	16.00	129.4	54.2	183.6	151,020
	Finish		283.26			288.1	378.9	667.0	488,573
C2.1_920_TW_2	1	1	-	15.00	-	45.0	-	45.0	41,440
	2	1	20.40	15.00	15.72	113.6	319.6	433.2	293,118
	3	2	205.60	15.00	15.00	75.7	122.3	198.0	141,779
	Finish		295.26			234.3	441.9	676.3	476,336
C2.1_920_TW_2.5	1	1	-	15.00	-	45.0	-	45.0	41,440
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	287,015
	3	3	211.93	15.00	15.00	70.1	131.0	201.1	141,757
	Finish		303.00			228.7	440.3	669.0	470,211
C2.1_920_TL_0.5	1	1	-	16.00	-	47.1	-	47.1	43,354
	2	1	19.13	16.00	17.92	118.9	358.0	476.9	320,607
	3	5	184.67	16.00	17.92	135.4	60.0	195.3	159,926
	Finish		259.26			301.4	418.0	719.4	523,887
C2.1_920_TL_1	1	1	-	15.43	-	45.9	-	45.9	42,261
	2	1	19.85	15.43	17.00	115.9	340.5	456.4	307,506
	3	5	193.53	15.43	17.00	132.0	57.0	189.0	155,054
	Finish		271.26			293.8	397.5	691.3	504,821
C2.1_920_TL_1.5	1	1	-	15.00	-	45.0	-	45.0	41,440
	2	1	20.40	15.00	16.06	113.6	324.5	438.2	296,017
	3	5	202.74	15.00	16.06	129.4	54.4	183.8	151,116
	Finish		283.26			288.1	378.9	667.0	488,573
C2.1_920_TL_2	1	1	-	15.00	-	45.0	-	45.0	41,440
	2	1	20.40	15.00	15.52	113.6	316.7	430.3	291,388
	3	2	207.39	15.00	15.52	75.7	125.3	200.9	143,508
	Finish		295.26			234.3	441.9	676.3	476,336
C2.1_920_TL_2.5	1	1	-	15.00	-	45.0	-	45.0	41,440
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	287,015
	3	3	211.93	15.00	15.00	70.1	131.0	201.1	141,757
	Finish		303.00			228.7	440.3	669.0	470,211

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_970_TW_0.5	1	1	-	16.00	-	47.1	-	47.1	45,710
	2	1	19.13	16.00	18.00	118.9	359.6	478.5	327,498
	3	5	184.10	16.00	17.42	135.4	58.4	193.7	165,748
	Finish		259.26			301.4	418.0	719.4	538,956
C2.1_970_TW_1	1	1	-	16.00	-	47.1	-	47.1	45,710
	2	1	19.13	16.00	17.10	118.9	342.5	461.3	317,373
	3	2	190.25	16.00	17.00	79.2	134.7	213.8	156,237
	Finish		271.26			245.2	477.1	722.3	519,320
C2.1_970_TW_1.5	1	1	-	15.00	-	45.0	-	45.0	43,692
	2	1	20.40	15.00	16.79	113.6	337.0	450.6	309,043
	3	2	197.06	15.00	16.00	75.7	128.0	203.6	148,896
	Finish		283.26			234.3	464.9	699.3	501,630
C2.1_970_TW_2	1	1	-	15.00	-	45.0	-	45.0	43,692
	2	1	20.40	15.00	15.72	113.6	319.6	433.2	298,800
	3	2	205.60	15.00	15.00	75.7	122.3	198.0	145,562
	Finish		295.26			234.3	441.9	676.3	488,053
C2.1_970_TW_2.5	1	1	-	15.00	-	45.0	-	45.0	43,692
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	292,697
	3	3	211.93	15.00	15.00	70.1	131.0	201.1	145,260
	Finish		303.00			228.7	440.3	669.0	481,649
C2.1_970_TL_0.5	1	1	-	16.00	-	47.1	-	47.1	45,710
	2	1	19.13	16.00	17.92	118.9	358.0	476.9	326,552
	3	5	184.67	16.00	17.92	135.4	60.0	195.3	166,694
	Finish		259.26			301.4	418.0	719.4	538,956
C2.1_970_TL_1	1	1	-	16.00	-	47.1	-	47.1	45,710
	2	1	19.13	16.00	17.07	118.9	341.9	460.8	317,043
	3	2	190.46	16.00	17.07	79.2	135.2	214.4	156,567
	Finish		271.26			245.2	477.1	722.3	519,320
C2.1_970_TL_1.5	1	1	-	15.00	-	45.0	-	45.0	43,692
	2	1	20.40	15.00	16.57	113.6	333.2	446.8	306,799
	3	2	198.79	15.00	16.57	75.7	131.8	207.4	151,139
	Finish		283.26			234.3	464.9	699.3	501,630
C2.1_970_TL_2	1	1	-	15.00	-	45.0	-	45.0	43,692
	2	1	20.40	15.00	15.52	113.6	316.7	430.3	297,070
	3	2	207.39	15.00	15.52	75.7	125.3	200.9	147,291
	Finish		295.26			234.3	441.9	676.3	488,053
C2.1_970_TL_2.5	1	1	-	15.00	-	45.0	-	45.0	43,692
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	292,697
	3	3	211.93	15.00	15.00	70.1	131.0	201.1	145,260
	Finish		303.00			228.7	440.3	669.0	481,649

Situation	Leg	Chosen leg option	Start time [hours]	Speed		Fuel consumption			Costs
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_1020_TW_0.5	1	1	-	16.00	-	47.1	-	47.1	48,066
	2	1	19.13	16.00	18.51	118.9	370.5	489.4	339,879
	3	2	184.10	16.00	18.00	79.2	142.2	221.4	164,660
	Finish		259.26			245.2	512.8	757.9	552,606
C2.1_1020_TW_1	1	1	-	15.00	-	45.0	-	45.0	45,944
	2	1	19.13	15.00	18.00	113.6	359.6	473.3	328,088
	3	2	190.25	15.00	17.18	75.7	136.0	211.7	157,412
	Finish		271.26			234.3	495.6	730.0	531,444
C2.1_1020_TW_1.5	1	1	-	15.00	-	45.0	-	45.0	45,944
	2	1	20.40	15.00	16.79	113.6	337.0	450.6	314,724
	3	2	197.06	15.00	16.00	75.7	128.0	203.6	152,679
	Finish		283.26			234.3	464.9	699.3	513,347
C2.1_1020_TW_2	1	1	-	15.00	-	45.0	-	45.0	45,944
	2	1	20.40	15.00	15.72	113.6	319.6	433.2	304,481
	3	2	205.60	15.00	15.00	75.7	122.3	198.0	149,345
	Finish		295.26			234.3	441.9	676.3	499,770
C2.1_1020_TW_2.5	1	1	-	15.00	-	45.0	-	45.0	45,944
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	298,379
	3	3	211.93	15.00	15.00	70.1	131.0	201.1	148,763
	Finish		303.00			228.7	440.3	669.0	493,086
C2.1_1020_TL_0.5	1	1	-	16.00	-	47.1	-	47.1	48,066
	2	1	19.13	16.00	18.36	118.9	367.4	486.3	338,054
	3	2	184.67	16.00	18.36	79.2	145.3	224.5	166,485
	Finish		259.26			245.2	512.8	757.9	552,606
C2.1_1020_TL_1	1	1	-	15.00	-	45.0	-	45.0	45,944
	2	1	19.13	15.00	17.77	113.6	355.1	468.8	325,448
	3	2	190.46	15.00	17.77	75.7	140.5	216.1	160,051
	Finish		271.26			234.3	495.6	730.0	531,444
C2.1_1020_TL_1.5	1	1	-	15.00	-	45.0	-	45.0	45,944
	2	1	20.40	15.00	16.57	113.6	333.2	446.8	312,481
	3	2	198.79	15.00	16.57	75.7	131.8	207.4	154,922
	Finish		283.26			234.3	464.9	699.3	513,347
C2.1_1020_TL_2	1	1	-	15.00	-	45.0	-	45.0	45,944
	2	1	20.40	15.00	15.52	113.6	316.7	430.3	302,752
	3	2	207.39	15.00	15.52	75.7	125.3	200.9	151,074
	Finish		295.26			234.3	441.9	676.3	499,770
C2.1_1020_TL_2.5	1	1	-	15.00	-	45.0	-	45.0	45,944
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	298,379
	3	3	211.93	15.00	15.00	70.1	131.0	201.1	148,763
	Finish		303.00			228.7	440.3	669.0	493,086

Situation	**Leg**	**Chosen leg option**	**Start time**	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			[hours]	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_1200_TW_0.5	1	1	-	16.00	-	47.1	-	47.1	56,549
	2	1	19.13	16.00	18.51	118.9	370.5	489.4	361,279
	3	2	180.97	16.00	18.00	79.2	142.2	221.4	178,909
	Finish		259.26			245.2	512.8	757.9	596,736
C2.1_1200_TW_1	1	1	-	15.00	-	45.0	-	45.0	54,052
	2	1	20.40	15.00	18.00	113.6	359.6	473.3	348,543
	3	2	188.59	15.00	17.18	75.7	136.0	211.7	171,031
	Finish		271.26			234.3	495.6	730.0	573,626
C2.1_1200_TW_1.5	1	1	-	15.00	-	45.0	-	45.0	54,052
	2	1	20.40	15.00	16.79	113.6	337.0	450.6	335,179
	3	2	197.06	15.00	16.00	75.7	128.0	203.6	166,298
	Finish		283.26			234.3	464.9	699.3	555,529
C2.1_1200_TW_2	1	1	-	15.00	-	45.0	-	45.0	54,052
	2	1	20.40	15.00	15.88	113.6	321.9	435.5	326,284
	3	3	204.20	15.00	15.00	70.1	131.0	201.1	161,375
	Finish		295.26			228.7	452.9	681.7	541,712
C2.1_1200_TW_2.5	1	1	-	15.00	-	45.0	-	45.0	54,052
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	318,834
	3	3	211.93	15.00	15.00	70.1	131.0	201.1	161,375
	Finish		303.00			228.7	440.3	669.0	534,261
C2.1_1200_TL_0.5	1	1	-	16.00	-	47.1	-	47.1	56,549
	2	1	19.13	16.00	18.36	118.9	367.4	486.3	359,454
	3	2	181.86	16.00	18.36	79.2	145.3	224.5	180,733
	Finish		259.26			245.2	512.8	757.9	596,736
C2.1_1200_TL_1	1	1	-	15.00	-	45.0	-	45.0	54,052
	2	1	20.40	15.00	17.77	113.6	355.1	468.8	345,903
	3	2	190.19	15.00	17.77	75.7	140.5	216.1	173,670
	Finish		271.26			234.3	495.6	730.0	573,626
C2.1_1200_TL_1.5	1	1	-	15.00	-	45.0	-	45.0	54,052
	2	1	20.40	15.00	16.57	113.6	333.2	446.8	332,936
	3	2	198.79	15.00	16.57	75.7	131.8	207.4	168,541
	Finish		283.26			234.3	464.9	699.3	555,529
C2.1_1200_TL_2	1	1	-	15.00	-	45.0	-	45.0	54,052
	2	1	20.40	15.00	15.62	113.6	318.1	431.8	324,067
	3	3	206.50	15.00	15.62	70.1	134.8	204.8	163,592
	Finish		295.26			228.7	452.9	681.7	541,712
C2.1_1200_TL_2.5	1	1	-	15.00	-	45.0	-	45.0	54,052
	2	1	20.40	15.00	15.00	113.6	309.3	422.9	318,834
	3	3	211.93	15.00	15.00	70.1	131.0	201.1	161,375
	Finish		303.00			228.7	440.3	669.0	534,261

Situation	**Leg**	**Chosen leg option**	**Start time**	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			[hours]	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_2000_TW_0.5	1	1	-	15.00	-	45.0	-	45.0	90,086
	2	1	20.40	15.00	19.32	113.6	388.6	502.2	456,529
	3	3	180.69	15.00	19.00	70.1	161.4	231.5	235,371
	Finish		259.26			228.7	550.0	778.7	781,986
C2.1_2000_TW_1.5	1	1	-	15.00	-	45.0	-	45.0	90,086
	2	1	20.40	15.00	16.94	113.6	339.5	453.1	427,583
	3	3	195.90	15.00	16.00	70.1	137.1	207.1	221,000
	Finish		283.26			228.7	476.6	705.3	738,669
C2.1_2000_TW_2.5	1	1	-	15.00	-	45.0	-	45.0	90,086
	2	1	20.40	15.00	16.00	91.7	380.7	472.4	408,017
	3	3	216.43	15.00	15.06	70.1	131.4	201.5	217,658
	Finish		307.26			206.8	512.1	718.9	715,762
C2.1_2000_TL_0.5	1	1	-	15.00	-	45.0	-	45.0	90,086
	2	1	20.40	15.00	19.22	113.6	386.3	500.0	455,211
	3	3	181.21	15.00	19.22	70.1	163.7	233.7	236,689
	Finish		259.26			228.7	550.0	778.7	781,986
C2.1_2000_TL_1.5	1	1	-	15.00	-	45.0	-	45.0	90,086
	2	1	20.40	15.00	16.66	113.6	334.8	448.4	424,783
	3	3	198.07	15.00	16.66	70.1	141.8	211.9	223,800
	Finish		283.26			228.7	476.6	705.3	738,669
C2.1_2000_TL_2.5	1	1	-	15.00	-	45.0	-	45.0	90,086
	2	1	20.40	15.00	15.75	91.7	376.5	468.2	405,560
	3	3	218.99	15.00	15.75	70.1	135.6	205.6	220,115
	Finish		307.26			206.8	512.1	718.9	715,762

Situation	**Leg**	**Chosen leg option**	**Start time**	**Speed**		**Fuel consumption**			**Costs**
SHIP 1			[hours]	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_3000_TW_0.5	1	1	-	15.00	-	45.0	-	45.0	135,130
	2	1	20.40	15.00	20.43	91.7	488.9	580.6	563,568
	3	3	183.03	15.00	20.00	70.1	171.4	241.5	311,336
	Finish		259.26			206.8	660.3	867.1	1,010,034
C2.1_3000_TW_1.5	1	1	-	15.00	-	45.0	-	45.0	135,130
	2	1	20.40	15.00	18.00	91.7	423.1	514.8	524,760
	3	3	199.27	15.00	17.03	70.1	144.5	214.6	295,448
	Finish		283.26			206.8	567.6	774.4	955,338
C2.1_3000_TW_2.5	1	1	-	15.00	-	45.0	-	45.0	135,130
	2	1	20.40	15.00	16.06	91.7	381.8	473.5	500,402
	3	4	215.91	15.00	16.00	65.5	152.0	217.5	286,191
	Finish		307.26			202.3	533.8	736.1	921,723
C2.1_3000_TL_0.5	1	1	-	15.00	-	45.0	-	45.0	135,130
	2	1	20.40	15.00	20.31	91.7	485.5	577.2	561,570
	3	3	183.69	15.00	20.31	70.1	174.8	244.9	313,334
	Finish		259.26			206.8	660.3	867.1	1,010,034
C2.1_3000_TL_1.5	1	1	-	15.00	-	45.0	-	45.0	135,130
	2	1	20.40	15.00	17.74	91.7	417.3	509.1	521,353
	3	3	201.34	15.00	17.74	70.1	150.3	220.3	298,855
	Finish		283.26			206.8	567.6	774.4	955,338
C2.1_3000_TL_2.5	1	1	-	15.00	-	45.0	-	45.0	135,130
	2	1	20.40	15.00	16.04	91.7	381.5	473.2	500,208
	3	4	216.06	15.00	16.04	65.5	152.3	217.8	286,385
	Finish		307.26			202.3	533.8	736.1	921,723

Situation	**Average speed**		**Total fuel consumption**			**Costs**	**Total distance**	
SHIP 1	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*		*ECA*	*Non-ECA*
C2.1c_590_TW_1	16.84	16.84	361.4	340.5	701.9	414,128	2,264	2,101
C2.1c_590_TW_2	16.10	16.10	349.6	326.0	675.6	398,609	2,264	2,101
C2.1c_590_TW_3	15.43	15.43	342.6	312.6	655.2	386,542	2,264	2,101
C2.1c_590_TW_4	15.00	15.00	333.3	309.3	642.5	379,092	2,264	2,101
C2.1c_590_TW_5	15.00	15.00	333.3	309.3	642.5	379,092	2,264	2,101
C2.1c_590_TL_1	16.84	16.84	364.1	337.9	701.9	414,128	2,264	2,101
C2.1c_590_TL_2	16.10	16.10	350.4	325.2	675.6	398,609	2,264	2,101
C2.1c_590_TL_3	15.43	15.43	339.8	315.3	655.2	386,542	2,264	2,101
C2.1c_590_TL_4	15.00	15.00	333.3	309.3	642.5	379,092	2,264	2,101
C2.1c_590_TL_5	15.00	15.00	333.3	309.3	642.5	379,092	2,264	2,101
C2.1c_760_TW_1	16.70	17.00	361.4	340.5	701.9	471,957	2,264	2,101
C2.1c_760_TW_2	16.00	16.20	348.7	327.0	675.6	454,394	2,264	2,101
C2.1c_760_TW_3	15.06	16.00	288.9	377.8	666.7	439,565	1,957	2,453
C2.1c_760_TW_4	15.00	15.00	288.1	361.1	649.2	429,091	1,957	2,453
C2.1c_760_TW_5	15.00	15.00	288.1	361.1	649.2	429,091	1,957	2,453
C2.1c_760_TL_1	16.70	17.00	361.4	340.5	701.9	471,957	2,264	2,101
C2.1c_760_TL_2	16.00	16.20	348.7	327.0	675.6	454,394	2,264	2,101
C2.1c_760_TL_3	15.06	16.00	288.9	377.8	666.7	439,565	1,957	2,453
C2.1c_760_TL_4	15.00	15.00	288.1	361.1	649.2	429,091	1,957	2,453
C2.1c_760_TL_5	15.00	15.00	288.1	361.1	649.2	429,091	1,957	2,453
C2.1c_900_TW_1	16.00	17.92	301.4	418.0	719.4	517,860	1,957	2,453
C2.1c_900_TW_2	15.43	17.00	293.8	397.5	691.3	498,945	1,957	2,453
C2.1c_900_TW_3	15.00	16.06	288.1	378.9	667.0	482,812	1,957	2,453
C2.1c_900_TW_4	15.00	15.52	234.3	441.9	676.3	471,649	1,592	2,932
C2.1c_900_TW_5	15.00	15.00	234.3	431.6	665.9	465,546	1,592	2,932
C2.1c_900_TL_1	16.00	17.92	301.4	418.0	719.4	517,860	1,957	2,453
C2.1c_900_TL_2	15.43	17.00	293.8	397.5	691.3	498,945	1,957	2,453
C2.1c_900_TL_3	15.00	16.06	288.1	378.9	667.0	482,812	1,957	2,453
C2.1c_900_TL_4	15.00	15.52	234.3	441.9	676.3	471,649	1,592	2,932
C2.1c_900_TL_5	15.00	15.00	234.3	431.6	665.9	465,546	1,592	2,932
C2.1c_920_TW_1	16.00	17.92	301.4	418.0	719.4	523,887	1,957	2,453
C2.1c_920_TW_2	15.43	17.00	293.8	397.5	691.3	504,821	1,957	2,453
C2.1c_920_TW_3	15.00	16.06	288.1	378.9	667.0	488,573	1,957	2,453
C2.1c_920_TW_4	15.00	15.52	234.3	441.9	676.3	476,336	1,592	2,932
C2.1c_920_TW_5	15.00	15.00	228.7	440.3	669.0	470,211	1,554	2,991
C2.1c_920_TL_1	16.00	17.92	301.4	418.0	719.4	523,887	1,957	2,453
C2.1c_920_TL_2	15.43	17.00	293.8	397.5	691.3	504,821	1,957	2,453
C2.1c_920_TL_3	15.00	16.06	288.1	378.9	667.0	488,573	1,957	2,453
C2.1c_920_TL_4	15.00	15.52	234.3	441.9	676.3	476,336	1,592	2,932
C2.1c_920_TL_5	15.00	15.00	228.7	440.3	669.0	470,211	1,554	2,991
C2.1c_970_TW_1	16.00	17.92	301.4	418.0	719.4	538,956	1,957	2,453
C2.1c_970_TW_2	16.00	17.07	245.2	477.1	722.3	519,320	1,592	2,932
C2.1c_970_TW_3	15.00	16.57	234.3	464.9	699.3	501,630	1,592	2,932
C2.1c_970_TW_4	15.00	15.52	234.3	441.9	676.3	488,053	1,592	2,932
C2.1c_970_TW_5	15.00	15.00	228.7	440.3	669.0	481,649	1,554	2,991
C2.1c_970_TL_1	16.00	17.92	301.4	418.0	719.4	538,956	1,957	2,453
C2.1c_970_TL_2	16.00	17.07	245.2	477.1	722.3	519,320	1,592	2,932
C2.1c_970_TL_3	15.00	16.57	234.3	464.9	699.3	501,630	1,592	2,932
C2.1c_970_TL_4	15.00	15.52	234.3	441.9	676.3	488,053	1,592	2,932
C2.1c_970_TL_5	15.00	15.00	228.7	440.3	669.0	481,649	1,554	2,991
C2.1c_1020_TW_1	16.00	18.36	245.2	512.8	757.9	552,606	1,592	2,932
C2.1c_1020_TW_2	15.00	17.77	234.3	495.6	730.0	531,444	1,592	2,932
C2.1c_1020_TW_3	15.00	16.57	234.3	464.9	699.3	513,347	1,592	2,932
C2.1c_1020_TW_4	15.00	15.52	234.3	441.9	676.3	499,770	1,592	2,932
C2.1c_1020_TW_5	15.00	15.00	228.7	440.3	669.0	493,086	1,554	2,991
C2.1c_1020_TL_1	16.00	18.36	245.2	512.8	757.9	552,606	1,592	2,932
C2.1c_1020_TL_2	15.00	17.77	234.3	495.6	730.0	531,444	1,592	2,932
C2.1c_1020_TL_3	15.00	16.57	234.3	464.9	699.3	513,347	1,592	2,932
C2.1c_1020_TL_4	15.00	15.52	234.3	441.9	676.3	499,770	1,592	2,932
C2.1c_1020_TL_5	15.00	15.00	228.7	440.3	669.0	493,086	1,554	2,991
C2.1c_1200_TW_1	16.00	18.36	245.2	512.8	757.9	596,736	1,592	2,932

C2.1c_1200_TW_2	15.00	17.77	234.3	495.6	730.0	573,626	1,592	2,932
C2.1c_1200_TW_3	15.00	16.57	234.3	464.9	699.3	555,529	1,592	2,932
C2.1c_1200_TW_4	15.00	15.62	228.7	452.9	681.7	541,712	1,554	2,991
C2.1c_1200_TW_5	15.00	15.00	228.7	440.3	669.0	534,261	1,554	2,991
C2.1c_1200_TL_1	16.00	18.36	245.2	512.8	757.9	596,736	1,592	2,932
C2.1c_1200_TL_2	15.00	17.77	234.3	495.6	730.0	573,626	1,592	2,932
C2.1c_1200_TL_3	15.00	16.57	234.3	464.9	699.3	555,529	1,592	2,932
C2.1c_1200_TL_4	15.00	15.62	228.7	452.9	681.7	541,712	1,554	2,991
C2.1c_1200_TL_5	15.00	15.00	228.7	440.3	669.0	534,261	1,554	2,991
C2.1c_2000_TW_1	15.00	19.22	228.7	550.0	778.7	781,986	1,554	2,991
C2.1c_2000_TW_3	15.00	16.66	228.7	476.6	705.3	738,669	1,554	2,991
C2.1c_2000_TW_5	15.00	15.75	206.8	512.1	718.9	715,762	1,405	3,362
C2.1c_2000_TL_1	15.00	19.22	228.7	550.0	778.7	781,986	1,554	2,991
C2.1c_2000_TL_3	15.00	16.66	228.7	476.6	705.3	738,669	1,554	2,991
C2.1c_2000_TL_5	15.00	15.75	206.8	512.1	718.9	715,762	1,405	3,362
C2.1c_3000_TW_1	15.00	20.31	206.8	660.3	867.1	1,010,034	1,405	3,362
C2.1c_3000_TW_3	15.00	17.74	206.8	567.6	774.4	955,338	1,405	3,362
C2.1c_3000_TW_5	15.00	16.04	202.3	533.8	736.1	921,723	1,374	3,459
C2.1c_3000_TL_1	15.00	20.31	206.8	660.3	867.1	1,010,034	1,405	3,362
C2.1c_3000_TL_3	15.00	17.74	206.8	567.6	774.4	955,338	1,405	3,362
C2.1c_3000_TL_5	15.00	16.04	202.3	533.8	736.1	921,723	1,374	3,459

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_590_TW_0.5	1	1	-	17.00	-	41.6	-	41.6	24,522
	2	1	18.00	16.76	16.76	104.1	283.4	387.5	228,648
	3	1	189.50	17.00	-	161.1	-	161.1	95,041
	Finish		259.26			306.8	283.4	590.2	348,211
C2.1_590_TW_1	1	1	-	16.00	-	40.4	-	40.4	23,809
	2	1	19.13	16.15	16.15	102.3	278.3	380.5	224,520
	3	1	197.14	16.00	-	156.4	-	156.4	92,278
	Finish		271.26			299.0	278.3	577.3	340,607
C2.1_590_TW_1.5	1	1	-	15.00	-	39.4	-	39.4	23,217
	2	1	20.40	15.65	15.65	100.9	274.6	375.5	221,574
	3	1	204.20	15.00	-	152.5	-	152.5	89,987
	Finish		283.26			292.8	274.6	567.4	334,778
C2.1_590_TW_2	1	1	-	15.00	-	39.4	-	39.4	23,217
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	217,986
	3	1	211.93	15.00	-	152.5	-	152.5	89,987
	Finish		291.00			291.2	270.2	561.3	331,190
C2.1_590_TW_2.5	1	1	-	15.00	-	39.4	-	39.4	23,217
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	217,986
	3	1	211.93	15.00	-	152.5	-	152.5	89,987
	Finish		291.00			291.2	270.2	561.3	331,190
C2.1_590_TL_0.5	1	1	-	16.84	-	41.4	-	41.4	24,411
	2	1	18.18	16.84	16.84	104.4	284.1	388.5	229,189
	3	1	188.82	16.84	-	160.4	-	160.4	94,611
	Finish		259.26			306.1	284.1	590.2	348,211
C2.1_590_TL_1	1	1	-	16.10	-	40.5	-	40.5	23,878
	2	1	19.02	16.10	16.10	102.1	277.9	380.0	224,184
	3	1	197.56	16.10	-	156.9	-	156.9	92,545
	Finish		271.26			299.4	277.9	577.3	340,607
C2.1_590_TL_1.5	1	1	-	15.43	-	39.8	-	39.8	23,469
	2	1	19.86	15.43	15.43	100.4	273.1	373.5	220,348
	3	1	206.30	15.43	-	154.2	-	154.2	90,962
	Finish		283.26			294.3	273.1	567.4	334,778
C2.1_590_TL_2	1	1	-	15.00	-	39.4	-	39.4	23,217
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	217,986
	3	1	211.93	15.00	-	152.5	-	152.5	89,987
	Finish		291.00			291.2	270.2	561.3	331,190
C2.1_590_TL_2.5	1	1	-	15.00	-	39.4	-	39.4	23,217
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	217,986
	3	1	211.93	15.00	-	152.5	-	152.5	89,987
	Finish		291.00			291.2	270.2	561.3	331,190

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_720_TW_0.5	1	1	-	16.00	-	40.4	-	40.4	29,055
	2	1	19.13	16.52	17.00	103.4	285.4	388.7	242,800
	3	1	189.50	17.00	-	161.1	-	161.1	115,982
	Finish		259.26			304.8	285.4	590.2	387,838
C2.1_720_TW_1	1	1	-	16.00	-	40.4	-	40.4	29,055
	2	1	19.13	16.00	16.20	101.8	278.7	380.5	237,755
	3	1	197.14	16.00	-	156.4	-	156.4	112,611
	Finish		271.26			298.6	278.7	577.3	379,420
C2.1_720_TW_1.5	1	1	-	15.00	-	39.4	-	39.4	28,333
	2	1	20.40	15.00	16.00	99.3	277.1	376.3	234,952
	3	5	203.18	15.14	16.00	113.4	46.4	159.9	109,069
	Finish		283.26			252.1	323.5	575.6	372,354
C2.1_720_TW_2	1	1	-	15.00	-	39.4	-	39.4	28,333
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	230,892
	3	5	211.93	15.00	15.00	113.0	45.3	158.3	108,096
	Finish		294.00			251.7	315.5	567.1	367,321
C2.1_720_TW_2.5	1	1	-	15.00	-	39.4	-	39.4	28,333
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	230,892
	3	5	211.93	15.00	15.00	113.0	45.3	158.3	108,096
	Finish		294.00			251.7	315.5	567.1	367,321
C2.1_720_TL_0.5	1	1	-	16.70	-	41.2	-	41.2	29,664
	2	1	18.34	16.70	17.00	103.9	285.4	389.3	243,203
	3	1	188.19	16.70	-	159.7	-	159.7	114,971
	Finish		259.26			304.8	285.4	590.2	387,838
C2.1_720_TL_1	1	1	-	16.00	-	40.4	-	40.4	29,055
	2	1	19.13	16.00	16.20	101.8	278.7	380.5	237,755
	3	1	197.14	16.00	-	156.4	-	156.4	112,611
	Finish		271.26			298.6	278.7	577.3	379,420
C2.1_720_TL_1.5	1	1	-	15.06	-	39.4	-	39.4	28,379
	2	1	20.32	15.06	16.00	99.4	277.1	376.5	235,067
	3	5	202.89	15.06	16.00	113.2	46.4	159.6	108,908
	Finish		283.26			252.1	323.5	575.6	372,354
C2.1_720_TL_2	1	1	-	15.00	-	39.4	-	39.4	28,333
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	230,892
	3	5	211.93	15.00	15.00	113.0	45.3	158.3	108,096
	Finish		294.00			251.7	315.5	567.1	367,321
C2.1_720_TL_2.5	1	1	-	15.00	-	39.4	-	39.4	28,333
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	230,892
	3	5	211.93	15.00	15.00	113.0	45.3	158.3	108,096
	Finish		294.00			251.7	315.5	567.1	367,321

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_880_TW_0.5	1	1	-	16.00	-	40.4	-	40.4	35,511
	2	1	19.13	16.00	18.00	101.8	295.0	396.8	263,615
	3	5	184.10	16.00	17.42	115.9	48.5	164.4	130,610
	Finish		259.26			258.1	343.4	601.5	429,737
C2.1_880_TW_1	1	1	-	16.00	-	40.4	-	40.4	35,511
	2	1	19.13	16.00	17.10	101.8	286.4	388.2	258,540
	3	2	190.25	16.00	17.00	67.8	112.9	180.7	126,243
	Finish		271.26			209.9	399.2	609.2	420,294
C2.1_880_TW_1.5	1	1	-	15.00	-	39.4	-	39.4	34,629
	2	1	20.40	15.00	16.79	99.3	283.6	382.9	254,715
	3	2	197.06	15.00	16.00	66.1	109.6	175.7	122,825
	Finish		283.26			204.7	393.2	598.0	412,170
C2.1_880_TW_2	1	1	-	15.00	-	39.4	-	39.4	34,629
	2	1	20.40	15.00	15.72	99.3	275.2	374.4	249,716
	3	2	205.60	15.00	15.00	66.1	106.9	173.0	121,220
	Finish		295.26			204.7	382.0	586.8	405,565
C2.1_880_TW_2.5	1	1	-	15.00	-	39.4	-	39.4	34,629
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	246,777
	3	2	211.93	15.00	15.00	66.1	106.9	173.0	121,220
	Finish		301.60			204.7	377.1	581.8	402,626
C2.1_880_TL_0.5	1	1	-	16.00	-	40.4	-	40.4	35,511
	2	1	19.13	16.00	17.92	101.8	294.2	396.0	263,141
	3	5	184.67	16.00	17.92	115.9	49.3	165.2	131,084
	Finish		259.26			258.1	343.4	601.5	429,737
C2.1_880_TL_1	1	1	-	16.00	-	40.4	-	40.4	35,511
	2	1	19.13	16.00	17.07	101.8	286.1	387.9	258,375
	3	2	190.46	16.00	17.07	67.8	113.1	180.9	126,408
	Finish		271.26			209.9	399.2	609.2	420,294
C2.1_880_TL_1.5	1	1	-	15.00	-	39.4	-	39.4	34,629
	2	1	20.40	15.00	16.57	99.3	281.8	381.1	253,616
	3	2	198.79	15.00	16.57	66.1	111.5	177.6	123,925
	Finish		283.26			204.7	393.2	598.0	412,170
C2.1_880_TL_2	1	1	-	15.00	-	39.4	-	39.4	34,629
	2	1	20.40	15.00	15.52	99.3	273.8	373.0	248,883
	3	2	207.39	15.00	15.52	66.1	108.3	174.4	122,053
	Finish		295.26			204.7	382.0	586.8	405,565
C2.1_880_TL_2.5	1	1	-	15.00	-	39.4	-	39.4	34,629
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	246,777
	3	2	211.93	15.00	15.00	66.1	106.9	173.0	121,220
	Finish		301.60			204.7	377.1	581.8	402,626

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_920_TW_0.5	1	1	-	16.00	-	40.4	-	40.4	37,125
	2	1	19.13	16.44	18.00	103.1	295.0	398.1	268,910
	3	2	182.86	17.00	18.00	69.8	116.7	186.5	133,059
	Finish		259.26			213.3	411.6	624.9	439,095
C2.1_920_TW_1	1	1	-	16.00	-	40.4	-	40.4	37,125
	2	1	19.13	16.00	17.10	101.8	286.4	388.2	262,612
	3	2	190.25	16.00	17.00	67.8	112.9	180.7	128,954
	Finish		271.26			209.9	399.2	609.2	428,692
C2.1_920_TW_1.5	1	1	-	15.00	-	39.4	-	39.4	36,203
	2	1	20.40	15.00	16.79	99.3	283.6	382.9	258,687
	3	2	197.06	15.00	16.00	66.1	109.6	175.7	125,469
	Finish		283.26			204.7	393.2	598.0	420,359
C2.1_920_TW_2	1	1	-	15.00	-	39.4	-	39.4	36,203
	2	1	20.40	15.00	15.72	99.3	275.2	374.4	253,687
	3	2	205.60	15.00	15.00	66.1	106.9	173.0	123,864
	Finish		295.26			204.7	382.0	586.8	413,754
C2.1_920_TW_2.5	1	1	-	15.00	-	39.4	-	39.4	36,203
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	250,748
	3	3	211.93	15.00	15.00	61.2	114.5	175.7	123,844
	Finish		303.00			199.8	384.6	584.5	410,796
C2.1_920_TL_0.5	1	1	-	16.53	-	41.0	-	41.0	37,719
	2	1	18.52	16.53	18.00	103.4	295.0	398.4	269,186
	3	2	181.98	16.53	18.00	68.9	116.7	185.5	132,190
	Finish		259.26			213.3	411.6	624.9	439,095
C2.1_920_TL_1	1	1	-	16.00	-	40.4	-	40.4	37,125
	2	1	19.13	16.00	17.07	101.8	286.1	387.9	262,447
	3	2	190.46	16.00	17.07	67.8	113.1	180.9	129,119
	Finish		271.26			209.9	399.2	609.2	428,692
C2.1_920_TL_1.5	1	1	-	15.00	-	39.4	-	39.4	36,203
	2	1	20.40	15.00	16.57	99.3	281.8	381.1	257,587
	3	2	198.79	15.00	16.57	66.1	111.5	177.6	126,569
	Finish		283.26			204.7	393.2	598.0	420,359
C2.1_920_TL_2	1	1	-	15.00	-	39.4	-	39.4	36,203
	2	1	20.40	15.00	15.52	99.3	273.8	373.0	252,854
	3	2	207.39	15.00	15.52	66.1	108.3	174.4	124,697
	Finish		295.26			204.7	382.0	586.8	413,754
C2.1_920_TL_2.5	1	1	-	15.00	-	39.4	-	39.4	36,203
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	250,748
	3	3	211.93	15.00	15.00	61.2	114.5	175.7	123,844
	Finish		303.00			199.8	384.6	584.5	410,796

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_970_TW_0.5	1	1	-	16.00	-	40.4	-	40.4	39,143
	2	1	19.13	16.00	18.51	101.8	300.5	402.3	276,019
	3	2	180.97	16.00	18.00	67.8	116.7	184.4	134,582
	Finish		259.26			209.9	417.1	627.1	449,744
C2.1_970_TW_1	1	1	-	16.00	-	40.4	-	40.4	39,143
	2	1	19.13	16.00	17.10	101.8	286.4	388.2	267,703
	3	2	190.25	16.00	17.00	67.8	112.9	180.7	132,343
	Finish		271.26			209.9	399.2	609.2	439,189
C2.1_970_TW_1.5	1	1	-	15.00	-	39.4	-	39.4	38,171
	2	1	20.40	15.00	16.79	99.3	283.6	382.9	263,651
	3	2	197.06	15.00	16.00	66.1	109.6	175.7	128,774
	Finish		283.26			204.7	393.2	598.0	430,596
C2.1_970_TW_2	1	1	-	15.00	-	39.4	-	39.4	38,171
	2	1	20.40	15.00	15.72	99.3	275.2	374.4	258,651
	3	2	205.60	15.00	15.00	66.1	106.9	173.0	127,169
	Finish		295.26			204.7	382.0	586.8	423,991
C2.1_970_TW_2.5	1	1	-	15.00	-	39.4	-	39.4	38,171
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	255,712
	3	3	211.93	15.00	15.00	61.2	114.5	175.7	126,905
	Finish		303.00			199.8	384.6	584.5	420,788
C2.1_970_TL_0.5	1	1	-	16.00	-	40.4	-	40.4	39,143
	2	1	19.13	16.00	18.36	101.8	298.9	400.7	275,101
	3	2	181.86	16.00	18.36	67.8	118.2	186.0	135,500
	Finish		259.26			209.9	417.1	627.1	449,744
C2.1_970_TL_1	1	1	-	16.00	-	40.4	-	40.4	39,143
	2	1	19.13	16.00	17.07	101.8	286.1	387.9	267,537
	3	2	190.46	16.00	17.07	67.8	113.1	180.9	132,509
	Finish		271.26			209.9	399.2	609.2	439,189
C2.1_970_TL_1.5	1	1	-	15.00	-	39.4	-	39.4	38,171
	2	1	20.40	15.00	16.57	99.3	281.8	381.1	262,551
	3	2	198.79	15.00	16.57	66.1	111.5	177.6	129,874
	Finish		283.26			204.7	393.2	598.0	430,596
C2.1_970_TL_2	1	1	-	15.00	-	39.4	-	39.4	38,171
	2	1	20.40	15.00	15.52	99.3	273.8	373.0	257,818
	3	2	207.39	15.00	15.52	66.1	108.3	174.4	128,002
	Finish		295.26			204.7	382.0	586.8	423,991
C2.1_970_TL_2.5	1	1	-	15.00	-	39.4	-	39.4	38,171
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	255,712
	3	3	211.93	15.00	15.00	61.2	114.5	175.7	126,905
	Finish		303.00			199.8	384.6	584.5	420,788

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_1020_TW_0.5	1	1	-	16.00	-	40.4	-	40.4	41,161
	2	1	19.13	16.00	18.51	101.8	300.5	402.3	281,110
	3	2	180.97	16.00	18.00	67.8	116.7	184.4	137,971
	Finish		259.26			209.9	417.1	627.1	460,241
C2.1_1020_TW_1	1	1	-	16.00	-	40.4	-	40.4	41,161
	2	1	19.13	16.00	17.10	101.8	286.4	388.2	272,793
	3	2	190.25	16.00	17.00	67.8	112.9	180.7	135,732
	Finish		271.26			209.9	399.2	609.2	449,686
C2.1_1020_TW_1.5	1	1	-	15.00	-	39.4	-	39.4	40,139
	2	1	20.40	15.00	16.79	99.3	283.6	382.9	268,614
	3	2	197.06	15.00	16.00	66.1	109.6	175.7	132,079
	Finish		283.26			204.7	393.2	598.0	440,833
C2.1_1020_TW_2	1	1	-	15.00	-	39.4	-	39.4	40,139
	2	1	20.40	15.00	15.72	99.3	275.2	374.4	263,615
	3	2	205.60	15.00	15.00	66.1	106.9	173.0	130,474
	Finish		295.26			204.7	382.0	586.8	434,228
C2.1_1020_TW_2.5	1	1	-	15.00	-	39.4	-	39.4	40,139
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	260,676
	3	3	211.93	15.00	15.00	61.2	114.5	175.7	129,966
	Finish		303.00			199.8	384.6	584.5	430,780

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_1200_TW_0.5	1	1	-	16.00	-	40.4	-	40.4	48,425
	2	1	19.13	16.00	18.66	101.8	302.0	403.8	300,371
	3	3	180.07	16.00	18.00	62.8	124.9	187.7	149,045
	Finish		259.26			204.9	427.0	631.9	497,841
C2.1_1200_TW_1	1	1	-	15.00	-	39.4	-	39.4	47,222
	2	1	20.40	15.00	18.00	99.3	295.0	394.2	293,160
	3	3	188.59	15.00	17.49	61.2	122.9	184.1	145,942
	Finish		271.26			199.8	417.8	617.7	486,324
C2.1_1200_TW_1.5	1	1	-	15.00	-	39.4	-	39.4	47,222
	2	1	20.40	15.00	16.52	99.3	281.4	380.6	285,143
	3	3	199.18	15.00	17.00	61.2	120.9	182.1	144,777
	Finish		283.26			199.8	402.3	602.1	477,142
C2.1_1200_TW_2	1	1	-	15.00	-	39.4	-	39.4	47,222
	2	1	20.40	15.00	15.88	99.3	276.3	375.5	282,135
	3	3	204.20	15.00	15.00	61.2	114.5	175.7	140,984
	Finish		295.26			199.8	390.7	590.6	470,341
C2.1_1200_TW_2.5	1	1	-	15.00	-	39.4	-	39.4	47,222
	2	1	20.40	15.00	15.00	99.3	270.2	369.5	278,546
	3	3	211.93	15.00	15.00	61.2	114.5	175.7	140,984
	Finish		303.00			199.8	384.6	584.5	466,752

Situation	Leg	Chosen leg option	Start time [hours]	Speed		Fuel consumption			Costs
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.1_2000_TW_0.5	1	1	-	15.00	-	39.4	-	39.4	78,703
	2	1	20.40	15.00	19.32	99.3	309.6	408.9	381,209
	3	3	180.69	15.00	19.00	61.2	129.5	190.7	198,843
	Finish		259.26			199.8	439.1	638.9	658,755
C2.1_2000_TW_1.5	1	1	-	15.00	-	39.4	-	39.4	78,703
	2	1	20.40	15.00	18.00	99.3	295.0	394.2	372,583
	3	3	188.59	15.00	17.49	61.2	122.9	184.1	194,913
	Finish		271.26			199.8	417.8	617.7	646,199
C2.1_2000_TW_2.5	1	1	-	15.00	-	39.4	-	39.4	78,703
	2	1	20.40	15.00	16.52	99.3	281.4	380.6	364,566
	3	3	199.18	15.00	17.00	61.2	120.9	182.1	193,748
	Finish		283.26			199.8	402.3	602.1	637,017
C2.1_2000_TL_0.5	1	1	-	15.00	-	39.4	-	39.4	78,703
	2	1	20.40	15.00	16.58	80.1	331.6	411.8	355,904
	3	3	211.18	15.00	17.00	61.2	120.9	182.1	193,748
	Finish		295.26			180.7	452.5	633.2	628,355
C2.1_2000_TL_1.5	1	1	-	15.00	-	39.4	-	39.4	78,703
	2	1	20.40	15.00	16.00	80.1	326.0	406.1	352,573
	3	3	216.43	15.00	15.06	61.2	114.6	175.9	190,065
	Finish		307.26			180.7	440.6	621.3	621,341
C2.1_2000_TL_2.5	1	1	-	15.00	-	39.4	-	39.4	78,703
	2	1	20.40	15.00	19.32	99.3	309.6	408.9	381,209
	3	3	180.69	15.00	19.00	61.2	129.5	190.7	198,843
	Finish		259.26			199.8	439.1	638.9	658,755

Situation	Average speed		Total fuel consumption			Costs	Total distance	
SHIP 2	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*		*ECA*	*Non-ECA*
C2.1c_590_TW_1	16.84	16.84	306.8	283.4	590.2	348,211	2,264	2,101
C2.1c_590_TW_2	16.10	16.10	299.0	278.3	577.3	340,607	2,264	2,101
C2.1c_590_TW_3	15.43	15.43	292.8	274.6	567.4	334,778	2,264	2,101
C2.1c_590_TW_4	15.00	15.00	291.2	270.2	561.3	331,190	2,264	2,101
C2.1c_590_TW_5	15.00	15.00	291.2	270.2	561.3	331,190	2,264	2,101
C2.1c_590_TL_1	16.84	16.84	306.1	284.1	590.2	348,211	2,264	2,101
C2.1c_590_TL_2	16.10	16.10	299.4	277.9	577.3	340,607	2,264	2,101
C2.1c_590_TL_3	15.43	15.43	294.3	273.1	567.4	334,778	2,264	2,101
C2.1c_590_TL_4	15.00	15.00	291.2	270.2	561.3	331,190	2,264	2,101
C2.1c_590_TL_5	15.00	15.00	291.2	270.2	561.3	331,190	2,264	2,101
C2.1c_720_TW_1	16.70	17.00	304.8	285.4	590.2	387,838	2,264	2,101
C2.1c_720_TW_2	16.00	16.20	298.6	278.7	577.3	379,420	2,264	2,101
C2.1c_720_TW_3	15.06	16.00	252.1	323.5	575.6	372,354	1,957	2,453
C2.1c_720_TW_4	15.00	15.00	251.7	315.5	567.1	367,321	1,957	2,453
C2.1c_720_TW_5	15.00	15.00	251.7	315.5	567.1	367,321	1,957	2,453
C2.1c_720_TL_1	16.70	17.00	304.8	285.4	590.2	387,838	2,264	2,101
C2.1c_720_TL_2	16.00	16.20	298.6	278.7	577.3	379,420	2,264	2,101
C2.1c_720_TL_3	15.06	16.00	252.1	323.5	575.6	372,354	1,957	2,453
C2.1c_720_TL_4	15.00	15.00	251.7	315.5	567.1	367,321	1,957	2,453
C2.1c_720_TL_5	15.00	15.00	251.7	315.5	567.1	367,321	1,957	2,453
C2.1c_880_TW_1	16.00	17.92	258.1	343.4	601.5	429,737	1,957	2,453
C2.1c_880_TW_2	16.00	17.07	209.9	399.2	609.2	420,294	1,592	2,932
C2.1c_880_TW_3	15.00	16.57	204.7	393.2	598.0	412,170	1,592	2,932
C2.1c_880_TW_4	15.00	15.52	204.7	382.0	586.8	405,565	1,592	2,932
C2.1c_880_TW_5	15.00	15.00	204.7	377.1	581.8	402,626	1,592	2,932
C2.1c_880_TL_1	16.00	17.92	258.1	343.4	601.5	429,737	1,957	2,453
C2.1c_880_TL_2	16.00	17.07	209.9	399.2	609.2	420,294	1,592	2,932
C2.1c_880_TL_3	15.00	16.57	204.7	393.2	598.0	412,170	1,592	2,932

C2.1c_880_TL_4	15.00	15.52	204.7	382.0	586.8	405,565	1,592	2,932
C2.1c_880_TL_5	15.00	15.00	204.7	377.1	581.8	402,626	1,592	2,932
C2.1c_920_TW_1	16.53	18.00	213.3	411.6	624.9	439,095	1,592	2,932
C2.1c_920_TW_2	16.00	17.07	209.9	399.2	609.2	428,692	1,592	2,932
C2.1c_920_TW_3	15.00	16.57	204.7	393.2	598.0	420,359	1,592	2,932
C2.1c_920_TW_4	15.00	15.52	204.7	382.0	586.8	413,754	1,592	2,932
C2.1c_920_TW_5	15.00	15.00	199.8	384.6	584.5	410,796	1,554	2,991
C2.1c_920_TL_1	16.53	18.00	213.3	411.6	624.9	439,095	1,592	2,932
C2.1c_920_TL_2	16.00	17.07	209.9	399.2	609.2	428,692	1,592	2,932
C2.1c_920_TL_3	15.00	16.57	204.7	393.2	598.0	420,359	1,592	2,932
C2.1c_920_TL_4	15.00	15.52	204.7	382.0	586.8	413,754	1,592	2,932
C2.1c_920_TL_5	15.00	15.00	199.8	384.6	584.5	410,796	1,554	2,991
C2.1c_970_TW_1	16.00	18.36	209.9	417.1	627.1	449,744	1,592	2,932
C2.1c_970_TW_2	16.00	17.07	209.9	399.2	609.2	439,189	1,592	2,932
C2.1c_970_TW_3	15.00	16.57	204.7	393.2	598.0	430,596	1,592	2,932
C2.1c_970_TW_4	15.00	15.52	204.7	382.0	586.8	423,991	1,592	2,932
C2.1c_970_TW_5	15.00	15.00	199.8	384.6	584.5	420,788	1,554	2,991
C2.1c_970_TL_1	16.00	18.36	209.9	417.1	627.1	449,744	1,592	2,932
C2.1c_970_TL_2	16.00	17.07	209.9	399.2	609.2	439,189	1,592	2,932
C2.1c_970_TL_3	15.00	16.57	204.7	393.2	598.0	430,596	1,592	2,932
C2.1c_970_TL_4	15.00	15.52	204.7	382.0	586.8	423,991	1,592	2,932
C2.1c_970_TL_5	15.00	15.00	199.8	384.6	584.5	420,788	1,554	2,991
C2.1c_1020_TW_1	16.00	18.36	209.9	417.1	627.1	460,241	1,592	2,932
C2.1c_1020_TW_2	16.00	17.07	209.9	399.2	609.2	449,686	1,592	2,932
C2.1c_1020_TW_3	15.00	16.57	204.7	393.2	598.0	440,833	1,592	2,932
C2.1c_1020_TW_4	15.00	15.52	204.7	382.0	586.8	434,228	1,592	2,932
C2.1c_1020_TW_5	15.00	15.00	199.8	384.6	584.5	430,780	1,554	2,991
C2.1c_1200_TW_1	16.00	18.46	204.9	427.0	631.9	497,841	1,554	2,991
C2.1c_1200_TW_2	15.00	17.85	199.8	417.8	617.7	486,324	1,554	2,991
C2.1c_1200_TW_3	15.00	16.66	199.8	402.3	602.1	477,142	1,554	2,991
C2.1c_1200_TW_4	15.00	15.62	199.8	390.7	590.6	470,341	1,554	2,991
C2.1c_1200_TW_5	15.00	15.00	199.8	384.6	584.5	466,752	1,554	2,991
C2.1c_2000_TW_1	15.00	19.22	199.8	439.1	638.9	658,755	1,554	2,991
C2.1c_2000_TW_2	15.00	17.85	199.8	417.8	617.7	646,199	1,554	2,991
C2.1c_2000_TW_3	15.00	16.66	199.8	402.3	602.1	637,017	1,554	2,991
C2.1c_2000_TW_4	15.00	16.69	180.7	452.5	633.2	628,355	1,405	3,362
C2.1c_2000_TW_5	15.00	15.75	180.7	440.6	621.3	621,341	1,405	3,362
C2.1c_2000_TL_1	15.00	19.22	199.8	439.1	638.9	658,755	1,554	2,991
C2.1c_2000_TL_2	15.00	17.85	199.8	417.8	617.7	646,199	1,554	2,991
C2.1c_2000_TL_3	15.00	16.66	199.8	402.3	602.1	637,017	1,554	2,991
C2.1c_2000_TL_4	15.00	16.69	180.7	452.5	633.2	628,355	1,405	3,362
C2.1c_2000_TL_5	15.00	15.75	180.7	440.6	621.3	621,341	1,405	3,362

Appendix A.4: Case outputs C2.2

Situation	**Leg**	**Number of leg options**	**Reference speed**	**Time limits**		**Situation**	**Time limits**	
				Lower	Upper		Lower	Upper
TW_1	1	1	18.67	-	-	TL_1	-	-
	2	5	17.69	7.59	9.59		-	16.37
	3	1	17.32	11.09	13.09		-	16.37
	Finish			14.37	16.37		-	16.37
TW_2	1	1	18.67	-	-	TL_2	-	-
	2	5	17.69	6.59	10.59		-	17.37
	3	1	17.32	10.09	14.09		-	17.37
	Finish			13.37	17.37		-	17.37
TW_3	1	1	18.67	-	-	TL_3	-	-
	2	5	17.69	5.59	11.59		-	18.37
	3	1	17.32	9.09	15.09		-	18.37
	Finish			12.37	18.37		-	18.37
TW_4	1	1	18.67	-	-	TL_4	-	-
	2	5	17.69	4.59	12.59		-	19.37
	3	1	17.32	8.09	16.09		-	19.37
	Finish			11.37	19.37		-	19.37

Leg	**Leg option**	**Distance**	
		ECA	*Non-ECA*
1	-	320	3,527
2	1	1,486	0
	2	799	840
	3	714	1,008
	4	656	1,159
	5	458	1,509
3	-	72	1,291

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.2_590_TW_1	1	1	-	17.09	17.09	52.1	574.6	626.7	369,777
	2	1	225.23	17.00	-	240.8	-	240.8	142,083
	3	1	312.64	17.00	17.00	11.7	209.2	220.9	130,323
	Finish		392.82			304.6	783.8	1,088.4	642,183
C2.2_590_TW_2	1	1	-	16.12	16.12	49.6	546.8	596.4	351,889
	2	1	238.75	16.00	-	228.8	-	228.8	135,018
	3	1	331.63	16.00	16.00	11.1	198.8	209.9	123,842
	Finish		416.82			289.5	745.6	1,035.2	610,749
C2.2_590_TW_3	1	1	-	15.00	15.00	47.1	519.3	566.4	334,191
	2	1	256.53	15.91	-	228.0	-	228.0	134,498
	3	1	349.95	15.00	15.00	10.6	190.0	200.6	118,374
	Finish		440.82			285.7	709.4	995.0	587,063
C2.2_590_TW_4	1	1	-	15.00	15.00	47.1	519.3	566.4	334,191
	2	1	256.53	15.00	-	218.7	-	218.7	129,056
	3	1	355.60	15.00	15.00	10.6	190.0	200.6	118,374
	Finish		446.47			276.4	709.4	985.8	581,621
C2.2_590_TL_1	1	1	-	17.05	17.05	52.0	573.4	625.4	368,989
	2	1	225.71	17.05	-	241.5	-	241.5	142,494
	3	1	312.87	17.05	17.05	11.7	209.8	221.5	130,700
	Finish		392.82			305.2	783.2	1,088.4	642,183
C2.2_590_TL_2	1	1	-	16.07	16.07	49.5	545.3	594.8	350,928
	2	1	239.50	16.07	-	229.7	-	229.7	135,519
	3	1	331.98	16.07	16.07	11.1	199.6	210.7	124,302
	Finish		416.82			290.3	744.9	1,035.2	610,749
C2.2_590_TL_3	1	1	-	15.20	15.20	47.5	524.2	571.7	337,318
	2	1	253.29	15.20	-	220.8	-	220.8	130,264
	3	1	351.10	15.20	15.20	10.7	191.8	202.5	119,481
	Finish		440.82			279.0	716.0	995.0	587,063
C2.2_590_TL_4	1	1	-	15.00	15.00	47.1	519.3	566.4	334,191
	2	1	256.53	15.00	-	218.7	-	218.7	129,056
	3	1	373.95	15.00	15.00	10.6	190.0	200.6	118,374
	Finish		464.82			276.4	709.4	985.8	581,621

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.2_840_TW_1	1	1	-	16.00	17.70	49.3	594.1	643.4	391,928
	2	1	219.50	16.00	-	228.8	-	228.8	192,229
	3	1	312.37	16.00	17.00	11.1	209.2	220.3	132,753
	Finish		392.82			289.2	803.3	1,092.6	716,910
C2.2_840_TW_2	1	1	-	15.00	16.74	47.1	564.3	611.4	372,501
	2	1	232.26	15.00	-	218.7	-	218.7	183,741
	3	1	331.33	15.00	16.00	10.6	198.8	209.4	126,203
	Finish		416.82			276.4	763.1	1,039.5	682,445
C2.2_840_TW_3	1	1	-	15.00	16.00	47.1	543.3	590.4	360,121
	2	2	241.83	15.00	15.00	117.6	123.6	241.3	171,747
	3	1	351.10	15.00	15.21	10.6	191.9	202.5	122,132
	Finish		440.82			175.3	858.9	1,034.2	654,001
C2.2_840_TW_4	1	1	-	15.00	15.00	47.1	519.3	566.4	345,967
	2	2	256.53	15.00	15.00	117.6	123.6	241.3	171,747
	3	1	365.80	15.00	15.00	10.6	190.0	200.6	121,023
	Finish		456.67			175.3	833.0	1,008.3	638,738
C2.2_840_TL_1	1	1	-	16.00	17.51	49.3	588.1	637.4	388,391
	2	1	221.65	16.00	-	228.8	-	228.8	192,229
	3	1	314.53	16.00	17.51	11.1	215.2	226.3	136,290
	Finish		392.82			289.2	803.3	1,092.6	716,910
C2.2_840_TL_2	1	1	-	15.00	16.54	47.1	558.7	605.8	369,185
	2	1	234.83	15.00	-	218.7	-	218.7	183,741
	3	1	333.89	15.00	16.54	10.6	204.4	215.0	129,519
	Finish		416.82			276.4	763.1	1,039.5	682,445
C2.2_840_TL_3	1	1	-	15.00	15.67	47.1	535.4	582.6	355,483
	2	2	246.65	15.00	15.67	117.6	127.5	245.1	174,013
	3	1	353.56	15.00	15.67	10.6	195.9	206.5	124,505
	Finish		440.82			175.3	858.9	1,034.2	654,001
C2.2_840_TL_4	1	1	-	15.00	15.00	47.1	519.3	566.4	345,967
	2	2	256.53	15.00	15.00	117.6	123.6	241.3	171,747
	3	1	373.95	15.00	15.00	10.6	190.0	200.6	121,023
	Finish		464.82			175.3	833.0	1,008.3	638,738

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.2_860_TW_1	1	1	-	16.00	18.00	49.3	603.9	653.2	398,668
	2	2	216.00	16.00	17.45	123.0	139.6	262.6	188,157
	3	1	314.12	16.00	17.41	11.1	214.1	225.2	135,845
	Finish		392.82			183.4	957.5	1,140.9	722,670
C2.2_860_TW_2	1	1	-	15.00	17.00	47.1	571.7	618.8	377,838
	2	2	228.86	15.00	16.00	117.6	129.4	247.0	177,469
	3	1	334.63	15.00	16.70	10.6	206.1	216.6	130,685
	Finish		416.82			175.3	907.2	1,082.5	685,992
C2.2_860_TW_3	1	1	-	15.00	16.00	47.1	543.3	590.4	361,064
	2	2	241.83	15.00	15.00	117.6	123.6	241.3	174,099
	3	1	351.10	15.00	15.21	10.6	191.9	202.5	122,344
	Finish		440.82			175.3	858.9	1,034.2	657,507
C2.2_860_TW_4	1	1	-	15.00	15.00	47.1	519.3	566.4	346,909
	2	2	256.53	15.00	15.00	117.6	123.6	241.3	174,099
	3	1	365.80	15.00	15.00	10.6	190.0	200.6	121,235
	Finish		456.67			175.3	833.0	1,008.3	642,244
C2.2_860_TL_1	1	1	-	16.00	17.78	49.3	596.9	646.2	394,578
	2	2	218.49	16.00	17.78	123.0	142.1	265.2	189,676
	3	1	315.68	16.00	17.78	11.1	218.4	229.5	138,415
	Finish		392.82			183.4	957.5	1,140.9	722,670
C2.2_860_TL_2	1	1	-	15.00	16.78	47.1	565.5	612.7	374,183
	2	2	231.69	15.00	16.78	117.6	134.7	252.3	180,593
	3	1	335.04	15.00	16.78	10.6	207.0	217.5	131,216
	Finish		416.82			175.3	907.2	1,082.5	685,992
C2.2_860_TL_3	1	1	-	15.00	15.67	47.1	535.4	582.6	356,425
	2	2	246.65	15.00	15.67	117.6	127.5	245.1	176,365
	3	1	353.56	15.00	15.67	10.6	195.9	206.5	124,717
	Finish		440.82			175.3	858.9	1,034.2	657,507
C2.2_860_TL_4	1	1	-	15.00	15.00	47.1	519.3	566.4	346,909
	2	2	256.53	15.00	15.00	117.6	123.6	241.3	174,099
	3	1	373.95	15.00	15.00	10.6	190.0	200.6	121,235
	Finish		464.82			175.3	833.0	1,008.3	642,244

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.2_920_TW_1	1	1	-	16.00	18.00	49.3	603.9	653.2	401,624
	2	2	216.00	16.00	17.45	123.0	139.6	262.6	195,540
	3	1	314.12	16.00	17.41	11.1	214.1	225.2	136,510
	Finish		392.82			183.4	957.5	1,140.9	733,675
C2.2_920_TW_2	1	1	-	15.00	17.00	47.1	571.7	618.8	380,664
	2	2	228.86	15.00	16.00	117.6	129.4	247.0	184,526
	3	1	334.63	15.00	16.70	10.6	206.1	216.6	131,321
	Finish		416.82			175.3	907.2	1,082.5	696,511
C2.2_920_TW_3	1	1	-	15.00	16.00	47.1	543.3	590.4	363,890
	2	2	241.83	15.00	15.00	117.6	123.6	241.3	181,156
	3	1	351.10	15.00	15.21	10.6	191.9	202.5	122,980
	Finish		440.82			175.3	858.9	1,034.2	668,026
C2.2_920_TW_4	1	1	-	15.00	15.00	47.1	519.3	566.4	349,735
	2	2	256.53	15.00	15.00	117.6	123.6	241.3	181,156
	3	1	365.80	15.00	15.00	10.6	190.0	200.6	121,871
	Finish		456.67			175.3	833.0	1,008.3	652,763
C2.2_920_TL_1	1	1	-	16.00	17.78	49.3	596.9	646.2	397,535
	2	2	218.49	16.00	17.78	123.0	142.1	265.2	197,059
	3	1	315.68	16.00	17.78	11.1	218.4	229.5	139,081
	Finish		392.82			183.4	957.5	1,140.9	733,675
C2.2_920_TL_2	1	1	-	15.00	16.78	47.1	565.5	612.7	377,010
	2	2	231.69	15.00	16.78	117.6	134.7	252.3	187,650
	3	1	335.04	15.00	16.78	10.6	207.0	217.5	131,852
	Finish		416.82			175.3	907.2	1,082.5	696,511
C2.2_920_TL_3	1	1	-	15.00	15.67	47.1	535.4	582.6	359,251
	2	2	246.65	15.00	15.67	117.6	127.5	245.1	183,422
	3	1	353.56	15.00	15.67	10.6	195.9	206.5	125,353
	Finish		440.82			175.3	858.9	1,034.2	668,026
C2.2_920_TL_4	1	1	-	15.00	15.00	47.1	519.3	566.4	349,735
	2	2	256.53	15.00	15.00	117.6	123.6	241.3	181,156
	3	1	373.95	15.00	15.00	10.6	190.0	200.6	121,871
	Finish		464.82			175.3	833.0	1,008.3	652,763

Situation	**Average speed**		**Distance**		**Total fuel consumption**			**Costs**
SHIP 1	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.2_590_TW_1	17.05	17.05	1,878	4,819	304.6	783.8	1,088.4	642,183
C2.2_590_TW_2	16.07	16.07	1,878	4,819	289.5	745.6	1,035.2	610,749
C2.2_590_TW_3	15.20	15.20	1,878	4,819	285.7	709.4	995.0	587,063
C2.2_590_TW_4	15.00	15.00	1,878	4,819	276.4	709.4	985.8	581,621
C2.2_590_TL_1	17.05	17.05	1,878	4,819	305.2	783.2	1,088.4	642,183
C2.2_590_TL_2	16.07	16.07	1,878	4,819	290.3	744.9	1,035.2	610,749
C2.2_590_TL_3	15.20	15.20	1,878	4,819	279.0	716.0	995.0	587,063
C2.2_590_TL_4	15.00	15.00	1,878	4,819	276.4	709.4	985.8	581,621
C2.2_840_TW_1	16.00	17.51	1,878	4,819	289.2	803.3	1,092.6	716,910
C2.2_840_TW_2	15.00	16.54	1,878	4,819	276.4	763.1	1,039.5	682,445
C2.2_840_TW_3	15.00	15.67	1,191	5,659	175.3	858.9	1,034.2	654,001
C2.2_840_TW_4	15.00	15.00	1,191	5,659	175.3	833.0	1,008.3	638,738
C2.2_840_TL_1	16.00	17.51	1,878	4,819	289.2	803.3	1,092.6	716,910
C2.2_840_TL_2	15.00	16.54	1,878	4,819	276.4	763.1	1,039.5	682,445
C2.2_840_TL_3	15.00	15.67	1,191	5,659	175.3	858.9	1,034.2	654,001
C2.2_840_TL_4	15.00	15.00	1,191	5,659	175.3	833.0	1,008.3	638,738
C2.2_860_TW_1	16.00	17.78	1,191	5,659	183.4	957.5	1,140.9	722,670
C2.2_860_TW_2	15.00	16.78	1,191	5,659	175.3	907.2	1,082.5	685,992
C2.2_860_TW_3	15.00	15.67	1,191	5,659	175.3	858.9	1,034.2	657,507
C2.2_860_TW_4	15.00	15.00	1,191	5,659	175.3	833.0	1,008.3	642,244
C2.2_860_TL_1	16.00	17.78	1,191	5,659	183.4	957.5	1,140.9	722,670
C2.2_860_TL_2	15.00	16.78	1,191	5,659	175.3	907.2	1,082.5	685,992
C2.2_860_TL_3	15.00	15.67	1,191	5,659	175.3	858.9	1,034.2	657,507
C2.2_860_TL_4	15.00	15.00	1,191	5,659	175.3	833.0	1,008.3	642,244
C2.2_920_TW_1	16.00	17.78	1,191	5,659	183.4	957.5	1,140.9	733,675
C2.2_920_TW_2	15.00	16.78	1,191	5,659	175.3	907.2	1,082.5	696,511
C2.2_920_TW_3	15.00	15.67	1,191	5,659	175.3	858.9	1,034.2	668,026
C2.2_920_TW_4	15.00	15.00	1,191	5,659	175.3	833.0	1,008.3	652,763
C2.2_920_TL_1	16.00	17.78	1,191	5,659	183.4	957.5	1,140.9	733,675
C2.2_920_TL_2	15.00	16.78	1,191	5,659	175.3	907.2	1,082.5	696,511
C2.2_920_TL_3	15.00	15.67	1,191	5,659	175.3	858.9	1,034.2	668,026
C2.2_920_TL_4	15.00	15.00	1,191	5,659	175.3	833.0	1,008.3	652,763

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.2_590_TW_1	1	1	-	17.09	17.09	43.6	480.6	524.2	309,291
	2	1	225.23	17.00	-	201.8	-	201.8	119,082
	3	1	312.64	17.00	17.00	9.8	175.3	185.1	109,225
	Finish		392.82			255.2	656.0	911.2	537,598
C2.2_590_TW_2	1	1	-	16.12	16.12	42.4	467.0	509.3	300,506
	2	1	238.75	16.00	-	196.0	-	196.0	115,620
	3	1	331.63	16.00	16.00	9.5	170.3	179.7	106,050
	Finish		416.82			247.8	637.2	885.0	522,176
C2.2_590_TW_3	1	1	-	15.35	15.35	41.5	457.8	499.3	294,584
	2	1	250.88	15.00	-	191.1	-	191.1	112,749
	3	1	349.95	15.00	15.00	9.3	166.0	175.3	103,416
	Finish		440.82			241.9	623.8	865.7	510,749
C2.2_590_TW_4	1	1	-	15.00	15.00	41.2	453.7	494.9	291,963
	2	1	256.53	15.00	-	191.1	-	191.1	112,749
	3	1	355.60	15.00	15.00	9.3	166.0	175.3	103,416
	Finish		446.47			241.5	619.7	861.2	508,128

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.2_800_TW_1	1	1	-	16.00	17.70	42.2	490.4	532.6	323,098
	2	1	219.50	16.00	-	196.0	-	196.0	156,773
	3	1	312.37	16.00	17.00	9.5	175.3	184.8	111,051
	Finish		392.82			247.7	665.8	913.4	590,923
C2.2_800_TW_2	1	1	-	16.00	16.87	42.2	477.4	519.6	315,427
	2	2	229.19	16.00	16.00	105.4	110.8	216.1	149,652
	3	1	331.63	16.00	16.00	9.5	170.3	179.7	108,044
	Finish		416.82			157.1	758.4	915.5	573,123
C2.2_800_TW_3	1	1	-	15.00	16.00	41.2	465.3	506.4	307,422
	2	2	241.83	15.00	15.00	102.8	108.0	210.8	145,935
	3	1	351.10	15.00	15.21	9.3	166.9	176.2	105,895
	Finish		440.82			153.2	740.2	893.4	559,252
C2.2_800_TW_4	1	1	-	15.00	15.00	41.2	453.7	494.9	300,605
	2	2	256.53	15.00	15.00	102.8	108.0	210.8	145,935
	3	1	365.80	15.00	15.00	9.3	166.0	175.3	105,361
	Finish		456.67			153.2	727.7	880.9	551,901

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.2_840_TW_1	1	1	-	16.00	18.00	42.2	495.3	537.5	327,670
	2	2	216.00	16.00	17.45	105.4	115.8	221.2	156,836
	3	1	314.12	16.00	17.41	9.5	177.8	187.3	112,870
	Finish		392.82			157.1	788.9	946.0	597,377
C2.2_840_TW_2	1	1	-	15.00	17.00	41.2	479.2	520.3	317,287
	2	2	228.86	15.00	16.00	102.8	110.8	213.5	151,668
	3	1	334.63	15.00	16.70	9.3	173.8	183.1	110,318
	Finish		416.82			153.2	763.8	916.9	579,273
C2.2_840_TW_3	1	1	-	15.00	16.00	41.2	465.3	506.4	309,068
	2	2	241.83	15.00	15.00	102.8	108.0	210.8	150,045
	3	1	351.10	15.00	15.21	9.3	166.9	176.2	106,265
	Finish		440.82			153.2	740.2	893.4	565,378
C2.2_840_TW_4	1	1	-	15.00	15.00	41.2	453.7	494.9	302,251
	2	2	256.53	15.00	15.00	102.8	108.0	210.8	150,045
	3	1	365.80	15.00	15.00	9.3	166.0	175.3	105,731
	Finish		456.67			153.2	727.7	880.9	558,028

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.2_860_TW_1	1	1	-	16.00	18.00	42.2	495.3	537.5	328,514
	2	2	216.00	16.00	17.45	105.4	115.8	221.2	158,944
	3	1	314.12	16.00	17.41	9.5	177.8	187.3	113,060
	Finish		392.82			157.1	788.9	946.0	600,518
C2.2_860_TW_2	1	1	-	15.00	17.00	41.2	479.2	520.3	318,110
	2	2	228.86	15.00	16.00	102.8	110.8	213.5	153,723
	3	1	334.63	15.00	16.70	9.3	173.8	183.1	110,503
	Finish		416.82			153.2	763.8	916.9	582,336
C2.2_860_TW_3	1	1	-	15.00	16.00	41.2	465.3	506.4	309,891
	2	2	241.83	15.00	15.00	102.8	108.0	210.8	152,100
	3	1	351.10	15.00	15.21	9.3	166.9	176.2	106,450
	Finish		440.82			153.2	740.2	893.4	568,442
C2.2_860_TW_4	1	1	-	15.00	15.00	41.2	453.7	494.9	303,074
	2	2	256.53	15.00	15.00	102.8	108.0	210.8	152,100
	3	1	365.80	15.00	15.00	9.3	166.0	175.3	105,916
	Finish		456.67			153.2	727.7	880.9	561,091

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.2_920_TW_1	1	1	-	16.00	18.00	42.2	495.3	537.5	331,046
	2	2	216.00	16.00	17.45	105.4	115.8	221.2	165,266
	3	1	314.12	16.00	17.41	9.5	177.8	187.3	113,630
	Finish		392.82			157.1	788.9	946.0	609,942
C2.2_920_TW_2	1	1	-	15.00	17.00	41.2	479.2	520.3	320,579
	2	2	228.86	15.00	16.00	102.8	110.8	213.5	159,889
	3	1	334.63	15.00	16.70	9.3	173.8	183.1	111,058
	Finish		416.82			153.2	763.8	916.9	591,526
C2.2_920_TW_3	1	1	-	15.00	16.00	41.2	465.3	506.4	312,360
	2	2	241.83	15.00	15.00	102.8	108.0	210.8	158,265
	3	1	351.10	15.00	15.21	9.3	166.9	176.2	107,006
	Finish		440.82			153.2	740.2	893.4	577,631
C2.2_920_TW_4	1	1	-	15.00	15.00	41.2	453.7	494.9	305,543
	2	2	256.53	15.00	15.00	102.8	108.0	210.8	158,265
	3	1	365.80	15.00	15.00	9.3	166.0	175.3	106,472
	Finish		456.67			153.2	727.7	880.9	570,281

Situation	**Average speed**		**Distance**		**Total fuel consumption**			**Costs**
SHIP 2	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.2_590_TW_1	17.05	17.05	1,878	4,819	255.2	656.0	911.2	537,598
C2.2_590_TW_2	16.07	16.07	1,878	4,819	247.8	637.2	885.0	522,176
C2.2_590_TW_3	15.20	15.20	1,878	4,819	241.9	623.8	865.7	510,749
C2.2_590_TW_4	15.00	15.00	1,878	4,819	241.5	619.7	861.2	508,128
C2.2_800_TW_1	16.00	17.51	1,878	4,819	247.7	665.8	913.4	590,923
C2.2_800_TW_2	16.00	16.54	1,191	5,659	157.1	758.4	915.5	573,123
C2.2_800_TW_3	15.00	15.67	1,191	5,659	153.2	740.2	893.4	559,252
C2.2_800_TW_4	15.00	15.00	1,191	5,659	153.2	727.7	880.9	551,901
C2.2_840_TW_1	16.00	17.78	1,191	5,659	157.1	788.9	946.0	597,377
C2.2_840_TW_2	15.00	16.78	1,191	5,659	153.2	763.8	916.9	579,273
C2.2_840_TW_3	15.00	15.67	1,191	5,659	153.2	740.2	893.4	565,378
C2.2_840_TW_4	15.00	15.00	1,191	5,659	153.2	727.7	880.9	558,028
C2.2_860_TW_1	16.00	17.78	1,191	5,659	157.1	788.9	946.0	600,518
C2.2_860_TW_2	15.00	16.78	1,191	5,659	153.2	763.8	916.9	582,336
C2.2_860_TW_3	15.00	15.67	1,191	5,659	153.2	740.2	893.4	568,442
C2.2_860_TW_4	15.00	15.00	1,191	5,659	153.2	727.7	880.9	561,091
C2.2_920_TW_1	16.00	17.78	1,191	5,659	157.1	788.9	946.0	609,942
C2.2_920_TW_2	15.00	16.78	1,191	5,659	153.2	763.8	916.9	591,526
C2.2_920_TW_3	15.00	15.67	1,191	5,659	153.2	740.2	893.4	577,631
C2.2_920_TW_4	15.00	15.00	1,191	5,659	153.2	727.7	880.9	570,281

Appendix A.5: Case outputs C2.3

Case	**Situation**	**Leg**	**Number of leg options**	**Reference speed**	**Time limits**	
					Lower	Upper
C2.3b	TL_0.25	Finish	3	18.67	0	2.75
	TL_0.5	Finish	3	18.67	0	3.00
	TL_0.75	Finish	3	18.67	0	3.25
	TL_1	Finish	3	18.67	0	3.50
	TL_1.25	Finish	3	18.67	0	3.75
	TL_1.5	Finish	3	18.67	0	4.00
C2.3c	TL_0.25	Finish	3	18.67	0	2.81
	TL_0.5	Finish	3	18.67	0	3.06
	TL_0.75	Finish	3	18.67	0	3.31
	TL_1	Finish	3	18.67	0	3.56
	TL_1.25	Finish	3	18.67	0	3.81
	TL_1.5	Finish	3	18.67	0	4.06
C2.3d	TL_0.25	Finish	3	18.67	0	3.01
	TL_0.5	Finish	3	18.67	0	3.26
	TL_0.75	Finish	3	18.67	0	3.51
	TL_1	Finish	3	18.67	0	3.76
	TL_1.25	Finish	3	18.67	0	4.01
	TL_1.5	Finish	3	18.67	0	4.26
C2.3e	TL_0.25	Finish	3	18.67	0	3.13
	TL_0.5	Finish	3	18.67	0	3.38
	TL_0.75	Finish	3	18.67	0	3.63
	TL_1	Finish	3	18.67	0	3.88
	TL_1.25	Finish	3	18.67	0	4.13
	TL_1.5	Finish	3	18.67	0	4.38

Case	**Leg option**	**Distance**	
		ECA	*Non-ECA*
C2.3b	1	760	361
	2	340	1,030
	3	275	1,400
C2.3c	1	790	362
	2	310	1,065
	3	230	1,430
C2.3d	1	872	365
	2	277	1,020
	3	120	1,420
C2.3e	1	927	365
	2	307	1,022
	3	34	1,425

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**
SHIP 1		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.3b_590_TL_0.25	1	16.97	16.97	123.0	58.4	181.4	107,046
C2.3b_590_TL_0.5	1	15.57	15.57	114.8	54.6	169.4	99,942
C2.3b_590_TL_0.75	1	15.00	15.00	111.9	53.1	165.0	97,357
C2.3b_590_TL_1	1	15.00	15.00	111.9	53.1	165.0	97,357
C2.3b_590_TL_1.25	1	15.00	15.00	111.9	53.1	165.0	97,357
C2.3b_590_TL_1.5	1	15.00	15.00	111.9	53.1	165.0	97,357
C2.3b_920_TL_0.25	1	16.54	18.00	120.3	61.8	182.1	147,173
C2.3b_920_TL_0.5	1	15.00	16.89	111.9	58.2	170.1	137,250
C2.3b_920_TL_0.75	1	15.00	15.00	111.9	53.1	165.0	134,274
C2.3b_920_TL_1	1	15.00	15.00	111.9	53.1	165.0	134,274
C2.3b_920_TL_1.25	1	15.00	15.00	111.9	53.1	165.0	134,274
C2.3b_920_TL_1.5	1	15.00	15.00	111.9	53.1	165.0	134,274
C2.3b_1420_TL_0.25	1	16.00	19.48	117.0	67.4	184.4	205,964
C2.3b_1420_TL_0.5	1	15.00	16.89	111.9	58.2	170.1	193,186
C2.3b_1420_TL_0.75	2	15.54	19.00	55.8	186.8	242.6	189,477
C2.3b_1420_TL_1	2	15.00	17.36	54.5	170.3	224.7	177,806
C2.3b_1420_TL_1.25	2	15.00	15.77	54.5	157.0	211.4	169,955
C2.3b_1420_TL_1.5	2	15.00	15.00	54.5	151.6	206.1	166,792

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**
SHIP 1		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.3c_590_TL_0.25	1	17.01	17.01	126.9	58.8	185.8	109,614
C2.3c_590_TL_0.5	1	15.63	15.63	118.6	55.0	173.6	102,429
C2.3c_590_TL_0.75	1	15.00	15.00	115.3	53.4	168.7	99,528
C2.3c_590_TL_1	1	15.00	15.00	115.3	53.4	168.7	99,528
C2.3c_590_TL_1.25	1	15.00	15.00	115.3	53.4	168.7	99,528
C2.3c_590_TL_1.5	1	15.00	15.00	115.3	53.4	168.7	99,528
C2.3c_920_TL_0.25	1	16.60	18.00	124.3	62.1	186.5	151,056
C2.3c_920_TL_0.5	1	15.05	17.00	115.5	58.8	174.4	140,994
C2.3c_920_TL_0.75	1	15.00	15.00	115.3	53.4	168.7	137,563
C2.3c_920_TL_1	1	15.00	15.00	115.3	53.4	168.7	137,563
C2.3c_920_TL_1.25	2	15.00	15.06	45.6	157.2	202.9	134,743
C2.3c_920_TL_1.5	2	15.00	15.00	45.6	156.8	202.4	134,475
C2.3c_1120_TL_0.25	1	16.23	19.00	122.0	65.8	187.9	175,504
C2.3c_1120_TL_0.5	1	15.00	17.14	115.3	59.3	174.5	164,069
C2.3c_1120_TL_0.75	2	15.35	18.00	46.4	182.3	228.7	159,475
C2.3c_1120_TL_1	2	15.00	16.47	45.6	168.0	213.7	150,256
C2.3c_1120_TL_1.25	2	15.00	15.06	45.6	157.2	202.9	143,870
C2.3c_1120_TL_1.5	2	15.00	15.00	45.6	156.8	202.4	143,601

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**
SHIP 1		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.3d_590_TW_0.25	1	17.12	17.12	142.3	59.6	201.9	119,102
C2.3d_590_TW_0.5	1	15.82	15.82	133.2	55.8	188.9	111,480
C2.3d_590_TW_0.75	1	15.00	15.00	128.4	53.7	182.1	107,431
C2.3d_590_TW_1	1	15.00	15.00	128.4	53.7	182.1	107,431
C2.3d_590_TW_1.25	1	15.00	15.00	128.4	53.7	182.1	107,431
C2.3d_590_TW_1.5	1	15.00	15.00	128.4	53.7	182.1	107,431
C2.3d_680_TW_0.25	1	17.00	17.42	141.3	60.6	201.9	131,820
C2.3d_680_TW_0.5	1	15.74	16.00	132.7	56.2	188.9	123,426
C2.3d_680_TW_0.75	2	15.00	15.52	40.8	153.7	194.5	118,434
C2.3d_680_TW_1	2	15.00	15.00	40.8	150.1	190.9	116,312
C2.3d_680_TW_1.25	2	15.00	15.00	40.8	150.1	190.9	116,312
C2.3d_680_TW_1.5	2	15.00	15.00	40.8	150.1	190.9	116,312
C2.3d_920_TW_0.25	2	17.00	18.23	44.9	177.0	221.9	145,746
C2.3d_920_TW_0.5	2	15.18	17.00	41.1	165.3	206.4	135,347
C2.3d_920_TW_0.75	2	15.00	15.52	40.8	153.7	194.5	128,220
C2.3d_920_TW_1	2	15.00	15.00	40.8	150.1	190.9	126,097
C2.3d_920_TW_1.25	2	15.00	15.00	40.8	150.1	190.9	126,097
C2.3d_920_TW_1.5	2	15.00	15.00	40.8	150.1	190.9	126,097
C2.3d_2200_TW_0.25	2	15.00	18.96	40.8	184.6	225.4	198,622
C2.3d_2200_TW_0.5	2	15.00	17.06	40.8	165.9	206.6	187,567
C2.3d_2200_TW_0.75	2	15.00	15.52	40.8	153.7	194.5	180,411
C2.3d_2200_TW_1	3	15.00	17.27	17.7	233.7	251.3	176,718
C2.3d_2200_TW_1.25	3	15.00	16.09	17.7	219.7	237.4	168,513
C2.3d_2200_TW_1.5	3	15.00	15.07	17.7	209.7	227.3	162,575

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**
SHIP 1		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.3e_590_TW_0.25	1	17.19	17.19	151.8	59.8	211.6	124,836
C2.3e_590_TW_0.5	1	15.91	15.91	142.2	56.0	198.2	116,950
C2.3e_590_TW_0.75	1	15.00	15.00	136.5	53.7	190.2	112,208
C2.3e_590_TW_1	1	15.00	15.00	136.5	53.7	190.2	112,208
C2.3e_590_TW_1.25	1	15.00	15.00	136.5	53.7	190.2	112,208
C2.3e_590_TW_1.5	1	15.00	15.00	136.5	53.7	190.2	112,208
C2.3e_660_TW_0.25	1	17.00	17.66	150.2	61.4	211.6	135,352
C2.3e_660_TW_0.5	2	16.00	16.49	47.3	161.5	208.7	126,461
C2.3e_660_TW_0.75	2	15.00	15.33	45.2	152.7	197.9	119,924
C2.3e_660_TW_1	2	15.00	15.00	45.2	150.4	195.6	118,584
C2.3e_660_TW_1.25	2	15.00	15.00	45.2	150.4	195.6	118,584
C2.3e_660_TW_1.5	2	15.00	15.00	45.2	150.4	195.6	118,584
C2.3e_920_TW_0.25	2	16.67	18.00	48.9	174.9	223.9	148,233
C2.3e_920_TW_0.5	2	15.00	16.83	45.2	164.3	209.4	138,487
C2.3e_920_TW_0.75	2	15.00	15.33	45.2	152.7	197.9	131,674
C2.3e_920_TW_1	2	15.00	15.00	45.2	150.4	195.6	130,334
C2.3e_920_TW_1.25	3	15.00	15.00	5.0	209.8	214.8	128,363
C2.3e_920_TW_1.5	3	15.00	15.00	5.0	209.8	214.8	128,363
C2.3e_980_TW_0.25	2	16.00	18.25	47.3	177.6	224.9	151,101
C2.3e_980_TW_0.5	2	15.00	16.83	45.2	164.3	209.4	141,198
C2.3e_980_TW_0.75	2	15.00	15.33	45.2	152.7	197.9	134,385
C2.3e_980_TW_1	3	15.00	15.68	5.0	216.4	221.4	132,571
C2.3e_980_TW_1.25	3	15.00	15.00	5.0	209.8	214.8	128,663
C2.3e_980_TW_1.5	3	15.00	15.00	5.0	209.8	214.8	128,663
C2.3e_1120_TW_0.25	2	16.00	18.25	47.3	177.6	224.9	157,720
C2.3e_1120_TW_0.5	2	15.00	16.83	45.2	164.3	209.4	147,525
C2.3e_1120_TW_0.75	3	15.00	16.79	5.0	228.5	233.5	140,410
C2.3e_1120_TW_1	3	15.00	15.68	5.0	216.4	221.4	133,272
C2.3e_1120_TW_1.25	3	15.00	15.00	5.0	209.8	214.8	129,364
C2.3e_1120_TW_1.5	3	15.00	15.00	5.0	209.8	214.8	129,364

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**
SHIP 2		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.3b_590_TL_0.25	1	16.97	16.97	103.1	49.0	152.1	89,764
C2.3b_590_TL_0.5	1	15.57	15.57	99.2	47.1	146.3	86,300
C2.3b_590_TL_0.75	1	15.00	15.00	97.7	46.4	144.2	85,055
C2.3b_590_TL_1	1	15.00	15.00	97.7	46.4	144.2	85,055
C2.3b_590_TL_1.25	1	15.00	15.00	97.7	46.4	144.2	85,055
C2.3b_590_TL_1.5	1	15.00	15.00	97.7	46.4	144.2	85,055
C2.3b_920_TL_0.25	1	16.54	18.00	101.8	50.7	152.5	123,598
C2.3b_920_TL_0.5	1	15.00	16.89	97.7	48.9	146.6	118,753
C2.3b_920_TL_0.75	1	15.00	15.00	97.7	46.4	144.2	117,308
C2.3b_920_TL_1	1	15.00	15.00	97.7	46.4	144.2	117,308
C2.3b_920_TL_1.25	1	15.00	15.00	97.7	46.4	144.2	117,308
C2.3b_920_TL_1.5	1	15.00	15.00	97.7	46.4	144.2	117,308
C2.3b_1420_TL_0.25	1	16.00	19.48	100.2	53.5	153.7	173,895
C2.3b_1420_TL_0.5	2	17.00	20.50	50.3	159.0	209.3	165,196
C2.3b_1420_TL_0.75	2	15.54	19.00	48.2	149.9	198.1	156,928
C2.3b_1420_TL_1	2	15.00	17.36	47.6	141.6	189.2	151,101
C2.3b_1420_TL_1.25	2	15.00	15.77	47.6	135.0	182.6	147,240
C2.3b_1420_TL_1.5	2	15.00	15.00	47.6	132.5	180.0	145,717

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**
SHIP 2		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.3c_590_TL_0.25	1	17.01	17.01	106.4	49.3	155.7	91,856
C2.3c_590_TL_0.5	1	15.63	15.63	102.3	47.4	149.7	88,349
C2.3c_590_TL_0.75	1	15.00	15.00	100.7	46.7	147.4	86,952
C2.3c_590_TL_1	1	15.00	15.00	100.7	46.7	147.4	86,952
C2.3c_590_TL_1.25	1	15.00	15.00	100.7	46.7	147.4	86,952
C2.3c_590_TL_1.5	1	15.00	15.00	100.7	46.7	147.4	86,952
C2.3c_920_TL_0.25	1	16.60	18.00	105.1	51.0	156.1	126,761
C2.3c_920_TL_0.5	1	15.05	17.00	100.8	49.3	150.1	121,847
C2.3c_920_TL_0.75	1	15.00	15.00	100.7	46.7	147.4	120,181
C2.3c_920_TL_1	1	15.00	15.00	100.7	46.7	147.4	120,181
C2.3c_920_TL_1.25	2	15.00	15.06	39.9	137.2	177.0	117,612
C2.3c_920_TL_1.5	2	15.00	15.00	39.9	137.0	176.8	117,483
C2.3c_1120_TL_0.25	1	16.23	19.00	104.0	52.8	156.8	147,605
C2.3c_1120_TL_0.5	2	17.00	19.32	42.1	156.9	199.0	139,755
C2.3c_1120_TL_0.75	2	15.35	18.00	40.2	149.5	189.7	133,256
C2.3c_1120_TL_1	2	15.00	16.47	39.9	142.4	182.3	128,681
C2.3c_1120_TL_1.25	2	15.00	15.06	39.9	137.2	177.0	125,585
C2.3c_1120_TL_1.5	2	15.00	15.00	39.9	137.0	176.8	125,456

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**
SHIP 2		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.3d_590_TW_0.25	1	17.12	17.12	118.9	49.8	168.7	99,542
C2.3d_590_TW_0.5	1	15.82	15.82	114.5	47.9	162.4	95,806
C2.3d_590_TW_0.75	1	15.00	15.00	112.1	46.9	159.1	93,856
C2.3d_590_TW_1	1	15.00	15.00	112.1	46.9	159.1	93,856
C2.3d_590_TW_1.25	1	15.00	15.00	112.1	46.9	159.1	93,856
C2.3d_590_TW_1.5	1	15.00	15.00	112.1	46.9	159.1	93,856
C2.3d_680_TW_0.25	1	17.00	17.42	118.4	50.3	168.7	110,202
C2.3d_680_TW_0.5	2	16.00	16.75	36.5	137.5	174.0	105,977
C2.3d_680_TW_0.75	2	15.00	15.52	35.6	132.9	168.5	102,637
C2.3d_680_TW_1	2	15.00	15.00	35.6	131.2	166.8	101,615
C2.3d_680_TW_1.25	2	15.00	15.00	35.6	131.2	166.8	101,615
C2.3d_680_TW_1.5	2	15.00	15.00	35.6	131.2	166.8	101,615
C2.3d_920_TW_0.25	2	17.00	18.23	37.6	144.4	182.0	119,824
C2.3d_920_TW_0.5	2	15.18	17.00	35.8	138.5	174.3	114,659
C2.3d_920_TW_0.75	2	15.00	15.52	35.6	132.9	168.5	111,186
C2.3d_920_TW_1	2	15.00	15.00	35.6	131.2	166.8	110,164
C2.3d_920_TW_1.25	2	15.00	15.00	35.6	131.2	166.8	110,164
C2.3d_920_TW_1.5	2	15.00	15.00	35.6	131.2	166.8	110,164
C2.3d_2200_TW_0.25	2	15.00	18.96	35.6	148.2	183.9	165,831
C2.3d_2200_TW_0.5	2	15.00	17.06	35.6	138.8	174.4	160,276
C2.3d_2200_TW_0.75	3	15.00	18.63	15.4	204.0	219.4	154,291
C2.3d_2200_TW_1	3	15.00	17.27	15.4	194.6	210.1	148,788
C2.3d_2200_TW_1.25	3	15.00	16.09	15.4	187.8	203.2	144,744
C2.3d_2200_TW_1.5	3	15.00	15.07	15.4	182.9	198.4	141,879

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**
SHIP 2		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C2.3e_590_TW_0.25	1	17.19	17.19	126.7	49.9	176.6	104,188
C2.3e_590_TW_0.5	1	15.91	15.91	122.0	48.0	170.0	100,313
C2.3e_590_TW_0.75	1	15.00	15.00	119.2	46.9	166.2	98,029
C2.3e_590_TW_1	1	15.00	15.00	119.2	46.9	166.2	98,029
C2.3e_590_TW_1.25	1	15.00	15.00	119.2	46.9	166.2	98,029
C2.3e_590_TW_1.5	1	15.00	15.00	119.2	46.9	166.2	98,029
C2.3e_660_TW_0.25	2	17.00	17.89	41.7	143.0	184.7	111,866
C2.3e_660_TW_0.5	2	16.00	16.49	40.5	136.8	177.3	107,414
C2.3e_660_TW_0.75	2	15.00	15.33	39.5	132.5	172.0	104,246
C2.3e_660_TW_1	2	15.00	15.00	39.5	131.4	170.9	103,600
C2.3e_660_TW_1.25	2	15.00	15.00	39.5	131.4	170.9	103,600
C2.3e_660_TW_1.5	2	15.00	15.00	39.5	131.4	170.9	103,600
C2.3e_920_TW_0.25	2	16.67	18.00	41.3	143.5	184.8	122,647
C2.3e_920_TW_0.5	2	15.00	16.83	39.5	138.1	177.6	117,825
C2.3e_920_TW_0.75	2	15.00	15.33	39.5	132.5	172.0	114,510
C2.3e_920_TW_1	2	15.00	15.00	39.5	131.4	170.9	113,865
C2.3e_920_TW_1.25	3	15.00	15.00	4.4	183.3	187.6	112,143
C2.3e_920_TW_1.5	3	15.00	15.00	4.4	183.3	187.6	112,143
C2.3e_980_TW_0.25	2	16.00	18.25	40.5	144.8	185.3	125,112
C2.3e_980_TW_0.5	2	15.00	16.83	39.5	138.1	177.6	120,194
C2.3e_980_TW_0.75	2	15.00	15.33	39.5	132.5	172.0	116,879
C2.3e_980_TW_1	3	15.00	15.68	4.4	186.4	190.8	114,287
C2.3e_980_TW_1.25	3	15.00	15.00	4.4	183.3	187.6	112,405
C2.3e_980_TW_1.5	3	15.00	15.00	4.4	183.3	187.6	112,405
C2.3e_1120_TW_0.25	3	17.00	19.48	4.6	211.3	215.9	129,823
C2.3e_1120_TW_0.5	3	16.00	18.02	4.5	200.2	204.7	123,140
C2.3e_1120_TW_0.75	3	15.00	16.79	4.4	192.3	196.7	118,382
C2.3e_1120_TW_1	3	15.00	15.68	4.4	186.4	190.8	114,900
C2.3e_1120_TW_1.25	3	15.00	15.00	4.4	183.3	187.6	113,018
C2.3e_1120_TW_1.5	3	15.00	15.00	4.4	183.3	187.6	113,018

Appendix A.6: Case outputs C2.4

Case	**Situation**	**Leg**	**Number of leg options**	**Reference speed**	**Time limits**	
					Lower	Upper
C2.4a	TL_1	Finish	2	18.67	0	19.28
	TL_2	Finish	2	18.67	0	20.28
	TL_3	Finish	2	18.67	0	21.28
	TL_4	Finish	2	18.67	0	22.28
	TL_5	Finish	2	18.67	0	23.28
C2.4b	TL_1	Finish	2	18.67	0	20.13
	TL_2	Finish	2	18.67	0	21.13
	TL_3	Finish	2	18.67	0	22.13
	TL_4	Finish	2	18.67	0	23.13
	TL_5	Finish	2	18.67	0	24.13
C2.4c	TL_1	Finish	2	18.67	0	21.60
	TL_2	Finish	2	18.67	0	22.60
	TL_3	Finish	2	18.67	0	23.60
	TL_4	Finish	2	18.67	0	24.60
	TL_5	Finish	2	18.67	0	25.60

Case	**Leg option**	**Distance**	
		ECA	*Non-ECA*
C2.4a	1	2,140	6,051
	2	180	11,454
C2.4b	1	2,140	6,429
	2	180	11,045
C2.4c	1	2,140	7,088
	2	180	10,983

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**	
SHIP 1		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	Fuel	Total
C2.4a_590_TW_1	1	17.71	17.71	360.7	1,019.9	1,380.5	814,519	1,271,519
C2.4a_590_TW_2	1	16.84	16.84	344.0	972.6	1,316.6	776,790	1,233,790
C2.4a_590_TW_3	1	16.04	16.04	330.2	933.8	1,264.0	745,751	1,202,751
C2.4a_590_TW_4	1	15.33	15.33	319.8	904.3	1,224.2	722,254	1,179,254
C2.4a_590_TW_5	1	15.00	15.00	315.0	890.7	1,205.7	711,372	1,168,372
C2.4a_920_TW_1	1	16.91	18.00	345.2	1,035.7	1,381.0	928,698	1,385,698
C2.4a_920_TW_2	1	16.00	17.15	329.6	988.8	1,318.3	886,572	1,343,572
C2.4a_920_TW_3	1	15.00	16.45	315.0	954.0	1,269.0	852,650	1,309,650
C2.4a_920_TW_4	1	15.00	15.45	315.0	909.2	1,224.2	826,207	1,283,207
C2.4a_920_TW_5	1	15.00	15.00	315.0	890.7	1,205.7	815,325	1,272,325
C2.4a_1900_TW_1	1	15.00	18.91	315.0	1,091.8	1,406.8	1,242,673	1,699,673
C2.4a_1900_TW_2	1	15.00	17.60	315.0	1,013.6	1,328.6	1,196,554	1,653,554
C2.4a_1900_TW_3	2	17.00	22.90	29.2	2,640.4	2,669.6	1,613,265	1,613,265
C2.4a_1900_TW_4	2	16.00	21.88	27.7	2,478.0	2,505.7	1,514,680	1,514,680
C2.4a_1900_TW_5	2	15.00	20.95	26.5	2,338.5	2,365.0	1,430,067	1,430,067

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**	
SHIP 1		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	Fuel	Total
C2.4b_590_TW_1	1	17.75	17.75	361.5	1,085.9	1,447.3	853,929	1,310,929
C2.4b_590_TW_2	1	16.91	16.91	345.2	1,037.0	1,382.2	815,502	1,272,502
C2.4b_590_TW_3	1	16.14	16.14	332.1	997.5	1,329.6	784,463	1,241,463
C2.4b_590_TW_4	1	15.46	15.46	321.6	966.3	1,287.9	759,851	1,216,851
C2.4b_590_TW_5	1	15.00	15.00	315.0	946.3	1,261.4	744,201	1,201,201
C2.4b_920_TW_1	1	17.00	18.00	346.8	1,100.6	1,447.4	968,389	1,425,389
C2.4b_920_TW_2	1	16.00	17.23	329.6	1,055.6	1,385.1	925,981	1,382,981
C2.4b_920_TW_3	1	15.00	16.57	315.0	1,019.6	1,334.6	891,362	1,348,362
C2.4b_920_TW_4	1	15.00	15.61	315.0	972.9	1,287.9	863,803	1,320,803
C2.4b_920_TW_5	2	17.00	19.76	29.2	2,131.3	2,160.5	1,284,311	1,284,311
C2.4b_1500_TW_1	1	15.00	18.89	315.0	1,159.1	1,474.1	1,156,391	1,613,391
C2.4b_1500_TW_2	2	18.00	22.60	30.8	2,539.2	2,570.0	1,544,324	1,544,324
C2.4b_1500_TW_3	2	17.00	21.58	29.2	2,383.8	2,413.0	1,450,194	1,450,194
C2.4b_1500_TW_4	2	16.00	20.65	27.7	2,251.3	2,279.0	1,369,822	1,369,822
C2.4b_1500_TW_5	2	16.00	19.78	27.7	2,134.1	2,161.9	1,300,721	1,300,721

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**	
SHIP 1		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	Fuel	Total
C2.4c_590_TW_1	1	17.81	17.81	362.6	1,201.1	1,563.8	922,635	1,379,635
C2.4c_590_TW_2	2	20.60	20.60	36.0	2,194.9	2,230.9	1,316,223	1,316,223
C2.4c_590_TW_3	2	19.72	19.72	34.1	2,081.0	2,115.2	1,247,940	1,247,940
C2.4c_590_TW_4	2	18.91	18.91	32.5	1,982.4	2,014.9	1,188,786	1,188,786
C2.4c_590_TW_5	2	18.18	18.18	31.1	1,900.0	1,931.2	1,139,381	1,139,381
C2.4c_920_TW_1	2	19.00	21.60	32.6	2,334.6	2,367.3	1,407,455	1,407,455
C2.4c_920_TW_2	2	18.00	20.64	30.8	2,201.3	2,232.1	1,327,128	1,327,128
C2.4c_920_TW_3	2	17.00	19.77	29.2	2,087.3	2,116.4	1,258,322	1,258,322
C2.4c_920_TW_4	2	17.00	18.95	29.2	1,986.1	2,015.3	1,198,656	1,198,656
C2.4c_920_TW_5	2	17.00	18.20	29.2	1,902.4	1,931.6	1,149,251	1,149,251

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**	
SHIP 2		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	Fuel	Total
C2.4a_590_TW_1	1	17.71	17.71	297.6	841.5	1,139.2	672,102	1,129,102
C2.4a_590_TW_2	1	16.84	16.84	289.3	817.9	1,107.2	653,262	1,110,262
C2.4a_590_TW_3	1	16.04	16.04	282.5	798.9	1,081.4	638,054	1,095,054
C2.4a_590_TW_4	1	15.33	15.33	277.5	784.7	1,062.2	626,725	1,083,725
C2.4a_590_TW_5	2	20.83	20.83	28.2	1,792.8	1,821.0	1,074,386	1,074,386
C2.4a_920_TW_1	1	16.91	18.00	289.9	849.5	1,139.4	767,903	1,224,903
C2.4a_920_TW_2	1	16.00	17.15	282.2	826.0	1,108.2	746,950	1,203,950
C2.4a_920_TW_3	1	15.00	16.45	275.2	808.8	1,084.0	730,386	1,187,386
C2.4a_920_TW_4	1	15.00	15.45	275.2	787.0	1,062.2	717,542	1,174,542
C2.4a_920_TW_5	2	18.00	20.88	25.3	1,796.4	1,821.7	1,083,150	1,083,150
C2.4a_1900_TW_1	1	15.00	18.91	275.2	877.7	1,152.9	1,040,746	1,497,746
C2.4a_1900_TW_2	1	15.00	17.60	275.2	838.4	1,113.6	1,017,551	1,474,551
C2.4a_1900_TW_3	1	15.00	16.45	275.2	808.8	1,084.0	1,000,086	1,457,086
C2.4a_1900_TW_4	1	15.00	15.45	275.2	787.0	1,062.2	987,242	1,444,242
C2.4a_1900_TW_5	2	16.00	20.92	23.7	1,799.8	1,823.5	1,106,976	1,106,976

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**	
SHIP 2		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	Fuel	Total
C2.4b_590_TW_1	1	17.75	17.75	298.0	895.3	1,193.3	704,031	1,161,031
C2.4b_590_TW_2	1	16.91	16.91	289.9	870.8	1,160.7	684,812	1,141,812
C2.4b_590_TW_3	1	16.14	16.14	283.4	851.5	1,134.9	669,605	1,126,605
C2.4b_590_TW_4	2	20.56	20.56	27.9	1,737.9	1,765.8	1,041,801	1,041,801
C2.4b_590_TW_5	2	19.71	19.71	26.9	1,679.0	1,705.9	1,006,508	1,006,508
C2.4b_920_TW_1	1	17.00	18.00	290.7	902.6	1,193.3	799,957	1,256,957
C2.4b_920_TW_2	1	16.00	17.23	282.2	880.1	1,162.3	778,879	1,235,879
C2.4b_920_TW_3	1	15.00	16.57	275.2	862.3	1,137.5	761,937	1,218,937
C2.4b_920_TW_4	2	18.00	20.61	25.3	1,741.2	1,766.5	1,050,565	1,050,565
C2.4b_920_TW_5	2	17.00	19.76	24.4	1,682.2	1,706.6	1,014,976	1,014,976
C2.4b_1500_TW_1	1	15.00	18.89	275.2	932.1	1,207.3	962,753	1,419,753
C2.4b_1500_TW_2	1	15.00	17.66	275.2	892.5	1,167.7	939,399	1,396,399
C2.4b_1500_TW_3	1	15.00	16.57	275.2	862.3	1,137.5	921,555	1,378,555
C2.4b_1500_TW_4	2	16.00	20.65	23.7	1,744.6	1,768.3	1,064,896	1,064,896
C2.4b_1500_TW_5	2	16.00	19.78	23.7	1,683.6	1,707.4	1,028,939	1,028,939

Situation	**Chosen leg option**	**Speed**		**Fuel consumption**			**Costs**	
SHIP 2		*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	Fuel	Total
C2.4c_590_TW_1	1	17.81	17.81	298.6	989.0	1,287.6	759,696	1,216,696
C2.4c_590_TW_2	2	20.60	20.60	27.9	1,702.9	1,730.8	1,021,152	1,021,152
C2.4c_590_TW_3	2	19.72	19.72	26.9	1,643.7	1,670.6	985,682	985,682
C2.4c_590_TW_4	2	18.91	18.91	26.1	1,593.5	1,619.6	955,572	955,572
C2.4c_590_TW_5	2	18.18	18.18	25.4	1,552.0	1,577.4	930,693	930,693
C2.4c_920_TW_1	1	17.00	18.06	290.7	997.4	1,288.1	855,900	1,312,900
C2.4c_920_TW_2	2	18.00	20.64	25.3	1,706.2	1,731.5	1,029,916	1,029,916
C2.4c_920_TW_3	2	17.00	19.77	24.4	1,646.9	1,671.3	994,150	994,150
C2.4c_920_TW_4	2	17.00	18.95	24.4	1,595.4	1,619.8	963,765	963,765
C2.4c_920_TW_5	2	17.00	18.20	24.4	1,553.2	1,577.7	938,885	938,885

Appendix A.7: Case outputs C3

Situation	**Leg**	**Reference speed**	**Time limits**	
			Lower	Upper
TL_0.5	1	18.67	-	-
	2	17.69	-	9.13
	3	17.32	-	9.13
	Finish		-	9.13
TL_1	1	18.67	-	-
	2	17.69	-	9.63
	3	17.32	-	9.63
	Finish		-	9.63
TL_1.5	1	18.67	-	-
	2	17.69	-	10.13
	3	17.32	-	10.13
	Finish		-	10.13
TL_2	1	18.67	-	-
	2	17.69	-	10.63
	3	17.32	-	10.63
	Finish		-	10.63
TL_2.5	1	18.67	-	-
	2	17.69	-	11.13
	3	17.32	-	11.13
	Finish		-	11.13

Sequence	**Leg**	**Distance**	
		ECA	*Non-ECA*
1	1	1,465	349
	2	200	411
	3	0	1,404
2	1	953	942
	2	200	411
	3	204	1,283

Situation	**Leg**	**Chosen sequence**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C3_590_TL_0.5	1	1	-	18.00	18.00	250.8	59.7	310.5	183,193
	2		100.78	17.00	17.00	32.4	66.6	99.0	58,421
	3		136.72	-	17.02	-	227.8	227.8	134,404
	Finish		219.21			283.2	354.1	637.3	376,017
C3_590_TL_1	1	1	-	17.00	17.00	237.4	56.6	294.0	173,445
	2		106.71	16.00	16.00	30.8	63.3	94.1	55,515
	3		144.89	-	16.28	-	219.4	219.4	129,422
	Finish		231.21			268.2	339.2	607.4	358,383
C3_590_TL_1.5	1	1	-	15.82	15.82	223.8	53.3	277.2	163,519
	2		114.73	15.00	15.00	29.4	60.5	89.9	53,064
	3		155.46	-	16.00	-	216.2	216.2	127,567
	Finish		243.21			253.3	330.0	583.3	344,151
C3_590_TL_2	1	1	-	15.01	15.01	215.7	51.4	267.1	157,597
	2		120.88	15.00	15.00	29.4	60.5	89.9	53,064
	3		161.61	-	15.00	-	206.7	206.7	121,935
	Finish		255.21			245.2	318.6	563.7	332,596
C3_590_TL_2.5	1	1	-	15.00	15.00	215.6	51.4	267.0	157,542
	2		120.93	15.00	15.00	29.4	60.5	89.9	53,064
	3		161.67	-	15.00	-	206.7	206.7	121,935
	Finish		267.21			245.1	318.5	563.6	332,541

Situation	**Leg**	**Chosen sequence**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C3_920_TL_0.5	1	1	-	16.81	18.00	235.1	59.7	294.9	251,558
	2		106.61	17.00	18.00	32.4	70.3	102.8	71,325
	3		141.21	-	18.00	-	240.3	240.3	141,788
	Finish		219.21			267.5	370.4	637.9	464,671
C3_920_TL_1	1	1	-	16.00	17.00	225.6	56.6	282.2	240,931
	2		112.09	16.00	17.00	30.8	66.6	97.4	67,634
	3		148.77	-	17.03	-	227.9	227.9	134,485
	Finish		231.21			256.4	351.1	607.5	443,049
C3_920_TL_1.5	1	1	-	15.00	16.00	215.6	53.7	269.4	230,106
	2		119.48	15.00	16.00	29.4	63.3	92.7	64,428
	3		158.50	-	16.59	-	222.9	222.9	131,500
	Finish		243.21			245.1	339.9	585.0	426,034
C3_920_TL_2	1	1	-	15.00	15.00	215.6	51.4	267.0	228,706
	2		120.93	15.00	15.00	29.4	60.5	89.9	62,779
	3		161.67	-	15.01	-	206.8	206.8	121,990
	Finish		255.21			245.1	318.6	563.7	413,475
C3_920_TL_2.5	1	2	-	15.00	15.00	140.3	138.7	278.9	210,870
	2		126.33	15.00	15.00	29.4	60.5	89.9	62,779
	3		167.07	15.00	15.00	30.0	188.9	218.9	139,052
	Finish		267.21			245.1	318.5	563.6	332,541

Situation	**Leg**	**Chosen sequence**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C3_1200_TL_0.5	1	1	-	16.00	18.00	225.6	59.7	285.3	305,977
	2		110.95	16.00	18.81	30.8	73.7	104.5	80,463
	3		145.31	-	19.00	-	254.6	254.6	150,238
	Finish		219.21			256.4	388.1	644.5	536,678
C3_1200_TL_1	1	1	-	15.00	18.00	215.7	59.7	275.4	294,048
	2		117.04	15.00	18.00	29.4	70.3	99.8	76,834
	3		153.21	-	18.00	-	240.3	240.3	141,788
	Finish		231.21			245.1	370.4	615.5	512,669
C3_1200_TL_1.5	1	1	-	15.00	16.00	215.6	53.7	269.4	290,488
	2		119.48	15.00	16.00	29.4	63.3	92.7	72,671
	3		158.50	-	16.59	-	222.9	222.9	131,500
	Finish		243.21			245.1	339.9	585.0	494,659
C3_1200_TL_2	1	2	-	15.00	16.00	140.3	145.1	285.3	253,928
	2		122.41	15.00	16.00	29.4	63.3	92.7	72,671
	3		161.43	15.00	16.00	30.0	197.6	227.6	152,617
	Finish		255.21			199.8	406.0	605.7	479,217
C3_1200_TL_2.5	1	2	-	15.00	15.00	140.3	138.7	278.9	250,149
	2		126.33	15.00	15.00	29.4	60.5	89.9	71,023
	3		167.07	15.00	15.00	30.0	188.9	218.9	147,461
	Finish		267.21			199.8	388.0	587.8	468,632

Situation	**Leg**	**Chosen sequence**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C3_590_TL_0.5	1	1	-	17.68	17.68	203.5	48.5	252.0	148,687
	2		102.68	18.00	18.00	28.1	57.7	85.8	50,609
	3		136.62	-	17.00	-	190.7	190.7	112,511
	Finish		219.21			231.6	296.9	528.5	311,807
C3_590_TL_1	1	1	-	16.88	16.88	198.3	47.2	245.5	144,852
	2		107.52	17.00	17.00	27.2	55.8	83.0	48,963
	3		143.46	-	16.00	-	185.2	185.2	109,240
	Finish		231.21			225.4	288.2	513.7	303,055
C3_590_TL_1.5	1	1	-	15.82	15.82	192.3	45.8	238.2	140,514
	2		114.73	15.00	15.00	25.7	52.9	78.6	46,359
	3		155.46	-	16.00	-	185.2	185.2	109,240
	Finish		243.21			218.1	283.8	501.9	296,113
C3_590_TL_2	1	1	-	15.01	15.01	188.4	44.9	233.3	137,662
	2		120.88	15.00	15.00	25.7	52.9	78.6	46,359
	3		161.61	-	15.00	-	180.6	180.6	106,527
	Finish		255.21			214.2	278.3	492.5	290,548
C3_590_TL_2.5	1	1	-	15.00	15.00	188.4	44.9	233.3	137,635
	2		120.93	15.00	15.00	25.7	52.9	78.6	46,359
	3		161.67	-	15.00	-	180.6	180.6	106,527
	Finish		267.21			214.1	278.3	492.4	290,522

Situation	**Leg**	**Chosen sequence**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C3_920_TL_0.5	1	1	-	16.94	18.00	198.6	49.0	247.6	-
	2		105.88	16.00	18.00	26.4	57.7	84.1	105.88
	3		141.21	-	18.00	-	197.1	197.1	141.21
	Finish		219.21			225.0	303.8	528.8	219.21
C3_920_TL_1	1	1	-	16.00	17.00	193.2	47.4	240.6	-
	2		112.09	16.00	17.00	26.4	55.8	82.2	112.09
	3		148.77	-	17.03	-	190.9	190.9	148.77
	Finish		231.21			219.6	294.1	513.7	231.21
C3_920_TL_1.5	1	1	-	15.00	16.00	188.4	46.0	234.4	-
	2		119.48	15.00	16.00	25.7	54.2	79.9	119.48
	3		158.50	-	16.59	-	188.4	188.4	158.50
	Finish		243.21			214.1	288.6	502.8	243.21
C3_920_TL_2	1	1	-	15.00	15.04	188.4	44.9	233.3	-
	2		120.88	15.00	15.00	25.7	52.9	78.6	120.88
	3		161.61	-	15.00	-	180.6	180.6	161.61
	Finish		255.21			214.1	278.3	492.5	255.21
C3_920_TL_2.5	1	2	-	15.00	15.00	122.6	121.1	243.7	-
	2		126.33	15.00	15.00	25.7	52.9	78.6	126.33
	3		167.07	15.00	15.00	26.2	165.0	191.2	167.07
	Finish		267.21			174.5	339.0	513.5	267.21

Situation	**Leg**	**Chosen sequence**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C3_1080_TL_0.5	1	1	-	16.00	18.00	193.2	49.0	242.2	237,560
	2		110.95	16.00	18.81	26.4	59.4	85.8	63,533
	3		145.31	-	19.00	-	204.3	204.3	120,548
	Finish		219.21			219.6	312.7	532.3	421,642
C3_1080_TL_1	1	1	-	15.00	18.00	188.4	49.0	237.4	232,389
	2		117.04	15.00	18.00	25.7	57.7	83.4	61,821
	3		153.21	-	18.00	-	197.1	197.1	116,293
	Finish		231.21			214.1	303.8	517.9	410,502
C3_1080_TL_1.5	1	1	-	15.00	17.00	188.4	47.4	235.8	231,438
	2		118.20	15.00	16.00	25.7	54.2	79.9	59,756
	3		157.22	-	16.34	-	187.0	187.0	110,354
	Finish		243.21			214.1	288.6	502.8	401,548
C3_1080_TL_2	1	2	-	15.00	16.00	122.6	124.2	246.8	205,654
	2		122.41	15.00	16.00	25.7	54.2	79.9	59,756
	3		161.43	15.00	16.00	26.2	169.2	195.4	128,163
	Finish		255.21			174.5	347.6	522.1	393,573
C3_1080_TL_2.5	1	2	-	15.00	15.00	122.6	121.1	243.7	203,834
	2		126.33	15.00	15.00	25.7	52.9	78.6	58,962
	3		167.07	15.00	15.00	26.2	165.0	191.2	125,679
	Finish		267.21			174.5	339.0	513.5	388,475

Situation	**Leg**	**Chosen sequence**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C3_1200_TL_0.5	1	2	-	16.00	19.39	125.7	139.2	264.9	232,929
	2		108.18	16.00	19.00	26.4	59.8	86.2	66,939
	3		142.31	16.00	20.00	26.9	194.1	221.0	146,775
	Finish		219.21			179.0	393.0	572.0	446,643
C3_1200_TL_1	1	2	-	16.00	18.00	125.7	132.2	257.9	228,838
	2		111.90	16.00	18.00	26.4	57.7	84.1	65,693
	3		147.23	16.00	18.01	26.9	180.2	207.1	138,602
	Finish		231.21			179.0	370.1	549.1	433,133
C3_1200_TL_1.5	1	2	-	15.00	17.00	122.6	127.9	250.5	222,555
	2		118.95	15.00	17.00	25.7	55.8	81.5	63,800
	3		156.45	15.00	17.55	26.2	177.5	203.7	136,205
	Finish		243.21			174.5	361.3	535.8	422,559
C3_1200_TL_2	1	2	-	15.00	16.00	122.6	124.2	246.8	220,360
	2		122.41	15.00	16.00	25.7	54.2	79.9	62,842
	3		161.43	15.00	16.00	26.2	169.2	195.4	131,311
	Finish		255.21			174.5	347.6	522.1	414,514
C3_1200_TL_2.5	1	2	-	15.00	15.00	122.6	121.1	243.7	218,540
	2		126.33	15.00	15.00	25.7	52.9	78.6	62,048
	3		167.07	15.00	15.00	26.2	165.0	191.2	128,828
	Finish		267.21			174.5	339.0	513.5	409,416

Situation	**Average speed**		**Total fuel consumption**			**Costs**	**Total distance**	
SHIP 1	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*		*ECA*	*Non-ECA*
C3.1_590_0.5	17.48	17.48	283.2	354.1	637.3	376,017	1,665	2,164
C3.1_590_1	16.58	16.58	268.2	339.2	607.4	358,383	1,665	2,164
C3.1_590_1.5	15.76	15.76	253.3	330.0	583.3	344,151	1,665	2,164
C3.1_590_2	15.00	15.00	245.2	318.6	563.7	332,596	1,665	2,164
C3.1_590_2.5	15.00	15.00	245.1	318.5	563.6	332,541	1,665	2,164
C3.1_920_0.5	16.83	18.00	267.5	370.4	637.9	464,671	1,665	2,164
C3.1_920_1	16.00	17.02	256.4	351.1	607.5	443,049	1,665	2,164
C3.1_920_1.5	15.00	16.38	245.1	339.9	585.0	426,034	1,665	2,164
C3.1_920_2	15.00	15.01	245.1	318.6	563.7	413,475	1,665	2,164
C3.1_920_2.5	15.00	15.00	199.8	388.0	587.8	412,702	1,357	2,636
C3.1_1200_0.5	16.00	18.80	256.4	388.1	644.5	536,678	1,665	2,164
C3.1_1200_1	15.00	18.00	245.1	370.4	615.5	512,669	1,665	2,164
C3.1_1200_1.5	15.00	16.38	245.1	339.9	585.0	494,659	1,665	2,164
C3.1_1200_2	15.00	16.00	199.8	406.0	605.7	479,217	1,357	2,636
C3.1_1200_2.5	15.00	15.00	199.8	388.0	587.8	468,632	1,357	2,636

Situation	**Average speed**		**Total fuel consumption**			**Costs**	**Total distance**	
SHIP 2	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*		*ECA*	*Non-ECA*
C3.1_590_0.5	17.48	17.48	231.6	296.9	528.5	311,807	1,665	2,164
C3.1_590_1	16.58	16.58	225.4	288.2	513.7	303,055	1,665	2,164
C3.1_590_1.5	15.76	15.76	218.1	283.8	501.9	296,113	1,665	2,164
C3.1_590_2	15.00	15.00	214.2	278.3	492.5	290,548	1,665	2,164
C3.1_590_2.5	15.00	15.00	214.1	278.3	492.4	290,522	1,665	2,164
C3.1_920_0.5	16.83	18.00	225.0	303.8	528.8	386,264	1,665	2,164
C3.1_920_1	16.00	17.02	219.6	294.1	513.7	375,542	1,665	2,164
C3.1_920_1.5	15.00	16.38	214.1	288.6	502.8	367,289	1,665	2,164
C3.1_920_2	15.00	15.01	214.1	278.3	492.5	361,207	1,665	2,164
C3.1_920_2.5	15.00	15.00	174.5	339.0	513.5	360,553	1,357	2,636
C3.1_1200_0.5	16.00	19.63	179.0	393.0	572.0	446,643	1,357	2,636
C3.1_1200_1	16.00	18.01	179.0	370.1	549.1	433,133	1,357	2,636
C3.1_1200_1.5	15.00	17.27	174.5	361.3	535.8	422,559	1,357	2,636
C3.1_1200_2	15.00	16.00	174.5	347.6	522.1	414,514	1,357	2,636
C3.1_1200_2.5	15.00	15.00	174.5	339.0	513.5	409,416	1,357	2,636
C3.1_1080_0.5	16.00	18.80	219.6	312.7	532.3	421,642	1,665	2,164
C3.1_1080_1	15.00	18.00	214.1	303.8	517.9	410,502	1,665	2,164
C3.1_1080_1.5	15.00	16.38	214.1	288.6	502.8	401,548	1,665	2,164
C3.1_1080_2	15.00	16.00	174.5	347.6	522.1	393,573	1,357	2,636
C3.1_1080_2.5	15.00	15.00	174.5	339.0	513.5	388,475	1,357	2,636

Appendix A.8: Case outputs C4

Situation	**Leg**	**Reference speed**	**Time limits**	
			Lower	Upper
TL_0.5	1	18.67	-	-
	2	17.69	-	9.32
	3	17.32	-	9.32
	Finish		-	9.32
TL_1	1	18.67	-	-
	2	17.69	-	9.82
	3	17.32	-	9.82
	Finish		-	9.82
TL_1.5	1	18.67	-	-
	2	17.69	-	10.32
	3	17.32	-	10.32
	Finish		-	10.32
TL_2	1	18.67	-	-
	2	17.69	-	10.82
	3	17.32	-	10.82
	Finish		-	10.82
TL_2.5	1	18.67	-	-
	2	17.69	-	11.32
	3	17.32	-	11.32
	Finish		-	11.32

Sequence	**Leg**	**Leg option**	**Distance**	
			ECA	*Non-ECA*
1	1	1	1,465	349
		2	565	1,679
		3	913	1,010
		4	614	1,493
	2	-	200	411
	3	-	0	1,404
2	1	1	953	942
		2	363	1,919
		3	440	1,639
		4	716	1,210
		5	413	1,735
	2	-	200	411
	3	-	204	1,283

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C4_590_TL_0.5	1	1	-	17.25	17.25	240.8	57.4	298.1	175,903
	2	-	105.21	17.00	17.00	32.4	66.6	99.0	58,421
	3	-	141.15	-	17.00	-	227.5	227.5	134,243
	Finish		223.74			273.2	351.5	624.7	368,566
C4_590_TL_1	1	1	-	16.20	16.20	228.0	54.3	282.3	166,534
	2	-	112.05	17.00	17.00	32.4	66.6	99.0	58,421
	3	-	147.99	-	16.00	-	216.2	216.2	127,567
	Finish		235.74			260.4	337.1	597.5	352,522
C4_590_TL_1.5	1	1	-	16.00	16.00	225.6	53.7	279.3	164,789
	2	-	113.41	15.00	15.00	29.4	60.5	89.9	53,064
	3	-	154.14	-	15.00	-	206.7	206.7	121,935
	Finish		247.74			255.0	320.9	575.9	339,788
C4_590_TL_2	1	1	-	15.00	15.00	215.6	51.4	267.0	157,542
	2	-	120.93	15.00	15.00	29.4	60.5	89.9	53,064
	3	-	161.67	-	15.00	-	206.7	206.7	121,935
	Finish		259.74			245.1	318.5	563.6	332,541
C4_590_TL_2.5	1	1	-	15.00	15.00	215.6	51.4	267.0	157,542
	2	-	120.93	15.00	15.00	29.4	60.5	89.9	53,064
	3	-	161.67	-	15.00	-	206.7	206.7	121,935
	Finish		271.74			245.1	318.5	563.6	332,541

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C4_920_TL_0.5	1	3	-	16.82	18.00	146.7	172.9	319.5	236,931
	2	-	110.41	16.00	18.00	30.8	70.3	101.1	69,842
	3	-	145.74	-	18.00	-	240.3	240.3	141,788
	Finish		223.74			177.5	483.5	661.0	448,560
C4_920_TL_1	1	3	-	16.00	17.00	140.6	163.7	304.3	225,925
	2	-	116.47	16.00	17.00	30.8	66.6	97.4	67,631
	3	-	153.15	-	17.00	-	227.5	227.5	134,243
	Finish		235.74			171.4	457.8	629.2	427,799
C4_920_TL_1.5	1	3	-	15.00	16.00	134.4	155.5	289.9	215,411
	2	-	123.99	15.00	16.00	29.4	63.3	92.7	64,428
	3	-	163.01	-	16.59	-	222.8	222.8	131,476
	Finish		247.74			163.8	441.7	605.5	411,314
C4_920_TL_2	1	3	-	15.00	15.00	134.4	148.7	283.1	211,359
	2	-	128.20	15.00	15.00	29.4	60.5	89.9	62,779
	3	-	168.93	-	15.48	-	211.2	211.2	124,624
	Finish		259.74			163.8	420.4	584.2	398,762
C4_920_TL_2.5	1	3	-	15.00	15.00	134.4	148.7	283.1	211,359
	2	-	128.20	15.00	15.00	29.4	60.5	89.9	62,779
	3	-	168.93	-	15.00	-	206.7	206.7	121,935
	Finish		271.74			163.8	415.8	579.7	396,073

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 1				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C4_1300_TL_0.5	1	3	-	15.00	19.00	134.4	183.2	317.6	282,789
	2	-	114.02	15.00	18.29	29.4	71.6	101.0	80,489
	3	-	149.85	-	19.00	-	254.6	254.6	150,238
	Finish		223.74			163.8	509.4	673.2	513,516
C4_1300_TL_1	1	3	-	15.00	17.00	134.4	163.7	298.1	271,283
	2	-	120.28	15.00	18.00	29.4	70.3	99.8	79,778
	3	-	156.45	-	17.72	-	236.7	236.7	139,657
	Finish		235.74			163.8	470.7	634.6	490,718
C4_1300_TL_1.5	1	3	-	15.00	16.00	134.4	155.5	289.9	266,480
	2	-	123.99	15.00	16.00	29.4	63.3	92.7	75,615
	3	-	163.01	-	16.59	-	222.8	222.8	131,476
	Finish		247.74			163.8	441.7	605.5	473,571
C4_1300_TL_2	1	4	-	15.00	16.23	90.4	232.7	323.1	254,799
	2	-	132.97	15.00	16.00	29.4	63.3	92.7	75,615
	3	-	171.99	-	16.00	-	216.2	216.2	127,567
	Finish		259.74			19.8	512.2	632.0	457,982
C4_1300_TL_2.5	1	4	-	15.00	15.49	90.4	224.8	315.1	250,105
	2	-	137.41	15.00	15.00	29.4	60.5	89.9	73,967
	3	-	178.14	-	15.00	-	206.7	206.7	121,935
	Finish		271.74			19.8	491.9	611.8	446,006

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C4_590_TL_0.5	1	1	-	17.25	17.25	200.7	47.8	248.5	146,598
	2	-	105.21	17.00	17.00	27.2	55.8	83.0	48,963
	3	-	141.15	-	17.00	-	190.7	190.7	112,511
	Finish		223.74			227.8	294.3	522.2	308,072
C4_590_TL_1	1	1	-	16.54	16.54	196.3	46.8	243.1	143,404
	2	-	109.80	16.00	16.00	26.4	54.2	80.6	47,540
	3	-	147.99	-	16.00	-	185.2	185.2	109,240
	Finish		235.74			222.7	286.1	508.8	300,183
C4_590_TL_1.5	1	1	-	16.00	16.00	193.2	46.0	239.2	141,126
	2	-	113.41	15.00	15.00	25.7	52.9	78.6	46,359
	3	-	154.14	-	15.00	-	180.6	180.6	106,527
	Finish		247.74			218.9	279.4	498.3	294,012
C4_590_TL_2	1	1	-	15.00	15.00	188.4	44.9	233.3	137,635
	2	-	120.93	15.00	15.00	25.7	52.9	78.6	46,359
	3	-	161.67	-	15.00	-	180.6	180.6	106,527
	Finish		259.74			214.1	278.3	492.4	290,522
C4_590_TL_2.5	1	1	-	15.00	15.00	188.4	44.9	233.3	137,635
	2	-	120.93	15.00	15.00	25.7	52.9	78.6	46,359
	3	-	161.67	-	15.00	-	180.6	180.6	106,527
	Finish		271.74			214.1	278.3	492.4	290,522

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C4_920_TL_0.5	1	3	-	16.82	18.00	123.4	141.8	265.2	197,161
	2	-	110.41	16.00	18.00	26.4	57.7	84.1	58,308
	3	-	145.74	-	18.00	-	197.1	197.1	116,293
	Finish		223.74			149.7	396.6	546.3	371,761
C4_920_TL_1	1	3	-	16.00	17.00	120.4	137.2	257.6	191,707
	2	-	116.47	16.00	17.00	26.4	55.8	82.2	57,200
	3	-	153.15	-	17.00	-	190.7	190.7	112,511
	Finish		235.74			146.8	383.7	530.5	361,417
C4_920_TL_1.5	1	3	-	15.00	16.00	117.4	133.2	250.6	186,603
	2	-	123.99	15.00	16.00	25.7	54.2	79.9	55,641
	3	-	163.01	-	16.59	-	188.4	188.4	111,155
	Finish		247.74			143.1	375.8	518.9	353,399
C4_920_TL_2	1	3	-	15.00	15.00	117.4	129.9	247.3	184,652
	2	-	128.20	15.00	15.00	25.7	52.9	78.6	54,847
	3	-	168.93	-	15.48	-	182.7	182.7	107,822
	Finish		259.74			143.1	365.5	508.6	347,320
C4_920_TL_2.5	1	3	-	15.00	15.00	117.4	129.9	247.3	184,652
	2	-	128.20	15.00	15.00	25.7	52.9	78.6	54,847
	3	-	168.93	-	15.00	-	180.6	180.6	106,527
	Finish		271.74			143.1	363.3	506.4	346,025

Situation	**Leg**	**Chosen leg option**	**Start time** [hours]	**Speed**		**Fuel consumption**			**Costs**
SHIP 2				*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*	
C4_1300_TL_0.5	1	4	-	16.00	19.32	81.0	220.0	300.9	235,043
	2	-	115.71	16.00	19.00	26.4	59.8	86.2	69,576
	3	-	149.85	-	19.00	-	204.3	204.3	120,548
	Finish		223.74			107.3	484.1	591.4	425,167
C4_1300_TL_1	1	4	-	15.90	18.00	80.8	209.6	290.4	228,667
	2	-	121.57	15.00	18.00	25.7	57.7	83.4	67,479
	3	-	157.74	-	18.00	-	197.1	197.1	116,293
	Finish		235.74			106.5	464.4	570.9	412,438
C4_1300_TL_1.5	1	4	-	15.00	17.23	79.0	204.3	283.3	223,210
	2	-	127.64	15.00	17.00	25.7	55.8	81.5	66,372
	3	-	165.15	-	17.00	-	190.7	190.7	112,511
	Finish		247.74			104.7	450.9	555.5	402,092
C4_1300_TL_2	1	4	-	15.00	16.23	79.0	198.3	277.2	219,622
	2	-	132.97	15.00	16.00	25.7	54.2	79.9	65,414
	3	-	171.99	-	16.00	-	185.2	185.2	109,240
	Finish		259.74			104.7	437.6	542.3	394,276
C4_1300_TL_2.5	1	4	-	15.00	15.49	79.0	194.4	273.4	217,347
	2	-	137.41	15.00	15.00	25.7	52.9	78.6	64,620
	3	-	178.14	-	15.00	-	180.6	180.6	106,527
	Finish		271.74			104.7	427.8	532.5	388,494

Situation	**Average speed**		**Total fuel consumption**			**Costs**	**Total distance**	
SHIP 1	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*		*ECA*	*Non-ECA*
C4.1_590_0.5	17.12	17.12	273.2	351.5	624.7	368,566	1,665	2,164
C4.1_590_1	16.25	16.25	260.4	337.1	597.5	352,522	1,665	2,164
C4.1_590_1.5	15.47	15.47	255.0	320.9	575.9	339,788	1,665	2,164
C4.1_590_2	15.00	15.00	245.1	318.5	563.6	332,541	1,665	2,164
C4.1_590_2.5	15.00	15.00	245.1	318.5	563.6	332,541	1,665	2,164
C4.1_920_0.5	16.68	18.00	177.5	483.5	661.0	448,560	1,113	2,825
C4.1_920_1	16.00	17.00	171.4	457.8	629.2	427,799	1,113	2,825
C4.1_920_1.5	15.00	16.29	163.8	441.7	605.5	411,314	1,113	2,825
C4.1_920_2	15.00	15.24	163.8	420.4	584.2	398,762	1,113	2,825
C4.1_920_2.5	15.00	15.00	163.8	415.8	579.7	396,073	1,113	2,825
C4.1_1300_0.5	15.00	18.90	163.8	509.4	673.2	513,516	1,113	2,825
C4.1_1300_1	15.00	17.50	163.8	470.7	634.6	490,718	1,113	2,825
C4.1_1300_1.5	15.00	16.29	163.8	441.7	605.5	473,571	1,113	2,825
C4.1_1300_2	15.00	16.10	119.8	512.2	632.0	457,982	814	3,308
C4.1_1300_2.5	15.00	15.22	119.8	491.9	611.8	446,006	814	3,308

Situation	**Average speed**		**Total fuel consumption**			**Costs**	**Total distance**	
SHIP 2	*ECA*	*Non-ECA*	*ECA*	*Non-ECA*	*Total*		*ECA*	*Non-ECA*
C4.1_590_0.5	17.12	17.12	227.8	294.3	522.2	308,072	1,665	2,164
C4.1_590_1	16.25	16.25	222.7	286.1	508.8	300,183	1,665	2,164
C4.1_590_1.5	15.47	15.47	218.9	279.4	498.3	294,012	1,665	2,164
C4.1_590_2	15.00	15.00	214.1	278.3	492.4	290,522	1,665	2,164
C4.1_590_2.5	15.00	15.00	214.1	278.3	492.4	290,522	1,665	2,164
C4.1_920_0.5	16.68	18.00	149.7	396.6	546.3	371,761	1,113	2,825
C4.1_920_1	16.00	17.00	146.8	383.7	530.5	361,417	1,113	2,825
C4.1_920_1.5	15.00	16.29	143.1	375.8	518.9	353,399	1,113	2,825
C4.1_920_2	15.00	15.24	143.1	365.5	508.6	347,320	1,113	2,825
C4.1_920_2.5	15.00	15.00	143.1	363.3	506.4	346,025	1,113	2,825
C4.1_1300_0.5	16.00	19.14	107.3	484.1	591.4	425,167	814	3,308
C4.1_1300_1	15.68	18.00	106.5	464.4	570.9	412,438	814	3,308
C4.1_1300_1.5	15.00	17.10	104.7	450.9	555.5	402,092	814	3,308
C4.1_1300_2	15.00	16.10	104.7	437.6	542.3	394,276	814	3,308
C4.1_1300_2.5	15.00	15.22	104.7	427.8	532.5	388,494	814	3,308