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MASTERKONTRAKT
- uttak av masteroppgave

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Studieprogram **Industriell økonomi og teknologiledelse**	Hovedprofil **Anvendt økonomi og optimering**

3. Masteroppgave

Oppstartsdato **15. jan 2013**	Innleveringsfrist **11. jun 2013**
Oppgavens (foreløpige) tittel **Decision support for tonnage allocation in dry bulk liner shipping**	

Oppgavetekst/Problembeskrivelse
.

The purpose of this work is to illustrate how optimization based methods can be used as decision support when planning fleet deployment in liner shipping.

MARINTEK will provide concrete information and actual data for the problem.

The following main points must be considered:

1. Give a verbal description of the studied planning problem
2. Formulate one or several models of the actual problem
3. Implement one or several of the model(s) by use of available software
4. Test the model(s) with relevant data
5. Discuss the model(s) and the test results with regard to how useful the model(s) are for practical planning.
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Hovedveileder ved institutt **Professor Bjørn Nygreen**	Medveileder(e) ved institutt
Ekstern bedrift/institusjon **MARINTEK**	Ekstern veileder ved bedrift/instutisjon **Research Scientist Inge Norstad**
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.

Trondheim 11 jan 2013
Sted og dato

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Hovedveileder

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

Abstract

Maritime transportation represents the major transportation mode of international trade and the world seaborne trade continues to grow. There exists however an oversupply of ships representing a serious challenge for ship owners as the freight rates are at unprofitable levels. It is therefore important to have an optimal utilization of the fleet. This thesis studies the tonnage allocation problem for a liner shipping company with the purpose to illustrate how optimisation based methods can be used as decision support when planning fleet deployment in liner shipping. In the context of data from a real shipping company is an optimisation model developed. A special emphasis has been on the implementation and preprocessing in order to obtain an efficient model. The model has then been the basis for a performance study and a thorough analysis of the effects when adjusting input parameters and constraints.

The company has two types of trades which they can sail; mandatory trades and optional trades. In addition all ships have to attend service once every third year. If the company is not able to sail voyages of mandatory trades themselves, they can hire spot ships. Every voyage of a trade has a time window for when the voyage can start, and there is also a requirement of fairly evenly spread voyages of the same trade. The strictness of the spread of voyages is regulated by a factor.

Aspects which have been analysed in this thesis are the timing of trades with regard to spread of voyages and time windows, cost of spot ships, service trades, origin port and earliest available time for each ship and the introduction of optional trades. An alternative, shorter way of sailing a voyage has also been introduced to the model in order to try to obtain a better utilization of the fleet.

The results show the value of flexibility, but also the impact it has on the computational time. Limitations should be added to the problem with careful consideration in order to not exclude possible solutions. The results also show how obligations done in one period put constraints on what a shipping company can do in the next period since the fleet is tied up.

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Sammendrag

Størstedelen av internasjonal handel skjer ved bruk av maritim transport og det er i stadig vekst. På bakgrunn av finanskrisen i 2009 eksisterer det en overkapasitet av skip som representerer en stor utfordring for skipseiere. Fraktrater er på nivå som ikke lenger gir profitt, og det er derfor viktig å utnytte flåten på en optimal måte.

Denne oppgaven studerer et tonnasje allokeringsproblem for et selskap som opererer i linjefart. Formålet med oppgaven er å vise hvordan en kan bruke optimering som beslutningsstøtte når det blir planlagt flåtestyring i linjefart. Basert på informasjon fra et reelt selskap er en optimeringsmodell utviklet. Det er brukt spesielt mye tid på implementering og pre-prosessering for å oppnå en modell som er så effektiv som mulig. Modellen har blitt testet og det er gjort grundige analyser av effektene ved å justere input parameter og restriksjoner.

Selskapet har to typer "handler" de kan seile; obligatoriske og frivillige. I tillegg må alle skipene til service en gang hvert tredje år. Dersom selskapet ikke klarer å seile alle reisene av de obligatoriske handlene selv, kan de leie inn spot skip. Hver reise av en handel har et tidsvindu for når reisen kan starte og det er også et krav om at reisene for samme handel er jevnt fordelt. Hvor strengt jevnt fordelt reisene må være, reguleres manuelt av en faktor.

Aspekt som har blitt analysert i denne rapporten er tidspunkt for reiser med tanke på spredning og tidsvinduer, kostnad for å leie inn spot skip, servicene skipene må ha, sted og tid skipet er ledig i starten av en plan-leggingsperiode og introduksjonen av de frivillige handlene. En alternativ, kortere måte å seile en reise på har blitt introdusert for å prøve og oppnå en bedre utnyttelse av flåten.

Resultatene viser verdien av å ha fleksibilitet i planleggingen, men også hvordan dette øker løsningstiden. Begrensninger bør legges til problemet etter nøye vurdering for ikke å utelukke mulige løsninger. Resultatene viser også hvordan forpliktelser gjort i en periode setter hindringer for hva en flåte kan gjøre i neste periode siden skipene er bundet opp i reiser.

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Preface

This master's thesis has been written as a part of the Master of Science degree within Managerial Economics and Operations Research at the Department of Industrial Economics and Technology Management, at the Norwegian University of Science and Technology.

Unlike many other master's thesis, this thesis is not a continuation of a project work. Optimisation of maritime transportation is a different area of expertice than what I wrote about in my specialization project. This has given me some challenges to provide myself with the foundation many other students obtain from the project work. Nevertheless, I have found this master's thesis both interesting and educational.

I would like to thank my main supervisor, Professor Bjørn Nygreen, from the Department of Industrial Economics and Technology Management (IOT) for valuable guidance in the work with my master's, especially in the implementation of the model and discussions regarding the analysis. I would also like to thank Inge Norstad, PhD candidate at IOT and Research Scientist at MARINTEK, for guidance during my work on this thesis, especially providing me with help regarding TurboRouter.

Trondheim, June 2013

Øydis Kristine Flateby

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1 Introduction

Maritime transportation is and has been the major way of international trade, representing about 80 per cent of global trade by volume and more than 70 per cent by value; these shares being even higher in the case of most developing countries. Population growth, increased standard of living, rapid industrialization and elimination of trade barriers are just some of the many factors contributing to the continuing growth of transportation by sea (UNCTAD, 2012).

Four years after the economic and financial crisis of 2008 has the world fleet experienced an increase of over 37 per cent. At the same time has there been a reduction in the world order book by one third due to continued deliveries and a drastic downturn in new orders. There exists therefore an oversupply of ships which has impacts on the freight rates. In 2011 and in the beginning of 2012 were the freight rates often at unprofitable levels for the ship owners. In an attempt to make savings were greater economies of scale by investing in large capacity ships in the tanker and dry bulk market segments done. This only led to more capacity in the world fleet, and the oversupply of ships represents now a serious challenge for ship owners and makes it even more important for shipping companies to have an optimal utilization of their fleet (UNCTAD, 2012).

This thesis presents a tonnage allocation model for a liner shipping company operating dry bulk carriers. The company has worldwide trade routes, both mandatory and optional, which they operate with their fleet. In addition the ships have to attend service which should be in periods with minimum consequences for the rest of the shipping company's operations. The purpose of the work in this thesis is to illustrate how optimisation based methods can be used as decision support when planning tonnage allocation in liner shipping. A model is developed and implemented, and computational studies have been performed. The major focus when performing analysis has been looking at the effects of adjusting input parameters and constraints in order to obtain an optimal utilization of the fleet with minimal use of spot ships.

The remainder of this thesis is structured as follows. Section 2 gives a short introduction to terminology used in this thesis and developments in international seaborne trade today. Section 3 presents different modes and planning levels in maritime transportation and gives the reader an introduction to liner shipping. Section 4 reviews some of the literature relevant for this thesis, while section 5 presents the problem formulation of the tonnage

allocation problem for a shipping company. The mathematical formulation is given in section 6, with the implementation of the model described in section 7. A computational study with both performance study and analysis of adjusting input parameters and constraints is conducted in section 8. An alternative say of sailing a voyage has also been studied. Section 9 gives an introduction to future work and alternative solution methods, while section 10 presents the concluding remark.

2 Maritime Transportation

This section seeks to give a short presentation of the field of maritime transportation. A sample of terminology most used in this thesis is presented before an introduction to the developments in international seaborne trade today is given.

2.1 Terminology

The following list explains the most central terms used in this thesis.

- **Shipping** refers to moving cargoes by ships and the **shipper** is the owner of the transported cargo. A **shipment** is a specified amount of cargo transported from origin to destination.

- A **trade (route)** describes a number of loading ports in one geographical region and a number of unloading ports in a different region.

- A **voyage** is one traversal of a trade.

- A **TC-trade** is an optional trade which the shipping company can choose to sail.

- A **dry docking** is a planned service of a ship done every third year in a port in Asia.

- **Routing** is the assignment of a sequence of ports to a ship, while **scheduling** is the assignment of times (or time window) to the events on the route of various ships.

- **Tonnage allocation** is the allocation of ships to voyages of trades in an optimal way. This is in literature referred to as **fleet deployment**.

- **Ballast** is when a ship sails to a designated port without cargo.

- **Freight rate** is the price the shipper agrees to pay for the transport of cargo.

- **Spot ship** is a ship which can be hired in to service a voyage of a trade when the shipping company can not sail the voyage themselves.

- **Start/end port** is the start and end port of a voyage of a trade.

- **Origin/destination port** is the origin and final position of a ship in the planning period.

2.2   Developments in international seaborne trade

Seaborne transportation represents the major transportation mode of international trade, and it has to be viewed in the context of the world economy and global merchandise trade. The world economic growth decreased in 2011, growing by only 2.7% compared to 4.1% in 2010. In tandem with the world economy, the growth in world merchandise trade by volume experienced a large drop from 13.9% recorded in 2010 to 5.9% in 2011. The debt crisis in Europe, difficulties facing advanced economies, heightened global financial risks, political and social unrest in North Africa and Western Asia, natural disasters in Japan and Thailand which disrupted regional and global supply chains, as well as rising oil prices and volatility have all been part of weighing down on global growth. Nevertheless, the values of world merchandise export increased by 19%, even though at a relative slowdown from 22% the year before (UNCTAD, 2012).

2.2.1   Status of the world seaborne trade

World seaborne trade experienced in 2011 a steady growth of 4%, reaching a total volume of 8.7 billion tons (figure 1). This expansion was driven by a rapid growth in dry cargo volumes of 5.6%, where container and major bulk trades grew by 8.6% and 5.4% respectively. Dry cargo which includes major and minor dry bulks, containerized trade and general cargo accounted for two-thirds of the total volume of global seaborne trade in 2011, while oil trade represented the last one-third. This picture turns out different if one considers the contribution of the market segments to the value of world
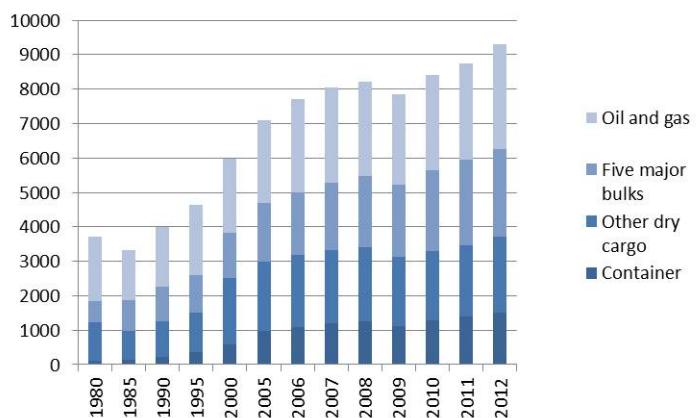
Figure 1: International seaborne trade by cargo type, selected years (millions of tons loaded) (UNCTAD, 2012)

seaborne trade. In 2007 [1] accounted containerized cargo for the largest share of global trade with more than 50%. This reflects the higher value of goods carried in container. Tanker trade on the other hand accounted for less than 25%, while general and dry cargo accounted for 20% and 6% respectively. Recent analysis of 2008 and 2009 show an increase in the value of dry bulk cargo, and this reflects the strong import demand for these commodities from emerging developing countries (UNCTAD, 2012).

2.2.2   World fleet

The world fleet continued to expand during 2011, reaching more than 1.5 billion deadweight tons (DWT) in January 2012 (figure 2). Three years after the economic and financial crisis of 2008 is this an increase of over 37%. The largest growth of tonnage is experienced in dry bulk carriers with an increase of 17% bringing it to 40.6% of the world total capacity. Containerships increased 7.7% and accounts now for 12.9% of the world tonnage. Even though the share of container ships is small, the role for container ships in global trade is extremely important as 52% of seaborne trade in terms of dollar is containerized (UNCTAD, 2012).
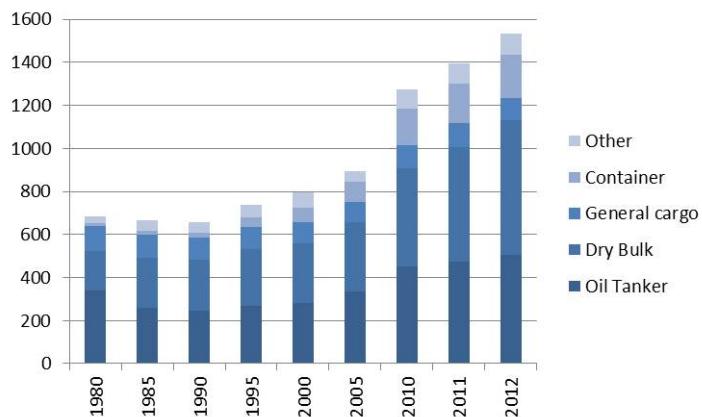
Figure 2: World fleet by principal vessel types (millions of DWT) (UNCTAD, 2012)

At the same time has the world order book experienced a reduction due to continued deliveries and a drastic downturn in new orders following the economic crisis. In January 2012 amounted the order book to approximately 21% of the existing fleet tonnage, down from 44% four years earlier. Even though the order book decreases are the major ship builders reluctant to

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[1]The newest numbers available (UNCTAD, 2012)

cancel or postpone deliveries. This results in an oversupply of ships and it represents a serious challenge for ship owners (UNCTAD, 2012).

Freight rates in 2011 and in the beginning of 2012 were often at unprofitable levels, especially within dry bulk, liquid bulk and containerized cargo, and an oversupply of ships can be identified as the major reason behind this development. Investing in large capacity ships within the tanker and the dry bulk segment accelerated competition as ship operators then were willing to accept freight rates below or close to operating costs. At the same time as freight rates declined or remained at historically low levels, ship operating costs grew moderately. This trend continues and it is therefore more important than ever to have an optimal fleet and tonnage allocation (UNCTAD, 2012).

2.2.3 Dry bulk shipping

Dry bulk shipping refers to the movement of commodities carried in bulk, as opposed to be carried in containers or other unit loads (Intercargo, 2013). Dry bulk cargo includes the major commodities iron ore, coal, grain, bauxite/alumina and phosphate rock and the minor bulks agribulks, fertilizers, metals, minerals, steel and forest products. In 2011 dry cargo increased by 5.6 %, taking the total to nearly 6 billion tons. Major dry bulks accounted for 42 % of all dry cargo and figure 3 shows the distribution between them. Looking isolated at dry bulk trade, it totally accounted for 3.7 billion tons in 2011, also an increase of 5.6 % (UNCTAD, 2012).
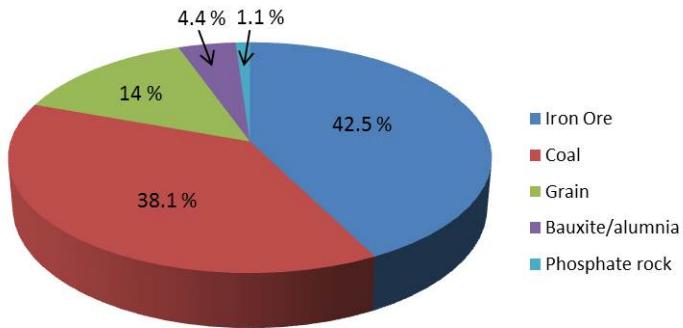
Figure 3: Major dry bulks (UNCTAD, 2012)

The growth in the five major dry bulks is closely linked to steel production, growing infrastructure development needs of emerging developing

countries, urbanization and the evolution of the global manufacturing base. World consumption and production of steel continued to expand in 2011 despite global economic uncertainties and volatilities, even though at a slower rate. The deceleration reflects the overall weakness of the world economy and the slight slowdown in the economic expansion of China (UNCTAD, 2012).

The importance of the dry bulk industry is major, especially the international steel industry is dependent of an efficient and cost effective maritime industry to transport raw materials as coal and iron ore, as well as the finished product around the world. Taking a look in an average home will one find links to the dry cargo industry all around. An example is toasting a piece of bread. There are metal components in the toaster manufactured using ores and alumina, grain is used in the bread and the toasting happens with coal-generated electricity (Intercargo, 2013).

2.2.4 Emerging trends affecting international shipping

The shipping industry is confronted by a rapidly changing operating environment and some trends contribute to reshaping the industry's future and altering global seaborne trade patterns. The main trends are: (UNCTAD, 2012)

- Emissions from the ships are at the centre stage of the current *climate change* debate and adaptations must be performed.

- There is a *shift of global economics influence* and economic mass from advanced economies to emerging developing countries which results in *changing trade patterns.*

- *Rising bunker fuel prices and operating costs* remains a great challenge in view of rising demand, supply pressures and increasing environmental regulation.

- There has been a significant increase of *maritime piracy* the recent years, in particular in the Gulf of Aden, Somali Basin and the Indian Ocean (Interpol, 2013).

- There is a *growing momentum of sustainability imperatives* and focus on the need to reduce the sector's energy consumption and air emissions.

3   Shipping characteristics

The purpose of this section is to give the reader a short presentation of modes of maritime transportation and different planning levels in shipping. An introduction to planning in liner shipping and characteristic of liner shipping is provided at the end.

3.1   Modes of maritime transportation

Lawrence (1972) makes a distinction between three separate modes of maritime transportation: industrial shipping, tramp shipping and liner shipping (Christiansen et al., 2007). Liners are similar to a bus line and operate according to a published itinerary or schedule. The demand depends among other things on their schedules. Tramp ships can be compared to a taxicab as they follow the available cargo. Often these ships engage in contracts of affreightment, contracts that specifiy a quantity of cargo that should be shipped between specified ports within a specific time frame for a predefined payment per unit of cargo. While liner and tramp operators try to maximize profits per time unit, industrial operators own both the cargoes shipped and the ships and they strive to minimize the cost of the shipments (Ronen, 1993).

When there is excess demand, the operator may be able to charter in additional vessels. Liners and tramp operators may give up the excess demand and related income since they have no obligations, while industrial operators have to ship all their cargoes. In case of excess fleet capacity may vessels be chartered out, laid-up or scrapped (Christiansen et al., 2007).

3.2   Planning levels

Planning problems in optimisation of maritime transportation can be categorized in three levels according to the planning horizon; strategic, tactical and operational planning. Although these are different levels, there is a strong interaction between them (Christiansen et al., 2007).

Strategic decisions are long-term decisions and they provide the basis for tactical and operational decisions. The strategic decisions are mostly on the supply side, containing market selection, fleet size and mix, transportation system, maritime supply chain and ship design. Maritime transportation markets are usually competitive and highly volatile over time which complicates strategic decisions. In order to make strategic decisions one usually needs some tactical or even operational information, and it is therefore a significant overlap between decisions.

Tactical planning concentrates on medium-term decisions and the focus is on routing and scheduling. Industrial operators try to ship all their cargoes at minimum cost, while tramp ships have a certain amount of contracted cargoes they are committed to carry while trying to maximize profit from optional cargoes.

Operational planning involves decisions with short-term impact. The uncertainty in the operational environment is high and the situation is dynamic. Decisions on this level can include speed, the next leg of the voyage, ship loading and booking of single orders. For tramp and industrial shipping, the appraisal between tactical and operational scheduling is vague. In some circumstances it is not practical to schedule ships beyond a single voyage, an example is when there is significant uncertainty in the supply of the product in the destination markets.

3.3 Liner shipping

A closer look at liner shipping and the main issues when planning follows as it differs significantly from industrial and tramp shipping (Christiansen et al., 2004).

Strategic planning Strategic decisions in liner shipping span 1-5 years. The major challenges are the design of liner routes and the associated frequency of service, fleet size and mix decisions and contract evaluation for long-term contracts. Numerous shippers, multiple ports and a wide variety of products shipped make the optimisation complex (Christiansen et al., 2007)

The market plays an important role in the strategic decisions. For each chosen trade route the company has to decide what market share they wish to obtain. This will influence the frequency that the shipping line must provide. The shipping line's expectations to market growth are also crucial and form the basis for the fleet size and mix problem together with trade routes and market share. With regard to port choices must the main ports on each traderoute be determined as well as the main transhipment ports that will connect the network (Kjeldsen, 2011).

Tactical planning The main decision at the tactical planning level for liner shipping companies is the allocation of available fleet to the various trade routes, in literature referred to as *fleet deployment*. This includes what ship to deploy on the schedule, at what speed and the actual timing of the port calls. The schedules resulting from the fleet deployment problem are

normally published well in advance in order to attract shipments. However, this published schedule may be changed later as a consequence of other tactical planning problems as dry docking, lay-up of ship and slow steam in case of excess ship capacity (Christiansen et al., 2007, Kjeldsen, 2011).

Operational planning   The tactical planning gives a set of shipments that has to be carried by a given fleet, but there may exist flexibility both in the shipments (size and timing) and in the available fleet (chartering in or out, lay ups and spot charters) in addition to the fact that there exists uncertainty in marine operations. Scheduling ships beyond 3-4 voyages involves high degree of speculations, and things may not turn out the way they were planned (Ronen, 1993).

A main task in operational planning is cargo booking, choosing what cargoes to accept and reject for a given voyage (Christiansen et al., 2004). Disruption management is also a frequent task and consists of getting the ships and cargoes back on the published schedule within a given recovery period with as little cost as possible (Kjeldsen, 2011).

Liner ships are employed on more or less fixed routes, calling regularly at many ports, and they serve demand of many shippers simultaneously. The published routes and frequencies of services attract demand which have to be met, but the availability of cargoes depends on the routing and scheduling decisions. The revenue of a liner shipping company depends on the quality of the service they deliver. There exists high uncertainty because of cargo availability and a relatively large number of ports of call in a voyage. Timing is therefore important. In case of low cargo supply, the ships may have to operate at low utilization levels in order to comply with the schedules (Ronen, 1983, Christiansen et al., 2007).

4 Literature review

The purpose of this thesis is to present a model for the tactical planning level in liner shipping, and this is therefore the main focus of the literature review. The shipping company studied in this thesis operates both mandatory and optional trades, where the optional trades have resemblance with tramp shipping and a short review of research conducted on relevant tramp shipping planning problems also follows. The review only presents a selection of contributions on the field and should not be considered as a complete survey. For further reading is the reader referred to the reviews by Ronen (1983, 1993), Christiansen et al. (2004), Christiansen et al. (2007) and Christiansen et al. (2013).

4.1 General literature concerning maritime transportation

Shipping industry involves enormous trade volumes and values and in order to be able have an optimal fleet utilization, decision tools are needed. Operations research (OR) provide a large number of methods for this purpose. Ronen published in 1983 the first review on OR in ship scheduling, followed by a second review ten years later (Ronen, 1993). Christiansen et al. (2004) followed with a third review, before Christiansen et al. (2013) this year present the forth and newest review. Table 1 and 2 summarizes the contents of these reviews (Christiansen et al., 2013).

Table 1: Number of new papers in review

Review	New papers
Ronen(1983)	22
Ronen(1993)	38
Christiansen et al(2004)	55
Christiansen et al(2013)	127

Table 2: Topics and publication year

Year	Total papers[1]	Liners	Industrial and tramp	General
1992-1996	11	2	7	2
1997-2001	28	6	22	3
2002-2006	26	8	16	3
2007-2011	104	49	55	3

[1] A paper may address more than one topic.

It can be seen from table 1 that the focus on maritime transportation
has increased over the last four decades. Christiansen et al. (2013) compare
the quantity of published research for the last decades on the same basis and
finds an almost doubling every decade. While Ronen (1983, 1993) showed
that the main focus had been on industrial and to some extent tramp ship-
ping, describe Christiansen et al. (2013) an increased focus on liner shipping
in the literature written (table 2). Research on liner network design and re-
lated topics, especially within container shipping which constitutes the major
segment of liner shipping, have experienced a fast growth.

Compared to the literature available from airline industry and land based
transportation services, operations research have received relatively little at-
tention within the shipping industry, and Ronen (1993) had explanations
which still can be regarded as valid. Shipping has *low visibility*, since every-
thing takes place at sea. Maritime transportation problem are *less structured*,
with much larger variety in problem structures and operating environments,
and *uncertainty* plays a major role. Weather conditions, mechanical prob-
lems and strikes can affect the shipments. It is also important to remem-
ber that the shipping industry has *long traditions* and is conservative, and
many small, family owned shipping companies does not simplify things either
(Christiansen et al., 2007).

In addition to the four reviews mentioned above published Christiansen
et al. in 2007 an article with a wider perspective of maritime transportation
including publications between 2002 and 2007.

4.2   Fleet Deployment Problem

The main topic in this thesis is to make a linear programming model as
a solution method for the tonnage allocation problem. This is often re-
ferred to as the fleet deployment problem in literature, according to Bradley
et al. (1977) first proposed in Everett et al. (1972) (Gelareh and Pisinger,
2011). The work on the fleet deployment problem in the late 80s and 90s
was strongly influenced by the Greek researchers A.N. Perakis and N. Pa-
padakis. Mathematical models for various variants of the fleet deployment
problem have been presented by Perakis and Jaramillo (1991), Jaramillo and
Perakis (1991), Powell and Perakis (1997), Papadakis and Perakis (1989),
Perakis and Papadakis (1987a) and Perakis and Papadakis (1987b). Perakis
published in 2002 an overview of the literature regarding fleet deployment
and operations present up to 2002 (Christiansen et al., 2004).

Perakis and Jaramillo (1991) formulated a model for optimisation of the
deployment of a liner fleet composed of both owned and chartered vessels.
The focus in the article is to determine the operating costs of the ships in

every one of the routes in which the company operates, and it is carried out by means of a realistic model. The optimal speed is calculated in a separate problem and used as a fixed value in the fleet deployment optimisation; the same applies to frequency of service and cargo movements.

Jaramillo and Perakis (1991) continued the work of Perakis and Jaramillo (1991) and developed a model for the optimal deployment of a liner fleet composed of both owned and chartered vessels subject to time, frequency and other realistic constraints. Non-linearities as the speed of the ships and the frequency of the service are fixed in each route and the authors arrived at a suitable liner programming formulation.

The work in Powell and Perakis (1997) is an extension and improvement of the work in Perakis and Jaramillo (1991) and Jaramillo and Perakis (1991). They present an integer programming fleet deployment model and test it on a real liner shipping problem. Substantial savings were reported compared to the actual deployment when using standard commercial software for formulation and solution.

Papadakis and Perakis (1989), Perakis and Papadakis (1987a), Perakis and Papadakis (1987b) and Perakis (1985) are earlier fleet deployment studies. Various models are represented where different speeds and additional constraints are considered (Ronen, 1993).

Gelareh and Meng (2010) propose a short-term fleet deployment model that takes into consideration speed decisions on sailing legs along each route, service frequency as a decision variable and possibility of handling maximal travel time requirement between port pairs. They obtain a mixed integer linear programming model which is solved by a standard mixed integer programming solver. Meng and Wang (2010) extend the model and consider uncertainty in container shipment demand, assuming that the demand follows a normal distribution. Wang et al. (2011) later pointed out that the formulation of the maximum number of voyages by Gelareh and Meng (2010) and Gelareh and Meng (2010) was incorrect and too optimistic, and they suggest a reformulation of the fleet deployment model that improves the computational efficiency (Christiansen et al., 2013).

4.2.1   Solution methods

There are two major approaches for modelling the fleet deployment problem; arc flow model and path flow model (Christiansen et al., 2007). An arc flow model is based on nodes and arc where the nodes represent voyages/ports and the arcs represent how the voyages/ports are connected. A binary variable is used to describe if a ship sails directly from voyage/port to voyage/port. The routes for each ship are constructed by assigning values to the variables.

There exists in addition variables to keep track of time for servicing the voyages and the load on each ship. An example of an arc flow model is found in Fagerholt et al. (2009a) and Christiansen and Nygreen (1998a).

A path flow model is based on predefined routes and uses a binary variable to represent if a specified ship sails a given route. A route consists of a full schedule specifying arrival times and loads, and only feasible routes are considered. Path flow models are widely used in literature, and an example can be found in Christiansen and Nygreen (1998b).

Feasible routes can be created based on a column generation approach. Generating all feasible harbor visit sequences may lead to great problem size and long computational time, and therefore creates column generation only the routes that improve the overall solution. The optimal solution is determined by iterating between the master problem (calculating the overall solution) and the sub problems (calculating new routes) until no new columns that lead to further improvements are found.

A real liner shipping problem of deciding optimal weekly routes for a given fleet of ships is considered in Fagerholt (2004a). The integer programming problem is solved by generating all feasible routes for each ship together with the cost and duration for each route and then using the pre-generated routes as input to the IP-formulation. Computational results show that the proposed solution is suitable for designing optimal routes in liner shipping problems.

Gelareh and Pisinger (2011) propose a mixed integer linear programming formulation for the simultaneous design of network and fleet deployment of liner service providers for deep-sea shipping, particularly tailored for the single rotation regional planning. The model offers considerable flexibility for incorporating additional constraints met in practice, and the flexibility of demand is a unique feature of the model. A primal decomposition approach is proposed to solve instances of the problem to optimality, using branch-and-cut with the help of Benders method.

Both the arc flow and the path model can be solved directly with use of standard commercial optimisation software for mixed integer linear programming after linearization of the nonlinear functions, but the model's complexity prevents large data instances to be solved. Reformulations are therefore done in order to solve larger data instances to optimality (Christiansen et al., 2007). Examples of reformulations are optimisation-based solution methods as Dantzig Wolfe approach and set partitioning approach. General algorithm for Dantzig Wolfe solution approach can be found in Desrosiers et al. (1995) and an example of a specific ship scheduling can be found in Christiansen and Nygreen (1998b). There exist numerous examples with the use of set partitioning approach in ship scheduling. Fagerholt (1999) presents a study

regarding the design of an optimal fleet and the correspondingly weekly routes for each ship for a liner shipping system along the Norwegian coast. The solution is based on a set partitioning formulation, with the priori generation of ship routes by means of a dynamic programming algorithm. This solution method only handles instances where the ships selected have the same speed. Fagerholt and Linstad (2000) therefore proposed a new solution algorithm handling ships with different speeds.

Another example with set partitioning can be found in Fagerholt and Christiansen (2000), while references to further examples both regarding set partitioning and Dantzig Wolfe can be found in Christiansen et al. (2007).

When optimisation-based solution approaches are not sufficient to provide a solution, can heuristic-based solution approaches be used. Fagerholt et al. (2009a) present a model for the fleet deployment problem in liner shipping which introduces more planning flexibility compared to models previously presented in the literature. A multi-start local search heuristic is proposed to solve the problem which is tested on a real case. The test indicated improvements between 2 % and 10 % compared to solutions from manual planning, and more importantly, this method eases the planning process for the shipping company.

4.2.2   Timing of trades

Sigurd et al. (2005) give a set partitioning model for a tender (transport offer) which was proposed to a number of shipping companies (using common ships). The model is solved by a heuristic branch and price algorithm. The optimal solution found substantial savings in making two-week planning periods compared to one-week planning, because it allowed greater flexibility in the length of the tours. They also investigate the relationship between costs and speed, and although higher speed increases variable costs, this could be outweighed by a reduction in the number of required ships, reduced inventory costs and the need to satisfy customers' lead-time requirements.

Halvorsen-Weare et al. (2012) investigate the supply vessel planning problem and determining the optimal fleet composition of vessels and their corresponding weekly voyages and schedules in the offshore industry. They perform what-if scenario analysis to see if it is possible to use one less supply vessel if some adjustments are made. The actual sailed schedule will in most cases differ from the planned one as they may face unpredictable happenings which result in rescheduling. Incorporating practical aspects and performing what-if scenario analysis exploit the problem nature and give planners valuable information regarding the capabilities of the fleet.

Belanger et al. (2006) study a fleet assignment problem with time win-

dows, spacing constraint and time dependent revenues for the airline industry. By allowing for some flexibility on flight departure times, the number of possible connections increases and as a consequence increases the solution quality both in terms of profit and number of aircrafts to cover the flights. The authors emphasize that this should be done with care, since it can make flights come too close and compete with each other and the demand can be overestimated. They consider a periodic scheduling horizon and propose a model where short spacing between consecutive flights which serve the same O-D pair are penalized while profit estimates are functions of both departure times and aircraft types. The mathematical model is based on a non-linear integer multi-commodity network flow structure. Their solution approach is a branch and price strategy applied to a decomposition of the model where columns are generated using a specialized longest path problem with time windows and linear costs on arc flows and on node visiting times.

4.3   TurboRouter

TurboRouter is a decision support system (DSS) for vessel fleet scheduling presented by Fagerholt (2004b) and Fagerholt and Linstad (2007) after marine technology researches in Trondheim had been developing it since 1996. The idea behind TurboRouter is to develop optimisation algorithms that can solve the fleet scheduling problem for shipping companies. The researchers found it hard to model all necessary constraints and information as it would require too much user input and the planners would not be confident with such a system. The planners wanted a system with high degree of user interaction and possibilities to evaluate a large number of scheduling alternatives. They wanted a system where aspects could be judged by an experienced planner from situation to situation. TurboRouter are therefore a tool to quickly evaluate a number of scenarios, but the planner based on his/her experience should make the final decision on fleet schedule. The solution method of TurboRouter is based on heuristics from Brønmo et al. (2007a), Korsvik et al. (2010), Korsvik et al. (2011) and Korsvik and Fagerholt (2010) (Christiansen et al. (2013), Fagerholt (2004b)).

   Fagerholt (2004b) emphasizes that the focus should be directed more to the interaction between the user and the system than the optimisation algorithm which often has been the case before. Fagerholt et al. (2009b) claim that planners often are more interested in a set of high-quality diverse solutions to choose from instead of only one (near-) optimal solution to the model as usually provided by the DSS. Ship routes and schedules are generated with a rolling horizon where schedules are updated when new relevant information appears. Many planners have often made commitments to cus-

tomers for example regarding arrival times and composition of ships and voyages. Fagerholt et al. (2009b) suggest a solution method that includes a persistence penalty function and distance measures to produce a set of high quality schedules close to the current (baseline) schedule in the near future and diverse from each other in more distant time.

4.4 Tramp shipping

Tramp shipping is similar to liner shipping, as it have long-term contracts of affreightments (COAs) which specify a number of cargoes that the company is committed to transport. In addition to the mandatory cargoes, there exists a spot market where cargo owners announce their transportation needs. The spot market represents optional cargoes that the shipping company can choose to carry if it finds it profitable and if there is has sufficient fleet capacity (Norstad et al., 2011).

Compared to industrial shipping has there been minimal attention to tramp shipping. One main reason is the large number of small operators in the tramp market, and it is also known for being a secondary market to exploit the resources already in the company (Christiansen et al., 2004).

A typical tramp ship scheduling problem is described in Appelgren (1969) and Appelgren (1971), the first one to use Dantzig Wolfe decomposition approach for ship routing and scheduling (Christiansen et al., 2004). Of recent literature in tramp shipping, it is worth mentioning Brønmo et al. (2007b) who suggest a multi-start local heuristic to solve the tramp cargo routing and scheduling problem. Korsvik et al. (2010) propose a unified tabu search heuristic which in contrast to Brønmo et al. (2007b) allows infeasible solutions with respect to ship capacity and time window constraints during the search, and therefore performs better especially for large and tightly constrained problems. Lin and Liu (2011) consider a real tramp ship routing and scheduling problem for a shipping company operating seven handy-max dry bulk ships for transportation of various types of dry cargoes in simple packaging. They suggest a genetic algorithm to solve the problem and show that it outperforms solving a mathematical formulation of the problem by commercial software.

When bulk cargoes are shipped under long-term contracts, the exact cargo size is not that important and the ship operator may have some flexibility in the size of the cargo. The problem then includes determining the optimal size of each cargo to transport within its interval. Such a problem is studied by Brønmo et al. (2007b), Brønmo et al. (2010) and Korsvik and Fagerholt (2010), and these studies show that this flexibility can be utilized to improve the profit significantly (Christiansen et al., 2013).

5   Problem formulation

This section gives a short introduction of the shipping company studied in this thesis in order to better understand their challenges in the tactical planning. Central aspects of the tonnage allocation problem are then presented. It would have been too comprehensive to include all aspects of the problem in the model, and a review of excluded topics is given at the end of this section.

5.1   The shipping company

The shipping company studied is an international shipping company specializing in the transportation of forest products and break-bulk cargoes using open-hatch gantry ships. They are travelling 10 different trade routes between Europe, North America, South America and the Far East. In addition to the 10 mandatory trade routes, the shipping company can sail optional TC-trades which generate profit. The optional trades can be identical to the mandatory trades, include parts of them or be unique. The shipping company's fleet currently consists of 31 ships, and each ship has to attend service, a dry docking, once every third year in a port in Asia.

5.2   Tonnage allocation problem

The tonnage allocation problem optimally assigns voyages on predefined trade routes to available ships in the fleet and determines ship routes and schedules in a way that minimizes costs or maximizes profit. The problem can be described as follow. A fleet of ships has known operating costs, known capacities, a set of potential spot ships and volumes of cargo to be transported among specified ports in predefined trade routes. The tonnage allocation problem seeks to minimize the total fleet operating cost function or maximize profit over a given short-term planning horizon with respect to decisions on how to allocate different types of ships to the set of routes, general scheduling regarding the service frequency and decisions on hiring in spot ship to fulfil commitments of contracts (Gelareh and Meng, 2010).

   The following paragraphs will review problem areas for the shipping company in the tonnage allocation problem. The fleet and the trade routes are given from the strategic planning and are assumed known and fixed.

Trade routes   The trade routes are determined after thorough analysis of the demand in the regions and then published in order to attract shipments and enter into contracts regarding transport of goods along the routes. The

demand for transport may differ between the different regions. This follows from a world market consisting of regions with different characteristics in terms of labour cost, available technology and access to raw material.

Figure 4 shows the trade routes of the shipping company, but this is a simplification as it only shows the origin and destination ports. Between origin and destination, the trade routes have several ports the ships visit, both in the region of origin for loading and in the region of destination for unloading. Note that different trade routes will have different ports in the same region. For example, trade route SAMEUR departs from Portocel, Brazil, and finishes in Vlissingen, The Netherlands, while EURSAM departs from Klaipeda, Lithunia, and finishes in Santos, Brazil.
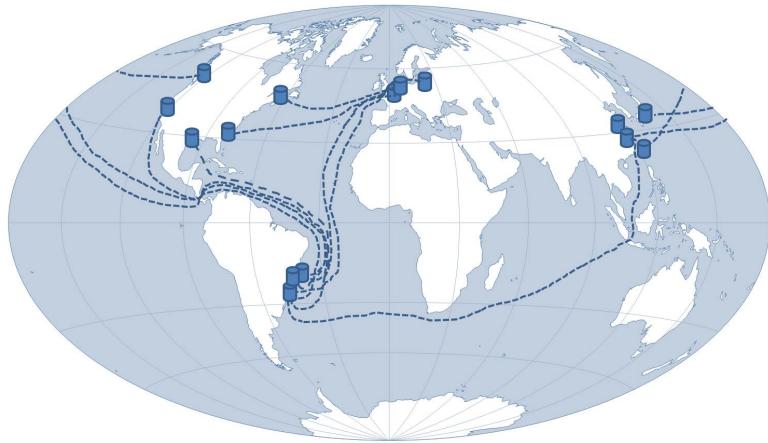
Figure 4: Illustration of the different trade routes. Note that only origin and destination ports are included.

Contract of affreightment   Contract of affreightment is a contract between the ship owner, the shipping company, and the owner of the transported cargo, the shipper, regarding transportation of cargo. The contract specifies the trade route, the number of voyages for the trade and time windows for the voyages. It also states the freight rate, the price the shipper agrees to pay for the transportation of cargo. The contract either specifies the total volume of cargo that needs to be transported in a period or the needed frequency of transportation, and it may specify if the shipper wants a private ship or if it can be shared, as well as if it is accepted to have a spot ship sailing the trade.

Fairly evenly spread   A common sentence in the contract of affreightment is to specify fairly evenly spread voyages for a trade during the period.

With only time windows for a voyage of a trade as restricting, results of the planning can give the first voyage at the end of its time window, the second voyage at the beginning of its time window and the third voyage at the end of its time window. This gives a short time span between voyage one and two and a long time span between voyage two and three. This is not desired as the shipper may have concerns regarding limits on inventory capacity and the production rate imposes limits on the volume of goods in inventory and when goods are ready for transport. The shipper therefore prefers fairly evenly spread voyages throughout the period.

However, the shipping company wishes to obtain the best possible utilization of the fleet and flexibility regarding time window is highly valued since it enables more alternatives in terms of available ships. Unpredictable weather conditions at sea make the shipping company vulnerable, but with more flexibility can the consequences be minor.

Overlapping time windows   Overlapping time windows is when the time window of a voyage of a trade has parts common with a time window of the previous or next voyage of the same trade. The two voyages can then happen at the same time, or voyage $x + 1$ can happen before voyage x.

It is preferred that the voyages are numbered chronologically by time, meaning that voyage 1 of a trade should be sailed before voyage 2 of the same trade.

Dry docking   Every ship has to attend one dry docking during a 3-year period. The shipping company has a fleet of 31 ships and the dry dockings are spread fairly. There will during a planning period therefore always be a ship that needs dry docking. A ship usually has a wide time window for the dry docking, implying that it can happen over several planning periods.

Ballast voyages and TC-trades   The ships do not have a common origin or destination and are located where the last voyage was finished. If there is no new voyage from the region where the ship currently is located, the ship has to sail ballast to another region for the next voyage. The shipping company want to minimize ballast sailing, and they therefore try to sail voyages of TC-trades, optional trades which are not contractual and only an additional income the shipping company can choose to have.

The introduction of optional TC-trades causes the problem to have elements of tramp shipping included as the company only sail voyages of TC-trades if there is available capacity in the fleet and the voyage generates profit.

Spot ship It is always possible to charter in a spot ship from other shipping companies to sail a voyage of a mandatory trade. This happens if none of the ships in their own fleet can reach the time window of the voyage, or if the cost of sailing the voyage is higher than the cost of getting a spot ship to sail it. Sailing ballast voyage for example from Europe to the Far East in order to make a voyage from the Far East to North America, and then to sail ballast to Europe to sail a voyage to South America is debatable whether is profitable or if a spot ship should be hired in.

There is also use of spot ship if weather conditions or problems with ships cause delays which makes it impossible for the assigned ship to reach the latest possible start for a voyage in its time window. The use of spot ships is nevertheless desirable to keep to a minimum and is only to be looked upon as a emergency situation.

Excess capacity If a ship has excess capacity after loading the mandatory cargo for a voyage, the ship can take on extra cargo for maximizing profit. When the head office makes a tonnage allocation, this spare capacity is not taken into consideration. The local office of a trade route is responsible for the operational planning, including loading of the ships and the amount of spot cargo to accept in a port. Trade routes which easily can fill up extra cargoes should therefore be sailed with larger ships than those trade routes which are harder to fill up with extra cargo. The income of a trade should take this into account.

5.3 Assumptions

There are many aspects of the tonnage allocation problem which have been omitted in this thesis. Ships are required to be empty between each voyage, and this model therefore does not consider overlapping voyages. The process of deciding which ports to visit and how often is not included, neither is the decisions regarding where to reload. Other aspects which are not looked at are for example choice of operational speed, cargo constraints, inventory in ports, capacity on board and making sure demand is delivered.

It is also important to remember that the tonnage allocation problem involves a great amount of uncertainty related to both amount of cargo and the sailing, and decisions are therefore made without all information available.

There may be seasonal variations when it comes to income, costs, shipments and amount of available TC-cargo, but this is not taken into consideration in this model.

6   Mathematical formulation

This section presents the mathematical formulation of the tonnage allocation problem for a liner shipping company. The model is based on an arc flow formulation and is formulated as a deterministic profit maximization problem. The model is also extended to include an alternative way of sailing a voyage of a trade.

6.1   Tonnage allocation model

The tonnage allocation problem is modelled by an arc flow formulation which consists of nodes and arcs. The nodes represent voyages, while the arcs describe how a ship sails from one voyage to the next. Each node and arc have information regarding cost and time.

All the ships are modelled uniquely and all ships can sail all trade routes. Spot ships can perform voyages of mandatory trades if there is not enough capacity in the shipping company's own fleet. Every voyage of a trade has the same cost and time, but the cost and time is dependent of the ship used. This also applies for the ballast voyages. A time window is given for each voyage with earliest and latest possible start.

The problem is formulated as a deterministic profit maximization problem.

Set, indices, parameters and variables

The sets, indices, parameters and variables used in the model follow.

Sets

$\mathcal{N}$	Set of voyages
$\mathcal{R}$	Set of trades
$\mathcal{V}$	Set of ships
$\mathcal{A}$	Set of arcs
$\mathcal{R}_M$	Set of mandatory trades
$\mathcal{R}_{TC}$	Set of optional TC-trades
$\mathcal{R}_{DD}$	Set of dry docking-trades
$\mathcal{V}_{DD}$	Set of ships needing dry docking
$\mathcal{N}_r$	Set of voyages for trade r
$\mathcal{R}_{DDv}$	Set of dry-docking trades for ship v

Indices

i,j	voyage, $i, j \in \mathcal{N}_r$
r,u	trade, $r, u \in \mathcal{R}$
v	ship, $v \in \mathcal{V}$
$o(v)$	origin for ship v
$d(v)$	destination for ship v

Parameters

P_{vr}	Income of sailing a voyage of trade r for a ship v
C_{vr}	Cost of sailing a voyage of trade r for a ship v
C_r^S	Cost of hiring a spotship to sail a voyage of trade r
C_{vru}^B	Cost of ballast sailing from a voyage of trade r to a voyage of trade u for ship v
C_{vr}^O	Cost of ballast sailing from origin to voyage of trade r for ship v
T_{vr}	Time spent for ship v to sail a voyage of trade r
T_{vru}^B	Time spent for ship v to sail ballast from a voyage of trade r to a voyage of trade u
T_{vr}^O	Time spent for ship v to sail ballast from origin to voyage of trade r
E_{ri}^{TW}	Earliest start of voyage (r, i) in time window
L_{ri}^{TW}	Latest start of voyage (r, i) in time winodow
E_v^O	Earliest start from origin for ship v
B_r	Constant for trade r securing fairly evenly spread voyages

Variables

$x_{vo(v)d(v)}^I$	equals 1 if ship v does not serve any voyage
$x_{vo(v)ri}^O$	equals 1 if ship v sails directly from origin to voyage (r, i)
x_{vriuj}^F	equals 1 if voyage (u, j) is sailed right after voyage (r, i) by ship v
$x_{vrid(v)}^D$	equals 1 if ship v goes directly to destination from end port of voyage (r, i)
$t_{vo(v)}^O$	start time from rigin for ship v
t_{ri}^S	start time for voyage (r, i)
s_{ri}	equals 1 if voyage (r, i) is sailed by a spotship
y_{vri}	equals 1 if ship v sails voyage (r, i)

Objective function

The objective function is to maximize profit and can be expressed as

$$max \sum_{v \in \mathcal{V}} \sum_{r \in \mathcal{R}} \sum_{i \in \mathcal{N}_r} \sum_{u \in \mathcal{R}} \sum_{j \in \mathcal{N}_u} (P_{vr} - C_{vr} - C_{vru}^B) x_{vriuj}^F$$
$$+ \sum_{v \in \mathcal{V}} \sum_{r \in \mathcal{R}} \sum_{i \in \mathcal{N}_r} (P_{vr} - C_{vr}) x_{vrid(v)}^D$$
$$- \sum_{v \in \mathcal{V}} \sum_{r \in \mathcal{R}} \sum_{i \in \mathcal{N}_r} C_{vr}^O x_{vo(v)ri}^O - \sum_{r \in \mathcal{R}_M} \sum_{i \in \mathcal{N}_r} C_r^S s_{ri} \quad (1)$$

The first and second term represent the revenue from a voyage of a trade, both mandatory and TC, subtracting the cost of the trade and cost of sailing ballast to the next trade if it is not the last trade. The third term is the cost of sailing ballast from origin port to the first voyage in the planning period, while the last term represents the cost of hiring a spot ship to sail a voyage.

Flow constraints

Figure 5 illustrates the flow of the tonnage allocation problem. All ships have to leave its origin. A ship can either sail a voyage or it is not in use and goes directly to the destination (which is the same as the origin). The starting point for the first voyage can be the same as the origin; this is expressed with zero cost of sailing the first ballast voyage.

$$\sum_{r \in \mathcal{R}} \sum_{i \in \mathcal{N}_r} x_{vo(v)ri}^O + x_{vo(v)d(v)}^I = 1, \qquad v \in \mathcal{V} \quad (2)$$

All ships have a destination, either directly from its origin (not being in use) or the same as the end port of the last voyage.

$$\sum_{r \in \mathcal{R}} \sum_{i \in \mathcal{N}_r} x_{vrid(v)}^D + x_{vo(v)d(v)}^I = 1, \qquad v \in \mathcal{V} \quad (3)$$

A node balance has to be included for all nodes except origin and destination where there is only one ship sailing out and one ship sailing in respectively. For all the other nodes, the following is valid. Ships can sail into the node from the initial position for the ship or from the end port of voyage of a trade. Ships can sail out of the node to do a voyage or directly to the destination port.
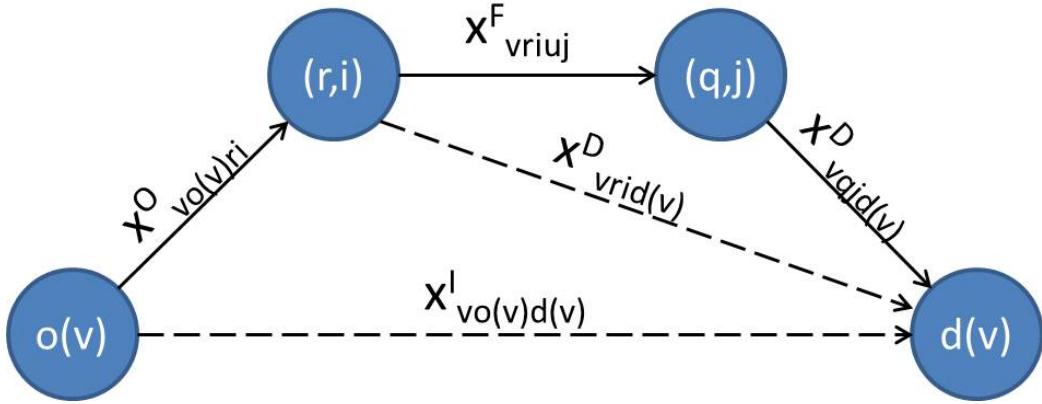
Figure 5: Illustration of node and arc flow. Note that both $x^D_{vrid(v)}$ and $x^D_{vqjd(v)}$ are denoted as $x^D_{vrid(v)}$ in the model.

A node balance for every node except the origin and destination has to be included.

$$\sum_{u\in\mathcal{R}}\sum_{j\in\mathcal{N}_u} x^F_{vriuj} + x^D_{vrid(v)} - \sum_{u\in\mathcal{R}}\sum_{j\in\mathcal{N}_u} x^F_{vujri} - x^O_{vo(v)ri} = 0,$$

$$v\in\mathcal{V}, r\in\mathcal{R}, i\in\mathcal{N}_r \quad (4)$$

Voyage completion

For a mandatory trade has every voyage to be sailed by either one of the company's ships or by a spot ship.

$$\sum_{v\in\mathcal{V}}\sum_{u\in\mathcal{R}}\sum_{j\in\mathcal{N}_u} x^F_{vriuj} + \sum_{v\in\mathcal{V}} x^D_{vrid(v)} + s_{ri} = 1, \qquad r\in\mathcal{R}_M, i\in\mathcal{N}_r \quad (5)$$

For a TC-trade are there two different ways of modelling the voyage completion. The first is when one node represents one TC-voyage, and therefore every TC-node can be visited maximum once.

$$\sum_{v\in\mathcal{V}}\sum_{u\in\mathcal{R}}\sum_{j\in\mathcal{N}_u} x^F_{vriuj} + \sum_{v\in\mathcal{V}} x^D_{vrid(v)} \le 1, \qquad r\in\mathcal{R}_{TC}, i\in\mathcal{N}_r \quad (6)$$

The other way of modelling is when one node represents a TC-trade with a maximum number of voyages. The constraint will then be

$$\sum_{v\in\mathcal{V}}\sum_{u\in\mathcal{R}}\sum_{j\in\mathcal{N}_u} x^F_{vriuj} + \sum_{v\in\mathcal{V}} x^D_{vrid(v)} \le M, \qquad r\in\mathcal{R}_{TC}, i\in\mathcal{N}_r \quad (7)$$

where M represents the maximum number of times a voyage of a TC-trade can be sailed.

The difference between the two modelling approaches can be shown in the number of nodes and in the time window. The second restriction (7) have fewer nodes than the first restriction (6), but the nodes can be visited more than once.

TC-voyages in the first restriction (6) have their own time windows, while a TC-trade in the second restriction only have one time window common for all voyages. This is typically an open time window, e.g. coincident with the whole planning period, which makes a more flexible model.

The impact of time windows is important in this model and the first modelling approach is chosen. A TC-trade will thus be represented in the same way as a mandatory trade.

Dry docking completion

The modelling of dry docking can be done in two different ways. The time windows for dry dockings usually last over several planning periods. The planner has to decide whether the dry dockings *have* to be done in current planning period or if it *can* be done with a positive result on the objective function to avoid exposing any problems for later. In this model, it is assumed that the dry dockings have to be done in the current planning period and three suggestions for modelling this restriction follow.

Common for all three modelling approaches is the following. A dry docking trade is ship specific and will therefore only contain one voyage. This voyage is modelled as a node which has to be visited once. This is the same as for mandatory trades and TC-trades. After a ship has performed a dry docking trade, the ship can either sail to a voyage of another trade or it has reached its destination.

The first way sums over all ships and makes sure that all voyages of dry docking-trades are covered exactly once.

$$\sum_{v \in \mathcal{V}} \sum_{u \in \mathcal{R}} \sum_{j \in \mathcal{N}_u} x^F_{vriuj} \; + \; \sum_{v \in \mathcal{V}} x^D_{vrid(v)} = 1, \qquad r \in \mathcal{R}_{DDv}, i \in \mathcal{N}_r \qquad (8)$$

A set of ships which have to attend dry docking is introduced in the second way of modelling. For each of the ships in this set, a voyage of a dry docking trade has to be done.

$$\sum_{u \in \mathcal{R}} \sum_{j \in \mathcal{N}_u} x^F_{vriuj} \; + \; \sum_{v \in \mathcal{V}} x^D_{vrid(v)} = 1, \qquad v \in \mathcal{V}_D, r \in \mathcal{R}_{DDv}, i \in \mathcal{N}_r \qquad (9)$$

The third possibility and the way the restriction is modelled in this thesis is an extension of (8). Instead of summing over all ships, it is only summed over the ships which are designated to the specific dry docking trade.

$$\sum_{v \in \mathcal{V} | \mathcal{R}_{DDv}=1} \sum_{u \in \mathcal{R}} \sum_{j \in \mathcal{N}_u} x^F_{vriuj} + \sum_{v \in \mathcal{V}} x^D_{vrid(v)} = 1, \qquad r \in \mathcal{R}_{DDv}, i \in \mathcal{N}_r \quad (10)$$

Time constraints

A ship's first voyage can not start before the earliest available time of the ship,

$$t^O_{vo(v)} \geq E^O_v \qquad v \in \mathcal{V} \tag{11}$$

and all voyages have a time window for earliest and latest start.

$$E^{TW}_{ri} \leq t^S_{ri} \leq L^{TW}_{ri} \qquad r \in \mathcal{R}, i \in \mathcal{N}_r \tag{12}$$

The start time for voyage j can not be before the start time for voyage i included the time voyage i takes and the time it takes to sail from the end port of voyage i to the start port of voyage j.

$$x^F_{vriuj}(t^S_{ri} + T_{vr} + T^B_{vru} - t^S_{uj}) \leq 0, \qquad v \in \mathcal{V}, (ri), (uj) \in \mathcal{A} \tag{13}$$

The start time for ship v on the first voyage of trade r can not be before the ship has arrived to the start port from the port of origin.

$$x^O_{vo(v)ri}(t^O_{vo(v)} + T^O_{vr} - t^S_{ri}) \leq 0, \qquad v \in \mathcal{V}, r \in \mathcal{R}, i \in \mathcal{N}_r \tag{14}$$

Linearization of time constraints Constraints (13) and (14) are non-linear and have to be linearized in order to use linear optimisation software tools. The linearization is done by using the big-M method (Williams, 1999) and can also be found in e.g. Desrosiers et al. (1995).

Constraint (13) is rewritten as

$$t^S_{ri} + T_{vr} + T^B_{vru} - t^S_{uj} \leq M^F_{vriuj}(1 - x^F_{vriuj}), \qquad v \in \mathcal{V}, (ri), (uj) \in \mathcal{A} \quad (15)$$

The value of M^F_{vriuj} can be calculated as follows. If x^F_{vriuj} is 1, then the equation becomes

$$t^S_{ri} + T_{vr} + T^B_{vru} - t^S_{uj} \leq 0, \qquad v \in \mathcal{V}, (ri), (uj) \in \mathcal{A} \tag{16}$$

stating what it is meant for. If x^F_{vriuj} equals 0, then the equation becomes

$$t_{ri}^S + T_{vr} + T_{vru}^B - t_{uj}^S \leq M_{vriuj}^F, \qquad v \in \mathcal{V}, (ri), (uj) \in \mathcal{A} \qquad (17)$$

The purpose of M_{vriuj}^F is to not be binding and therefore as large as possible. At the same time it should be as small as possible in order to limit the feasible range and make an efficient model. The biggest smallest value the left hand side of equation (17) can have is

$$\max \{t_{ri}^S + T_{vr} + T_{vru}^B - t_{uj}^S\} = L_{ri}^{TW} + T_{vr} + T_{vru}^B - E_{uj}^{TW}$$
$$v \in \mathcal{V}, (ri), (uj) \in \mathcal{A} \quad (18)$$

stating that M_{vriuj}^F has to at least not be binding for the latest a voyage can start and the earliest the following voyage can start.

Constraint (14) can be linearized in the same way and is rewritten as

$$t_{vo(v)}^O + T_{vr}^O - t_{ri}^S \leq M_{vr}^O (1 - x_{vo(v)ri}^O), \qquad v \in \mathcal{V}, r \in \mathcal{R}, i \in \mathcal{N}_r \qquad (19)$$

Finding a value on M_{vr}^O is done with the same purpose as for M_{vriuj}^F. If $x_{vo(v)ri}^O$ is 1, then the equation becomes

$$t_{vo(v)}^O + T_{vr}^O - t_{ri}^S \leq 0, \qquad v \in \mathcal{V}, r \in \mathcal{R}, i \in \mathcal{N}_r \qquad (20)$$

stating what it is meant for. If $x_{vo(v)ri}^O$ is 0, then the equation becomes

$$t_{vo(v)}^O + T_{vr}^O - t_{ri}^S \leq M_{vr}^O, \qquad v \in \mathcal{V}, r \in \mathcal{R}, i \in \mathcal{N}_r \qquad (21)$$
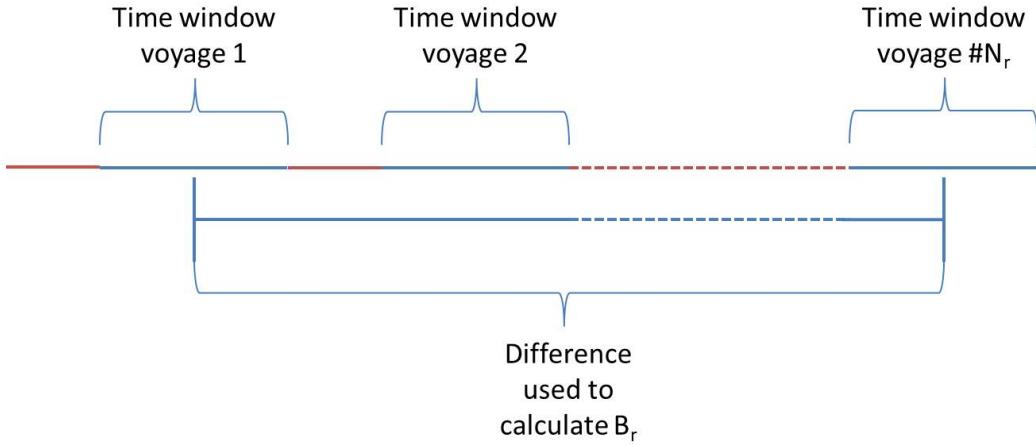
There is no time window for the start-up times, only the earliest time the ship is available. Therefore the biggest smallest value the left hand side of equation (21) can have is

$$\max \{t_{vo(v)}^O + T_{vr}^O - t_{ri}^S\} = E_v^O + T_{vr}^O \qquad v \in \mathcal{V}, (ri), (uj) \in \mathcal{A} \qquad (22)$$

stating that M_{vr}^O is at least not binding for the earliest possible start of a voyage for a spesific ship.

Fairly evenly spread

Arnulf and Bjørkli (2010) studied the situation with fairly evenly spread voyages and presented two ways of modelling it, either with a soft or a hard restriction. In this model a version of the hard restriction is used and the reader is referred to Arnulf and Bjørkli (2010) for explanations regarding the soft restriction.

Figure 6: How to calculate time spread constant B_r

When using a hard restriction to make sure of fairly evenly spread voyages, the time between to adjacent voyages has to be larger than a constant B_r. The value of the constant is for trade r given as the difference between the middle of the time window of the last voyage and the middle of the time window of the first voyage divided by the number of voyages for the trade minus 1 (figure 6).

$$B_r = \frac{(E_{r\#N_r}^{TW} + 0.5 \cdot (L_{r\#N_r}^{TW} - E_{r\#N_r}^{TW})) - (E_{r1}^{TW} + 0.5 \cdot (L_{r1}^{TW} - E_{r1}^{TW}))}{\#N_r - 1} \quad (23)$$

$$t_{r,i+1}^S - t_{ri}^S \geq B_r \qquad r \in \mathcal{R}, i \in \mathcal{N}_r \quad (24)$$

When introducing a strict time spread threshold, the planning flexibility provided by the time window of each voyage is corrupted. By multiplying the threshold basis with a fraction $\alpha \in \{0, 1\}$, a variety of less stricter threshold can be created in order to maintain some flexibility (figure 7).

$$t_{r,i+1}^S - t_{ri}^S \geq \alpha \cdot B_r \qquad r \in \mathcal{R}, i \in \mathcal{N}_r \quad (25)$$

where $\alpha = \{0, 1\}$

The risk when using a hard restriction is missing profitable cargo and be forced to sail ballast when it in real life is possible to negotiate arrivals outside the time window (Arnulf and Bjørkli, 2010).
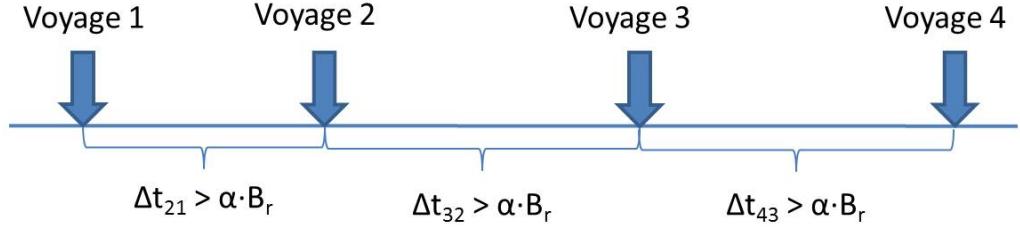
Figure 7: Introducing alfa to the time spread between voyages

Variable for analysing data

To make it easier to analyse the data, variable y_{vri} is introduced and equals 1 if ship v sails voyage (r, i) and 0 if not.

$$\sum_{u \in \mathcal{R}} \sum_{j \in \mathcal{N}_u} x^F_{vriuj} \; + \; x^D_{vrid(v)} \; - \; y_{vri} \;\; = \;\; 0 \qquad v \in \mathcal{V}, r \in \mathcal{R}, i \in \mathcal{N}_r \qquad (26)$$

Requirements for variables

$$x^I_{vo(v)d(v)} \in \{0, 1\} \qquad v \in \mathcal{V} \qquad (27)$$

$$x^O_{vo(v)ri} \in \{0, 1\} \qquad v \in \mathcal{V}, r \in \mathcal{R}, i \in \mathcal{N}_r \qquad (28)$$

$$x^F_{vriuj} \in \{0, 1\} \qquad v \in \mathcal{V}, (r, i), (u, j) \in \mathcal{A} \qquad (29)$$

$$x^D_{vrid(v)} \in \{0, 1\} \qquad v \in \mathcal{V}, r \in \mathcal{R}, i \in \mathcal{N}_r \qquad (30)$$

$$t^O_{vo(v)} \geq 0 \qquad v \in \mathcal{V} \qquad (31)$$

$$t^S_{ri} \geq 0 \qquad r \in \mathcal{R}, i \in \mathcal{N}_r \qquad (32)$$

$$s_{ri} \in \{0, 1\} \qquad r \in \mathcal{R}_M, i \in \mathcal{N}_r \qquad (33)$$

$$y_{vri} \in \{0, 1\} \qquad r \in \mathcal{R}, i \in \mathcal{N}_r \qquad (34)$$

6.2 Including alternative way

The industry experiences an oversupply of ships which has resulted in unprofitable levels of freight rates, and it is important to have an optimal utilization of the fleet. In addition is the shipping industry unpredictable and obstacles may happen. Delays due to weather conditions and problems with ships and ports can be reasons for having to make adjustments along the way.

This section introduces an alternative way of sailing a voyage of a trade. Sometimes it may be beneficial to skip some cargo and port stops on one voyage in order to reach the start of another voyage as this may result in one less hired spot ship or any other favourably. An alternative way of sailing is illustrated in figure 8.

With the introduction of an alternative way to sail a voyage of a trade, the income, cost and time of sailing a voyage of a trade become dependent of the way the voyage is sailed. A set of alternative ways of sailing a voyage of a trade, $\mathcal{W}$, is included with index w and the income, cost and time of a trade are expressed as P_{vrw}, C_{vrw} and T_{vrw} respectively. Array H_{ri} states in how many ways a voyage i of trade r can be sailed. As a result, the variables x^D_{vridv} and x^F_{vriuj} become dependent of the way the voyage (r, i) is sailed and are denoted x^D_{vridvw} and x^F_{vriujw}

The complete mathematical model with an alternative way of sailing a voyage included can be found in appendix A.
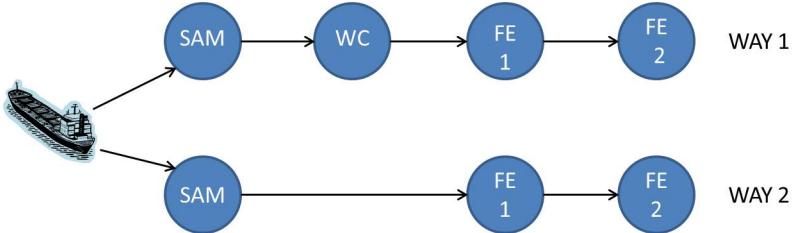
Figure 8: Alternative way to sail a voyage

7   Implementation

This section links the mathematical model in section 6 to the shipping company's tonnage allocation problem. It presents assumptions and simplifications done. The mathematical model has been written in the programming language Mosel and this section gives explanations for decisions made throughout the process of implementing with a special emphasis on preprocessing. At the end of the section a simple example is presented to illustrate the tonnage allocation problem.

7.1   Modelling description

The following paragraphs give a description of how the model handles many aspects of the real planning problem and the approaches chosen in this thesis.

Ship   The present fleet consists of 31 open-hatch ships (table 3). The ships are classified into five classes, categorized by the year they are built. The capacity of a ship is measured in deadweight tonnage (DWT) and states how much weight a ship can safely carry measured in tonnes.

As can be seen from table 3 are all ships within a class as near as identical and in addition ships can be identical across classes. This may give symmetrical solutions. The ships could have been modelled by ship type since they have many of the same characteristic. This thesis has however chosen to model each ship uniquely because they are located in different origins and are available at different start times.

$\mathcal{V}$, the set of available ships, varies between the test instances, but all combinations of ships used are subsets of the actual fleet. The ships will individually have the same origin port and earliest time available for all test instances if nothing else is specified. This is randomly set, trying to allocate to all regions and spread beyond the time period to illustrate a real situation.

Port constraints as cargo handling equipment available and limits on the size of the ships in the fleet affect the compatibility between ports and ships. However, this tonnage allocation model assumes that all the ships in the fleet can do all mandatory trades and TC-trades, allowing for flexibility and full interchangeability between ships within the trades, and ships may take on voyages of different trade routes. The fleet is heterogeneous, but in terms of ship and port compatibility the fleet has full interchangeability between ships for all the ports included. Nevertheless, a dry docking-trade belongs to a specified ship.

Table 3: The shipping company's fleet

Ship	Capacity (DWT)	Port of origin	Time available
Adventure-class			
Pioneer	46 800	Santos	01.01.13
Odyssey	46 882	Portocel	27.12.12
Navigator	46 882	Klaipeda	15.12.12
Journey	46 882	Nanjing	09.01.13
Frontier	46 882	Santos	24.12.12
Explorer	46 882	Osaka	02.01.13
Enterprise	46 882	Vlissingen	04.01.13
Discovery	46 882	Portocel	28.12.12
Adventure	46 882	Nanjing	19.12.12
Bird-class			
Viking	46 882	Portland	26.12.12
Voyager	46 882	Nanjing	07.01.13
Andorinha	47 000	Osaka	11.02.13
Tucano	47 032	Klaipeda	09.01.13
Jandaia	47 027	Santos	01.01.13
Beija Flor	46 990	Vlissingen	01.01.13
Tide-class			
Sky	47 034	Vlissingen	15.01.13
Horizon	47 016	Portocel	28.12.12
Wind	47 053	Osaka	10.01.13
Spray	47 076	Vlissingen	02.01.13
Crest	47 016	Klaipeda	01.01.13
Wave	47 062	Portocel	16.01.13
Tide	47 029	Beaumont	08.02.13
Mitsui-class			
Monal	56 800	Portocel	14.02.13
Morus	56 800	Shanghai	06.01.13
Future-class			
Falcon	54 930	Vitoria	01.01.13
Fantasy	54 930	Santos	28.12.12
Fjord	54 930	Savannah	25.12.12
Fortune	54 930	Nanjing	14.01.13
Fram	54 930	Osaka	25.01.13
Frigg	54 930	Vlissingen	29.01.13
Future	54 930	Vlissingen	03.03.13

Trade and voyages   The set of trades, $\mathcal{R}$, and the frequency of the voyages of a trade is obtained from the shipping company and reflects their typical sailing plan. The shipping company has 10 mandatory trade routes (table G.1 in appendix G). While some of them are served with up to four voyages a month, others may not be served more than once every six months. In addition the shipping company can serve TC-trades which can be identical to the mandatory trade routes, involving parts of the trade route or be a completely different route. Normally the TC-trades involves some of the same ports as the mandatory trade routes so they can sail a voyage of a TC-trade instead of a ballast voyage.

The majority of the mandatory trades have strict time windows for their voyages, while TC-trades have wide time windows. The shipping company does this to find out if there is a possibility of sailing a TC-voyage and thereafter finding cargo to put on the voyage in the suitable time period. The income of a TC-trade is difficult to calculate since the market is volatile and the cargo on it is not yet booked. In this thesis it is assumed that spot cargo is available in the ports of the TC-trades at any time.

Dry Docking   Each ship has to attend a dry docking once during a three year period. These take place in a port in Asia and optimal for the shipping company is to combine them with voyages sailing to and from Asia. In this way the ballast voyage associated with a dry docking is minimized. The dry docking trades usually have wide time windows, and in the implementation of the model the time window for all dry dockings are equal to the length of time period. This gives larger flexibility for longer planning periods than for shorter. Choosing equal time windows for all dry dockings might lead to them happening at the same time, something the shipping company wishes to avoid since having several ships in dock at the same time makes the fleet less flexible for unforeseen.

The dry dockings can be looked upon as a sunk cost since they are mandatory and ship specific. In the implementation, the cost and income of a dry docking are zero, but there are still costs related to sailing to and from the port where the dry docking is taking place.

With a fleet of 31 ships and dry docking for a ship every third year spread fairly evenly, one ship is in dry docking every month. With planning periods of 30, 60, 90, 120, 150 and 180 days, there are 1, 2, 3, 4, 5 and 6 dry dockings in each time period respectively.

Ports and regions   Each ship has an origin port for each planning period. The port can be the end port for the previous voyage the ship sailed or the

ship can be in a start port after sailed a ballast voyage, but not yet started a new voyage and is therefore available.

In this model it is assumed that for each instance of the model, the trades available in a particular instance are the "whole world", and the ships therefore have to be in one of the start or end ports for the trades included.

Spot ship If the shipping company is unable to sail a voyage of a mandatory trade, but does not want to cancel the shipment, a spot ship can be hired. A different shipping company is then paid to do the freight of the cargo. This often includes a loss and one tries to avoid hiring spot ships, but sometimes it is impossible, especially if there are several ships in dry docking at the same time.

The time a spot ship spends on sailing a voyage is not of interest in this thesis. It is assumed that the spot ship sails the voyage within the time window.

To calculate the cost of hiring a spot ship, a basis of a ship from the Adventure-class has been used with an addition of a 300 % penalty. The cost of using a spot ship on a trade is therefore the income of the trade subtracted with 3 times the cost of the trade.

In real life, spot ships are very seldom used, but when including spot ships in the optimisation model, there will "always" exists a solution, even though it is a poor one.

Cost and income Costs and incomes in this thesis represent realistic numbers, but they are not real contractual data. The freight rates are for example based on indexes.

The cost of sailing ballast from the final voyage (r, i) to the destination $d(v)$ for a ship is set to zero, since it is assumed that each ship not idling has its destination in the final voyage's end port.

Income of a trade for a specific ship is based on known data from contracts, but it also takes into consideration the possibilities of extra spot cargo. If the forecasts show high availability of extra cargo on a certain trade, a larger ship will have a higher income related to sailing the trade than a smaller ship.

This model assumes equal income and cost for all voyages of a trade. This can be discussed since there may be seasonal variations in weather conditions for sailing, available cargo and specifications in contracts.

Time spread The time spread constraint is introduced to achieve fairly evenly spread voyages. Together with the parameter calculated in section

6.1, the factor adjusts the strictness of number of days between voyages of the same trade. The factor is a manual input in the data file and is set on the basis of how strict the time spread restriction should be.

The basic case has the factor as close to one as possible, but for voyages of the same trade with overlapping time windows it may not be possible to achieve the same time spread as for equidistant voyages. The factor therefore has to be calculated manually for these cases and it varies dependent on the time period. Illustrations of calculations can be found in figure G.1 in appendix G.

Planning period   The duration of a planning period varies. In this thesis time periods of 30 days - 180 days are used as instances for the computational study. A planning period of 3-6 months is typically used for planners in the shipping companies when performing tactical planning.

7.2   Input

Input to the model can be divided in two parts; information about the shipping company (TurboRouterFile) and input from the programmer (DataFile). Example of an input file can be found in appendix B. Data representing the shipping company [2] is extracted using TurboRouter (Fagerholt and Linstad, 2007). TurboRouter contains compatibility matrix between ship and trade, time and cost matrices, costs for spot ships, time windows and information regarding ships and ports of trades. Input parameters to TurboRouter for each instance are the number of ships in the fleet, which trades to serve, the frequency of the trades (number of voyages), the origin and earliest time available for each ship. All necessary information for the optimisation is extracted in a .txt file. Input file from the programmer contains values of the factor in the time spread constraint, optimisation specific inputs and information regarding number of alternative ways. The next paragraphs present extra information regarding some of the input data.

7.2.1   Alternative way

Information regarding cost, income and time for alternative ways has been extracted using TurboRouter, but manually put into the existing TurboRouter-File. A compatibility matrix saying which voyages that can be sailed in an alternative way is made and put into the DataFile.

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[2]It is not real data, but representative for the shipping industry

7.2.2   Start Port

The origin port for each ship is given and it can either be a start port for a trade or an end port for a trade. The cost and time for the ballast voyage from the origin to the first voyage is found from two different parameters. If origin is a start port, parameters CostPortStart and TimePortStart include the cost and time for a ship to sail ballast from port of origin to start port of a trade. If origin is an end port, the cost and time for the ballast voyage is found from parameters CostBallast and TimeBallast. Using the values already provided by CostBallast and TimeBallast reduces the size of the input.

7.3   Preprocessing

Allocation problems are extensive both in terms of number of voyages, trades and ships, but also in terms of the length of the time period. It is therefore important to create variables and constraints as smartly as possible to reduce the problem size, while at the same time not omitting to create variables that might be part of the final solution or making the constraints cut of parts of the feasible region which could give the final solution. This section presents the work done with making the model as efficient as possible.

7.3.1   Compatibility used when creating variables

In order to know which ship can take what dry docking trade, a compatibility matrix TradeDDShip is introduced. If dry docking trade r is for ship v, TradeDDShip(v, r) has value 1. If not, TradeDDShip(v, r) has value 0. This can be used when creating variables, by only creating flow variables for ships that can sail a trade.

For all trades r and voyages i, there have been created a compatibility matrix WayVoyage(r, i) which gives the number of alternative ways of sailing a voyage of a trade. WayVoyage(r, i) is defined with value 1 for all combinations of (r, i), but if there exists more than one way of sailing a voyage, the number of ways is added to the matrix for the specific voyage. This is used when creating variables, by only creating variables including alternative ways for the trades and voyages which actually can be sailed in an alternative way.

Spot ships are only used when sailing mandatory trades and the spot ship variable is therefore not created for dry docking trades. The cost of spot ships is set equal to 0 for TC-trades, and the variable is created for these trades for reasons discussed in section 7.3.3.

7.3.2   Time Windows used when creating variables

Time windows are introduced to secure spread voyages throughout the time period and to keep track of when the different voyages are sailed. The time windows can be used to reduce the feasible region of the problem by only creating variables that are within the time windows. This could have been expanded to also reducing the size of the time windows if none of the ships can reach certain parts of the time windows. However, for bigger problem this is comprehensive and the bigger the problem gets, the more unlikely is it that parts of time windows can be eliminated. This is therefore not looked at in this thesis.

Table 4 gives a summary of the manual preprocessing done with the variables in the model.

Table 4: Summary of preprocessing

$x^I_{vo(v)d(v)}$	Only created if TradeDDShip(v,r) equals 0 for all TradeDD
$x^O_{vo(v)ri}$	If (r,i) is a TradeDD, $x^O_{vo(v)ri}$ is only created if TradeDDShip(v,r) equals 1 and if ship v reaches start of voyage i before the end of the time window
$x^D_{vrid(v)w}$	If (r,i) is a TradeDD, $x^D_{vrid(v)w}$ is only created if TradeDDShip(v,r) equals 1. It is also only created if way w exists for (r,i).
x^F_{vriujw}	If (r,i) and/or (u,j) is a TradeDD, x^F_{vriujw} is only created if TradeDDShip(v,r) and/or TradeDDShip(v,u) equals 1. It is only created if way w exists for (r,i), and it is only created if ship v can reach the start of (u,j) after sailing (r,i)
$t^O_{vo(v)}$	Time has to be after earliest possible start for ship v
t^S_{ri}	Time has to lie inside timewindow for (r,i)
y_{vri}	If (r,i) is a TradeDD, y_{vri} is only created if TradeDDShip(v,r) equals 1 and if $x^O_{vo(v)ri}$ exists.
s_{ri}	Only created if r is a mandatory or TC-trade

TradeDD is dry docking trades.

7.3.3 Voyage constraint

In section 6.1 three separate voyage constraints were made for mandatory trades (eq. 5), TC-trades (eq. 6) and dry docking trades (eq. 10) respectively. When creating the spot ship variable, this was only created for mandatory and TC-trades, with cost of using a spot ship on a TC-trade equal to 0. The three voyage constraints are therefore merged into one constraint with using y_{vri} (eq. 26).

$$\sum_{v \in V} y_{vri} + s_{ri} = 1 \qquad r \in R, i \in N_r \qquad (35)$$

7.3.4 Time constraint

The existence of variables is used when introducing the time constraints. The constraint which regards the time between two trades are only introduced if the flow variable between the two trades (x^F_{vriuj}) exists. The same applies for the constraint which regards the first sailed voyage after origin, it is only introduced if the ship can reach the start of the voyage inside the time window ($x^O_{vo(v)ri}$ exists).

7.4 Economic analysis

When performing analysis on the results of the model, a number of target values are used. It has especially been studied when each voyage happens since many of the voyages may have time windows close to the end. They can therefore cause obligations into the next period, preventing to obtain profit. Three expressions regarding profit are frequently used in the analysis. *Profit too late* is the profit obtained after the time period is over, while *real profit in period* is the profit obatined within the period. *Profit per ship* reflects the profit per ship in use. If any of the ships in the fleet are not in use, this is taken into account in this value.

Two expressions regarding the time are also of special importance. *Total duration on sea* is the sum of days between start of first voyage and end of last voyage for all ships, and *total time of trade* is the total time used on voyages of trades, included the ballast sailing. The difference between these two will be the time ships wait between voyages.

In addition are cost values as *total ballast costs* and *total ballast costs for dry docking trades* used when analysing.

All target values with explanations are presented in table F.1 in appendix F.

7.5   Optimisation

The complete Mosel code can be found in appendix C. All test instances introduced in this thesis have been implemented with use of the commercial optimisation software Xpress-IVE Version 1.23.00 64 bit, Xpress Mosel Version 3.4.0 and Xpress Optimizer Version 23.01.03. The computer used for optimisation is a HP Intel Core i7-3770, CPU 3.40GHz, 16 GB RAM running on Windows 7 Enterprise.

Xpress performs the optimisation of the maximization problem with a single call. It uses branch and bound to solve the problem, and it also generates cuts to find an optimal solution as fast as possible. After an optimal solution has been obtained or the optimisation has reached a predefined maximum time, the solution is written to a csv.file. This file is opened in Excel and used for analysis. Example of an Excel-file can be found in appendix D.

7.6   Simple instance example

To illustrate the tonnage allocation problem, a simple instance follows. Consider three regions with three mandatory trades and one optional trade. The planning horizon is two months; Jan 1st - Feb 28th. One trade has three voyages, while the other trades have two voyages during the time period. The shipping company's fleet consists of four ships; in addition spot ships are available on short notice. There are not included any dry dockings in this period. Table 5 gives a summary of the inputs.

Table 5: Example instance

Ship	ID	Origin	Earliest time
Adventure	AD	Klaipeda, Europe	01.01.13
Discovery	DI	Portocel, South America	01.01.13
Enterprise	EN	Portocel, South America	01.01.13
Explorer	EX	Osaka, Far East	01.01.13

Trade	ID	Time of voyages	Time window
South America - Europe	SAMEUR	14. jan, 3. feb, 23.feb	10 days
Europe - South America	EURSAM	1. jan, 1.feb	10 days
South America - Far East	SAMFE	6. jan, 3.feb	15 days
Far East - South America	TC FESAM	1. jan, 1.feb	30 days
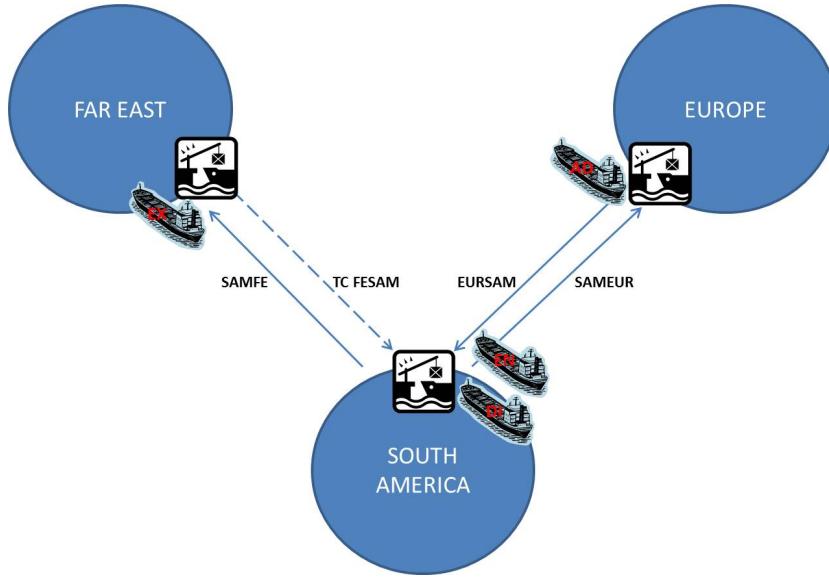
Figure 9: Illustration of simple test example

The example includes the regions Europe, South-America and Far East, and the trades SAMFE, SAMEUR, EURSAM and TC FESAM. Figure 9 illustrate the regions, trades and where the ships are at origin. In each region there are several ports and they can be different from trade to trade (figure 10).
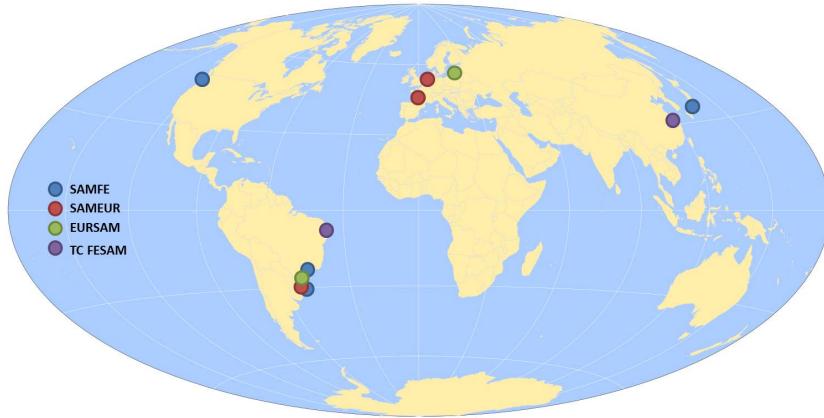
Figure 10: Illustration of ports of trades for simple test example

Figure 11 shows an illustration of the optimal result. T gives the time a voyage takes, t is the start time of a voyage, $ on an arrow is the cost of ballast, while $ under the voyage-node is the profit of sailing the voyage (ballast costs are not included). All costs and profits are in $ 1000. $o(v)$ and
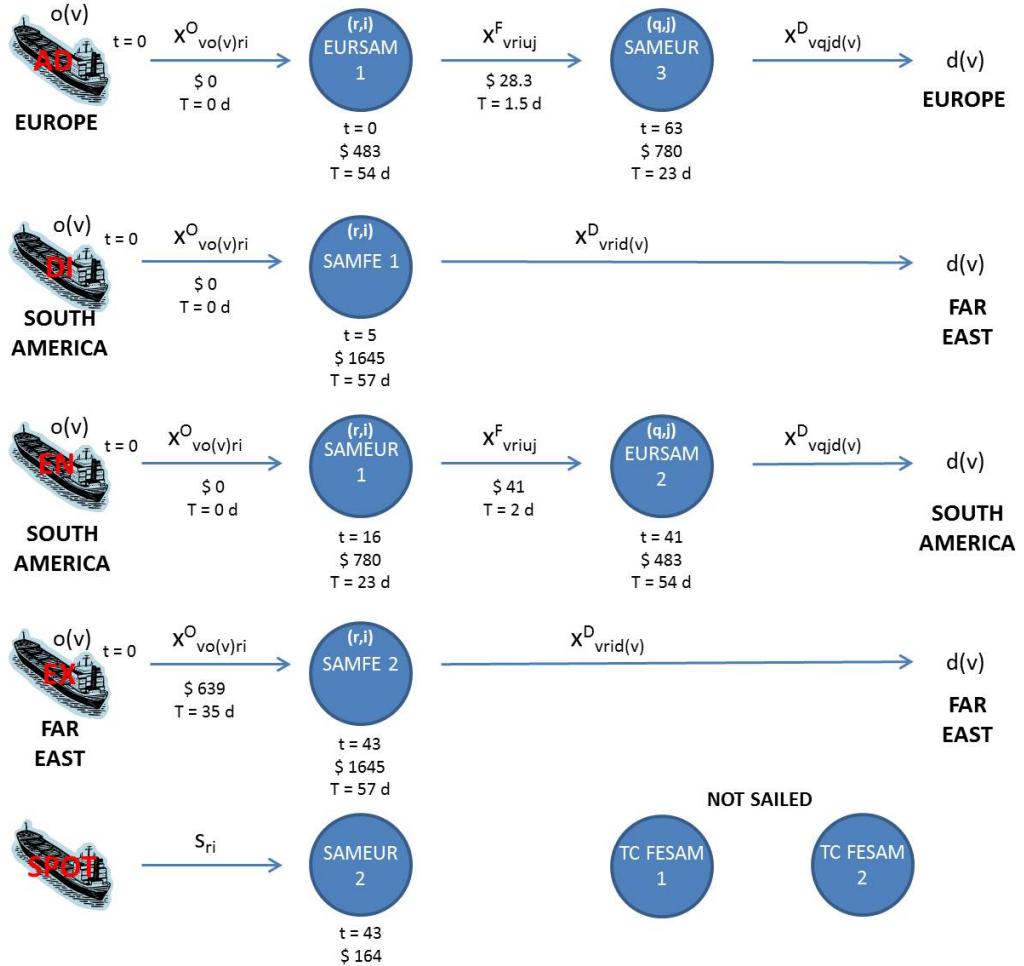
Figure 11: Results from simple test example. All costs and profits are in $ 1000.

$d(v)$ give the origin and destination for the ships.

The results show one voyage sailed by a spot ship, while none of the optional voyages are sailed. Ship EX has to sail a long ballast voyage from the Far East to South America before sailing SAMFE #2, and the ballast costs are therefore major for this example. It would here been beneficial to sail a voyage of TC FESAM, but there are unfortunately not enough time for that. The total profit for this instance is $ 5 272 000 and the solution time is 0.02s.

8 Computational study

This section includes a computational study of the tonnage allocation model. A performance study is presented where there is a gradual inclusion of trades, and the problem size is tested. Examples of rolling horizon as a solution approach are presented. The main part of this section is the analysis on effects of adjusting input parameters and constraints which has been performed on trades of a time period of 90 days. Many aspects are analysed, especially the timing of trades, the cost of spot ship and the inclusion of TC-trades. At the end an alternative way of sailing a voyage is included with subsequent analysis. This section only presents the central aspects and all results can be found in appendix D.

8.1 Performance study

The mathematical model is tested on instances which varies both in number of trades and days, and therefore also in number of voyages. The frequency of the trades is as close to the real planning problem as possible. The increase of trades will not always give an increase in number of voyages, since each trade not necessarily need to be served every month.

Table 6: Instances for performance study

	30D		60D		90D	
Inst	**#Voy***	**#Ship**	**#Voy***	**#Ship**	**#Voy***	**#Ship**
3T (+6TC)	9+1 (+6)	10	17+2 (+12)	13	26+3 (+18)	16
4T (+8TC)	11+1 (+8)	13	18+2 (+16)	15	31+3 (+24)	18
6T (+12TC)	12+1 (+12)	13	22+2 (+24)	15	34+3 (+36)	20
8T (+14TC)	14+1 (+14)	14	25+2 (+28)	18	39+3 (+42)	22
10T (+16TC)	14+1 (+16)	14	26+2 (+32)	19	40+3 (+48)	22

	120D		150D		180D	
Inst	**#Voy***	**#Ship**	**#Voy***	**#Ship**	**#Voy***	**#Ship**
3T (+6TC)	34+4 (+24)	19	43+5 (+30)	22	50+6 (+36)	26
4T (+8TC)	40+4 (+32)	19	51+5 (+40)	22	59+6 (+48)	26
6T (+12TC)	43+4 (+48)	21	55+5 (+60)	24	63+6 (+72)	28
8T (+14TC)	49+4 (+56)	23	63+5 (+70)	26	72+6 (+84)	30
10T (+16TC)	52+4 (+64)	24	66+5 (+80)	27	76+6 (+96)	31

* # Voy is mandatory voyages + dry docking voyages (+ TC-voyages).

The base of testing the performance is a set of five instances where the number of mandatory trades is varied. The mandatory trades with their frequency are presented in table G.1 in appendix G. The number of ships in

the fleet of each instance is chosen to try to meet the demand of mandatory voyages with no use of spot ship. The origin port and earliest time available for each ship is equal throughout all the instances. The number of voyages and the number of dry docking trades are dependent of the chosen time period.

The five instances are run with six different planning horizons, from one month (30 days) to six months (180 days). Table 6 shows the composition of the instances. The numbers in brackets are TC-trades and TC-voyages.

Mandatory and dry docking trades

In the first test of instances are there only mandatory trades and dry docking trades included. The results are presented in table 7.

Table 7: Performance without TC-trades

	30D			**60D test**		
Inst	**Profit***	**Time**	**SS/I****	**Profit***	**Time**	**SS/I****
3T	$ 8431	0.031s	-/1	$ 13279	0.063s	3/3
4T	$ 9313	0.031s	-/1	$ 15555	0.094s	1/-
6T	$ 10093	0.047s	-/1	$ 16173	0.093s	1/-
8T	$ 11616	0.047s	-/1	$ 19114	0.140s	2/-
10T	$ 11616	0.046s	-/1	$ 19941	0.172s	1/-

	90D			**120D**		
Inst	**Profit***	**Time**	**SS/I****	**Profit***	**Time**	**SS/I****
3T	$ 21810	0.218s	-/-	$ 27923	0.483s	1/1
4T	$ 24671	0.281s	-/-	$ 32800	0.717s	1/1
6T	$ 26001	0.499s	1/-	$ 35098	0.998s	-/-
8T	$ 30847	0.874s	-/-	$ 40764	1.763s	-/-
10T	$ 31350	0.811s	-/-	$ 42993	2.402s	1/-

	150D			**180D**		
Inst	**Profit***	**Time**	**SS/I****	**Profit***	**Time**	**SS/I****
3T	$ 37369	4.203s	-/3	$ 43539	3.254s	-/3
4T	$ 42390	3.213s	-/-	$ 49265	9.685s	-/3
6T	$ 45116	3.802s	-/-	$ 52219	10.86s	-/4
8T	$ 52577	5.772s	-/-	$ 60234	24.80s	-/3
10T	$ 54934	16.24s	-/1	$ 63581	75.60s	-/2

*All profits are given in $ 1000.

** SS represents spot ships, I represents the ships in the fleet not in use/idling.

Without TC-trades included, optimal solution is found for all instances within 76 seconds. For the periods up to 4 months, the results show use of

spot ship when there are available ships in the fleet. An example is 3T60D where there are three ships not in use and at the same time they are hiring three spot ships. The spot ships are used on three SAMEUR-voyages. SAMEUR is a trade that give profit when spot ships are used. If this is changed to a cost, the optimal solution includes no use of spot ships (appendix D).

For instances with time periods of 5 and 6 months are there no use of spot ships, and for 6 months are there ships in the fleet not in use for all instances. This indicates a better utilization of the fleet. The challenge with a longer perspective is that the computational time greatly increases. This can especially be seen for 5 and 6 months.

If the results of 30 days are compared to the results of the longer time periods, will it always be more profitable to plan for 30 days at a time. However, the profit does not reflect the obligations the ships have into the next time period. Many of the voyages may start late in the 30 days time period, which makes it impossible to have the same plan for the next 30 days. If 60 days are compared to 120 days and 180 days, is it favourable to look at the longer periods as they give better profit than repeating the 60 days plan. The same holds for 90 days compared to 180 days. This indicates that having a longer perspective when planning is favourable.

Mandatory-, TC- and dry docking trades

TC-trades are added with the size of the fleet kept constant. Inputs in the instances can be found in table 6. TC-trades have one voyage each month with a time window of 30 days, but it is optional to sail them. The model is terminated and forced to return a solution after one hour to make the results regarding gap comparable with the other tested instances.

Table 8 shows the results when including optional TC-trades to the set of instances. The total number of voyages the fleet can sail is presented in table 6, but the actual number of TC-voyages sailed is given from table 8.

The problem complexity is greatly increased with the introduction of TC-trades, and this can be shown in the computational time. The largest instances of 4 months and the smaller instances for 5 and 6 months did not find an optimal solution within 1 hour. Instance 8T for 5 and 6 months gave optimal solutions within short time; however, they were less profitable than smaller instances. Instance 10T for 6 months could not be solved.

The results may indicate that the model rather sails TC-voyages than the mandatory voyages and hires spot ships to sail some of the mandatory voyages. A deeper look shows that the majority of the TC-voyages sailed have small or no costs for ballast sailing to the start port of the trade, exception is for ships and trades in other regions than those which need spot ships

Table 8: Performance with TC-trades

	30D			60D		
Inst	**Profit***	**Time**	**SS/TC****	**Profit***	**Time**	**SS/TC****
3T	$ 10077	0.062s	1/4	$ 17530	0.234s	5/7
4T	$ 11299	0.062s	-/4	$ 19680	0.297s	4/8
6T	$ 12009	0.141s	-/3	$ 19383	0.874s	4/8
8T	$ 13355	0.156s	-/2	$ 23115	1.170s	5/9
10T	$ 13426	0.203s	-/3	$ 25770	2.449s	4/12

	90D			120D		
Inst	**Profit***	**Time**	**SS/TC****	**Profit***	**Time****	**SS/TC****
3T	$ 25169	1.139s	6/10	$ 34299	11.6s	5/15
4T	$ 28442	3.260s	4/10	$ 38666	63.2s	7/16
6T	$ 31395	16.60s	6/13	$ 42795	1431s	5/16
8T	$ 36361	12.90s	6/19	$ 48822	1h, 1.0 %	6/19
10T	$ 36380	53.80s	9/16	$ 49608	1h, 6.8 %	8/22

	150D			180D		
Inst	**Profit***	**Time****	**SS/TC****	**Profit***	**Time****	**SS/TC****
3T	$ 47945	1h, 2.4 %	3/22	$ 58306	1h, 0.43 %	-/30
4T	$ 53340	1h, 2.6 %	3/25	$ 63657	1h, 5.80 %	1/35
6T	$ 57149	1h, 6.4 %	7/30	$ 60047	1h, 25.2 %	5/34
8T	$ 45843	634s	11/26	$ 51751	1586s	14/40
10T	$ 45144	1h, 50 %	15/26	-	-	-

*All profits are given in $ 1000.

**SS is number of spot ships used, TC is number of TC-voyages sailed.

***% represents the gap of solutions which are not optimal.

(appendix D). The inclusion of TC-trades therefore gives a better utilization of the fleet and especially ballast voyages are exploited.

If the longer time periods are compared to the results from 30 days, will it give better profit to plan a 30 day period repeatedly than to plan for a longer period. As discussed in the previous section, this is a result of not take into consideration the consequences the obligations from the 30 days plan may have for the next period.

Testing problem size

The instances which did not give an optimal solution after one hour have been run for maximum 24h to find a better solution and to get an understanding of the problem size. The results are presented in table 9. All results show improvements in profit, mainly caused by a better utilization of the fleet in terms of decreased use of spot ship.

Table 9: Performance with TC-trades, 24 hours

120D			
Inst	**Profit**[*]	**Time**	**SS/TC**[**]
8T	$ 48822	2h 44m	6/19
10T	$ 51549	8h 14m	7/23

	150D			180D		
Inst	**Profit**[*]	**Time**[***]	**SS/TC**[**]	**Profit**[*]	**Time**[***]	**SS/TC**[**]
3T	$ 47989	24h, 1.71 %[***]	1/22		Out of memory	
4T		Out of memory		$ 65666	24h 2.37 %	3/38
6T	$ 58715	24h, 1.89 %	4/31	$ 71070	24h 5.40 %	1/43
8T		Obtained before			Obtained before	
10T	$ 67934	24h, 4.87 %	5/36		Obtained before	

[*]All profits are given in $ 1000.

[**]SS is number of spot ships used, TC is number of TC-voyages sailed.

[***]% represents the gap of solutions which are not optimal.

Reducing the number of TC-trades

The transition from only mandatory trades to both mandatory trades and optional TC-trades made the size of the model significantly greater, and it was especially difficult to find solutions for 150 days and 180 days. It is therefore looked at what happens if the number of TC-trades to choose among is halved from the original number found in table 6. Each trade will still have one voyage each month with a time window of 30 days. The results are found in table 10.

When the number of TC-trades is halved, all instances find solutions within 1 hour, although most of them are not optimal. For some of the instances can the solutions be characterized by high use of spot ships. If the model is extended to run for 24 hours, the solutions get better and for 180 days none of the solutions include use of spot ships. This indicates that the fleet is large enough to handle the company's obligations, and in addition they can take on a significantly large number of TC-voyages.

The results of 8T are better when the number of TC-trades is halved. The results for the full case showed poor optimal solutions for 8T for 5 and 6 months with high use of spot ships. Results obtained with the number of TC-trades halved show minimal use of spot ships and this is clearly a better solution for the shipping company.

Table 10: Performance with reduced number of TC-trades

	150D - 1h			180D - 1h		
Inst	**Profit***	**Time****	**SS/TC*****	**Profit***	**Time****	**SS/TC*****
3T	$ 43155	234s	-/10	$ 50546	1h, 0.23 %	-(1)/11
4T	$ 48725	113s	-/14	$ 57261	380s	-(1)/18
6T	$ 54122	1h, 2,08 %	-/22	$ 64952	1h, 0.10 %	-/35
8T	$ 61756	1h, 3.30 %	1/25	$ 72800	1h, 3.75 %	1(1)/33
10	$ 62495	1h, 6.80 %	3/23	$ 62515	1h, 26.5 %	13(1)/25

	150D - 24h			180D - 24h		
Inst	**Profit***	**Time****	**SS/TC*****	**Profit***	**Time****	**SS/TC*****
3T		Obtained before			Out of memory	
4T		Obtained before			Obtained before	
6T		Out of memory		$ 64956	8h 6 m	-/35
8T	$ 62484	24h, 1.95 %	-/24	$ 74335	24h 1.48 %	-/38
10	$ 64286	24h, 3.54 %	2/26	$ 77283	24h 2.21 %	-/36

*All profits are given in $ 1000.

**% represents the gap of solutions which are not optimal.

***SS is number of spot ships used, TC is number of TC-voyages sailed.

(-) shows the number of ships in the fleet not in use

Concluding remark of the performance of the model

The use of spot ships is one weakness in the model. In reality are spot ships nearly never used, but in optimization are spot ships an easy way of obtaining a solution to the problem (section 7.1). The cost of hiring a spot ship is in the model set to a realistic price, but increasing the cost may lead to a decrease in the use of spot ship and give a more realistic solution. Especially this accounts for the trades with a profit when using spot ships.

The use of spot ships is harder to avoid for the shorter time periods where the origin port and earliest time available for each ship have great influence. If all ships are far away, the cost of ballast sailing may be significantly higher than hiring a spot ship. If a large percentage of the fleet is not available until late, it may also be impossible to sail some voyages.

The number of trades increases the complexity of the problem as the number of different regions to cover increases. The length of the time period also increases the problem as the number of voyages increases. In the problem without TC-trades was an optimal solution found for all instances within 76 seconds, while the inclusion of TC-trades had greater impact. Large instances

were not able to find an optimal solution within one hour, and the largest instances of 5 and 6 months were not able to find a good optimal solution for the full case with TC-trades included.

For both the instances with and without TC-trades included is it always more profitable to plan for a 30 day-period repeatedly than for longer periods. However, this short planning period will probably cause obligations into the next period and it will therefore be impossible to obtain a 30 day-plan many times consecutively.

When reducing the number of possible TC-trades, the problem size gets smaller and all instances give solutions after one hour. For 180 days, the model gave solutions which did not include spot ships when it was run for 24 hours. This indicates that the shipping company has a big enough fleet to cover the obligations when having a longer perspective, but spot ships are an easy way of getting a solution in a short time.

SAMEUR is one trade "always" served by a spot ship. This is the trade with the highest frequency of voyages and it is therefore natural that there might be problems serving all trades, especially for the cases of few trades which mean a lot of ballast voyages to cover. This trade is also a trade with a profit when using spot ships on the trade. Most of the other trades have a loss related to the use of spot ship on the trade.

8.2 Examples of rolling horizon

Rolling horizon is a solution method which routinely updates or revises schedules, taking into consideration more reliable and recent data as they become available. This solution method has especially been found successful to deal with large MIP (Rakke et al., 2011). This section gives two examples with the use of rolling horizon.

6T 150D

A simple example of rolling horizon has been performed on the case of 6T and 150 days. The model is first run for 90 days and results are frozen after 60 days and withdrawn. This is then the basis for a new optimisation of the last 90 days.

Table 11 shows the results of using a rolling horizon compared to the results when running the model for 150 days continuously. The most significant result is the great saving in computational time for the minor reduction in profit when using a rolling horizon compared to the original results after 1 hour. The difference in profit is greater when comparing with the original

Table 11: Results for rolling horizon 6T 150days

	Profit*	Ballast*	SS/TC**	Time***	Best bound
150 days 1 h	$ 57149	$ 3644	7/30	1 h, 6.40%	60 800
150 days 24 h	$ 58715	$ 3179	4/31	24 h, 1.89%	59 825
First 60 days	$ 24128	$ 1731	-/13	80.564 s	
Last 90 days	$ 33033	$ 2184	2/16	3.186 s	
Total 60+90 days	$ 57160	$ 3915	2/29	-	

*All profit and ballast costs are given in $ 1000.

** SS is number of spot ships used, TC is number of TC-voyages sailed.

*** % represents the gap of solutions which are not optimal.

results after 24 hours. It shows a 2.7 % better solution when not using rolling horizon.

The results from using rolling horizon give fewer spot ships hired, followed by a decrease in the number of TC-voyages sailed and increased ballast costs.

8T 180D

The result from the case with 8T and TC-trades for 180 days is clearly not an optimal solution for the shipping company since the profit has decreased from the case of 6T, even though it is optimal for the optimisation programming tool (table 8). There is a high need of spot ships as well as high costs for ballast voyages (table 12). Several TC-voyages are done with high ballast costs, resulting in a negative profit which is not the goal when taking on optional voyages.

From the results of 180 days are profit and positions of ships withdrawn after 90 days and they thereafter constituted a basis for a new optimisation of the last 90 days. Dry dockings which are not completed in the first three months have to be completed during the last three months. In addition has the same case as 8T 180 days been run, but only for 90 days. The positions of ships after 90 days form the basis for a new period of 90 days. Dry dockings have been split in two; three have to be done the first three months and three have to be done the last three months. This analysis is run in order to compare the results, since the result from the 180 days period was poor.

The results are presented in table 12. The original case of 180 days has major ballast costs, and this is also the case for the first 90 days when status

Table 12: Results for rolling horizon 8T 180 days

		Profit[*]	**Ballast costs**[*]	**SS/TC**[**]
Original	180 days	$ 51751	$ 13586	14/40
	First 90 days	$ 22067	$ 8915[1]	11/19
Original	Last 90 days	$ 40315	$ 2694	-/29
	Total 90+90 days	$ 62382	$ 11609	11/48
90 days +	First 90 days	$ 43931	$ 3026	-/28
90 days	Last 90 days	$ 32964	$ 3255	5/22
	Total 90+90 days	$ 76895	$ 6281	5/50
60 days +	First 60 days	$ 28545	$ 2010	-/19
60 days +	Next 60 days	$ 24128	$ 1834	2/13
60 days	Last 60 days	$ 24133	$ 2710	3/15
	Total 60+60+60 days	$ 76806	$ 6554	5/47

[*] All profits and ballast costs are given in $ 1000.

[**] SS is number of spot ships used, TC is number of TC-voyages sailed.

[1] The ballast costs of the first 90 days of the original case are included $ 2714
to get to the start of the last 90 days

is withdrawn. The last 90 days has however significantly lower ballast costs and in addition no use of spot ships. The profit for the last 90 days is almost the double of the first 90 days. This shows that the optimisation of the whole time period of 180 days was not a good solution for the shipping company. This is a result of problem instance with a period length to extensive to calculate.

When the time period is divided in 90+90 days with no use of rolling horizon, it is clear that the obligations from the first 90 days set the stage for the last 90 days. There is a large increase in spot ships hired and the ballast costs are also higher. The total profit is however significantly higher because of better utilization of the fleet in the first 90 days.

There has additionally been performed another analysis as follow. The instance with 90 days is run and results are frozen after 60 days and positions for ships are withdrawn. This is the basis for a new planning period of 90 days where the results are frozen after 60 days and positions of ships are withdrawn. This forms the basis for planning the last 60 days. Ships that are sailing ballast voyage when withdrawing positions, will complete this voyage.

The results can be found in table 12. The use of a 60+60+60 days rolling horizon solution method gives almost the same solution as the instance where

90+90 days is run separate without rolling horizon. The ballast costs have increased, while the use of spot ships and number of TC-voyages are almost the same. This implies that the rolling horizon is not favourable when the time period is short enough to be solved to optimality. If the three 60 days-periods are compared, the first 60 days give a higher profit than the other two. This might be a result of fewer obligations from previous time period in the first 60 days than in the other 60 days (the origin and earliest time available set may be more favourable).

It is tested if the results of the 60+60+60 days can be a valid solution for the 180 days instance. A complete trade plan for each ship is made for 180 days on the basis of the results from 60+60+60 days. The trade plans are imported into an exported matrix from Xpress from the solution from 180 continuous days and then optimised using Xpress. This returns an infeasible solution because of the time spread constraint introduced in section 6. The time spread parameters depend on the length of the planning period. The solution from the example of 60+60+60 days will therefore not be valid for 180 days because it will include start-times for successive voyages of a trade that will "break" the 180 days time spread constraint. From the calculation of different factors in 7.1 it can be seen that there is a need to decrease the factor for trades with overlapping time windows when the time period is increased.

8.3   Effects of adjusting input and constraints

This section analyses the instances for 90 days with TC-trades included when adjusting input parameters and constraints. In an industry with freight rates at unprofitable levels is it required to have an optimal utilization of the fleet. A special emphasis will be put on trying to keep the use of spot ships at a minimum. Mainly percentage comparison results of profit and computational time will be discussed, but all results can be found in appendix D. Aspects of analysis in this section are timing of trades, cost of spot ships, dry docking trades, origin port and earliest time available for a ship and the TC-trades.

Change in profit can be a result of both the need for spot ships, opportunities to take on TC-voyages, costs linked to ballast voyages and the composition of ships and voyages. When analysing the results, it is not possible just to look at the profit and computational time. The routes for each ship must be looked at, analysing ballast costs, profit for each voyage and what voyages each ship sails. It is too comprehensive to present trade plans for all ships for all instances. One instance will therefore be presented more thoroughly in each section. This analysis is based on trade plans for all ships, which can be found in appendix D, and target values regarding profit and

actual time on sea presented in section 7.4.

8.3.1   Change factor of time spread

The factor in the time spread constraint controls the strictness of the requirements of fairly evenly spread trades (6.1). This section studies what happens if the factor is decreased, making the time spread less valid. All factors are changed equally, and the instances looked at are factors of 0.75, 0.5, 0.25 and 0.1, the latter giving the weakest time spread constraint. The results are compared against the original instances with factor of 1 and can be found in table 13.

Table 13: Factor change for 90 days

	Factor = 0.75		Factor = 0.50		Factor = 0.25		Factor = 0.10	
	Profit	**Time**	**Profit**	**Time**	**Profit**	**Time**	**Profit**	**Time**
3T	1.38 %	59.5 %	1.38 %	211 %	1.72 %	135 %	1.72 %	141 %
4T	2.38 %	47.4 %	2.38 %	68.9 %	2.38 %	83.7 %	2.38 %	124 %
6T	2.28 %	41.7 %	2.54 %	1199 %	4.22 %	61.1 %	4.22 %	-31.3 %
8T	3.09 %	54.6 %	3.36 %	76.1 %	4.02 %	53.5 %	4.02 %	49.4 %
10T	3.30 %	889 %	3.65 %	1436 %	4.63 %	1011 %	4.63 %	-38.5 %

	Factor = 0.75	Factor = 0.50	Factor = 0.25	Factor = 0.10
	Δ**SS/**Δ**TC***	Δ**SS/**Δ**TC***	Δ**SS/**Δ**TC***	Δ**SS/**Δ**TC***
3T	-/-	-/-	-2/-	-2/-
4T	-1/1	-1/1	-1/1	-1/1
6T	-/-	-1/1	-2/-1	-2/-1
8T	-1/-6	-3/-7	-3/-6	-3/-6
10T	-3/-1	-3/-1	-4/-	-4/-

* SS is the number of spot ships, TC is the number of TC-voyages

The results give a significant increase in profit. The change in profit when reducing the factor is either a result of less spot ships hired or an increase in TC-voyages sailed. Lowering the factor gives more flexibility when it comes to the start time of a voyage, and there is a prioritization to reduce the number of spot ships as this involves the biggest improvements in profit.

Changing the factor of the time spread constraint can give substantial improvements in profit, but it increases the computational time considerably for most cases since lowering the factor gives more possibilities.
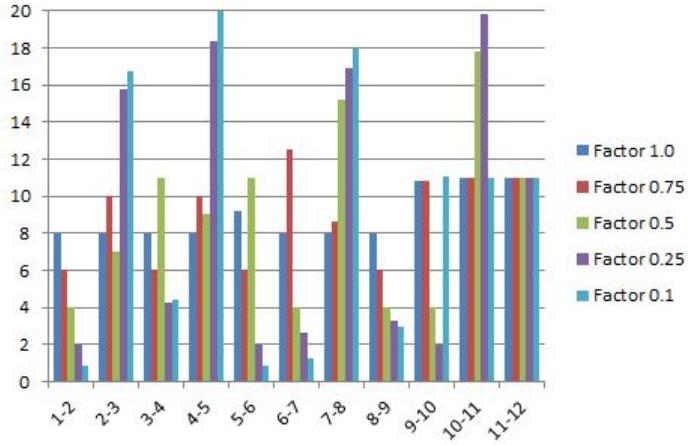
Figure 12: Days between voyages of trade SAMEUR for 10T

10T   Figure 12 shows how the number of days between voyages for trade
SAMEUR varies with the factor. When the factor is 1, the minimum time
between voyages is 8 days with no spread larger than 11 days. Decreasing
the factor leads to bigger variations, the largest number is 20 days between
voyages 4-5 and the smallest number is 0.8 days between voyages 1-2 and
5-6, both happen when the factor is 0.1. The main observation is that the
lower the factor gets, the greater is the flexibility between the trades.
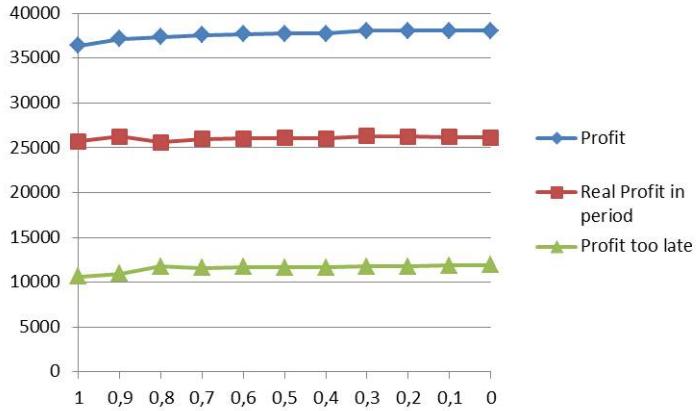
Figure 13: Profit (\$ 1000) when changing factor for 10T.

A closer look at the how the factor affects the profit, ballast costs, number
of TC-voyages and spot ships can be found in figures 13, 14 and 15. When
the factor is changed, the first consequence is a reduction in the number of
spot ships. This causes a reduction in the number of TC-voyages and an
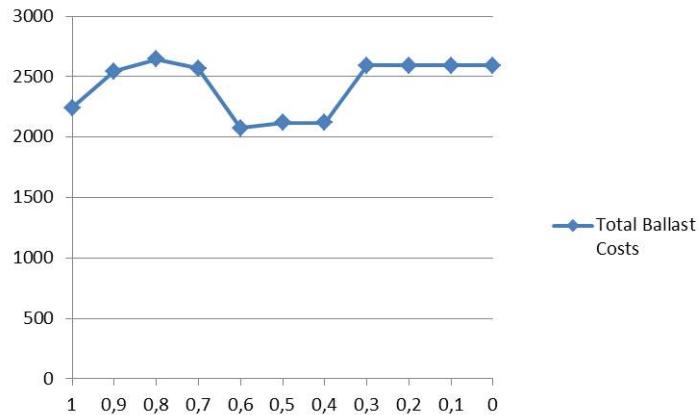
Figure 14: Ballast costs ($ 1000) when changing factor for 10T
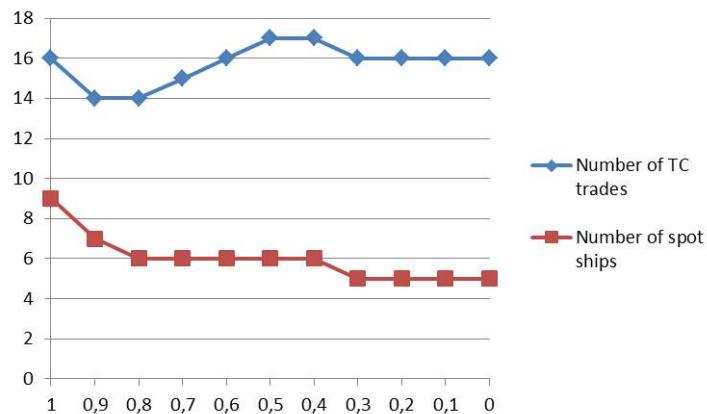
Figure 15: Number of TC-voyages and spot ships when changing factor

increase in ballast costs, since they now have time to sail mandatory trades which might be far away. If a ship in the fleet has time to sail a voyage, this will almost always be more profitable than hiring a spot ship. When a reduction of the factor is not enough to reduce the number of spot ships, there is an increase in the number of TC-voyages and the ballast costs decrease. The ships which did not have time to sail a TC-voyage between two voyages before, now have the time, and ballast costs are saved. As long as profit is achieved on a voyage, ballast costs are no barrier from sailing the voyage.

An example of how the factor affects the use of spot ships is given in table 14. When the factor is 1, SAMEUR #4 is sailed by a spot ship, but as the factor decreases, the flexibility in the fleet increases. For factor 0.75, a ship in the fleet can sail the voyage before sailing a voyage of SAMFE. Note

that ballast costs are no barrier from sailing a voyage. When the factor is 0.25, the same ship sails a TC-voyage before reaching a later voyage of SAMFE and great ballast costs are saved. This shows how flexibility can improve a solution.

Table 14: Example of allocation when decreasing the factor

| | | **Factor = 1.0** | | | |
Ship	**Trade**	**Start**	**End**	**Ballast**[*]	**Profit**[*]
Spot	SAMEUR#4				$ 164

| | | **Factor = 0.75** | | | |
Ship	**Trade**	**Start**	**End**	**Ballast**[*]	**Profit**[*]
	SAMEUR#4	39	61.8	$ 277	$ 503
EN	↓				
	SAMFE#6	77	133.7	$ 277	$ 1368

| | | **Factor = 0.25** | | | |
Ship	**Trade**	**Start**	**End**	**Ballast**[*]	**Profit**[*]
	SAMEUR#4	39	61.8	$ 277	$ 503
	↓				
EN	TC EURSAM 40#2	62	102.3	$ 3.9	$ 177
	↓				
	SAMFE#8	103	159.7	$ 2.3	$ 1643

[*] All profits and ballast costs are in $ 1000

8.3.2   Change time window

Time windows are a way of securing spread voyages over the planning period, and this section investigates what happens if the time windows of mandatory trades are increased or decreased. The changes in time window are done with keeping the midpoint constant and changing the width from the middle to the start and end of the window. The instances in this computational study involved trades with overlapping voyages. For the original case with a factor of 1, a decrease of the time window will give infeasible solutions for these trades. When calculating a factor, this was set to the maximum it could be with current time windows. Decreasing the time window will make it impossible to obtain the given time spread because there are not enough days in the time windows. The factor has therefore been reduced for some of the trades in order to obtain results [3].

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[3]This accounts for SAMFE, SAMEUR and EURSAM. Examples of calculations are shown in section 7.1.

Table 15: Change of time window combined with change of time spread factor

| | **Factor = 1** | | | | | | | |
| | **0.75TW** | | **0.9TW** | | **1.1TW** | | **1.25TW** | |
	Profit	**Time**	**Profit**	**Time**	**Profit**	**Time**	**Profit**	**Time**
3T	-0.33 %	-21.9 %	0 %	27.5 %	0%	49.3 %	0.23 %	103 %
4T	-1.90 %	-26.7 %	-1.51 %	-28.8 %	1.87 %	20.6 %	2.34 %	68.5 %
6T	-1.57 %	-58.8 %	-0.93 %	-55.3 %	0.23 %	-48.7 %	2.45 %	-44.1 %
8T	-1.16 %	-28.9 %	-0.70 %	-21.7 %	2.39 %	4.09 %	2.55 %	603 %
10T	-0.97 %	-70.8 %	-0.70 %	-32.8 %	2.51 %	-49.1 %	2.88 %	921 %

| | **Factor = 0.75** | | | | | | | |
| | **0.75TW** | | **0.9TW** | | **1.1TW** | | **1.25TW** | |
	Profit	**Time**	**Profit**	**Time**	**Profit**	**Time**	**Profit**	**Time**
3T	-1.33 %	-21.2 %	0 %	-33.0 %	0 %	-1.26 %	0.22 %	210 %
4T	-3.57 %	-44.4 %	-1.60 %	-53.2 %	0 %	16.2 %	0.68 %	1253 %
6T	-1.93 %	-28.8 %	-1.15 %	-59.6 %	0 %	-47.7 %	1.51 %	276 %
8T	-3.20 %	-40.0 %	-1.80 %	-31.2 %	0.14 %	441 %	0.36 %	8727 %
10T	-3.30 %	-90.9 %	-1.80 %	-86.2 %	0.3 %	9.76 %	0.48 %	577 %

| | **Factor = 0.25** | | | | | | | |
| | **0.75TW** | | **0.9TW** | | **1.1TW** | | **1.25TW** | |
	Profit	**Time**	**Profit**	**Time**	**Profit**	**Time**	**Profit**	**Time**
3T	-1.32 %	-22.0 %	0.33 %	-26.7 %	0 %	0.67 %	0.55 %	0.67 %
4T	-3.99 %	-38.8 %	-1.55 %	-17.7 %	0.26 %	18.2 %	0.68 %	316 %
6T	-2.53 %	-73.9 %	-1.66 %	-47.9 %	0 %	23.1 %	0 %	520 %
8T	-3.27 %	-26.8 %	-2.00 %	238 %	0.22 %	3733 %	1.18 %	2728 %
10T	-3.74 %	-67.8 %	-2.52 %	230 %	0.08 %	349 %	1.71 %	235 %

The results are compared against the original case with factor of 1 and can be found in table 15. Increasing the time window will lead to more flexibility regarding when to perform the voyages and will therefore increase the profit. The increase in flexibility is for most cases followed by an increase in computational time. When decreasing the time window, the profit decreases, but the main difference lies in the improvement of computational time which is significantly shorter. This indicates that the more specific the time windows are, the shorter time takes the optimisation.

The changes of time windows are also looked at when the factor is decreased. The results are compared to the results when only the factor was decreased (results from 8.3.1 in table 13) and can be found in table 15. Increasing the time window with 10% when the factor has been reduced, gives little or no increase in profit, while increasing the time window with 25% gives a greater increase in profit, followed by a significant increase in com-

putational time. This is valid for both factor 0.25 and 0.75. Decreasing the
time window when the factor is 0.75, show significant savings both in com-
putational time and profit. This can also be found when the factor is 0.25,
but there is a need for a larger decrease in time window. This indicates that
the value of flexibility in one area decreases if flexibility in correlating areas
increases which is the case here since both the time window and the factor
of time spread controls when a voyage can be started. The more flexibility
you have, the more flexibility is needed in order to notice improvements.

10T   A more thoroughly analysis of the case of 10 trades with TC-trades
follows. Figure G.2 in appendix G shows the start times for voyages SAMEUR
and SAMFE for the different factors and changes in time window. When only
decreasing the time window, there still has to be a certain spread between
the voyages which can be seen in the figure. When also decreasing the factor,
there is greater flexibility and the start time of a voyage is more random. This
can especially be seen for SAMFE where the three first voyages for factor 0.25
have great variations in when they start compared to the factor of 1.

Common for all instances is an increase of profit when the time window
increases and a decrease of profit when the time window decreases. This can
be shown in figure 16 for factor 1 and in figure 17 for factor 0.25. When
increasing the time window, more voyages have their time windows into the
next period and with this increase the obligations on the fleet into the next
period. This can be seen for factor 1.0 when the majority of the increase
in profit is obtained after the time period is over (figure 16). The profit
obtained outside the time period is also increased when decreasing the time
window. Less flexibility in when a voyage can start makes the model postpone
voyages as long as possible waiting for available capacity. When the factor
also decreases and the time spread becomes less crucial, the influence from
this diminishes and the majority of the changes in profit is obtained in the
time period (figure 17).

It is no clear connection between profit and the size of ballast costs,
number of TC-voyages or number of spot ship (figures in appendix F). This
may be explained from the composition of voyages sailed, prioritizing the
most profitable voyages even though they are TC-voyages or involve long
ballast voyages. However, for most cases the number of spot ships decreases
when the time window increases, and with this follows a decrease in the
number of TC-voyages sailed. The opposite is true when the time window
decreases.

The results for a 90 % time window with a factor of 0.25 show significant
increase in computational time for instances 8T and 10T, when the natural
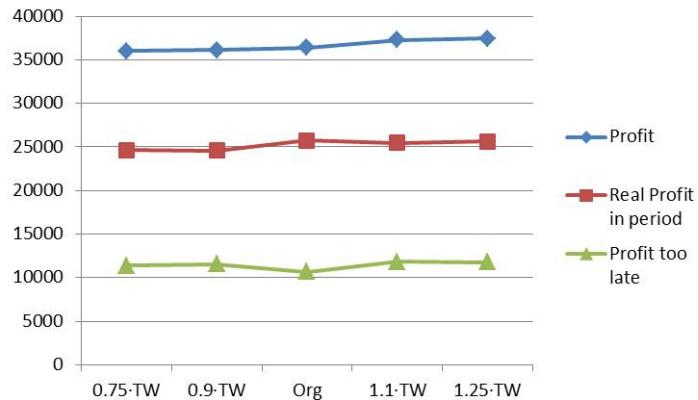
Figure 16: Profit ($ 1000) when changing time window for factor 1.0
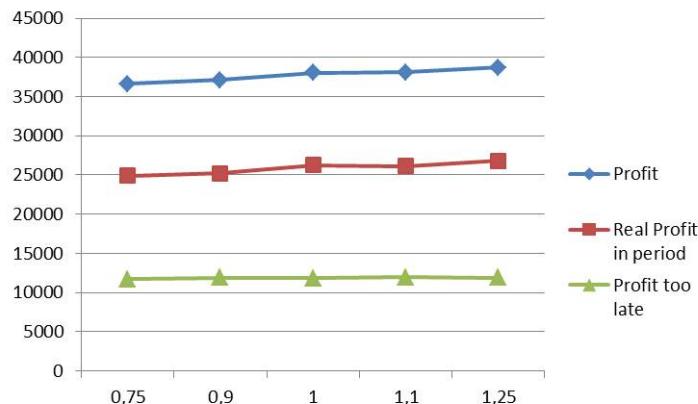
Figure 17: Profit ($ 1000) when changing time window for factor 0.25

would be a decrease of computational time. Further analysis of time window change for a factor of 0.25 shows a decrease in variables and constraints as the time windows decrease. When the time windows decrease to 90 %, the number of nodes to seek through before finding optimal solutions increases significantly which is a result of the problem being more difficult to solve. These results can be found in table F.2 in appendix F.

8.3.3 Change cost on spot ship

Spot ships are an easy way of securing solutions to optimisation of the tonnage allocation problem, but it is not used very often in real planning. The results of the performance study showed cases where spot ships were used even though there was available capacity in the fleet. This gives reason to

Table 16: Changing the cost of spot ships

	Cost > $ 0			Cost > $ 250 000		
	Profit	**Time**	**ΔSS/ΔTC***	**Profit**	**Time**	**ΔSS/ΔTC**
3T	-4.4 %	-5.5 %	-4/-4	-5.6 %	-5.4 %	-4/-4
4T	-2.9 %	19.6 %	-1/-1	-3.9 %	31.1 %	-1/-1
6T	-3.4 %	20.5 %	-1/-2	-4.5 %	-51.8 %	-2/-3
8T	-3.0 %	126 %	-1/-7	-3.5 %	103 %	-4/-10
10T	-2.9 %	773 %	-6/-5	-3.9 %	23.1 %	-6/-5

	Cost > $ 500 000			Cost > $ 750 000		
	Profit	**Time**	**ΔSS/ΔTC**	**Profit**	**Time**	**ΔSS/ΔTC**
3T	-7.4 %	-21.0 %	-1/-5	-8.4 %	6.80 %	-5/-5
4T	-4.6 %	30.6 %	-3/-3	-5.3 %	34.4 %	-4/-5
6T	-6.3 %	-51.7 %	-3/-4	-7.5 %	-48.4 %	-4/-6
8T	-4.4 %	4.6 %	-5/-11	-5.1 %	3.13 %	-5/-11
10T	-5.4 %	595 %	-7/-6	-6.3 %	-44.7%	-8/-8

	Cost > $ 1 000 000		
	Profit	**Time**	**ΔSS/ΔTC**
3T	-9.4 %	-1.3 %	-5/-5
4T	-5.3 %	4.8 %	-4/-5
6T	-8.1 %	-53.5 %	-4/-5
8T	-5.2 %	-15.5 %	-6/-13
10T	-7.0 %	-53.9 %	-8/-8

* SS is number of spot ships, TC is number of TC-voyages.

believe that the cost of hiring spot ship in this model does not give a good representation of the real case. This section looks at what happens if the cost of spot ship is increased.

When calculating the cost of spot ship, the income of a trade was subtracted with three times the cost of the trade (section 7.1). If the income was high enough, this could give to a positive number, giving profit when hiring spot ships. In this section five cases are looked at. The first case is to give all trades a cost, not a profit, related to using spot ships, then increasing the cost to be at least above $ 250 000, then above $ 500 000, then above $ 750 000 and finally above $ 1 000 000.

The results are compared to the original instances and can be found in table 16. All percentages and numbers of spot ships and TC-voyages are against the original 90 days instances.

The results show a decrease in profit when the cost of spot ships goes

up. The number of spot ship hired decreases when the cost of spot ships is increased as the model wishes to eliminate as many of the spot ships as possible to maximize profit. Followed by the decrease in number of spot ship is a significant decrease in number of TC-voyages which can be explained by not having enough time to sail them as they prioritize the mandatory trades.

It is difficult to draw any conclusion regarding the computational time from these results, as there is not a clear correlation between cost, instance and time.

10T The graph in figure 18 shows a decrease in the number of spot ships and TC-voyages when the cost of spot ships is increased, while the graph in figure 19 shows that ballast costs increase. This is a result of sailing voyages of mandatory trades far away which are no longer favourable to hire spot ships to sail, and this affects the number of TC-voyages to sail since there is not enough time and capacity in the fleet. Profit will naturally decrease when the cost of spot ships increases, something the graph in figure 20 shows. For the cases when having a positive cost or cost above $ 250 000 and $ 500 000, the profit obtained after the time period is over increases. This imply that several of the voyages sailed lie close to the end of the period, a result of ships postponing voyages. This flexibility decreases as the costs increase and there is a need to take on more mandatory voyages.
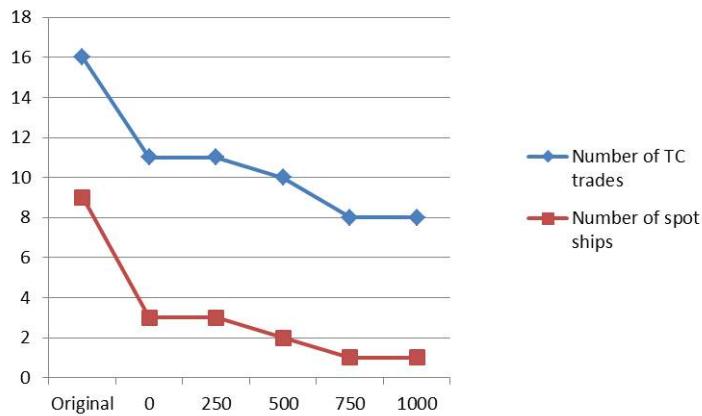
Figure 18: Number of spot ships and TC-voyages when changing the cost of spot ship. Note that cost is in $ 1000.

In the performance study trade SAMEUR had profit when using spot ship and it was the trade "always" sailed by spot ships. In the case of 10 trades and 90 days, voyage numbers 3, 4, 5, 7, 10, 11 and 12 were sailed by a spot ship. When increasing the cost of spot ships to a cost for all trades, there is
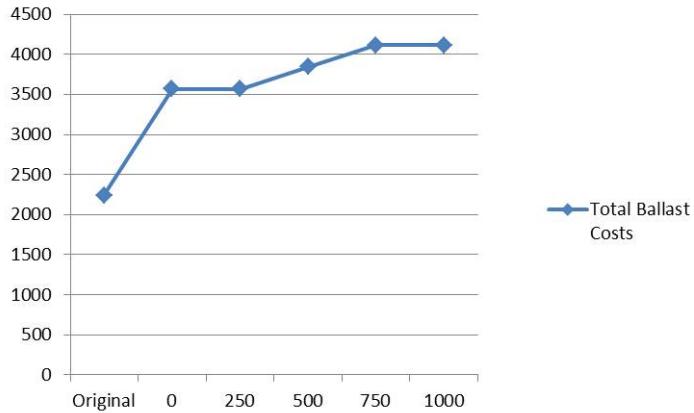
Figure 19: Ballast costs when changing the cost of spot ship ($ 1000)
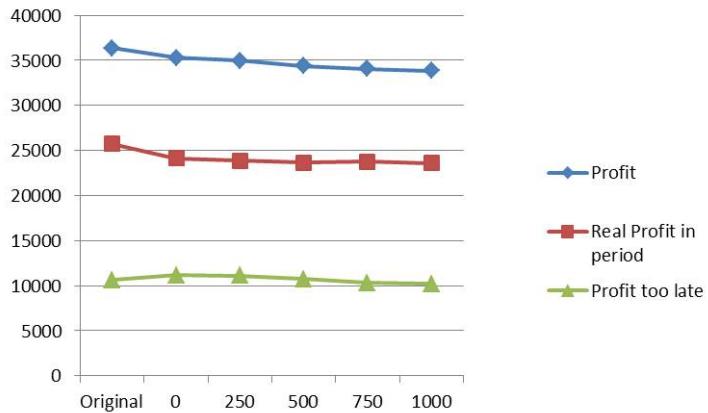
Figure 20: Profit when changing the cost of spot ship ($ 1000)

only one voyage (number 10) sailed by a spot ship (table 17). When the cost is above $ 500 000, none of the SAMEUR-voyages are sailed by spot ships. This implies a use of only costs of spot ships if the goal of tonnage allocation is to use as few spot ships as possible. Even though the profit from hiring a spot ship is very low, as long as it is a profit it will always be favourable to use spot ships if there exists TC-voyages more profitable. This will give a wrong picture of the real situation.

8.3.4   Dry docking analysis

When a ship is in dry docking, it is unable to perform any other voyage which generates profit. It is therefore in the shipping company's interest to plan the dry dockings in periods when there are less voyages to sail or at least

Table 17: Implications for SAMEUR when changing the cost of spot ship

		Original			Cost > $ 0		
Trade	**VoyNO**	**Ship**	**Ballast**[*]	**Profit**[*]	**Ship**	**Ballast**[*]	**Profit**[*]
SAMEUR	1	OD	-	$ 780	OD	$ 0	$ 780
SAMEUR	2	JA	$ 28	$ 752	PI	$ 28	$ 752
SAMEUR	3	Spot	-	$ 164	JA	$ 28	$ 752
SAMEUR	4	Spot	-	$ 164	SP	$ 277	$ 503
SAMEUR	5	Spot	-	$ 164	SK	$ 277	$ 503
SAMEUR	6	NA	$ 2	$ 778	BJ	$ 2	$ 778
SAMEUR	7	Spot	-	$ 164	ML	$ 0	$ 679
SAMEUR	8	CR	$ 28	$ 752	JA	$ 277	$ 503
SAMEUR	9	BJ	$ 28	$ 752	TU	$ 28	$ 752
SAMEUR	10	Spot	-	$ 164	Spot	-	$ -100
SAMEUR	11	Spot	-	$ 164	OD	$ 3	$ 778
SAMEUR	12	Spot	-	$ 164	VO	$ 28	$ 752

* All profit and ballast costs are in $ 1000.

securing that not several ships are in dock at the same time in busy periods.

The first column in table 18 shows the start times for dry dockings for the original instances of 90 days. For the smallest cases, there are difficulties in spreading the dry dockings because of the lack of capacity in the fleet. Instance 3T has all dry dockings at the end of the period, while instance 4T has two dockings postponed to the end. As the number of trades (and ships) increases, it is easier to obtain a spread in the start times of the dry dockings.

The three ships that need dry docking are for all instances Adventure, Frontier and Horizon. Adventure and Frontier have their origin port and time early enough to take the dry docking as part of a voyage to Asia; therefore there are no significant ballast costs associated with the dry docking. Horizon on the other hand is not available before late, and its origin is also in another region (table 3). For a planning period of three months, there is not enough time to sail a voyage of a trade to Asia and it is therefore significant ballast costs related to Horizon's dry docking.

In this section it is looked at what happens if Horizon is not among the ships that need dry docking. The first alternative is to delete Horizon from the list of ships that need dry docking. This leads to spread dry dockings for all instances except 3T (table 18). The other alternative is to replace Horizon with another ship which is available earlier in the time period. Discovery has origin in Portocel, South America, on 28.12.12 and is therefore put on the dry docking list. This gives no change in the spread of the dry dockings for the instance of 3T, while the dry dockings are spread evenly in the time

Table 18: Start times for the ships in dry dockings

	Original	Deleting a DD	Changing a DD
3T	AD: 101 FR: 101 HO: 98.3	AD: 100 FR: 101	AD: 101 FR: 101 DI: 101
4T	AD: 16 FR: 105 HO: 105	AD: 16 FR: 92.81	AD: 16 FR: 71.75 DI: 105
6T	AD: 12 FR: 66.24 HO: 101	AD: 12 FR: 67.75	AD:12 FR: 67.75 DI:101
8T	AD: 16 FR: 71.75 HO: 105	AD: 43.64 FR: 71.75	AD: 16 FR: 71.75 DI: 105
10T	AD: 16 FR: 71.24 HO: 102.79	AD: 16 FR: 71.24	AD: 43.43 FR: 71.75 DI: 105

period for the other instances.

Table 19 gives the results of profit and computational time from changing and deleting a ship in dry docking compared to the original instance. Both changes lead to significant improvements in profit, with deleting a dry docking as the most profitable. The main reason for the improvements is related to avoiding a ballast voyage for Horizon. The computational time is increased when changing one ship in dry docking because there is more flexibility related to performing the dry docking for a ship which is available earlier in the time period. Deleting a ship in dry docking has no clear impact on the computational time as it can both decrease and increase.

Table 19: Change of ships in dry docking

	Deleting a DD		Changing a DD	
	Profitt	Time	Profitt	Time
3T	6.59 %	21.7 %	6.13 %	78.1 %
4T	5.83 %	15.4 %	5.17 %	176 %
6T	5.71 %	-59.7 %	5.25 %	16.3 %
8T	5.09 %	-2.77 %	4.43 %	753 %
10T	5.28 %	223 %	4.63 %	1350 %

A way of securing fairly evenly spread dry dockings could have been an adding of a constraint which says that the all dry docking voyages needs to be fairly evenly spread.

10T   The ballast costs related to dry docking trades are significantly decreased when Horizon is replaced and deleted from having a dry docking (figure 21). This affects the total ballast costs, but when deleting a dry docking trade, the total ballast costs increase as there is time to sail other voyages. An increase in the number of TC-voyages when deleting a dry docking supports this (figure 22). The profit is greatly increased (table 19) and it is clear that Horizon was the wrong ship to have in dry dock since it was not available until late in the period. The increase in profit is however followed by longer computational time since there is now more flexibility.
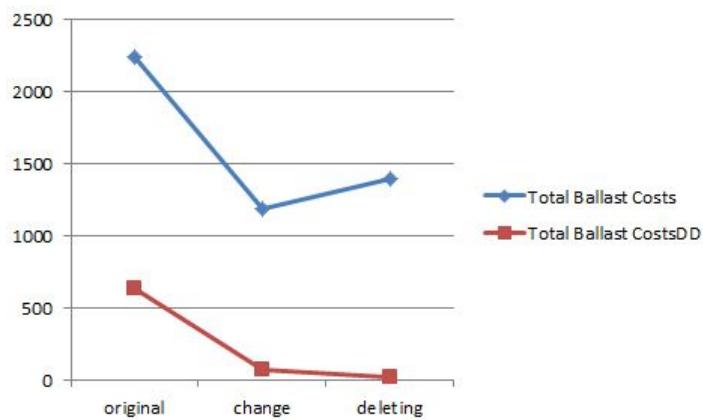
Figure 21: Ballast costs ($ 1000) when changing and deleting a dry docking
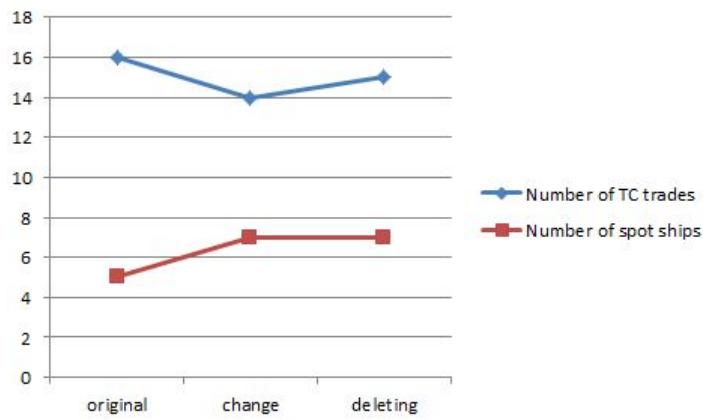
Figure 22: Number of spot ships and TC-voyages when changing and deleting a dry docking

8.3.5   Change timeperiod

When planning how the tonnage allocation should be in the next time period, the ship's origin port and earliest time available have big influence. It decides the number of ships available at a certain time, and the locations of ships have an impact on the composition of ships and voyages and if ballast voyages need to be sailed. To examine the impact of earliest time available, the time windows have been moved 30 days ahead with the origin port and earliest time available kept the same. The results compared to the original instances are given in table 20.

Table 20: Change of time period

	Profit	Time
3T	10.5 %	111 %
4T	9.3 %	91.8 %
6T	12.0 %	205 %
8T	9.7 %	41.4 %
10T	10.3 %	489 %

The results show a great increase in profit, but also a significantly longer computational time. When moving the planning period one month ahead, there will be more ships available at the start of the period and the ships can then sail a greater proportion of the voyages. This increases the size of the problem and therefore also the computational time.

10T   Properties of the optimisation for instance 10T can be found in table 21, and it shows the reason for the significant increase in computational time. Variables and constraints for a ship are in this model created depending on if the ship reaches the start of the voyage in the time window (section 7.3). Since the time windows for all voyages are moved a month ahead, more ships will be able to reach the start of more voyages, and compared to the original instance, the number of constraints and variables are almost doubled.

Table 21: Optimisation analysis for change of origin for 10T

	Original	Change time period	Change origin
Presolved constraints	10 644	18 991	9 450
Presolved variables	17 663	30 507	14 976
Presolved nonzero elements	71 927	130 123	60 916
Presolved global entities	17 609	30 454	14 922
Total nodes	10 881	11 723	789
No. integer feasible solutions	20	26	9
Time	56 s	329 s	39 s

Table 22: Economic analysis for change of period and origin for 10T

	Original[*]	**Change time period**[*]	**Change origin**[*]
Profit	$ 36380	$ 40114	$ 34639
Real profit in period	$ 25735	$ 29278	$ 24178
Profit outside of period	$ 10645	$ 10836	$ 10461
Profit per ship	$ 1654	$ 1823	$ 1574
Real profit per ship	$ 1170	$ 1331	$ 1099
Profit per day on sea	$ 15.1	$ 16.0	$ 14.8
Total ballast costs	$ 2242	$ 69	$ 2387
Total ballast time	122 days	4 days	128 days
Total ballast costs TC	$ 372	$ 845	$ 751
Number of TC-voyages	16	17	14
Number of spot ships	9	5	7
Total duration on sea	2405 days	2500 days	2329 days
Total time of trade	2306 days	2446 days	2253 days
Days waiting between voyages	99 days	54 days	76 days

[*] All profits and costs are in $ 1000.

When moving the time period a month ahead, the total increase in profit is of 10.3% and this can be seen both in profit per ship and the real profit per ship (table 22). Even though the profit obtained after the time period is over also increases, the increase in profit inside the time period is greater. The increase in profit is caused by more flexibility in the planning and a different composition of voyages to sail for each ship, which gives a decrease in the need for spot ships and the possibility to take on one more TC-voyage. The main reason is however the reduction in ballast costs and time which reaches a minimum. The days ships are waiting between voyages are also significantly reduced, while the profit per day on the sea is increased. All this indicates a better utilization of the fleet. However, having so much time and capacity available in the tonnage allocation planning is very rare. This just underpins the value of information, flexibility and availability in the fleet.

8.3.6 Change origin

This section examines the impacts of changing the origin port of the ships. The destinations of the ships in the 90 days performance study are used as origins for this analysis and they will therefore represent the actual trade frequency and where ships are after a typical planning period of 90 days. The

results can be found in table 23 and show a decrease in profit for all instances, but at the same time also a significant decrease in computational time. This can be explained looking at the trades, where many of the trades have the same destination, and at the same time high frequency of some trades gives equal destinations. Examples of this are FESAM and EURSAM which both have their end port in Santos, and SAMFE with destination Osaka, which has three voyages near the end of the month. These ports are not start ports for any mandatory trades and this may result in ballast voyages to get to their next voyage. Since many ships are located in the same ports, this will also give fewer TC-voyages sailed.

Table 23: Change of origin

	Profit	**Time**
3T	-12.1 %	-35.6 %
4T	-11.3 %	-40.6 %
6T	-7.22 %	-55.4 %
8T	-4.64 %	-9.84 %
10T	-4.79 %	-26.6 %

10T   The analysis of 10 trades supports the explanation above (table 22). Even though the profit decreases, the need for spot ship is also decreased and the ships use more of their time on sea sailing (the days waiting between voyages decreases). Reasons for the decrease in profit can be found in a decrease in TC-voyages, but also in the geographical spread of the ships which both give higher ballast costs. A special emphasis should be at the ballast costs of TC-voyages. Since many of the TC-trades are economically beneficial, the results show a large increase in the ballast costs of TC-voyages.

A closer look at the properties of the optimisation can be found in table 21. Less variables and constraints as a result of the preprocessing in section 7.3 lead to shorter computational time. There is less flexibility related to the composition of ships and voyages since the ships are located more geographically similar, and this can especially be seen in the total number of nodes investigated in the optimisation and the number of integer feasible solutions.

8.3.7   TC-trade analysis

When the shipping company perform their tonnage allocation, they set up a number of TC-trades with large time windows in order to investigate the possibilities in the next time period. The results can give some TC-trades sailed each month, while they might only have enough spot cargo to sail

one voyage of a TC-trade every third month since there are both mandatory trades and TC-trades sailing the same distance. The inclusion of TC-trades also makes the problem more complex and the computational time is longer. This section analyses the addition of extra constraints for TC-trades which can give an easier problem with more realistic results.

Table 24: Restrictions on TC-trades

	Max 2 voy		Max 1 voy		Max 2 voy + 40d	
	Profitt	**Time**	**Profitt**	**Time**	**Profitt**	**Time**
3T	-0.78 %	20.3 %	-5.98 %	0.09 %	-1.77 %	-52.6 %
4T	-0.26 %	3.99 %	-4.54 %	3.68 %	-2.00 %	-60.7 %
6T	-1.19 %	-48.8 %	-5.43 %	-43 %	-6.52 %	-86.8 %
8T	-1.19 %	21.4 %	-4.31 %	59.1 %	-1.76 %	-72.5 %
10T	-0.79 %	1403 %	-3.34 %	145 %	-1.34 %	-89.9 %

	50 %		TW decrease I		TW decrease II	
	Profitt	**Time**	**Profitt**	**Time**	**Profitt**	**Time**
3T	-3.94 %	-39.8 %	-1.68 %	-51.7 %	-3.14 %	-53.5 %
4T	-5.50 %	-59.3 %	-1.52 %	-61.7 %	-2.94 %	-62 %
6T	-4.61 %	-39.7 %	-2.75 %	-85.4 %	-5.34 %	-90 %
8T	-3.84 %	-52.7 %	-2.53 %	-58.9 %	-3.23 %	-53 %
10T	-3.90 %	-8.76 %	-1.88 %	-87.3 %	-2.24 %	-91 %

Table 25: Optimisation properties for TC-trade analysis of 10T

	Max 2	**Max 1**	**Max 2+40d**	**50 %**	**TW I**	**TW II**
Presolved constraints	14 455	14 401	4 099	4 848	5 474	4 988
Presolved variables	21 521	21 476	11 700	8 803	12 846	12 065
Non-zero elements	84 213	83 482	39 887	35 113	46 677	46 151
Global entities	21 467	21 422	11 657	8 766	12 797	12 014
Nodes	92 528	3 085	1	18 237	7	1
No. integer solutions	15	19	10	13	9	1
Time	829 s	130 s	4 s	51 s	6 s	4 s

Introducing restriction on number of TC-voyages Three different cases with restrictions on the number of TC-voyages are analysed; maximum one voyage of the same TC-trade, maximum two voyages of the same TC-trade and maximum two voyages of the same TC-trade with 40 days time

spread. The results can be found in the first half of table 24. When introducing restrictions on only the number of voyages of each TC-trade, the profit decreases since there are fewer voyages they can take. The consequences are highest for maximum one voyage. However, this does not lead to a shorter computational time since there are just as many voyages to choose among, only more restrictions.

When introducing both a maximum number of voyages and a time spread between them, the feasible region gets substantially smaller and the computational time is greatly decreased since the number of possible TC-voyages-compositions decreases. The profit is naturally decreased, but it is higher than for the case with maximum one voyage since they can take on more TC-voyages.

Optimisation properties for the instance of 10 trades are found in table 25. The results support the analysis above. The properties of the original instance can be found in table 21. When introducing only a maximum number of TC-voyages they can sail, the number of constraints and variables increases and therefore also the computational time. When additionally introducing a minimum time spread higher than computed from the fairly evenly spread constraint, the number of constraint and variables experiences a significant decrease and the computational time is greatly reduced.
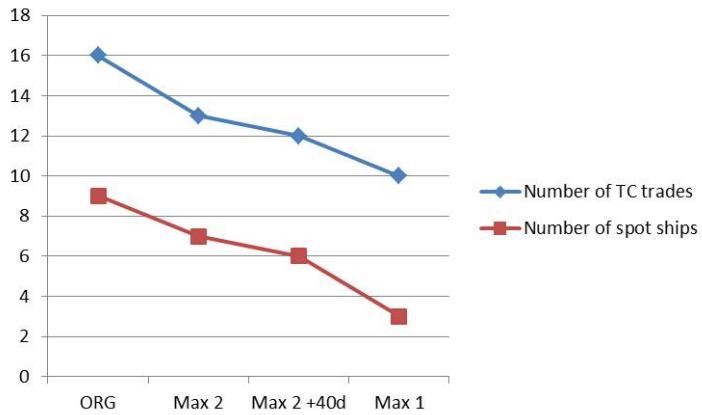
Figure 23: Number of spot ships and TC-voyages when introducing restrictions on number of TC-voyages

A closer look at the case of 10 trades shows that the fewer TC-voyages they can sail, the more they can concentrate on their own mandatory trades and therefore the number of spot ships is reduced. This is illustrated in figure 23. Costs of ballast voyages increase as they now have to sail ballast voyages without the option of taking on TC-cargo, as well as they have capacity to
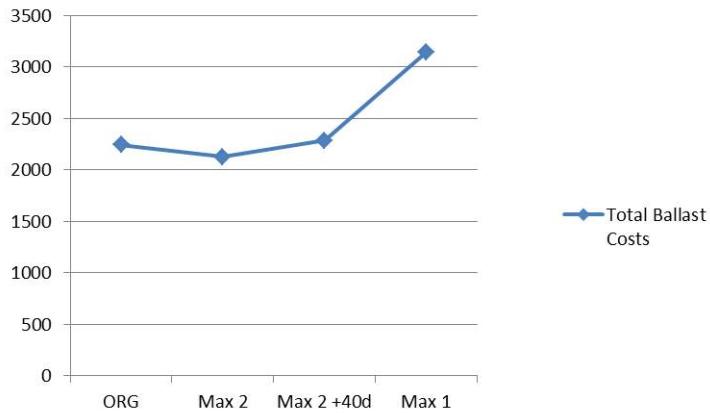
Figure 24: Ballast costs ($ 1000) when introducing restrictions on number of TC-voyages

take on voyages which may have been served by spot ships. The increase of ballast costs can be shown in figure 24.

Decreasing the number of trades When including a large number of possible TC-trades the fleet can sail, the size of the optimisation problem becomes larger. It is investigated what the consequences are if the number of different TC-trades is decreased and table 24 presents the results if there are 50% less TC-trades to choose among. The results show a decrease in the profit and also a shorter computational time for all instances.

The optimisation properties for instance 10T in table 25 show a great decrease in number of constraints and variables compared to the original instance, but an increase in the total number of nodes investigated and therefore is not the computational time significantly decreased.

A consequence of having a less TC-voyages to choose among is a decrease in the profit (table 26). This can be seen in connection with the increase in ballast costs which is a direct result of not having TC-voyages to sail instead of ballast voyages. However, the number of spot ships is decreased since the fleet now have capacity to sail the voyages which had long ballast voyages earlier and where not profitable. Worth noticing is that the profit per day on sea increases as well as the number of days waiting between voyages are decreased. This indicates a better utilization of the fleet

Decreasing the time window The original instances had 30 days time window for each voyage of a TC-trade. The time windows are now decreased to two weeks in order to see how this affects the problem. One instance (I)

Table 26: 50 % TC-trades to choose among

	Original	50%
Profit	$ 36380	$ 34961
Profit per day on sea	$ 15.1	$ 15.4
Ballast cost	$ 2242	$ 3257
Number of TC-voyages	16	10
Number of hired spot ships	9	4
Total duration on sea	2405 days	2265 days
Total time of trade	2306 days	2190 days
Time waiting between voyages	99 days	75 days

All profits and costs are in $ 1000.

is when half of the trades are placed the first 14 days of each month and half of the trades are placed the last 14 days of each month, while the second instance (II) is when half of the trades are placed the first 14 days of each month and the other half are placed with the middle of the month being the centre point.

The main observation from decreasing the time windows of the TC-voyages is that the computational time is greatly decreased and as there is less flexibility, the profit also gets poorer (table 24). The first instance (I) with more spread TC-voyages gives better results in profit for approximately the same decrease in time.

Table 27: Decreasing the time windows of TC-voyages

	Original	TWdecrease I	TWdecrease II
Profit	$ 36380	$ 35695	$ 35565
Profit per day on sea	$ 15.1	$ 15.5	$ 15.6
Ballast cost	$ 2242	$ 2440	$ 2564
Number of TC-voyages	16	12	11
Number of hired spot ships	9	5	6
Total duration on sea	2405 days	2298 days	2274 days
Total time of trade	2306 days	2200 days	2175 days
Time waiting between voyages	99 days	98 days	99 days

All profits and costs are in $ 1000.

A closer look at the instance of 10 trades shows that decreasing the time window leads to fewer TC-voyages sailed, fewer spot ships hired and higher costs of ballast voyages. The results can be found in table 27. Instance I with more spread TC-voyages gives a better solution both in terms of profit and number of spot ships as the voyages are more spread. As for the case with decreased number of TC-trades to choose among, the profit per day on

sea increases which indicates a better utilization of the fleet despite that the number of days waiting remains the same. The computational time reduces as a consequence of fewer constraints and variables created (table 25), and the number of nodes investigated to find the optimal solution is significantly reduced.

Table 28: TC-voyage composition

Trade	Profit*	10T	Max 2	Max 1	Max2 +40d	DI	DII	50%**
TC EUREC	$ 156	1	1	1	1	1	0	-
TC EUREUR	$ 86	1	1	1	1	2	2	2
TC EURFE	$ 968	3	2	2	2	3	3	3
TC EURSAM 26	$ -144	0	0	0	0	0	0	-
TC EURSAM 40	$ 181	2	1	2	1	2	1	-
TC EURSAM 53	$ 215	1	1	1	1	1	1	-
TC EURUSG	$ 139	0	0	0	0	0	0	-
TC FESAFRSAM	$ 153	1	1	0	0	0	1	1
TC FESAM	$ 115	0	0	0	0	0	0	-
TC FEUSG	$ 121	0	0	0	0	0	0	0
TC SAMEUR	$ 425	1	0	0	0	1	0	-
TC SAMFE	$ 1019	3	2	2	1	1	2	-
TC USGSAM	$ 160	1	1	1	1	0	0	1
TC WCEUR	$ 451	1	1	1	1	1	0	-
TC WCFE	$ 656	1	1	2	1	0	1	2
TC WCSAM	$ 134	0	0	0	0	0	0	0

* All profits are in $ 1000.

** - means that it is not possible to choose this TC-trade.

TC-trade analysis The analysis of TC-voyages shows that introducing a maximum limit on the number of voyages of the same trade might give a more realistic solution, but do not lead to shorter computational time. If on the other hand a time spread between the voyages is introduced, the feasible region gets smaller and the computational time is significantly decreased. The same accounts for the introduction of tighter time windows for TC-voyages. This reduces the possibilities which can be shown in the number of constraints and variables created and also in the number of nodes solved before the optimal solution is found. Reducing the number of TC-trades to choose among results in fewer constraints and variables created, but it has to solve more nodes before finding the optimal solution.

Unfortunately, all limitations lead to a smaller profit and should therefore be added with careful consideration.

Table 28 gives a summary of the distribution of voyages of TC-trades for the original instance and the introductions in this section, and it gives the profit for sailing a voyage of each of them. The most profitable trades are the once being prioritized, one example is TC EURFE, while the trades with small or no profit never are sailed, examples are TC EURSAM 26 and TC FEUSG.

8.4   Introducing an alternative way

When planning the tonnage allocation, it could be interesting to analyse what the result would be if there existed a shorter alternative of sailing a voyage, only covering some of the original route and cargo. Saving time may give the opportunity of servicing one extra voyage which in turn will generate additional profit to the company since they do not have to hire spot ship.

This section investigates what happens if the model has the choice between sailing A-B-C-D or A-D directly. The latter will take shorter time and cost less, but the income will also be reduced. For the instances in this computational study there are four trades which have been presented with an alternative way to be sailed (appendix E). This could easily have been expanded to apply for all trades and several alternatives for each trade could have been added. Note that not every voyage of a trade needs to have an alternative way; neither does it need to apply for all ships. This is regulated in the input files.

Table 29: Alternative way of sailing a trade

	Profit	**Time**	**Way II***	**ΔSS/ΔTC****
3T	0 %	14.1 %	-	-/-
4T	0.07 %	-0.31 %	1	-/1
6T	0 %	-49.4 %	-	-/-
8T	0.01 %	349 %	1	-1/-1
10T	0.16 %	442 %	1	-1/-1

* Way II is the number of voyages sailed the alternative way.

** SS is number of spot ships, TC is number of TC-voyages

The results when introducing an alternative way of sailing four of the trades compared to the original instances are found in table 29. The alternative way of sailing a voyage only affects the decisions in instances 4T, 8T and 10T, but the improvements in profit are poor and the computational time is significantly increased for the larger instances. This indicates that having an alternative way of sailing a voyage may not be as beneficial when making an optimal plan. However, shipping is an unpredictable industry and performing these analyses will make the planner more prepared when obstacles

occur and there is a need to look at other possibilities.

The next paragraphs take a closer look at what happens when changing the factor of time spread, changing the time window and increasing the cost of spot ships if you have an alternative way of sailing a voyage of a trade. All analysis is done by comparing the results to the results when there are no alternative way.

8.4.1 Time spread

The results from decreasing the factor of time spread can be found in table 30. The results show poor or no improvements in profit for most cases, but significant increases in computational time. When introducing flexibility, the value of more flexibility is not that significant.

Table 30: Change of factor of time spread with alternative way

	Factor = 0.75		Factor = 0.50		Factor = 0.25		Factor = 0.10	
	Profitt	**Time**	**Profitt**	**Time**	**Profitt**	**Time**	**Profitt**	**Time**
3T	0 %	33.9 %	0 %	11.3 %	0 %	0.67 %	0 %	18.6 %
4T	0.06 %	4.50 %	0.06 %	1.7 %	0.06 %	9.4 %	0.06 %	-12.8 %
6T	0 %	-6.15 %	0.24 %	-35.5 %	0 %	-0.99 %	0.03 %	183 %
8T	0 %	41 %	0%	669 %	0.06 %	18.3 %	0.06 %	649 %
10T	0 %	95 %	0.35 %	76.6 %	0 %	37.6 %	0 %	3289 %

	Factor = 0.75	Factor = 0.50	Factor = 0.25	Factor = 0.10
	Way II**	**Way II****	**Way II****	**Way II****
3T	-	-	-	-
4T	1	1	1	1
6T	-	1	-	1
8T	-	-	1	1
10T	-	1	-	-

** Way II is the number of voyages sailed the alternative way.

10T The improvement in profit for 10 trades of 0.35% when the factor is 0.5 is caused by a reduction in the need for spot ship (table 31). By allowing for EUREC #1 to be sailed in an alternative way which takes shorter time, ship PIONEER have time to sail SAMEUR #2 in advance. This again gives ship WAVE the opportunity to sail SAMEUR #4 before SAMFE #9 and therefore reduces the need for a spot ship. However, this affects the ballast costs which are increased since SAMFE #3 now is sailed by a ship not located in South-America instead of PIONEER which was originally used.

Table 31: Example of allocation when changing the factor of time spread

Factor = 0.5

Ship	Trade	Start	End	Ballast*	Profit*
Spot	SAMEUR#4				$ 164
PI	SAMFE#3	40.75	97.47	$ 28.3	$ 1617
	↓				
	TC FESAFRSAM#3	105	155.92	$ 55.1	$ 98
OD	SAMEUR#2	21	43.8	$ 0	$ 780
	↓				
	TC EUREUR#2	53.8	64.6	$ 16.3	$70
	↓				
	TC EURSAM 40#2	64.6	104.9	$ 0	$ 181
	↓				
	SAMFE#9	105	161.7	$ 2.3	$ 1643
CR	TC EUREUR#1	18.9	29.7	$ 28.5	$ 58
	↓				
	EUREC#1	37	64.9	$ 14.6	$ 460
	↓				
	ECSAM#1	68.8	99.2	$ 70.2	$ 234
	↓				
	SAMFE#8	101.1	157.8	$ 2.6	$ 1642

Factor = 0.5 with alternative way

Ship	Trade	Start	End	Ballast*	Profit*	Way**
PI	SAMEUR#2	21	43.8	$ 28.3	$ 752	-
	↓					
	EUREC#1	46.3	66.7	$ 16.3	$ 331	2
	↓					
	ECSAM#1	70.6	101	$ 70.2	$ 234	-
	↓					
	SAMFE#8	101.1	157.8	$ 2.6	$ 1642	1
WA	SAMEUR#4	39	61.8	$ 0	$ 780	-
	↓					
	TC EURSAM 40#2	64.6	104.9	$ 3.9	$ 177	-
	↓					
	SAMFE#9	105	161.7	$ 2.3	$ 1643	1
CR	TC EUREUR#1	18.9	29.7	$ 28.5	$ 58	-
	↓					
	SAMFE#3	44.9	101.6	$ 279.7	$ 1365	1
	↓					
	TC FESAFRSAM#3	105	155.92	$ 55.1	$ 98	-

*All profit and costs are in $ 1000.
** If the voyage can be sailed in an alternativ way: 1 or 2
if not an alternative way: -

8.4.2 Time window

The results from changing the time window when including an alternative way can be found in table 32.

Table 32: Change of time window combined with change of factor of time spread with alternative way

| | Factor = 1.0 | | | | | | | |
| | 0.75TW | | 0.9TW | | 1.1TW | | 1.25TW | |
	Profit	**Time**	**Profit**	**Time**	**Profit**	**Time**	**Profit**	**Time**
3T	0 %	21.1 %	0 %	41.6 %	0 %	5.5 %	0%	15.2 %
4T	0 %	1.47 %	0 %	-1.9 %	0.06 %	-7.53 %	0 %	62.2 %
6T	0 %	-2.40 %	0.05 %	-8.8 %	0 %	-1.27 %	0.27 %	6.6 %
8T	0.06 %	17.1 %	0.01 %	9.2 %	0.01 %	17.9 %	0.37 %	-72.4 %
10T	0.01 %	30.5 %	0.01 %	24.3 %	0.01 %	1849 %	0.27 %	216 %

| | Factor = 0.75 | | | | | | | |
| | 0.75W | | 0.9TW | | 1.1TW | | 1.25TW | |
	Profit	**Time**	**Profit**	**Time**	**Profit**	**Time**	**Profit**	**Time**
3T	0 %	13.3 %	0 %	15.6 %	0 %	47.5 %	0 %	13.6 %
4T	0 %	-3.60 %	0 %	26.4 %	0.06 %	32.5 %	0 %	-78.1 %
6T	0.10 %	-50.1 %	0.13 %	-0.45 %	0 %	141 %	0 %	32.78 %
8T	0.34 %	-2.96 %	0.58 %	-3.53 %	0%	129 %	0.78 %	105 % *
10T	0.15 %	-54.1 %	0.35 %	72.9 %	0.06%	461 % *	1.03 %	- **

| | Factor = 0.25 | | | | | | | |
| | 0.75TW | | 0.9TW | | 1.1TW | | 1.25TW | |
	Profit	**Time**	**Profit**	**Time**	**Profit**	**Time**	**Profit**	**Time**
3T	0 %	-7.46 %	0 %	1.63 %	0 %	3.45 %	0 %	14.4 %
4T	0 %	-1.25 %	0 %	-0.63 %	0.06 %	-9.46 %	0 %	137 %
6T	0.13 %	1.56 %	0.13 %	-30.3 %	0 %	60.4 %	0.28 %	-16.8 %
8T	0.11 %	284 %	0.48 %	-52.9 %	0.14 %	25.5 %	0.66 %	33.2 %
10T	0.10 %	202 %	0.63 %	-40 %	0 %	45.6* %	0.54 %	80.2* %

* Solution from alternative way is not optimal

** Neither original instance or instance with alternative way is optimal

Common for all instances are an increase in profit, but some improvements are more considerable than others. When increasing the time window, significant changes must be done if it should have any effect to include an alternative way. There is little to gain in profit from small increases and the computational time gets longer. When decreasing the time window, small changes give an improvement in profit with decrease in computational time for most cases. A larger decrease in the time window does not give any substantial improvements, only longer computational time. The same holds

Table 33: Change in number of spot ships and TC-voyages when changing the time window and the time spread factor for 10T

	0.75TW	0.9TW	1.1TW	1.25TW
	ΔSS/ΔTC*	ΔSS/ΔTC*	ΔSS/ΔTC*	ΔSS/ΔTC*
Factor = 1.0	-1/1	-1/-	-/-	1/3
Factor = 0.75	-1/-	1/-	-/-	-/1
Factor = 0.25	-1/-3	-1/-1		-/1
	Way II*	**Way II***	**Way II***	**Way II***
Factor = 1.0	1	1	1	1
Factor = 0.75	1	1	2	1
Factor = 0.25	1	1		1

*SS is the number of spot ships, TC is the number of TC-voyages.

** Way II is the number of voyages sailed the alternative way.

when decreasing the factor, but the improvements in profit are for some instances greater.

10T An analysis of the case with 10 trades shows that the main improvements are found when smaller decreases or larger increases are done to the time window. How the introduction of an alternative way affects the number of spot ships and TC-voyages can be seen in table 33. This table also gives the number of voyages sailed the alternative way. There are cases when voyages are sailed the alternative way, but it does not have any effect on the number of spot ships or the number of sailed TC-voyages. The change can here be found in the specific TC-voyages sailed, where more profitable voyages are sailed.

With a factor of 1, the maximum improvement for 10T is 0.27% when the time window has increased 25%. This is a result of an increase of three TC-voyages sailed, but the need for spot ships has also increased. Including an alternative way when decreasing the time window does not improve the profit, it only increases the computational time. Illustrations of the change of profit and number of spot ships and TC-voyages when the factor is 1 can be found in figure 25 and figure 26.

When decreasing the factor, greatest improvements in profit are found for the cases of 90 % time window and 125 % time window. For the factor of 0.75, this is a result of one voyage sailed the alternative way, as well as one extra TC-voyage sailed for 125 % time window. A significant decrease in ballast voyages for 90 % time window is found. For the factor of 0.25, a 0.63

% improvement in profit when decreasing the time window to 90 % is caused by one voyage done the alternative way leading to one less hired spot ship (table 33). An example of a part of a trade plan for the factor of 0.25 can be found in table F.3 in appendix F. The example shows how the introduction of an alternative way leads to one less hired spot ship.
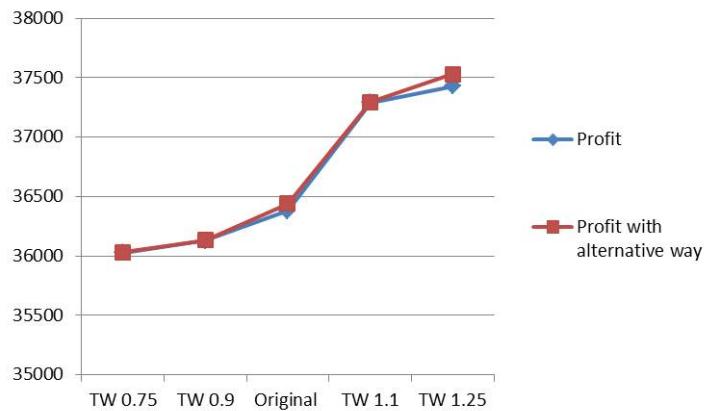
Figure 25: Profit ($ 1000) when changing the time window for factor 1.0 with an alternative way
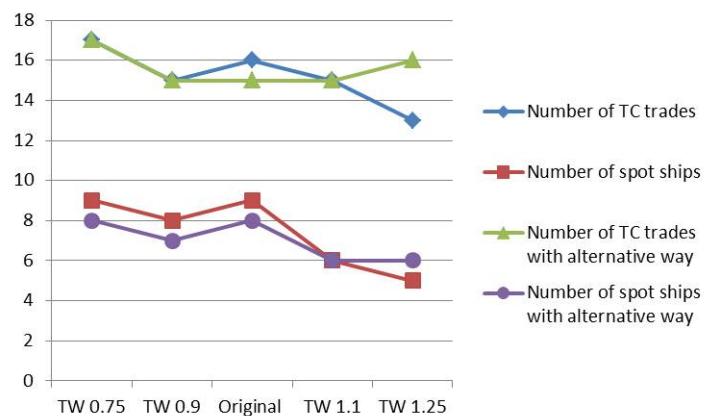
Figure 26: Number of spot ships and TC-voyages when changing the time window for factor 1.0 with an alternative way

8.4.3   Cost of spot ship

The results when changing the cost of spot ship can be found in table 34.

Table 34: Change in the price of spot ships with alternative way

	Cost > $ 0				Cost > $ 250 000			
	Profit	**Time**	**ΔSS/ΔTC***	**Way II***	**Profit**	**Time**	**ΔSS/ΔTC***	**Way II***
3T	0.08 %	20.6 %	-/1	1	0.08 %	9.3 %	-/1	1
4T	0.07 %	6.15 %	-/1	1	0.07 %	0.07 %	-/1	1
6T	0 %	10.2 %	-/-	-	0 %	21.7 %	-/-	-
8T	0 %	191 %	-/-	-	0.1 %	146 %	-/-	1
10T	0.10 %	144 %	-/-	1	0.1 %	1214 %	-/-	1

	Cost > $ 500 000				Cost > $ 750 000			
	Profit	**Time**	**ΔSS/ΔTC***	**Way II***	**Profit**	**Time**	**ΔSS/ΔTC***	**Way II***
3T	0.08 %	17.6 %	-/1	1	0.09 %	0.33 %	-/1	1
4T	0.07 %	86.3 %	-/1	1	0.07 %	-6.67 %	-/1	1
6T	-6.3 %	18.8 %	-/-	-	0.33 %	266 %	-/1	1
8T	0.16 %	551 %	-/1	4	0.26 %	30.1 %	-1/-	5
10T	0.15 %	328 %	-/-	2	0.34 %	2286 %	-/1	3

	Cost > $ 1 000 000			
	Profit	**Time**	**ΔSS ΔTC***	**Way II***
3T	0.07 %	24.5 %	-/1	1
4T	0.07 %	23.1 %	-/1	1
6T	0.82 %	-2.93 %	-/-	1
8T	0.35 %	695 %	-/2	5
10T	0.88 %	1603 %	-1/-1	5

*SS is the number of spot ships, TC is the number of TC-voyages.

** Way II is the number of voyages sailed the alternative way.

The inclusion of an alternative way leads to significantly longer computational time. For small increases in the cost of spot ships, the profit will not get much better when they have the option of choosing an alternative way. For a cost of $ 750 000 or more, there are larger improvements in profit for instances 6T, 8T and 10T. The implications of having an alternative way of sailing a voyage are therefore greatest in the largest instances when the cost of spot ships is increased, though it should be emphasized that the improvements are minor.

10T   A closer look at 10 trades follows. For small increases in the cost of spot ships, the choice of having an alternative way to sail a voyage does

Table 35: Example of allocation when changing the cost of spot ships

Example

Cost > $ 1 000 000

Ship	Trade	Start	End	Ballast*	Profit*
Spot	EURSAM#3				$ 1000
	SAMEUR#4	42.2	65	$ 0	$ 780
	↓				
DI	SAMEUR#9	82.2	105	$ 277	$ 503
	↓				
	TC EURFE#3	105	158.8	$ 0	$ 968
	WCEUR#1	24	74.5	$ 0	$ 1041
VI	↓				
	SAMEUR#10	93	115.8	$ 277	$ 503

Cost > $ 1 000 000 with alternative way

Ship	Trade	Start	End	Ballast*	Profit*	Way**
	SAMEUR#4	41	63.8	$ 277	$ 503	-
EN	↓					
	EURSAM#3	68	121.6	$ 41	$ 441	-
	WCEUR#1	24	65	$ 0	$ 848	2
	↓					
VI	SAMEUR#9	82.2	105	$ 277	$ 503	-
	↓					
	TC EURFE#2	105	158.8	$ 0	$ 968	-

* All profits and costs are in $ 1000.

** If the voyage can be sailed in an alternative way: 1 or 2

if not an alternative way: -

not lead to major increases in profit, only significantly longer computational time. When the cost of spot ships is increased to $ 750 000 and $ 1 000 000, the increases in profit are 0.34% and 0.88% respectively which are results of three and five voyages sailed the alternative way (table 34). For a cost of $ 1 000 000 the alternative way also releases the need of a spot ship, while at the same time reducing the number of TC-voyages with one.

An example of a trade plan when the cost of spot ships is higher than $ 1 000 000 can be found in table 35. The option of sailing a voyage of WCEUR in an alternative way makes a ship available earlier and it therefore reaches an earlier voyage of trade SAMEUR. It should be noted that this includes a long ballast voyage from Europe to South America.

9   Future work

This section presents suggestions on improvements that can be made, both regarding solution methods and modelling alternatives.

9.1   Solution methods

The model presented in this thesis is a mixed integer programming problem (MIP) based on a classic arc flow formulation. It has been solved with the built-in solution strategy of Xpress; branch and bound with cut. The results show shortcomings particular with respect to computational time when longer planning periods with TC-trades are considers. In addition to the performed preprocessing, there are several possible problem reformulations which will reduce the computational time further. These will however lead to major changes in the model. Section 4 gave an introduction to the literature on reformulations. This section gives a short presentation of the different solution approaches which can be used for large data instances.

9.1.1   Set partitioning

While the arc flow formulation in this thesis have flow variables indicating if a ship sails directly from voyage to voyage and therefore constructs the whole voyage plan/route for each ship, is a set partitioning problem based on a path flow formulation described in section 4.2.1. A set partitioning formulation uses predefined routes where one variable is created for each feasible sequence of voyages. A route is therefore in this context a list of voyages for a specific ship. The routes are usually full schedules with specified arrival times and load on board, and all generated routes are feasible. Fagerholt (1999) formulates a set partitioning problem for a minimization problem in liner shipping as

$$\min \sum_{r \in \mathcal{R}} (C_r^F + C_r^{OP}) x_r \tag{36}$$

$$\sum_{r \in \mathcal{R}} A_{ir} x_r = 1, \qquad i \in \mathcal{N} \tag{37}$$

$$x_r \in 0, 1, \qquad r \in \mathcal{R} \tag{38}$$

$\mathcal{R}$ is the set of all routes generated indexed by r, $\mathcal{N}$ is the set of nodes or ports to be serviced by the fleet of ships indexed by i. C_r^F is the fixed cost, while C_r^{OP} is the operational cost of route r for the least cost ship that has sufficient capacity to perform the given route. C_r^F and C_r^{OP} are calculated in the route generation. x_r is a binary variable which equals 1 if route r is

chosen in the optimal solution. By selecting route r, the ship corresponding to that route is selected (Fagerholt, 1999).

A set partitioning approach has fewer constraints, but possibly more variables than an arc flow model. In addition there may be an extensive work creating the possible routes. However, only one variable per route gives a better structured problem and reduces the computational time of the problem. Crucial for this approach is creating the routes cleverly. Column generation is an approach where the routes are created dynamically as they are needed in the solution process (Lundgren et al., 2010). Another way of creating routes is by enumerating all feasible combinations of routes for a given set of cargoes (Christiansen et al., 2007).

9.1.2 Dantzig Wolfe

Dantzig Wolfe decomposition is based on the dynamic column generation. It is a method which exploits the structure of a problem and systematically decomposes large LP-problems into one master problem and many sub problems. The master problem contains a common constraint ensuring that each voyage is served by a ship exactly or at most once, and it includes the ship routing constraints which do not involve interaction between ships. They are found in the sub problems, and there is one sub problem for each ship. In each sub problem new feasible routes (variables) are created with regard to all given ship specific constraints. Each of the feasible combinations of routes for a ship are called a ship schedule or a route. A more thoroughly introduction to this solution approach can be found in (Desrosiers et al. 1995, Christiansen et al. 2007).

The Dantzig Wolfe decomposition approach has been used in numerous ship scheduling applications and the procedure is well suited for the tonnage allocation problem. It has a clever utilization of the problem structure as well as it makes ship specific restrictions easy to handle (Berg et al., 2007).

9.1.3 Heuristics

Heuristic algorithms are solution approaches which do not guarantee to find the optimal solution; they do not even have a bound on how bad they can perform. However, they are often used to solve difficult optimisation problems, especially integer programming problems.

A heuristic generates, without guarantees on the quality, a good solution within a limited amount of time. The solution is often near-optimal, even though it is not possible to measure how close. Reasons for choosing a heuristic as a solution method can be that an optimisation method takes too

long time and requires a large amount of computer memory, the input data to a problem is uncertain and therefore it is enough to find a near-optimal solution, or that a simple heuristic is easier to understand and accept by a "non-expert" user (Lundgren et al., 2010).

Brønmo et al. (2007a) describes a multi-start local search heuristic for a tramp ship scheduling problem where a number of different initial solutions are generated by a constructive heuristic and improved by local search. Multi-start heuristics are efficient for problems where solutions can be easily constructed and where it is difficult to make local search neighbourhoods that can move far in the feasible search space. These characteristics are common for ship scheduling problems as they are often tightly constrained.

Another heuristic solution method is tabu search heuristic where the algorithm starts from an initial solution and moves at iteration from the current solution to the best solution in a neighbourhood (Korsvik et al., 2010). The approach has the important feature of considering infeasible solutions during the search which extends the solution space and is a useful characteristic for the often tightly constrained ship scheduling problems. Some attributes of recently visited solutions are declared forbidden, tabu, for a number of iterations unless they constitute a new incumbent. This is to avoid cycling. In addition a continuous diversification mechanism is put in place in order to reduce the likelihood of becoming trapped in a local optimum, and periodic re-optimisation of the current or best known solution is performed.

9.2   Modelling alternatives

This section provides the reader with modelling alternatives regarding some aspects of the tonnage allocation model presented in this thesis.

9.2.1   Voyages

In this model a voyage of a trade is represented as a node. An alternative way of modelling, and much more complicated, would be to let each port of a voyage be denoted with a node, and then include the planning of what actual ports should be visited and when. This would have increased the problem since each port may for example have time constraints and constraints regarding cargo and inventory just to present some of the challenges.

9.2.2   Ships

A tonnage allocation model will vary among different segments of liner shipping. The problem in this thesis is for dry bulk, open-hatch gantry ships.

The ships are modelled uniquely since they have different origins and earliest time available, and they may take on voyages of different trade routes in the same planning period. By modelling the ships by groups instead, the problem size could decrease.

Another segment which has received significant attention the last years is container liner shipping, and Christiansen et al. (2013) presented a model based on Powell and Perakis (1997) and Gelareh and Meng (2010). Here each ship is assigned to only one single route during the whole planning horizon and ships are considers as groups of ship types. Looking at ships as groups can be a problem in short-term planning problems as it may result in practically infeasible solutions because initial positions and/or ship ongoing voyages may restrict some ships from performing the number of voyages on the route that the model calculates.

9.2.3   Spot ships

When using realistic numbers on income and cost for the use of spot ship, some of the trades had profit related to the performance and the results therefore showed a high use of spot ship. When increasing the cost on spot ships, the use was reduced. However this does not give a good presentation of the reality.

Another modelling alternative could be similar to the soft restriction for fairly evenly spread voyages where a penalty term was added in the objective function when performing the optimisation and thereafter subtracted to get the real profit value (section 9.2). By modelling this way, the objective value and trade plans obtained would give a better representation of the reality.

9.2.4   The objective function

When planning the tonnage allocation for the next period and calculating maximum profit, a central point is the time the voyages start and the time of the income. The first possible start of a voyage has to be in the time period, but the time window may lead to voyages starting outside of the time period. Voyages starting close to the end or after the time period is over will affect the availability of the fleet in the next period and therefore also the profit possible to obtain. At the same time is all profit for these voyages accounted for in current time period. It may be discussed if the profit should be divided between the periods, depending on the number of days sailing the voyage in each period.

Even though there are a certain number of ships available in a fleet, it is not given that the entire fleet is used. It should be taken into consideration

the number of ships used to cover the obligations.

With this in mind, it may be questioned if the right objective function for profit is used when optimising. There may be other targets than total profit which are more favourable for the company. Examples could be to maximize the profit per day a ship is in use or maximize the profit obtained in the time period per ship, taken into consideration the number of days outside the time period.

9.2.5   Dry Docking trades

The dry dockings are in this thesis modelled as individual trades for each ship and they are therefore not included in the fairly evenly spread restrictions. It is important for the shipping company to have these voyages spread in the time period as they do not want to have several ships tied up at the same time. Introducing a common fairly evenly spread restriction for all dry docking trades would have guaranteed this; even though the results in the performance study gave rather spread dry dockings.

Dry docking trades have large time windows and these may range over several planning periods. In this thesis the trades are forced to happen within one planning period, but this could have been modelled differently. An alternative way is by introducing a penalty term in the objective function if the trade is postponed to next period.

9.2.6   Time spread

Time spread constraint was introduced in section 6.1 and it was chosen a hard restriction to model the minimum amount of time between two voyages of the same trade. This could instead have been modelled as a soft restriction introduced in Arnulf and Bjørkli (2010). Here the minimum time between two voyages can be less than the calculated time spread, but the violations are then penalized by an artificial penalty in the objective function. The penalty term will grow proportional to the violation of the spread. The challenge with this method of modelling is to get the penalty term to reflect the actual costs, economically or non-economically, with the real life. This penalty should be added to the objective after the optimisation is performed in order to state the real profit.

The parameter of the time spread constraint is ideal for trades which have equidistant voyages. The shipping company in this thesis has trades with voyages which are not equidistant and in some cases the voyages have overlapping time windows. This leads to complications for some of the trades and the factor the trades can have must be calculated manually for each

time period. It should be tried to model this in another way in order to be applicable for trades with overlapping time windows without manually calculating it.

10   Concluding remark

This report has presented a tonnage allocation model for a liner shipping company with the purpose to illustrate how optimisation based methods can be used as decision support when planning the fleet deployment in liner shipping. The shipping industry experiences an oversupply of ships and the freight rates are at unprofitable levels. This makes it important to have an optimal utilization of the fleet. In addition, the shipping industry is unpredictable and having an overview of what a fleet is capable of is valuable information for the planners when facing sudden obstacles.

A special focus has been on the implementation and preprocessing in order to achieve an efficient model, and variables and constraints are created with careful consideration.

The performance study indicated that the greater the problem size, the longer was the computational time, and especially the inclusion of TC-trades resulted in a major increase in computational time. For time periods longer than 4 months, there were problems achieving optimal solution even for cases with few trades.

Spot ships are an easy way of securing a solution to the tonnage allocation problem, but they are seldom used in the real shipping plan. The results from the performance study contained an extensive use of spot ships for some instances.

The main focus in this thesis has been to analyse the effects of adjusting input parameters and constraints, and especially the timing of trades has been investigated in order to achieve a better utilization of the fleet. The factor of time spread and the width of the time windows have been changed, and major improvements in profits are found when increasing the flexibility. However, a significant increase in computational time also follows.

The effects of increasing the cost of spot ships have also been investigated, in order to see if the use of spot ships can be reduced. Naturally, an increase in costs leads to a large reduction in the number of hired spot ships and a decrease in number of TC-voyages sailed and profit obtained.

Dry docking trades are mandatory for a given ship, but it is crucial to find the appropriate ship to be in dry docking as it ties up the ship and prevents the ship from sailing voyages which generate profit. It should also be avoided to have several ships in dock at the same time.

Aspects which have been analysed in order to obtain a deeper understanding of the challenges a liner shipping company faces are the origin and earliest time available for each ship. The results show that these have great impact on what the fleet is capable of in the time period. What the fleet does in one period determines also what the fleet is capable of in the next

time period.

In order to achieve a better representation of available cargo on TC-trades, restrictions on the number of TC-voyages were introduced. The introduction of TC-trades led to a significant increase in computational time, and by increasing the time spread between voyages of TC-trades, decreasing the selection of TC-trades to choose among and decrease in the time windows for TC-voyages the problem size has been reduced, the most significantly being the reduction of time window and increase of time spread between voyages. This indicates that the introduction of optional trades should be done with care, limiting it to only actual possible voyages.

An alternative, shorter way of sailing a voyage of a trade was introduced to investigate the possibilities of obtaining a better utilization of the fleet, avoiding use of spot ships. The results were poor and led to maximum one less spot ship hired. However, including an alternative way resulted in an increase in profit and the results can be useful when experiencing sudden obstacles in the daily planning. It is valuable for the planner to have information about the fleet's capabilities.

Extensions can be introduced in order to obtain a more realistic and efficient model. It is normal for shipping companies to plan for 3-6 months ahead, and the performance study of this model showed problems with solving the instances when the length of the planning period was more than four months. Many aspects of the real tonnage allocation problem are omitted and they should be included in order to obtain a more realistic model. Reformulations can be introduced in order to achieve a more efficient decision support model for tonnage allocation planning.

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A Extension of mathematical formulation

This appendix gives the mathematical formulation of the tonnage allocation problem with an alternative way of sailing a voyage of a trade included. No further explanations are given in this section as they can be found in section 6.

Indicies, sets, parameters and variables

The indicies, sets, parameters and variables used in the model follow.

Sets

$\mathcal{N}$	Set of voyages
$\mathcal{R}$	Set of trades
$\mathcal{V}$	Set of ship
$\mathcal{A}$	Set of arcs
$\mathcal{W}$	Set of ways of sailing a voyage of a trade
$\mathcal{R}_M$	Set of mandatory trades
$\mathcal{R}_{TC}$	Set of optional TC-trades
$\mathcal{R}_{DD}$	Set of dry docking-trades
$\mathcal{N}_r$	Set of voyages for trade r
$\mathcal{R}_{DDv}$	Set of dry-docking trades for ship v

Indices

i,j	voyage, $i, j \in \mathcal{N}_r$
r,u	trade, $r, u \in \mathcal{R}$
v	ship, $v \in \mathcal{V}$
w	way, $w \in \mathcal{W}$
$o(v)$	origin for ship v
$d(v)$	destination for ship v

Parameters

P_{vrw}	Income of sailing a voyage of trade r for a ship v in way w
C_{vrw}	Cost of sailing a voyage of trade r for a ship v in way w
C_r^S	Cost of hiring a spotship to sail a voyage of trade r
C_{vru}^B	Cost of ballast sailing from a voyage of trade r to a voyage of trade u for ship v
C_{vr}^O	Cost of ballast sailing from origin to voyage of trade r for ship v
T_{vrw}	Time spent for ship v to sail a voyage of trade r in way w
T_{vru}^B	Time spent for ship v to sail ballast from a voyage of trade r to a voyage of trade u
T_{vr}^O	Time spent for ship v to sail ballast from origin to voyage of trade r
E_{ri}^{TW}	Earliest start of voyage (r, i) in time window
L_{ri}^{TW}	Latest start of voyage (r, i) in time window
E_v^O	Earliest start from origin for ship v
B_r	Constant for trade r securing fairly evenly spread voyages
H_{ri}	Number of alternative ways a voyage i of trade r can be sailed

Variables

$x^I_{vo(v)d(v)}$	equals 1 if ship v does not serve any voyage
$x^O_{vo(v)ri}$	equals 1 if ship v sails directly from origin to voyage (r,i)
x^F_{vriujw}	equals 1 if voyage (u,j) is sailed right after voyage (r,i) by ship v and (r,i) is sailed in way w
$x^D_{vrid(v)w}$	equals 1 if ship v goes directly from end port of voyage (r,i) to destination and (r,i) is sailed in way w
$t^O_{vo(v)}$	start time from origin for ship v
t^S_{ri}	start time for voyage (r,i)
s_{ri}	equals 1 if voyage (r,i) is sailed by a spotship
y_{vri}	equals 1 if ship v sails voyage (r,i)

Objective function

$$max \sum_{v\in\mathcal{V}} \sum_{r\in\mathcal{R}} \sum_{i\in\mathcal{N}_r} \sum_{u\in\mathcal{R}} \sum_{j\in\mathcal{N}_u} \sum_{w\in\mathcal{W}} (P_{vrw} - C_{vrw} - C^B_{vru}) x^F_{vriujw}$$

$$+ \sum_{v\in\mathcal{V}} \sum_{r\in\mathcal{R}} \sum_{i\in\mathcal{N}_r} \sum_{w\in\mathcal{W}} (P_{vrw} - C_{vrw}) x^D_{vrid(v)w}$$

$$- \sum_{v\in\mathcal{V}} \sum_{r\in\mathcal{R}} \sum_{i\in\mathcal{N}_r} C^O_{vr} x^O_{vo(v)ri} - \sum_{r\in\mathcal{R}_M} \sum_{i\in\mathcal{N}_r} C^S_r s_{ri} \quad (A.1)$$

Flow constraints:

$$\sum_{r\in\mathcal{R}} \sum_{i\in\mathcal{N}_r} x^O_{vo(v)ri} + x^I_{vo(v)d(v)} = 1, \qquad v\in\mathcal{V} \qquad (A.2)$$

$$\sum_{r\in\mathcal{R}} \sum_{i\in\mathcal{N}_r} \sum_{w\in\mathcal{W}} x^D_{vrid(v)w} + x^I_{vo(v)d(v)} = 1, \qquad v\in\mathcal{V} \qquad (A.3)$$

$$\sum_{u\in\mathcal{R}} \sum_{j\in\mathcal{N}_u} \sum_{w\in\mathcal{W}} x^F_{vriujw} + \sum_{w\in\mathcal{W}} x^D_{vrid(v)w} - \sum_{u\in\mathcal{R}} \sum_{j\in\mathcal{N}_u} \sum_{w\in\mathcal{W}} x^F_{vujriw} - x^O_{vo(v)ri} = 0,$$

$$v\in\mathcal{V}, r\in\mathcal{R}, i\in\mathcal{N}_r \quad (A.4)$$

Voyage completion

$$\sum_{v\in\mathcal{V}} \sum_{u\in\mathcal{R}} \sum_{j\in\mathcal{N}_u} \sum_{w\in\mathcal{W}} x^F_{vriujw} + \sum_{v\in\mathcal{V}} \sum_{w\in\mathcal{W}} x^D_{vrid(v)w} + s_{ri} = 1,$$

$$r\in\mathcal{R}_M, i\in\mathcal{N}_r \quad (A.5)$$

$$\sum_{v \in \mathcal{V}} \sum_{u \in \mathcal{R}} \sum_{j \in \mathcal{N}_u} \sum_{w \in \mathcal{W}} x^F_{vriujw} + \sum_{v \in \mathcal{V}} \sum_{w \in \mathcal{W}} x^D_{vrid(v)w} \leq 1,$$

$$r \in \mathcal{R}_{TC}, i \in \mathcal{N}_r \quad \text{(A.6)}$$

Dry docking completion

$$\sum_{v \in \mathcal{V} | \mathcal{R}_{DD_v} = 1} \sum_{u \in \mathcal{R}} \sum_{j \in \mathcal{N}_u} \sum_{w \in \mathcal{W}} x^F_{vriujw} + \sum_{v \in \mathcal{V}} \sum_{w \in \mathcal{W}} x^D_{vrid(v)w} = 1,$$

$$r \in \mathcal{R}_{DD_v}, i \in \mathcal{N}_r \quad \text{(A.7)}$$

Time constraints

$$t^O_{vo(v)} \geq E^O_v \qquad v \in \mathcal{V} \quad \text{(A.8)}$$

$$E^{TW}_{ri} \leq t^S_{ri} \leq L^{TW}_{ri} \qquad r \in \mathcal{R}, i \in \mathcal{N}_r \quad \text{(A.9)}$$

$$x^F_{vriujw}(t^S_{ri} + T_{vrw} + T^B_{vru} - t^S_{uj}) \leq 0,$$

$$v \in \mathcal{V}, (ri), (uj) \in \mathcal{A}, w \in \mathcal{W} \quad \text{(A.10)}$$

$$x^O_{vo(v)ri}(t^O_{vo(v)} + T^O_{vr} - t^S_{ri}) \leq 0, \qquad v \in \mathcal{V}, r \in \mathcal{R}, i \in \mathcal{N}_r \quad \text{(A.11)}$$

Linearization of constraints (A.10) and (A.10) is conducted as presented in section 6.1.

Fairly evenly spread

$$t^S_{r,i+1} - t^S_{ri} \geq \alpha \cdot B_r \qquad r \in \mathcal{R}, i \in \mathcal{N}_r \quad \text{(A.12)}$$

where $\alpha = \{0, 1\}$

Variable for analysing data

$$\sum_{u \in \mathcal{R}} \sum_{j \in \mathcal{N}_u} \sum_{w \in \mathcal{W}} x^F_{vriujw} + \sum_{w \in \mathcal{W}} x^D_{vrid(v)w} - y_{vri} = 0$$

$$v \in \mathcal{V}, r \in \mathcal{R}, i \in \mathcal{N}_r \quad \text{(A.13)}$$

Requirements for variables

$$x^O_{vo(v)ri} \in \{0, 1\} \qquad v \in \mathcal{V}, r \in \mathcal{R}, i \in \mathcal{N}_r \tag{A.14}$$

$$x^F_{vriujw} \in \{0, 1\} \qquad v \in \mathcal{V}, (r, i), (u, j) \in \mathcal{A}, w \in \mathcal{W} \tag{A.15}$$

$$x^D_{vrid(v)w} \in \{0, 1\} \qquad v \in \mathcal{V}, r \in \mathcal{R}, i \in \mathcal{N}_r, w \in \mathcal{W} \tag{A.16}$$

$$x^I_{vo(v)d(v)} \in \{0, 1\} \qquad v \in \mathcal{V} \tag{A.17}$$

$$s_{ri} \in \{0, 1\} \qquad r \in \mathcal{R}_M, i \in \mathcal{N}_r \tag{A.18}$$

$$y_{vri} \in \{0, 1\} \qquad r \in \mathcal{R}, i \in \mathcal{N}_r \tag{A.19}$$

$$t^O_{vo(v)} \geq 0 \qquad v \in \mathcal{V} \tag{A.20}$$

$$t^S_{ri} \geq 0 \qquad r \in \mathcal{R}, i \in \mathcal{N}_r \tag{A.21}$$

B   Input file

The input files used in the simple instance example follow. This is an example of how all the input file are composed. The datas included in the input file are not real, but they are based on realistic numbers.

! TextFile.txt !

! ** !
!   Master's thesis SPRING 2013
!   Fleet Deployment Problem - dataset
!   Øydis Kristine Flateby

! ** !

! Parameters for optimization
IPRECUT: 1
ICPU: 0

! Number of ways of making a trade
NumWay : 1

! Factor for the TimeSpreadConstraint
Factor: [
(1) 1   (2)   1   (3)   1   (4) 1
]

! (Trade,Voyage) For which voyage of trade rr is the other way of making a voyage an alternative
WayVoyage: [
]

! TurboRouterFile.txt !

! Dataset SagaForestCarriers for Stud. Tech. Øydis Flateby, NTNU
! File generated by MARINTEK TurboRouter
!
C:/Users/Øydis/Dropbox/MASTEROPPGÅVE/TURBOROUTER_datasett_180413/testcase/SagaDataSet_TestCase_AFH.txt

!Number of ships in the fleet:
NumShip : 4

!Number of Trades:
NumTradeM   : 3   ! Mandatory trades
NumTradeTC   : 1   ! TC-optional trades
NumTradeDD   : 0   ! Dry-docking trades

!(Trade) Number of voyages for each trade rr:
NumVoyage : [(1) 3   (2) 2   (3) 2   (4) 2   ]

!The origin/startport for each ship vv
StartPort : [(1) 3   (2) 2   (3) 1   (4) 6   ]

!Compability between TradeDD rr and ship vv
TradeDDShip:[
]

!Names of ships:
ShipNames : [(1) "AD"   (2) "DI"   (3) "EN"   (4) "EX"   ]

!Names of Trades:
TradeMNames : [(1) 'SAMEUR'   (2) 'SAMFE'   (3) 'EURSAM'   ]

TradeTCNames : [(4) 'TC FESAM'   ]

TradeDDNames : []

! Names of ports
! Start ports for trades
TradeStartNames : [(1) 'PORTOCEL'   (2) 'PORTOCEL'   (3) 'KLAIPEDA'   (4) 'SHANGHAI'   ]

! Stop ports for trades
TradeStopNames : [(1) 'VLISSINGEN'   (2) 'OSAKA'   (3) 'SANTOS'   (4) 'RECIFE'   ]

!(Trade) Costs using chartership on trade r
CostTradeSpot: [
(1)-164.386   (2)-98.212   (3)406.171
        ]

!(Ship) Earliest time available for each ship (a ship can start)
TimeEarliestStart: [
(1) 0.77   (2) 0.78   (3) 0.79   (4) 0.00
        ]

!(Ship, Trade, Way) Cost of performing a voyage of trade rr in way ww for ship vv
CostTrade: [

```
(1,1,1) 307.935  (1,2,1) 773.403  (1,3,1) 444.438  (1,4,1) 677.792
(2,1,1) 307.935  (2,2,1) 773.403  (2,3,1) 444.438  (2,4,1) 677.792
(3,1,1) 307.935  (3,2,1) 773.403  (3,3,1) 444.438  (3,4,1) 677.792
(4,1,1) 307.935  (4,2,1) 773.403  (4,3,1) 444.438  (4,4,1) 677.792
]
```

! (Ship, Trade, Way) Income of performing a voyage of trade rr in way ww for ship vv
```
IncomeTrade:      [
(1,1,1) 1088.191         (1,2,1) 2418.421         (1,3,1) 927.142 (1,4,1) 793.115
(2,1,1) 1088.191         (2,2,1) 2418.421         (2,3,1) 927.142 (2,4,1) 793.115
(3,1,1) 1088.191         (3,2,1) 2418.421         (3,3,1) 927.142 (3,4,1) 793.115
(4,1,1) 1088.191         (4,2,1) 2418.421         (4,3,1) 927.142 (4,4,1) 793.115
                   ]
```

! (Ship, Trade, Way) Time it takes to do a trade rr i way ww for ship vv
```
TimeTrade:        [
(1,1,1) 22.81    (1,2,1) 56.72    (1,3,1) 53.63    (1,4,1) 57.66
(2,1,1) 22.81    (2,2,1) 56.72    (2,3,1) 53.63    (2,4,1) 57.66
(3,1,1) 22.81    (3,2,1) 56.72    (3,3,1) 53.63    (3,4,1) 57.66
(4,1,1) 22.81    (4,2,1) 56.72    (4,3,1) 53.63    (4,4,1) 57.66
                   ]
```

!TimeWindow for each voyage -
!(Trade, Voyage) Earliest start for a voyage ii of trade rr
```
TimeEarliest:     [
(1,1) 13         (1,2) 33         (1,3) 53
(2,1) 5 (2,2) 33
(3,1) 0 (3,2) 31
(4,1) 0 (4,2) 30
                   ]
```

!(Trade, Voyage) Latest start for a voyage ii of trade rr
```
TimeLatest:       [
(1,1) 23         (1,2) 43         (1,3) 63
(2,1) 15         (2,2) 43
(3,1) 10         (3,2) 41
(4,1) 30         (4,2) 60
                   ]
```

!!(Ship, Trade, Trade) Cost of sailing ballast between trade rr and uu for ship vv
```
CostBallast:      [
(1,1,1) 277.126 (1,1,2) 277.126 (1,1,3) 41.311   (1,1,4) 621.237
(1,2,1) 638.538 (1,2,2) 638.538 (1,2,3) 690.153 (1,2,4) 47.161
(1,3,1) 28.342  (1,3,2) 28.342  (1,3,3) 344.301 (1,3,4) 618.616
(1,4,1) 43.814  (1,4,2) 43.814  (1,4,3) 272.793 (1,4,4) 618.872

(2,1,1) 277.126 (2,1,2) 277.126 (2,1,3) 41.311   (2,1,4) 621.237
(2,2,1) 638.538 (2,2,2) 638.538 (2,2,3) 690.153 (2,2,4) 47.161
(2,3,1) 28.342  (2,3,2) 28.342  (2,3,3) 344.301 (2,3,4) 618.616
(2,4,1) 43.814  (2,4,2) 43.814  (2,4,3) 272.793 (2,4,4) 618.872

(3,1,1) 277.126 (3,1,2) 277.126 (3,1,3) 41.311   (3,1,4) 621.237
(3,2,1) 638.538 (3,2,2) 638.538 (3,2,3) 690.153 (3,2,4) 47.161
(3,3,1) 28.342  (3,3,2) 28.342  (3,3,3) 344.301 (3,3,4) 618.616
(3,4,1) 43.814  (3,4,2) 43.814  (3,4,3) 272.793 (3,4,4) 618.872

(4,1,1) 277.126 (4,1,2) 277.126 (4,1,3) 41.311   (4,1,4) 621.237
(4,2,1) 638.538 (4,2,2) 638.538 (4,2,3) 690.153 (4,2,4) 47.161
(4,3,1) 28.342  (4,3,2) 28.342  (4,3,3) 344.301 (4,3,4) 618.616
(4,4,1) 43.814  (4,4,2) 43.814  (4,4,3) 272.793 (4,4,4) 618.872

]
```

!(Ship, Trade, Trade) Time sailing a ballast voyage between trade rr and trade uu for ship vv
```
TimeBallast:      [
(1,1,1) 15.07   (1,1,2) 15.07   (1,1,3) 2.25    (1,1,4) 33.79
(1,2,1) 34.73   (1,2,2) 34.73   (1,2,3) 37.54   (1,2,4) 2.57
(1,3,1) 1.54    (1,3,2) 1.54    (1,3,3) 18.73   (1,3,4) 33.65
(1,4,1) 2.38    (1,4,2) 2.38    (1,4,3) 14.84   (1,4,4) 33.66

(2,1,1) 15.07   (2,1,2) 15.07   (2,1,3) 2.25    (2,1,4) 33.79
(2,2,1) 34.73   (2,2,2) 34.73   (2,2,3) 37.54   (2,2,4) 2.57
(2,3,1) 1.54    (2,3,2) 1.54    (2,3,3) 18.73   (2,3,4) 33.65
(2,4,1) 2.38    (2,4,2) 2.38    (2,4,3) 14.84   (2,4,4) 33.66

(3,1,1) 15.07   (3,1,2) 15.07   (3,1,3) 2.25    (3,1,4) 33.79
(3,2,1) 34.73   (3,2,2) 34.73   (3,2,3) 37.54   (3,2,4) 2.57
(3,3,1) 1.54    (3,3,2) 1.54    (3,3,3) 18.73   (3,3,4) 33.65
(3,4,1) 2.38    (3,4,2) 2.38    (3,4,3) 14.84   (3,4,4) 33.66

(4,1,1) 15.07   (4,1,2) 15.07   (4,1,3) 2.25    (4,1,4) 33.79
(4,2,1) 34.73   (4,2,2) 34.73   (4,2,3) 37.54   (4,2,4) 2.57
(4,3,1) 1.54    (4,3,2) 1.54    (4,3,3) 18.73   (4,3,4) 33.65
(4,4,1) 2.38    (4,4,2) 2.38    (4,4,3) 14.84   (4,4,4) 33.66
]
```

!(Ship, Port/Trade, Trade) Cost of sailing ballast from startport to startport for ship vv
CostPortStart: [
(1, 1, 1) 0.000   (1, 1, 2) 0.000   (1, 1, 3) 316.565 (1, 1, 4) 611.188
(1, 2, 1) 0.000   (1, 2, 2) 0.000   (1, 2, 3) 316.565 (1, 2, 4) 611.188
(1, 3, 1) 316.565 (1, 3, 2) 316.565 (1, 3, 3) 0.000   (1, 3, 4) 660.676
(1, 4, 1) 611.188 (1, 4, 2) 611.188 (1, 4, 3) 660.676 (1, 4, 4) 0.000

(2, 1, 1) 0.000   (2, 1, 2) 0.000   (2, 1, 3) 316.565 (2, 1, 4) 611.188
(2, 2, 1) 0.000   (2, 2, 2) 0.000   (2, 2, 3) 316.565 (2, 2, 4) 611.188
(2, 3, 1) 316.565 (2, 3, 2) 316.565 (2, 3, 3) 0.000   (2, 3, 4) 660.676
(2, 4, 1) 611.188 (2, 4, 2) 611.188 (2, 4, 3) 660.676 (2, 4, 4) 0.000

(3, 1, 1) 0.000   (3, 1, 2) 0.000   (3, 1, 3) 316.565 (3, 1, 4) 611.188
(3, 2, 1) 0.000   (3, 2, 2) 0.000   (3, 2, 3) 316.565 (3, 2, 4) 611.188
(3, 3, 1) 316.565 (3, 3, 2) 316.565 (3, 3, 3) 0.000   (3, 3, 4) 660.676
(3, 4, 1) 611.188 (3, 4, 2) 611.188 (3, 4, 3) 660.676 (3, 4, 4) 0.000

(4, 1, 1) 0.000   (4, 1, 2) 0.000   (4, 1, 3) 316.565 (4, 1, 4) 611.188
(4, 2, 1) 0.000   (4, 2, 2) 0.000   (4, 2, 3) 316.565 (4, 2, 4) 611.188
(4, 3, 1) 316.565 (4, 3, 2) 316.565 (4, 3, 3) 0.000   (4, 3, 4) 660.676
(4, 4, 1) 611.188 (4, 4, 2) 611.188 (4, 4, 3) 660.676 (4, 4, 4) 0.000

        ]

!(Ship, Port/Trade, Trade) Time of sailing ballast from startport to startport for ship vv
TimePortStart: [
(1, 1, 1) 0.00   (1, 1, 2) 0.00   (1, 1, 3) 17.22   (1, 1, 4) 33.24
(1, 2, 1) 0.00   (1, 2, 2) 0.00   (1, 2, 3) 17.22   (1, 2, 4) 33.24
(1, 3, 1) 17.22   (1, 3, 2) 17.22   (1, 3, 3) 0.00   (1, 3, 4) 35.94
(1, 4, 1) 33.24   (1, 4, 2) 33.24   (1, 4, 3) 35.94   (1, 4, 4) 0.00

(2, 1, 1) 0.00   (2, 1, 2) 0.00   (2, 1, 3) 17.22   (2, 1, 4) 33.24
(2, 2, 1) 0.00   (2, 2, 2) 0.00   (2, 2, 3) 17.22   (2, 2, 4) 33.24
(2, 3, 1) 17.22   (2, 3, 2) 17.22   (2, 3, 3) 0.00   (2, 3, 4) 35.94
(2, 4, 1) 33.24   (2, 4, 2) 33.24   (2, 4, 3) 35.94   (2, 4, 4) 0.00

(3, 1, 1) 0.00   (3, 1, 2) 0.00   (3, 1, 3) 17.22   (3, 1, 4) 33.24
(3, 2, 1) 0.00   (3, 2, 2) 0.00   (3, 2, 3) 17.22   (3, 2, 4) 33.24
(3, 3, 1) 17.22   (3, 3, 2) 17.22   (3, 3, 3) 0.00   (3, 3, 4) 35.94
(3, 4, 1) 33.24   (3, 4, 2) 33.24   (3, 4, 3) 35.94   (3, 4, 4) 0.00

(4, 1, 1) 0.00   (4, 1, 2) 0.00   (4, 1, 3) 17.22   (4, 1, 4) 33.24
(4, 2, 1) 0.00   (4, 2, 2) 0.00   (4, 2, 3) 17.22   (4, 2, 4) 33.24
(4, 3, 1) 17.22   (4, 3, 2) 17.22   (4, 3, 3) 0.00   (4, 3, 4) 35.94
(4, 4, 1) 33.24   (4, 4, 2) 33.24   (4, 4, 3) 35.94   (4, 4, 4) 0.00

        ]

C   Mosel code

```
! ********************************************* !
! Master's thesis SPRING 2013                   !
! Tonnage Allocation Problem                    !
! Øydis Kristine Flateby                        !
! ********************************************* !

model TonnageAllocation

options explterm
options noimplicit

uses "mmxprs", "mmive", "mmsystem", "mmodbc";

parameters
    TurboRouterFile = "3T_withTC.txt";
    DataFile = "DataFile_3T.txt";

    MODELNAME = 'TonnageAllocation_problem';
    DATETIME = ""+ getday(datetime(SYS_NOW)) + "-" + getmonth(datetime(SYS_NOW))
             + "-" + getyear(datetime(SYS_NOW)) + " " + gethour(datetime(SYS_NOW))
             + "-" + getminute(datetime(SYS_NOW)) ;

end-parameters

declarations
    Time:           real;           ! Time when performing optimization
    IPRECUT:        integer;        ! Parameter for optimization
    ICPU:           integer;        ! Parameter for optimization

    Ship:           set of integer; ! Set of ships
    TradeM:         set of integer; ! Set of trades that are mandatory
    TradeTC:        set of integer; ! Set of trades that are optional, TC-trades
    TradeDD:        set of integer; ! Set of dry-docking "trades"
    Trade:          set of integer; ! All of the trades, the union of the three above
    Way:            set of integer; ! Set of ways of performing a voyage

    NumShip:        integer;        ! Number of ships
    NumTradeM:      integer;        ! Number of mandatory trades
    NumTradeTC:     integer;        ! Number of optional, TC, trades
    NumTradeDD:     integer;        ! Number of dry-docking "trades", how many ships need drydocking
    NumTrade:       integer;        ! Total number of trades
    NumWay:         integer;        ! Number of ways to perform a voyage
end-declarations

initializations from TurboRouterFile
    NumShip;
    NumTradeM;
    NumTradeTC;
    NumTradeDD;
end-initializations

initializations from DataFile
    NumWay;
    IPRECUT;
    ICPU;
end-initializations

Time := gettime;
```

```
Ship := 1..NumShip;

if not (NumTradeM = 0) then
    TradeM  := 1..NumTradeM;
end-if
if not (NumTradeTC = 0) then
    TradeTC := NumTradeM+1..NumTradeM+NumTradeTC;
end-if
if not (NumTradeDD = 0) then
    TradeDD := NumTradeM+NumTradeTC+1..NumTradeM+NumTradeTC+NumTradeDD;
end-if

Way := 1..NumWay;

finalize(Ship);
finalize(TradeM);
finalize(TradeTC);
finalize(TradeDD);
finalize(Way);

NumTrade := NumTradeM + NumTradeTC + NumTradeDD;
Trade    := 1..NumTrade;

finalize(Trade);

declarations
    maxVoyage:          integer;                                  ! Maximum number of voyages in one of the trades
    Voyage:             set of integer;                          ! Set of voyage for trade
    NumVoyage:          dynamic array(Trade)        of integer;  ! Number of voyages on each trade

    ShipNames:          array(Ship)                 of string;   ! Names of ships
    TradeMNames:        array(TradeM)               of string;   ! Names of the mandatory trades
    TradeTCNames:       array(TradeTC)              of string;   ! Names of TC-trades, optional trades
    TradeDDNames:       array(TradeDD)              of string;   ! Names of dry-docking "trades"
    TradeNames:         array(Trade)                of string;   ! Names of all trades
    TradeStartNames:    array(Trade)                of string;   ! Names of start ports of the trades
    TradeStopNames:     array(Trade)                of string;   ! Names of stop ports of the trades

    TradeDDShip:        dynamic array(TradeDD,Ship) of integer;  ! Compatibility between TradeDD and Ship
    StartPort:          array(Ship)                 of integer;  ! The start port for ship in this timeperiod.

end-declarations

initializations from TurboRouterFile
    NumVoyage;
    StartPort;
    TradeDDShip;
    ShipNames;
    TradeMNames;
    TradeTCNames;
    TradeDDNames;
    TradeStartNames;
    TradeStopNames;
end-initializations

maxVoyage := max (rr in Trade) NumVoyage(rr);    ! Find the largest number of voyages
Voyage    := 1..maxVoyage;
```

```
finalize(Voyage);

declarations
  !Parameters
  CostBallast:         dynamic array(Ship,Trade,Trade)                   of real;   ! BallastCost between two trades for ship
  CostBallastStart:    dynamic array(Ship,Trade)                         of real;   ! BallastCost from start to first trade
  CostPortStart:       dynamic array(Ship,Trade,Trade)                   of real;   ! BallastCost from startport to startport
  CostTrade:           dynamic array(Ship,Trade,Way)                     of real;   ! CostTrade for ship, regardless of voyage
  CostTradeSpot:       dynamic array(Trade)                              of real;   ! Cost of hiring a spotship to do trade
  IncomeTrade:         dynamic array(Ship,Trade,Way)                     of real;   ! IncomeTrade for ship, regardless of voyage
  TimeBallast:         dynamic array(Ship,Trade,Trade)                   of real;   ! BallastTime between two trades for ship
  TimeBallastStart:    dynamic array(Ship,Trade)                         of real;   ! BallastTime from start to first trade
  TimeEarliest:        dynamic array(Trade,Voyage)                       of real;   ! Earliest start for voyage of trade
  TimeEarliestStart:   dynamic array(Ship)                               of real;   ! Earliest start for ship
  TimeLatest:          dynamic array(Trade,Voyage)                       of real;   ! Latest start for voyage of trade
  TimeTradeSpread:     dynamic array(Trade)                              of real;   ! Time Spread for each trade
  TimePortStart:       dynamic array(Ship,Trade,Trade)                   of real;   ! BallastTime from startport to startport
  TimeTrade:           dynamic array(Ship,Trade,Way)                     of real;   ! TimeTrade for ship, regardless of voyage

  !Variables
  s_ri:       dynamic array(Trade,Voyage)                                of mpvar;  ! = 1 if spotship is used on (r,i)
  t_vov:      dynamic array(Ship)                                        of mpvar;  ! When ship starts from origin
  t_ri:       dynamic array(Trade,Voyage)                                of mpvar;  ! When voyage (r,i) starts
  x_vovdv:    dynamic array(Ship)                                        of mpvar;  ! = 1 if ship is not in use
  x_vovri:    dynamic array(Ship,Trade,Voyage)                           of mpvar;  ! = 1 if ship sails from origin to (r,i)
  x_vridvw:   dynamic array(Ship,Trade,Voyage,Way)                       of mpvar;  ! = 1 if (r,i) is last for ship in period
  x_vriujw:   dynamic array(Ship,Trade,Voyage,Trade,Voyage,Way)          of mpvar;  ! = 1 if ship goes from (r,i) to (u,j)
  y_vri:      dynamic array(Ship,Trade,Voyage)                           of mpvar;  ! = 1 if ship v serves (r,i)

  ! Constraints
  FlowStart:          dynamic array(Ship)                                of linctr;
  FlowStop:           dynamic array(Ship)                                of linctr;
  FlowBalance:        dynamic array(Ship,Trade,Voyage)                   of linctr;
  VoyageServed:       dynamic array(Trade,Voyage)                        of linctr;
  TimeBetweenTrades:  dynamic array(Ship,Trade,Voyage,Trade,Voyage,Way)  of linctr;
  TimeStart:          dynamic array(Ship,Trade,Voyage)                   of linctr;
  TimeSpread:         dynamic array(Trade,Voyage)                        of linctr;
  TimeStarting:       dynamic array(Ship,Trade)                          of linctr;
  ServeTrade:         dynamic array(Ship,Trade,Voyage)                   of linctr;
  WayServe:           dynamic array(Ship,Trade,Voyage)                   of linctr;

  ! Objective value
  Profit:     linctr;

  ! PARAMETERS FOR TIMESPREAD-CONSTRAINT
  A:          real;                          ! Constant: middle of first voyage-TW
  B:          real;                          ! Constant: middle of last voyage-TW
  Factor:     dynamic array(Trade)           of real;   ! Faktor, UsedTime divided by TotalTime

  ! Way Voyage
  WayVoyage:  dynamic array(Trade,Voyage)                of integer;  ! Parameter: how many ways a voyage can be sailed
  WayExists:  dynamic array(Ship,Trade,Voyage,Way)       of integer;  ! Does an alternative way exist?

  ! Change Time window
  ChangeWindow:   real;   ! Parameter to change time window
end-declarations

initializations from DataFile
  Factor;
```

```
    WayVoyage;
end-initializations

initializations from TurboRouterFile
    CostTradeSpot;
    TimeEarliestStart;
    CostTrade;
    IncomeTrade;
    TimeTrade;
    TimeEarliest;
    TimeLatest;
    CostBallast;
    TimeBallast;
    CostPortStart;
    TimePortStart;
end-initializations

! Finding out if voyage ii of trade rr can be done in an alternative way I
forall(rr in Trade, ii in Voyage) do
    if (exists(WayVoyage(rr,ii))) then
        WayVoyage(rr,ii) := WayVoyage(rr,ii);
    else
        WayVoyage(rr,ii) := 1;
    end-if
end-do

! Finding out if voyage ii of trade rr can be done in an alternative way II
forall(vv in Ship,rr in Trade,ii in Voyage, ww in Way) do
    if (exists(TimeTrade(vv,rr,ww)) and exists(IncomeTrade(vv,rr,ww)) and exists(CostTrade(vv,rr,ww))
    and WayVoyage(rr,ii) >= ww) then
        WayExists(vv,rr,ii,ww) := 1;
    else
        WayExists(vv,rr,ii,ww) := 0;
    end-if
end-do

! Setting names in TradeNames from TradeM, TradeTC and TradeDD
forall(rr in Trade) do
    if (rr <= NumTradeM) then
        TradeNames(rr) := TradeMNames(rr);
    elif (rr > NumTradeM and rr <= (NumTradeM+NumTradeTC)) then
        TradeNames(rr) := TradeTCNames(rr);
    elif (rr > (NumTradeM+NumTradeTC)) then
        TradeNames(rr) := TradeDDNames(rr);
    end-if
end-do

! Finding time and cost for ballast travel from startport for ship v
forall(vv in Ship, rr in Trade) do
    if (StartPort(vv) > NumTrade) then
        TimeBallastStart(vv,rr) := TimeBallast(vv,StartPort(vv)-NumTrade,rr);
        CostBallastStart(vv,rr) := CostBallast(vv,StartPort(vv)-NumTrade,rr);
    elif (StartPort(vv) <= NumTrade) then
        TimeBallastStart(vv,rr) := TimePortStart(vv,StartPort(vv),rr);
        CostBallastStart(vv,rr) := CostPortStart(vv,StartPort(vv),rr);
    end-if
end-do
```

```
! Calculating time spread between voyages
forall (rr in Trade) do
    if (NumVoyage(rr) > 1) then
        A := TimeEarliest(rr,1) + 0.5 * (TimeLatest(rr,1) - TimeEarliest(rr,1));
        B := TimeEarliest(rr,NumVoyage(rr)) + 0.5 *(TimeLatest(rr,NumVoyage(rr)) - TimeEarliest(rr,NumVoyage(rr)));
        TimeTradeSpread(rr) := (B - A) / (NumVoyage(rr)-1);
    end-if
end-do

! ***********************************************************************************
! CREATING VARIABLES
! ***********************************************************************************

!Creates variable x_vovdv, binary, equals 1 if ship vv can choose not to be used. For ship that needs
!dry-docking, this variable is not created.
forall(vv in Ship) do
    if(sum(rr in TradeDD) TradeDDShip(rr,vv) = 0)then
        create(x_vovdv(vv));
        x_vovdv(vv) is_binary;
    end-if
end-do

!Creates variable x_vovri if ship makes it to start of (r,i) before the timewindow ends (NB! CAN WAIT!)
forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr) | not (rr in TradeDD and TradeDDShip(rr,vv) = 0)) do
    if (TimeEarliestStart(vv) + TimeBallastStart(vv,rr) <= TimeLatest(rr,ii)) then
        create(x_vovri(vv,rr,ii));
        x_vovri(vv,rr,ii) is_binary;
    end-if
end-do

! Creates variable x_vridvw, binary, equals 1 if (rr,ii) is the last voyage in timeperiod
forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr), ww in Way| not (rr in TradeDD and TradeDDShip(rr,vv) = 0)) do
    if (WayExists(vv,rr,ii,ww) > 0.5) then
        create(x_vridvw(vv,rr,ii,ww));
        x_vridvw(vv,rr,ii,ww) is_binary;
    end-if
end-do

!Creates variable x_vriujw if ship makes it from (r,i) to (u,j) before the timewindow closes.
!Ship can come and wait.
forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr),uu in Trade, jj in 1..NumVoyage(uu), ww in Way
| not (rr in TradeDD and TradeDDShip(rr,vv) = 0) and not (uu in TradeDD and TradeDDShip(uu,vv) = 0) ) do
    if (TimeEarliest(rr,ii) + TimeTrade(vv,rr,ww) + TimeBallast(vv,rr,uu) <= TimeLatest(uu,jj)
    and WayExists(vv,rr,ii,ww) > 0.5) then
        create(x_vriujw(vv,rr,ii,uu,jj,ww));
        x_vriujw(vv,rr,ii,uu,jj,ww) is_binary;
    end-if
end-do

!Time to start from origin is later than earliest possible start for ship v
forall(vv in Ship) do
    create(t_vov(vv));
    t_vov(vv) >= TimeEarliestStart(vv);
end-do

!Voyage (r,i) has to start within the timewindow
forall(rr in Trade, ii in 1..NumVoyage(rr)) do
    create(t_ri(rr,ii));
    t_ri(rr,ii) >= TimeEarliest(rr,ii);
```

```
    t_ri(rr,ii) <= TimeLatest(rr,ii);
end-do

!Creates spotship-variable for voyages of trades, except dry-docking,
!those have to be done by their own ships.
forall(rr in Trade, ii in 1..NumVoyage(rr) | not rr in TradeDD ) do
    create(s_ri(rr,ii));
    s_ri(rr,ii) is_binary;
end-do

!Creates binaryvariable, equals 1 if ship v does voyage and trade (rr,ii)
forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr) | exists(x_vovri(vv,rr,ii))) do
    if not (rr in TradeDD and TradeDDShip(rr,vv) = 0) then
        create(y_vri(vv,rr,ii));
    end-if
end-do

! *******************************************************************
! CONSTRAINTS
! *******************************************************************

! FLOW CONSTRAINTS
!All ships have to leave origin or they are not in use
forall(vv in Ship) do
    FlowStart(vv) :=
    x_vovdv(vv) + sum(rr in Trade,ii in 1..NumVoyage(rr)) x_vovri(vv,rr,ii) = 1;
end-do

!All ships have to reach destination or they are not in use
forall(vv in Ship) do
    FlowStop(vv) :=
    x_vovdv(vv) + sum(rr in Trade,ii in 1..NumVoyage(rr)) x_vovri(vv,rr,ii) = 1;
end-do

!Nodebalance - every ship that sails a voyage has to come from a place and finish it.
forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr)) do
    FlowBalance(vv,rr,ii) :=
    sum(uu in Trade, jj in 1..NumVoyage(uu), ww in Way) x_vriujw(vv,rr,ii,uu,jj,ww) + sum(ww in Way) x_vridvw(vv,rr,ii,ww) -
    sum(uu in Trade, jj in 1..NumVoyage(uu), ww in Way) x_vriujw(vv,uu,jj,rr,ii,ww) - x_vovri(vv,rr,ii) = 0;
end-do

! Constraint to get y_vri
forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr)) do
    ServeTrade(vv,rr,ii) :=
    y_vri(vv,rr,ii) = sum(uu in Trade, jj in 1..NumVoyage(uu),ww in Way) x_vriujw(vv,rr,ii,uu,jj,ww) +
    sum(ww in Way) x_vridvw(vv,rr,ii,ww);
end-do

! VOYAGE CONSTRAINTS: THREE CONSTRAINTS HAVE BEEN PUT TOGETHER TO ONE.
!Every "mandatory" voyage has to be done either with their own ship or by a spotship. The TC(optional)-trades
!can be done (not with spotship). The ships that need dry dock has to complete the dry-dock voyage. s_ri(rr,ii) for TC-ships
!are defined, but the cost and income is 0 and it has therefore no influence on the objective function. s_ri(rr,ii) for
!dry-dockings are not defined.
forall(rr in Trade, ii in 1..NumVoyage(rr)) do
    VoyageServed(rr,ii) :=
    sum(vv in Ship) y_vri(vv,rr,ii) + s_ri(rr,ii) = 1;
end-do
```

```
! TIME CONSTRAINTS
! Start time for voyage (u,j) cannot be before (r,i) is completed if ship v is doing both
forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr), uu in Trade, jj in 1..NumVoyage(uu), ww in Way |
exists(x_vriujw(vv,rr,ii,uu,jj,ww))) do
  TimeBetweenTrades(vv,rr,ii,uu,jj,ww) :=
  t_ri(rr,ii) + TimeTrade(vv,rr,ww) + TimeBallast(vv,rr,uu) - t_ri(uu,jj) <=
  ((TimeLatest(rr,ii) + TimeTrade(vv,rr,ww) + TimeBallast(vv,rr,uu) - TimeEarliest(uu,jj)) *
  (1 - x_vriujw(vv,rr,ii,uu,jj,ww)));
end-do

! Start time for voyage (r,i) cannot be before ship reaches the startpoint from origin
forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr) | exists(x_vovri(vv,rr,ii))) do
  TimeStart(vv,rr,ii) :=
  t_vov(vv) + TimeBallastStart(vv,rr) - t_ri(rr,ii) <=
  ((TimeEarliestStart(vv) + TimeBallastStart(vv,rr)) * (1 - x_vovri(vv,rr,ii)));
end-do

! Starttime for voyage (r,i) has to be after starttime for voyage (r,i-1) and the voyages have to fairly evenly spread
forall(rr in Trade, ii in 2..NumVoyage(rr)) do
  TimeSpread(rr,ii) :=
  t_ri(rr,ii) >= t_ri(rr,ii-1) + Factor(rr) * TimeTradeSpread(rr);
end-do

! Ensuring only sailing one way
forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr)) do
  WayServe(vv,rr,ii) :=
  sum(uu in Trade, jj in 1..NumVoyage(uu),ww in Way) x_vriujw(vv,rr,ii,uu,jj,ww) + sum(ww in Way) x_vridvw(vv,rr,ii,ww) <= 1;
end-do

! *************************************************************************************
! Objective function - maximizing profit
! *************************************************************************************

Profit :=
sum(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr), uu in Trade, jj in 1..NumVoyage(uu), ww in Way)
(IncomeTrade(vv,rr,ww) - CostTrade(vv,rr,ww) - CostBallast(vv,rr,uu)) * x_vriujw(vv,rr,ii,uu,jj,ww)
+ sum(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr), ww in Way)
(IncomeTrade(vv,rr,ww) - CostTrade(vv,rr,ww)) * x_vridvw(vv,rr,ii,ww)
- sum(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr)) (CostBallastStart(vv,rr) * x_vovri(vv,rr,ii))
- sum(rr in Trade, ii in 1..NumVoyage(rr)) (CostTradeSpot(rr) * s_ri(rr,ii));

! *************************************************************************************
! Setting parameters of the optimization
! *************************************************************************************

setparam("XPRS_VERBOSE",TRUE);

if (IPRECUT = 0) then
  setparam("XPRS_PRESOLVE",0);
  setparam("XPRS_CUTSTRATEGY",0);
end-if

if (ICPU <> 0) then
  !setparam("XPRS_MAXTIME", -30);
```

```
     setparam("XPRS_MAXTIME", ICPU);
end-if

! *******************************************************************************
! Optimization : Maximizing profit
! *******************************************************************************

maximize(Profit);

! *******************************************************************************
! WRITING OUT TO FILE
! *******************************************************************************

declarations
  x_vovdvValues:        dynamic  array(Ship)                            of  real;
  t_vovValues:          dynamic  array(Ship)                            of  real;
  x_vovriValues:        dynamic  array(Ship,Trade,Voyage)              of  real;
  x_vridvwValues:       dynamic  array(Ship,Trade,Voyage)              of  real;
  x_vriujwValues:       dynamic  array(Ship,Trade,Voyage,Trade,Voyage) of  real;
  y_vriValues:          dynamic  array(Ship,Trade,Voyage)              of  real;
  s_riValues:           dynamic  array(Trade,Voyage)                   of  real;
  t_riValues:           dynamic  array(Trade,Voyage)                   of  real;

  xTime_start:          dynamic  array(Ship,Trade,Voyage)              of  real;
  xTime_flow:           dynamic  array(Ship,Trade,Voyage)              of  real;
  xTime_last:           dynamic  array(Ship,Trade,Voyage)              of  real;
  xTime_spot:           dynamic  array(Trade,Voyage)                   of  real;

  TimeSpreadTrade:      dynamic  array(Trade,Voyage)                   of  real;
  Duration:             dynamic  array(Trade,Voyage)                   of  real;
  ProfitTrade:          dynamic  array(Trade,Voyage)                   of  real;
  CostBallastTrade:     dynamic  array(Trade,Voyage)                   of  real;
  TimeBallastTrade:     dynamic  array(Trade,Voyage)                   of  real;
  PreviousTrade:        dynamic  array(Trade,Voyage)                   of  string;

  IncomeTradeWay:       dynamic  array(Ship,Trade)                     of  real;
  CostTradeWay:         dynamic  array(Ship,Trade)                     of  real;
  TimeTradeWay:         dynamic  array(Ship,Trade)                     of  real;
  WayChosen:            dynamic  array(Ship,Trade)                     of  real;

  BestBound:            real;
  Gap:                  real;
  ProfitValue:          real;
  SolutionTime:         real;

  StartTime:            dynamic  array(Ship)                           of  real;
  FirstTrade:           dynamic  array(Ship)                           of  integer;
  FirstVoyage:          dynamic  array(Ship)                           of  integer;
  LastTrade:            dynamic  array(Ship)                           of  integer;
  LastVoyage:           dynamic  array(Ship)                           of  integer;
  FinishTime:           dynamic  array(Ship)                           of  real;
  ShipDurationOnSea:    dynamic  array(Ship)                           of  real;
  EndTimeOfTrade:       dynamic  array(Trade,Voyage)                   of  real;
  DaysOutOfPeriod:      dynamic  array(Trade,Voyage)                   of  real;
  ProfitOutOfPeriod:    dynamic  array(Ship)                           of  real;
  TimeOfTrade:          dynamic  array(Trade,Voyage)                   of  real;
```

```
StartTrade:                    integer;
StartVoyage:                   integer;
FinishTrade:                   integer;
FinishVoyage:                  integer;
TotalDurationOnSea:            real;
ProfitPerDayOnSea:             real;
StartTimeOfPeriod:             real;
EndDayOfPeriod:                real;
ProfitTooLate:                 real;
RealProfitInPeriod:            real;
TotalTimeOfTrade:              real;
TotalNumberOfShip:             real;
ProfitPerShip:                 real;
TotalBallastCosts:             real;
TotalBallastTime:              real;
TotalIncome:                   real;
TotalCosts:                    real;
TotalSpotCosts:                real;
TotalTradeCosts:               real;
PeriodLength:                  real;
TotalNumberOfTC:               real;
NumberOfDD:                    real;
TotalBallastTimeDD:            real;
TotalNumberOfSpotShip:         real;
TotalBallastCostsDD:           real;
TotalNumberOfVoyages:          real;
TotalDaysOutOfPeriod:          real;
ProfitTooLatePerDay:           real;
RealProfitInPeriodPerShip:     real;

temp:              string;
FileString:        string;
end-declarations

ProfitValue  := getobjval;
BestBound    := getparam("XPRS_bestbound");

forall(vv in Ship) do
  x_vovdvValues(vv) := getsol(x_vovdv(vv));
end-do

forall(vv in Ship) do
  t_vovValues(vv) := getsol(t_vov(vv));
end-do

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr))do
  x_vovriValues(vv,rr,ii) := getsol(x_vovri(vv,rr,ii));
end-do

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr))do
  x_vridvwValues(vv,rr,ii) := sum(ww in Way) getsol(x_vridvw(vv,rr,ii,ww));
end-do

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr), uu in Trade, jj in 1..NumVoyage(uu)) do
  x_vriujwValues(vv,rr,ii,uu,jj) := sum(ww in Way) getsol(x_vriujw(vv,rr,ii,uu,jj,ww));
end-do

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr))do
  y_vriValues(vv,rr,ii) := getsol(y_vri(vv,rr,ii));
```

```
  end-do

forall(rr in Trade, ii in 1..NumVoyage(rr)) do
    s_riValues(rr,ii) := getsol(s_ri(rr,ii));
end-do

forall(rr in Trade, ii in 1..NumVoyage(rr))do
    t_riValues(rr,ii) := getsol(t_ri(rr,ii));
end-do

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr))do
    if (x_vovriValues(vv,rr,ii) > 0.5) then
        xTime_start(vv,rr,ii) := getsol(t_ri(rr,ii));
    end-if
end-do

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr), uu in Trade, jj in 1..NumVoyage(uu)) do
    if (x_vriujwValues(vv,rr,ii,uu,jj) > 0.5) then
        xTime_flow(vv,rr,ii) := getsol(t_ri(rr,ii));
    end-if
end-do

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr)) do
    if (x_vridvwValues(vv,rr,ii) > 0.5) then
        xTime_last(vv,rr,ii) := getsol(t_ri(rr,ii));
    end-if
end-do

forall(rr in Trade, ii in 1..NumVoyage(rr))do
    if (s_riValues(rr,ii) > 0.5) then
        xTime_spot(rr,ii) := getsol(t_ri(rr,ii));
    end-if
end-do

forall(rr in Trade, ii in 2..NumVoyage(rr)) do
    TimeSpreadTrade(rr,ii) := t_riValues(rr,ii) - t_riValues(rr,ii-1);
end-do

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr), uu in Trade, jj in 1..NumVoyage(uu)) do
    if (y_vriValues(vv,uu,jj) > 0.5) then
        if (x_vriujwValues(vv,rr,ii,uu,jj) > 0.5) then
            CostBallastTrade(uu,jj) := CostBallast(vv,rr,uu);
            TimeBallastTrade(uu,jj) := TimeBallast(vv,rr,uu);
        elif (x_vovriValues(vv,uu,jj) > 0.5) then
            CostBallastTrade(uu,jj) := CostBallastStart(vv,uu);
            TimeBallastTrade(uu,jj) := TimeBallastStart(vv,uu);
        end-if
    end-if
end-do

forall(vv in Ship,rr in Trade,ii in 1..NumVoyage(rr),uu in Trade, jj in 1..NumVoyage(uu)) do
    if (x_vriujwValues(vv,rr,ii,uu,jj) > 0.5) then
        PreviousTrade(uu,jj) := TradeNames(rr)+" "+ii;
    end-if
end-do

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr),uu in Trade, jj in 1..NumVoyage(uu),ww in Way) do
    if (getsol(x_vriujw(vv,rr,ii,uu,jj,ww)) > 0.5) then
        IncomeTradeWay(vv,rr)   := IncomeTrade(vv,rr,ww);
```

```
                CostTradeWay(vv,rr)        := CostTrade(vv,rr,ww);
                TimeTradeWay(vv,rr)        := TimeTrade(vv,rr,ww);
                WayChosen(vv,rr)           := ww;
        elif (getsol(x_vridvw(vv,rr,ii,ww) > 0.5) then
                IncomeTradeWay(vv,rr)      := IncomeTrade(vv,rr,ww);
                CostTradeWay(vv,rr)        := CostTrade(vv,rr,ww);
                TimeTradeWay(vv,rr)        := TimeTrade(vv,rr,ww);
                WayChosen(vv,rr)           := ww;
        end-if
end-do

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr),uu in Trade, jj in 1..NumVoyage(uu),ww in Way) do
        if (getsol(x_vriujw(vv,rr,ii,uu,jj,ww)) > 0.5 or getsol(x_vridvw(vv,rr,ii,ww)) > 0.5) then
                Duration(rr,ii) := t_riValues(rr,ii) + TimeTradeWay(vv,rr);
                ProfitTrade(rr,ii) := IncomeTradeWay(vv,rr) - CostTradeWay(vv,rr) - CostBallastTrade(rr,ii);
        elif (s_riValues(rr,ii) > 0.5) then
                ProfitTrade(rr,ii) := -CostTradeSpot(rr);
        end-if
end-do

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr)) do
        if (x_vovriValues(vv,rr,ii) > 0.5) then
                FirstTrade(vv) := rr;
                FirstVoyage(vv) := ii;
        end-if
        if (x_vridvwValues(vv,rr,ii) > 0.5) then
                LastTrade(vv) := rr;
                LastVoyage(vv) := ii;
        end-if
end-do

forall(vv in Ship) do
        if (x_vovdvValues(vv) < 0.5) then
                StartTrade := FirstTrade(vv);
                StartVoyage := FirstVoyage(vv);
                StartTime(vv) := t_riValues(StartTrade,StartVoyage) - TimeBallastStart(vv,StartTrade);
                FinishTrade := LastTrade(vv);
                FinishVoyage := LastVoyage(vv);
                FinishTime(vv) := t_riValues(LastTrade(vv),LastVoyage(vv)) + TimeTradeWay(vv,LastTrade(vv));
                ShipDurationOnSea(vv) := FinishTime(vv) - StartTime(vv);
        end-if
end-do

forall(vv in Ship) do
        if (ShipNames(vv) = 'PI') then
                StartTimeOfPeriod := t_vovValues(vv);
        end-if
end-do

! The length of period is an input here. Since the analysis is conducted on the 90 days instances,
! the length is automatically set to 90 days.. If considering different time periods, this should have been
! an input to the model.

PeriodLength := 90;
EndDayOfPeriod := StartTimeOfPeriod + PeriodLength;

forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr)) do
        if(y_vriValues(vv,rr,ii) > 0.5) then
```

```
        EndTimeOfTrade(rr,ii) := t_riValues(rr,ii) + TimeTradeWay(vv,rr);
        ! PROFIT THAT IS NOT IN THIS PERIOD: HAVE TO GET PER DAY!!!
        DaysOutOfPeriod(rr,ii) := EndTimeOfTrade(rr,ii) - EndDayOfPeriod;
        ! TOTAL TIME OF TRADE INCLUDED BALLASTVOYAGE BEFORE
        TimeOfTrade(rr,ii) := TimeTradeWay(vv,rr) + TimeBallastTrade(rr,ii);
    end-if
end-do

TotalDaysOutOfPeriod := 0;
forall(rr in Trade, ii in 1..NumVoyage(rr)) do
    if (DaysOutOfPeriod(rr,ii) > 0) then
        TotalDaysOutOfPeriod := TotalDaysOutOfPeriod + DaysOutOfPeriod(rr,ii);
    end-if
end-do

TotalNumberOfShip := 0;
forall(vv in Ship) do
    if (x_vovdvValues(vv) < 0.5) then
        TotalNumberOfShip := TotalNumberOfShip + 1;
    end-if
end-do

TotalNumberOfTC := 0;
forall(vv in Ship, rr in TradeTC, ii in 1..NumVoyage(rr)) do
    if (y_vriValues(vv,rr,ii) > 0.5) then
        TotalNumberOfTC := TotalNumberOfTC + 1;
    end-if
end-do

TotalNumberOfVoyages := 0;
forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr)) do
    if (y_vriValues(vv,rr,ii) > 0.5) then
        TotalNumberOfVoyages := TotalNumberOfVoyages + 1;
    end-if
end-do

TotalIncome   := 0;
TotalCosts    := 0;
TotalTradeCosts := 0;
TotalBallastCosts := 0;
TotalBallastTime := 0;
forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr)) do
    if (y_vriValues(vv,rr,ii) > 0.5) then
        TotalIncome := TotalIncome + IncomeTradeWay(vv,rr);
        TotalCosts := TotalCosts + CostTradeWay(vv,rr)+CostBallastTrade(rr,ii);
        TotalTradeCosts := TotalTradeCosts + CostTradeWay(vv,rr);
        TotalBallastCosts := TotalBallastCosts + CostBallastTrade(rr,ii);
        TotalBallastTime := TotalBallastTime + TimeBallastTrade(rr,ii);
    end-if
end-do

TotalSpotCosts := 0;
TotalNumberOfSpotShip := 0;
forall(rr in TradeM, ii in 1..NumVoyage(rr)) do
    if (s_riValues(rr,ii) > 0.5) then
        TotalSpotCosts := TotalSpotCosts + CostTradeSpot(rr);
        TotalNumberOfSpotShip := TotalNumberOfSpotShip + 1;
```

```
        end-if
    end-do

NumberOfDD := 0;
TotalBallastCostsDD := 0;
TotalBallastTimeDD := 0;
forall(vv in Ship, rr in TradeDD, ii in 1..NumVoyage(rr)) do
    if (y_vriValues(vv,rr,ii) > 0.5) then
        NumberOfDD := NumberOfDD + 1;
        TotalBallastCostsDD := TotalBallastCostsDD + CostBallastTrade(rr,ii);
        TotalBallastTimeDD := TotalBallastTimeDD + TimeBallastTrade(rr,ii);
    end-if
end-do


TotalTimeOfTrade := sum(rr in Trade, ii in 1..NumVoyage(rr)) TimeOfTrade(rr,ii);
TotalDurationOnSea := sum(vv in Ship)ShipDurationOnSea(vv);
ProfitPerDayOnSea := ProfitValue/TotalDurationOnSea;
ProfitTooLate := ProfitPerDayOnSea * TotalDaysOutOfPeriod;
RealProfitInPeriod := ProfitPerDayOnSea * (TotalDurationOnSea-TotalDaysOutOfPeriod);
RealProfitInPeriodPerShip := RealProfitInPeriod / TotalNumberOfShip;
ProfitPerShip := ProfitValue / TotalNumberOfShip;

! ********************************************************************************
! WRITING TO FILE
! ********************************************************************************

!Creating a table which is written to a .csv file to make it compatible with Excel
!Write case info
FileString := " "+MODELNAME;
FileString += " "+DATETIME;
FileString += " "+DataFile;

! Calculating solution time
SolutionTime := gettime - Time;

makedir("output/"+FileString);

fopen("output/"+FileString+"/ flow.csv", F_OUTPUT);

writeln("ECONOMIC ANALYSIS: ");
!Writing information about timeperiod
writeln("TIME OF PERIOD: ");
writeln("StartTimeOfPeriod: ",StartTimeOfPeriod, " days");
writeln("Duration: ", PeriodLength, " days");    ! This analysis is foremost for the 90 day period an
writeln("EndTimeOfPeriod: ", EndDayOfPeriod, " days");
writeln("");

!Writing objective value, BestBound and Gap
writeln("Profit: ","$ ",ProfitValue);

if (ProfitValue <> 0) then
    Gap := (1 - BestBound/ProfitValue) * 100;
else
    Gap := 0;
end-if

writeln("Best bound: ","$ ", BestBound);
writeln("Gap: "," ", Gap, " %");
```

```
!Writing solution time
writeln("Solution time: ","""", SolutionTime, " sec");

!Writing profit calculations
writeln("");
writeln("PROFIT CALCULATIONS: ");
writeln("ProfitValue: , $ ",ProfitValue);
writeln("TotalDurationOnSea: ,",TotalDurationOnSea, ", days");
writeln("Total Time of Trade: ,",TotalTimeOfTrade, ", days");
writeln("ProfitPerDayOnSea: , $ ", ProfitPerDayOnSea);
writeln("TotalDaysOutOfPeriod: ,", TotalDaysOutOfPeriod, ", days");
writeln("ProfitTooLate: , $ ",ProfitTooLate);
writeln("RealProfit in Period: , $ ",RealProfitInPeriod);
writeln("");
writeln("TotalNumberOfShips: ",TotalNumberOfShip);
writeln("TotalNumberOfTC-trades: ",TotalNumberOfTC);
writeln("TotalNumberOfSpotShip: ", TotalNumberOfSpotShip);
writeln("TotalNumberOfVoyages: ",TotalNumberOfVoyages);
writeln("TotalNumberOfVoyages/on sea: ",TotalNumberOfVoyages/TotalDurationOnSea);
writeln("TotalNumberOfVoyages/daysperiod: ",TotalNumberOfVoyages/PeriodLength);
writeln("TotalNumberOfVoyages/total time of trade: ",TotalNumberOfVoyages/TotalTimeOfTrade);
writeln("");
writeln("RealProfitInPeriodPerShip: , $ ",RealProfitInPeriodPerShip);
writeln("ProfitPerShip: , $ ",ProfitPerShip);
writeln("");
writeln("Total Income: , $ ", TotalIncome);
writeln("Total Costs: , $ ", TotalCosts);
writeln("Total Trade Costs: , $ ",TotalTradeCosts);
writeln("Total Spot Costs: , $ ",TotalSpotCosts);
writeln("Total Ballast Costs: , $ ",TotalBallastCosts);
writeln("Total Ballast Time: ,", TotalBallastTime, ", days");

writeln("");
writeln("DRY DOCKINGS: ");
writeln("Number of dry dockings : , ", NumberOfDD);
writeln("TotalBallastCostsDD: , $ ",TotalBallastCostsDD);
writeln("TotalBallastTimeDD: ,", TotalBallastTimeDD, ", days");
writeln("");

writeln("SHIP AND TRADE MATRIX");
temp := "Ship,Use,Start-up time,";
forall(rr in Trade, ii in 1..NumVoyage(rr))do
   temp += "" +TradeNames(rr)+ii+",";
end-do

!Writing solution to file
writeln(temp);
forall(vv in Ship) do
   temp := ""+ShipNames(vv)+",";
   if (x_vovdvValues(vv) > 0.5) then
      temp += "NOT IN USE,";
   else
      temp += "IN USE,";
   end-if
   temp += "" +t_vovValues(vv)+",";
   forall(rr in Trade, ii in 1..NumVoyage(rr)) do
      if (exists(xTime_start(vv,rr,ii))) then
```

```
            temp += ""+xTime_start(vv,rr,ii);
        elif (exists(xTime_flow(vv,rr,ii))) then
            temp += ""+xTime_flow(vv,rr,ii);
        elif (exists(xTime_last(vv,rr,ii))) then
            temp += ""+xTime_last(vv,rr,ii);
        end-if
        temp += ",";
    end-do
    writeln(temp);
end-do

!Writing spot solutions to file
temp := "StartTime for SpotShip,,";
forall(rr in TradeM, ii in 1..NumVoyage(rr)) do
    if (exists(xTime_spot(rr,ii))) then
        temp += ""+xTime_spot(rr,ii);
    end-if
    temp+= ",";
end-do
writeln(temp);

!Writing time spread to file
temp := "Actual Time spread,,,";
forall(rr in Trade) do
    temp+= ",";
    forall(ii in 2..NumVoyage(rr)) do
        temp+= ""+TimeSpreadTrade(rr,ii);
        temp+= ",";
    end-do
end-do
writeln(temp);

writeln("");
writeln("");

writeln("TRADESPECIFIC");
temp := "Trade,VoyageNumber,ShipName,StartTime,TimeTrade,StopTime,IncomeTrade,CostTrade,CostBallastTrade,
TimeBallastTrade,ProfitTrade,Factor,WayChosen";

!Writing solution to file
writeln(temp);
forall(rr in Trade, ii in 1..NumVoyage(rr) | not rr in TradeTC) do
    temp := ""+TradeNames(rr)+"," +ii+",";
    if (s_riValues(rr,ii) > 0.5) then
        temp += ""+"SpotShip"+",";
        temp += ",,,"+CostTradeSpot(rr)+",,,"+ProfitTrade(rr,ii)+",";
    end-if
    forall(vv in Ship) do
        if (y_vriValues(vv,rr,ii) > 0.5) then
            temp += ""+ShipNames(vv)+",";
            temp += ""+t_riValues(rr,ii)+",";
            temp += ""+TimeTradeWay(vv,rr)+",";
            temp += ""+Duration(rr,ii)+",";
            temp += ""+IncomeTradeWay(vv,rr)+",";
            temp += ""+CostTradeWay(vv,rr)+",";
            temp += ""+CostBallastTrade(rr,ii)+",";
            temp += ""+TimeBallastTrade(rr,ii)+",";
            temp += ""+ProfitTrade(rr,ii)+",";
            temp += ""+Factor(rr)+",";
```

```
            temp += ""+WayChosen(vv,rr)+",";
        end-if
    end-do
    writeln(temp);
end-do

forall(rr in TradeTC, ii in 1..NumVoyage(rr)) do
    forall(vv in Ship) do
        if (y_vriValues(vv,rr,ii) > 0.5) then
            temp := ""+TradeNames(rr)+"," +ii+",";
            temp += ""+ShipNames(vv)+",";
            temp += ""+t_riValues(rr,ii)+",";
            temp += ""+TimeTradeWay(vv,rr)+",";
            temp += ""+Duration(rr,ii)+",";
            temp += ""+IncomeTradeWay(vv,rr)+",";
            temp += ""+CostTradeWay(vv,rr)+",";
            temp += ""+CostBallastTrade(rr,ii)+",";
            temp += ""+TimeBallastTrade(rr,ii)+",";
            temp += ""+ProfitTrade(rr,ii)+",";
            temp += ""+Factor(rr)+",";
            temp += ""+WayChosen(vv,rr)+",";
            writeln(temp);
        end-if
    end-do
end-do

writeln("");
writeln("");

writeln("SHIPSPECIFIC");

forall(vv in Ship) do
    temp := "ShipName: ,"+ShipNames(vv)+",";
    writeln(temp);
    temp := "Start: ,"+t_vovValues(vv)+",";
    writeln(temp);
    temp := "TradeName,VoyageNumber,PreviousTrade,StartTime,TimeTrade,StopTime,IncomeTrade,CostTrade,CostBallastTrade,
TimeBallastTrade,ProfitTrade,Factor,WayChosen";
    writeln(temp);
    forall(rr in Trade, ii in 1..NumVoyage(rr)) do
        if (y_vriValues(vv,rr,ii) > 0.5) then
            temp := ""+TradeNames(rr)+",";
            temp += ""+ii+",";
            temp += ""+PreviousTrade(rr,ii)+",";
            temp += ""+t_riValues(rr,ii)+",";
            temp += ""+TimeTradeWay(vv,rr)+",";
            temp += ""+Duration(rr,ii)+",";
            temp += ""+IncomeTradeWay(vv,rr)+",";
            temp += ""+CostTradeWay(vv,rr)+",";
            temp += ""+CostBallastTrade(rr,ii)+",";
            temp += ""+TimeBallastTrade(rr,ii)+",";
            temp += ""+ProfitTrade(rr,ii)+",";
            temp += ""+Factor(rr)+",";
            temp += ""+WayChosen(vv,rr)+",";
            writeln(temp);
        end-if
    end-do
    writeln("");
```

```
   end-do

   writeln("");
   writeln("DURATION ON SEA: ");
   forall(vv in Ship) do
      temp := "ShipName:   ,"+ShipNames(vv)+",";
      writeln(temp);
      temp := "StartTime:  ,"+StartTime(vv)+",";
      writeln(temp);
      temp := "FinishTime:  ,"+FinishTime(vv)+",";
      writeln(temp);
      temp := "Duration on Sea: ,"+ShipDurationOnSea(vv)+",";
      writeln(temp);
   end-do

   writeln("");
   writeln("");
   writeln("OUT OF PERIOD");

   temp := "TradeName, VoyageNumber, StartTime, TimeBallastTrade, TimeTrade, StopTime, TotalTimeOnTrade, DaysOutOfPeriod";
   writeln(temp);
   forall(vv in Ship, rr in Trade, ii in 1..NumVoyage(rr)) do
      if(y_vriValues(vv,rr,ii) > 0.5) then
         temp := ""+TradeNames(rr)+",";
         temp += ""+ii+",";
         temp += ""+t_riValues(rr,ii)+",";
         temp += ""+TimeBallastTrade(rr,ii)+",";
         temp += ""+TimeTradeWay(vv,rr)+",";
         temp += ""+Duration(rr,ii)+",";
         temp += ""+TimeOfTrade(rr,ii)+",";
         temp += ""+DaysOutOfPeriod(rr,ii)+",";
         writeln(temp);
      end-if
   end-do

   writeln("");
   writeln("");

   writeln("SPOTSHIP");

   temp := "TradeName, VoyageNumber, ProfitTrade";
   writeln(temp);
   forall(rr in TradeM, ii in 1..NumVoyage(rr)) do
      if (s_riValues(rr,ii) > 0.5) then
         temp := ""+TradeNames(rr)+",";
         temp += ""+ii+",";
         temp += ""+ProfitTrade(rr,ii)+",";
         writeln(temp);
      end-if
   end-do

   fclose(F_OUTPUT);

   end-model
```

D   Digital appendix

In the zip-file following this master's, results of all instances in the computational study can be found. The mosel code is also included.

E   Alternative ways

This section presents the alternative ways for four of the trades.

SAMFE

The trade between South America and Far East has a route as explained in table E.1. The other alternative is to not visist Vancouver, WA, which is the only port on the West Coast. The route sails therefore directly from Panama Canal to Yokohama, Asia. This is illustrated in figure E.1.

Table E.1: Route for SAMFE

	Port	Time in port
1	Portocel	2.05.00
2	Vila do Conde	4.00.00
3	Panama Canal	1.12.00
4	Vancouver, WA	2.05.00
5	Yokohama	2.00.00
6	Shimizu	1.00.00
7	Nagoya	2.12.00
8	Osaka	1.12.00
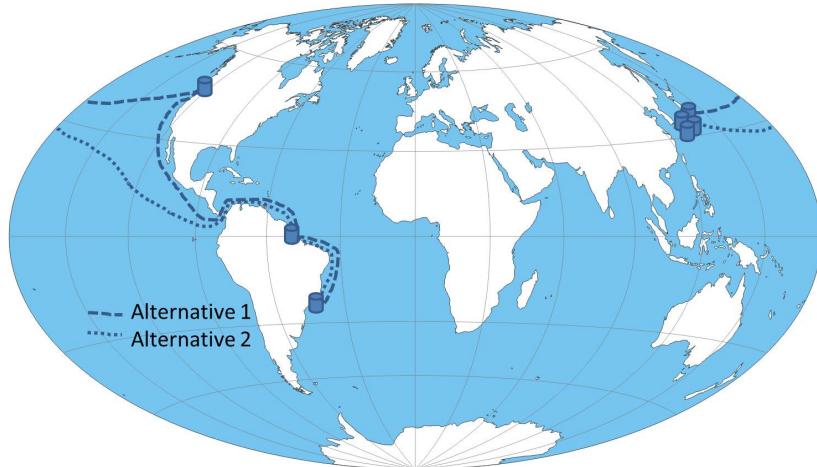
Figure E.1: Traderoute for SAMFE

WCEUR

The trade between West Coast of USA and Europe has a route as explained in table E.2. The other alternative is to not visist two ports in Canada, one port in California, USA, and one port in Belgium. Both alternatives are illustrated in figure E.2.

Table E.2: Route for WCEUR

|	Port	Time in port
1	Portland	1.12.00
2	Vancouver, BC	2.00.00
3	Port Mellon	2.18.00
4	Long Beach, CA	1.00.00
5	Los Angeles, CA	4.00.00
6	Panama Canal	1.12.00
7	Rotterdam	5.00.00
8	Antwerp	1.12.00
9	Vlissingen	2.00.00
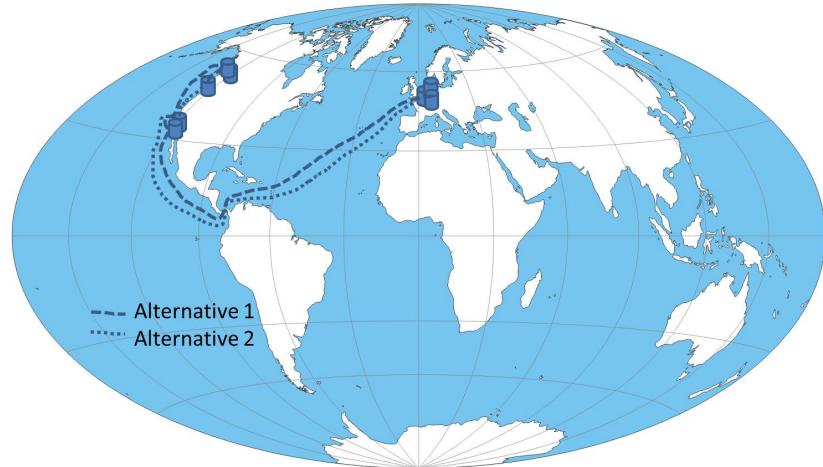
Figure E.2: Traderoute for WCEUR

FEWC

The trade between Far East and West Coast, USA, has a route as explained in table E.3. The other alternative is to go directly from Asia to New Westminster. Both alternatives are illustrated in figure E.3.

Table E.3: Route for FEWC

	Port	Time in port
1	Kaohsiung	8.00.00
2	Ulsan	4.00.00
3	Los Angeles, CA	5.00.00
4	San Francisco	1.00.00
5	Vancouver, WA	1.00.00
6	New Westminster	2.00.00
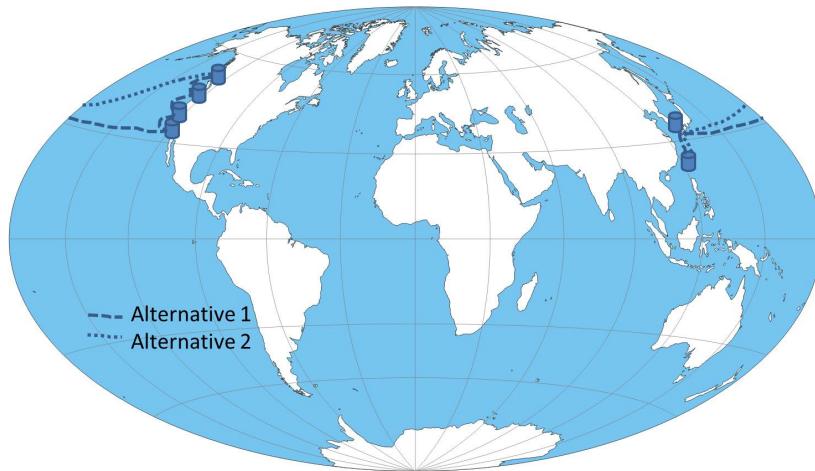
Figure E.3: Traderoute for FEWC

EUREC

The trade between Europe and East Coast, USA, has a route as explained in table E.4. The other alternative is to sail directly from Brake to Savannah, GA. Both alternatives are illustrated in figure E.4.

Table E.4: Route for EUREC

	Port	Time in port
1	Brake	6.00.00
2	New London, CT	2.00.00
3	Baltimore, MD	2.00.00
4	Wilmington, NC	2.00.00
5	Savannah, GA	2.00.00
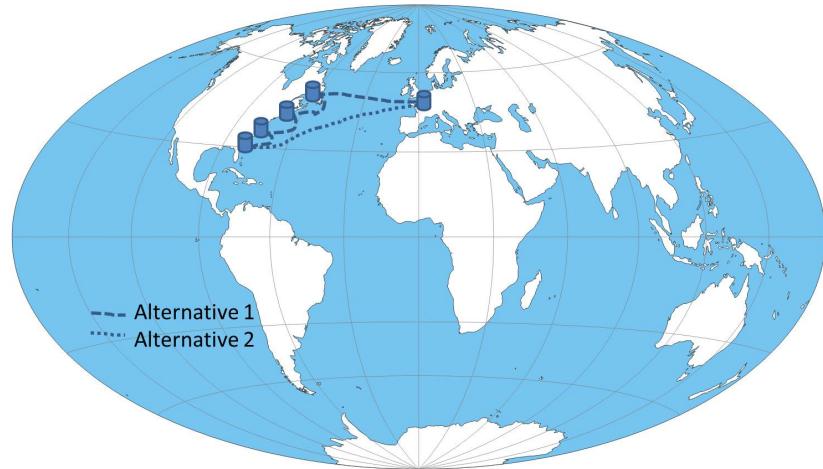
Figure E.4: Traderoute for EUREC

F   Appendix to the analysis

Table F.1 presents the target values used when performing analysis to the effects of adjusting input parameters and constraints. They are calculated in Xpress and analyzed in Excel.

Table F.1: Target values for computational study

Target value	Explanation
Time	
Ship duration on sea	Days between start of first voyage and end of last voyage for a ship
Total duration on sea	Sum of ship duration on sea for all ships
Time of trade	Time of trade included time of ballast sailing
Total time of trade	Total time of all trades
Days out of period	Days a ship sails after time period ends
Total days out of period	Sum of days out of period for all ships
Total ballast time	Total time on ballast voyages for all ships
Total ballast time for dry docking trades	Total time on ballast voyages for dry docking trades for all ships
Profit	
Profit per day on sea	Total profit divided by total duration on sea
Profit too late	Profit obtained after time period is over (Profit per day on sea · total days out of period)
Real profit in period	Profit obtained in time period (Profit per day on sea · days of duration in period)
Real profit in period per ship	Real profit in period divided by total number of ship
Profit per ship	Profit divided by total number of ship in use in period
Costs	
Total trade costs	Total costs for trades for all ships
Total spot costs	Total costs of using spot ships
Total ballast costs	Total costs for sailing ballast voyages for all ships
Total ballast costs for dry docking trades	Total costs for sailing ballast voyages before dockings

Table F.2 gives the optimisation characteristics for time window change when the factor is 0.25 used in the computational study.

Table F.2: Optimisation characteristics with time window change for factor 0.25

	0.75TW	0.9TW	Original	1.1TW	1.25TW
Rows(constraints)	40 170	41 259	42 091	42 707	43 648
Rows(constraints) presolved	11 671	12 304	13 020	13 656	14 369
Columns(variables)	37 694	38 792	39 630	40 253	41 200
Columns(variables) presolved	18 511	19 267	19 872	20 296	20 916
Non zero elements	245 486	253 109	258 912	263 245	269 820
Non zero elements presolved	77 113	80 614	83 969	87 286	90 727
Nodes	12 725	109 212	31 262	115 183	77 501
Number of IP solutions found	30	19	24	30	18
Computational time	189 s	1984 s	604 s	2701 s	1989 s

Table F.3 gives an example of parts of a trade plan when changing the time window when there is an alternative way of sailing a voyage.

Table F.3: Example of allocation when changing the time window with alternative way

Factor = 0.25					
Ship	**Trade**	**Start**	**End**	**Ballast***	**Profit***
Spot	EUREC#2				
	FESAM#1	20.8	75	$ 56.8	$ 322
EX	↓				
	SAMEUR#6	76.5	99.3	$ 28	$ 752
	↓				
	EURSAM#5	103.5	157	$ 41	$ $ 441
	FEWC#1	27.7	72	$ 44	$ 1064
	↓				
JO	TC WCFE#2	78	119	$ 2.4	$ 654

Factor = 0.25 with alternative way						
Ship	**Trade**	**Start**	**End**	**Ballast***	**Profit***	**Way[1]**
	FEWC#1	21.1	52.1	$ 64	$ 707	2
EX	↓					
	TC WCEUR#2	53.1	98.2	$ 19	$ 432	-
	↓					
	EURSAM#5	103.5	157	$ 43	$ 440	-
	FESAM#1	24.5	78.7	$ 0	$ 379	-
	↓					
VO	SAMEUR#8	80.2	103	$ 28.3	$ 752	-
	↓					
	EUREC#2	105.5	133.4	$ 16.3	$ 459	1

* All profit and costs are in $ 1000.

[1] Way: If the voyage can be done in alternativ way: 1 or 2, if not: -

The graphs which follow show ballast costs and number of TC-voyages and spot ships for factor 1.0 and 0.25 when changing the time window, and the profit, ballast costs and number of TC-voyages and spot ships for factor 0.75. Note that all costs and profits are in $ 1000.
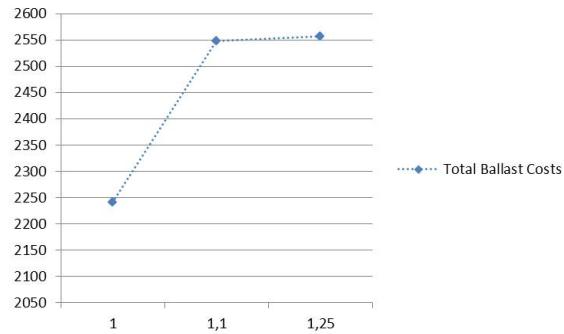

Figure F.1: Ballast costs when changing time window for factor 1.0
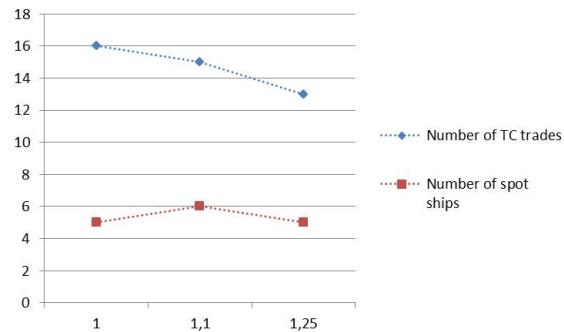
Figure F.2: Number of TC-voyages and spot ships when changing the time window for factor 1.0
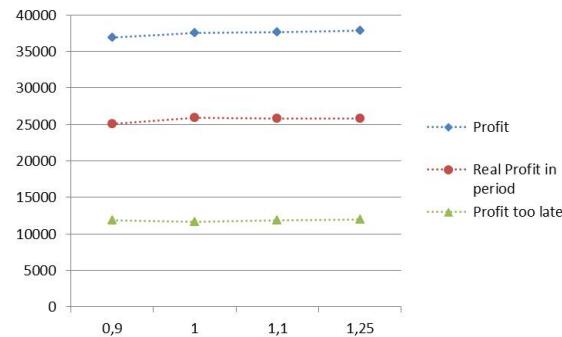
Figure F.3: Profit when changing time window for factor 0.75
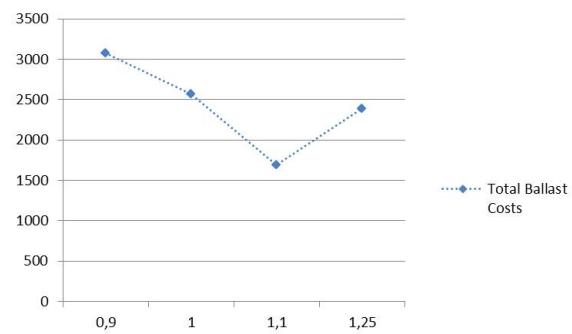
Figure F.4: Ballast costs when changing time window for factor 0.75
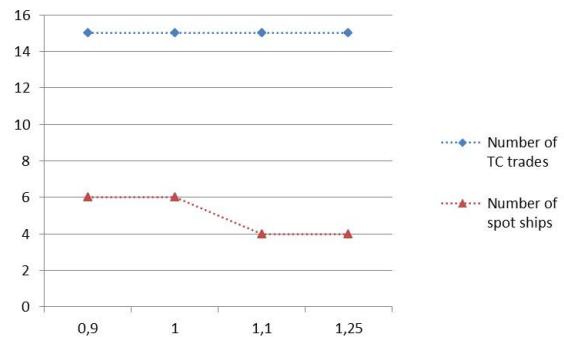
Figure F.5: Number of TC-voyages and spot ships when changing time window for factor 0.75
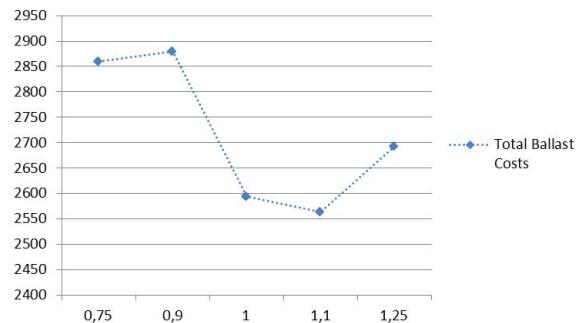
Figure F.6: Ballast costs when changing time window for factor 0.25
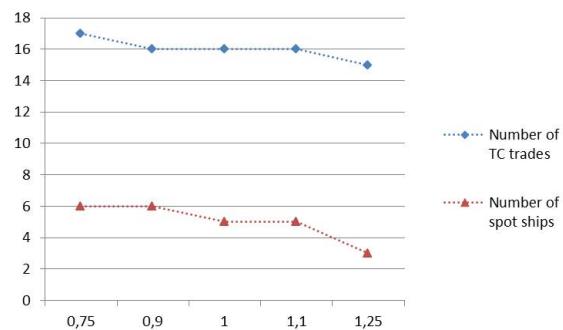
Figure F.7: Number of TC-voyages and spot ships when changing time window for factor 0.25

G   Information regarding trades

Table G.1 presents the 10 mandatory trades the shipping company operates.

Table G.1: Mandatory trades

Name	Start	Lay/Can
SAMFE	17.,18.,20. every month	10 days
SAMEUR	Every 11th day	10 days
	and 1 per month	30 days
FESAM	1. every month	15 days
	15. every second month (Jan,March..)	
EURSAM	12. every month	10 days
	20. every second month (Jan,March..)	
WCEUR	8. every second month (Jan,March..)	15 days
ECSAM	1 every sixth months (Feb)	30 days
FEWC	5. every month	10 days
EUREC	22. every second month (Jan,March..)	10 days
SAMWC	14. every second month (Feb,April..)	20 days
SAMAFRFE	1 every sixth month (April)	30 days

Figure G.1 gives an illustration of the calculation of factor of time spread for EURSAM and SAMFE. The figure can also be found in the zip file in appendix D.

Figure G.2 illustrates the start times of voyages for SAMEUR and SAMFE when the factor is 1.0, 0.75 and 0.25. This figure can also be found in the zip file in appendix D.
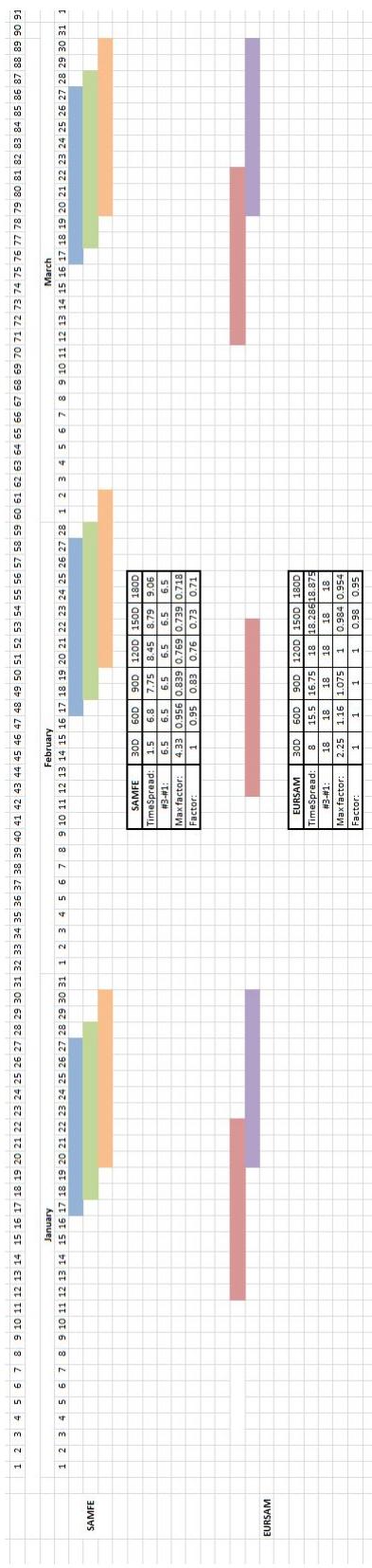
Figure G.1: Factor of time spread for SAMFE and EURSAM
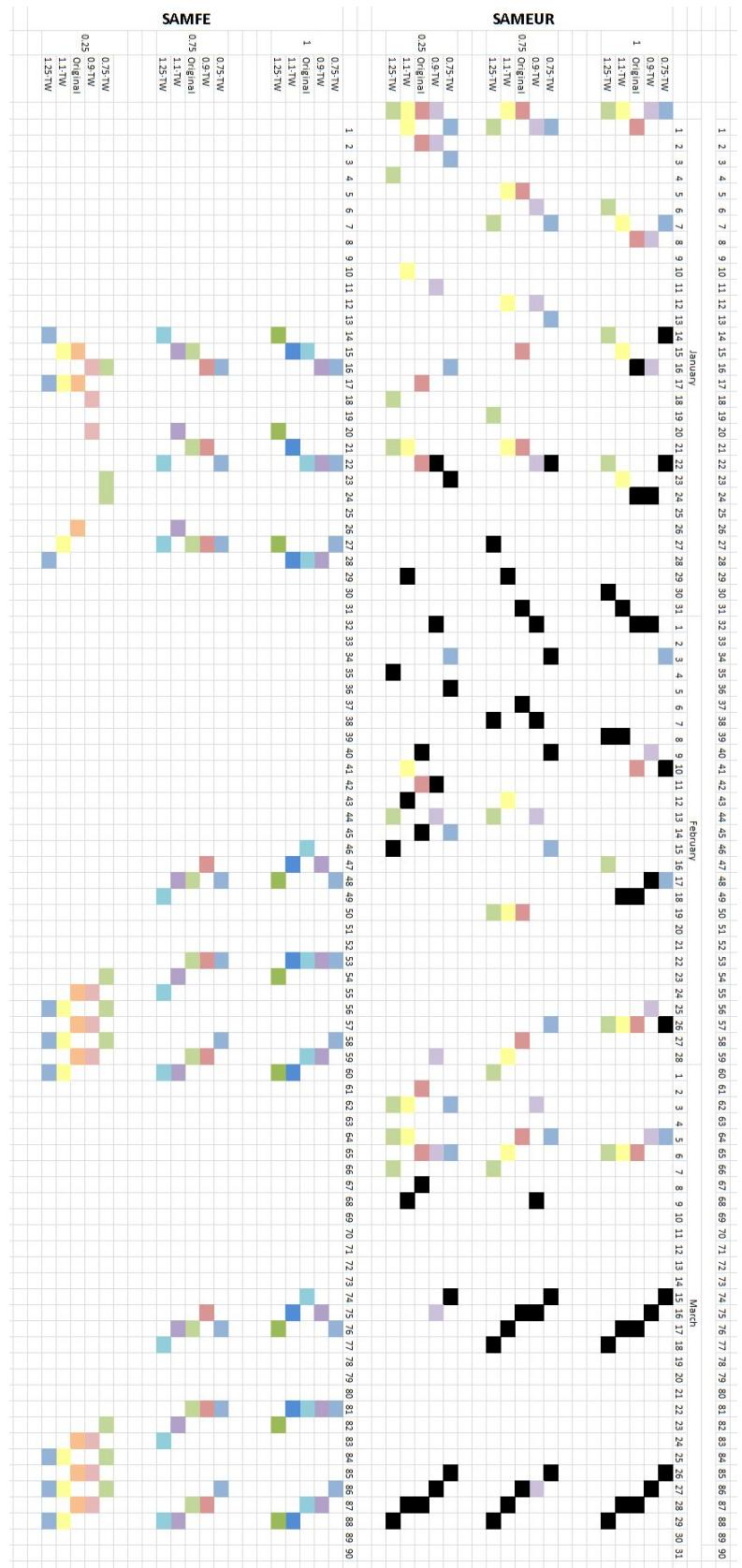
Figure G.2: Start time of voyages for SAMEUR and SAMFE when factor is 1.0, 0.75 and 0.25 and for time window changes