NTNU – Trondheim
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Maritime fleet size and mix problems

An optimization based modeling approach

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Marine Technology (2 year)
Submission date: June 2012
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Abstract

This master thesis addresses the maritime fleet size and mix problem (MFSMP). Finding the optimal fleet size and mix of ships for future needs is arguably the single most important decision of a ship owner. This thesis has examined the accuracy with which a developed mathematical formulation of the problem is at predicting fleet demand under various conditions. The FSM model that has been studied is an extension of a model already established by the MARFLIX project. The considered shipping segment is deep-sea Ro-Ro.

For testing how accurate the FSM model is at creating a fleet that can handle complex routing constraints a deployment model has been developed. The consistency of the model under different time frames, varying bunker costs and effects of using continuous instead of integer variables in the FSM model was also tested.

The major findings of the work was that the fleet proposed by the the FSM model, in its current form, often is undersized. The fleet size and mix problem is usually considered a strategic problem, with time horizons up to several years. However, this particular model performed better for shorter time frames. Using continuous variables on the different trips undertaken by the fleet proved to have little impact on the fleet composition, but the loss of a vessel could occur. The method proved, however, to be significantly faster than the using integer variables. Changes in the cost of fuel had immense impact on the fleet composition, and one should always be clear on the effects of fluctuations in fuel costs have on a fleet. In general, when the price increased the fleet got larger and slow steamed a larger portion of the fleet.

Further work should be made on improving the routing capabilities of the FSM model. In its present form the model cannot be relied upon as the only means for establishing the actual optimal fleet. It can, however, be used as a guidance

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Scope of work

MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2012

For stud.techn.

Martin-Alexander Steffensen

Maritime fleet size and mix problems

Background
The shipping world has in the later years experienced a boom, with high and persistent rate levels. However, nothing grows without limits into the sky, and with the financial crises emerging mid-2008; questions were raised whether all shipping prospects and new-building activity would see robust and viable commercial life. One of the key issues in ship-owner/ship-operator planning is the strategic planning of the size and mix of the fleet of vessels, known generically as fleet size and mix problems (FSMP). FSMPs are dominated by uncertainty in several dimensions, given fluctuating and changing market demands, changing opportunities that may become open for different types and sizes of vessels, redesign of transport networks, as well as upcoming or changing physical or regulatory “bottlenecks”. Questions like;

- Given transport demand and network, how may our current fleet be utilised in the best possible and/or emission effective way, and how should our fleet be developed to meet future market and network opportunities, as well as emission regulations?
- How may changing network structure or fleet mix best achieve a given improvement in performance measurements?

Are among the important decisions that ship-owners have to make to position their fleet of vessels in commercial market operations, as well as meet the regulatory requirements. From the regulators side, the same questions may be addressed with the focus of what the effect and cost of specific regulations could be, given available fleet applicable measures of technology.

Objective

The objective of solving maritime fleet size and mix problems is to find the optimal fleet composition for a given market condition. This thesis will examine the accuracy with which the result presented by the developed FSM model is at predicting fleet demand under various conditions.

Tasks

The FSM model to be considered will be an extension of a model already established by the MARFLIX project. Because of the thesis link to the MARFLIX project, the considered shipping segment is deep-sea Ro-Ro and the fleet in focus is the fleet and operation of Wallenius-Wilhelmsen Logistics, WWL.

Among the topics to be studied are:

1. The consistency of the model under different time frames, varying bunker costs and effects of using continuous instead of integer variables in the FSM.
2. Furthermore, a deployment model is to be developed in order to check the reliability of the FSM to construct a fleet that can fulfill routing requirements

General

In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Supervision:

Main supervisor: Professor Bjørn Egil Asbjørnslett
Sub-supervisor: Post. Doc. Jørgen Glomvik Rakke
Company contact: NA

Deadline: 10.06.2012

Preface

This master thesis was written as partial fulfillment of the degree Master of Science in Marine Technology, at the Norwegian University of Science and Technology. The report was written in its entirety by Martin-Alexander Steffensen, spring 2012.

I would like to thank my supervisors, Professor Bjørn Egil Asbjørnslett and Post Doc. Jørgen Glomvik Rakke, for their invaluable advice and support during the work with my thesis.

Trondheim, 09.06.2012

Martin-Alexander Steffensen

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Summary

This master thesis addresses the maritime fleet size and mix problem (MFSMP). The objective of solving maritime fleet size and mix problems is to find the optimal fleet composition for a given market condition. This thesis has examined the accuracy with which a developed mathematical formulation of the problem is at predicting fleet demand under various conditions. Among the studied topics are consistency of the model under different time frames, varying bunker costs and effects of using continuous instead of integer variables in the FSM. The bulk of the study, however, is concentrated around the routing of vessels. For this purpose a deployment model has been developed, in order to check the reliability of the FSM in this regard.

The FSM model that has been studied is an extension of a model already established by the MARFLIX project. Because of the thesis link to the MARFLIX project, the considered shipping segment is deep-sea Ro-Ro.

For generating test scenarios for the model an instance generator was made in MATLAB. A MATLAB file also conducted the processing of the fleet composition proposed by the FSM model into the form used by the deployment model. The tested scenarios all had the options of six different vessels, operating in three different speeds and carrying three different cargo types. Four to eight nodes were used in the scenarios with varying supply, demand and accessibility. The smaller scenarios with four nodes were used for comparison with the deployment model had time horizons of 60, 120, 180 and 360 days. The larger scenarios were in addition tested for five and ten years.

In the first trials using the deployment model on the proposed fleet the results were uplifting; in most scenario cases the proposed fleet managed to fulfill its shipping obligations without the need of additional tonnage. But, the tests showed that the desired spread in time for the different trade arcs were not good enough. Two extensions were therefore considered for the deployment model; the frequency spread and inventory routing. In the frequency spread a maximum number of days between each operation on an arc, based on the contracted obligations of the fleet, are used. The inventory routing extensions, on the other hand, model the supply of goods to be shipped off as a continuous production process with storage limitations. Both methods succeeded in getting the desired spread. But, the most effective method proved to be the frequency spread. However, with the stricter model extensions the

estimated fleet failed in an increasing degree to fulfill the contracted obligations of the fleet, and therefore had to rely on spot vessels to a much greater degree. The model extensions of the deployment model also made it difficult to solve bigger problems due to an increase in complexity. The most effective solution method of the two was the frequency spread.

The cost estimations of the FSM model far surpassed the deployment output, probably because of differences in how the fleet relate to the ending of the time horizon. The extra time available in the deployment model made it possible to slow down the speed of the fleet. This effect is reduced with an increase of the planning period. When the spread of the trips were considered in the deployment model the cost gap was sometimes eliminated.

Using continuous variables instead of integer variable for the number of arcs operated in the FSM model proved to be of little consequence to the result when establishing the optimal fleet. Both the accuracy of the result, compared to the integer solution and the gains connected to time savings, increased with the time horizon of the planning problem. In the test only the trips were defined as continuous, the other variable remained integer.

When scenarios were tested with different bunker prices the FSM model output changed as well. How large the change was varied from scenario to scenario. But in general, when the price increased the fleet got larger and slow steamed a larger portion of the fleet. The opposite was the case when the prices increased. Changes in the fleet mix also occurred, as the energy effectiveness of the fleet varied in importance.

FSM models are usually defined as strategic problems, with planning horizons spanning years. However, most of the tests use the same time frame on the FSM model and deployment model, which is a tactical problem. When the results of the FSM for a longer time horizon was tested on deployment scenario with a shorter time frame the results were negative. The FSM model work best for shorter time intervals than it is constructed for due to the margins created by simplification of the FSM routing; stating that all nodes must have as many visits in as out of a node for any given ship type. The impact of this simplification is marginalized as the time horizon< increase.

The FSM model in its present form can therefore not be relied upon as the only means for establishing the actual optimal fleet. It can, however, be used as a guidance. The formulation, as it is, is too loose and can therefore result in an undersized fleet.

Sammendrag

Denne masteroppgaven ser på det maritime flåtesammensetning problemet (MFSMP). Å finne den optimale flåtesammensetningen for å kunne dekke fremtidige behov er uten tvil den av de viktigste avgjørelsene av en skipsreder må ta. Denne oppgaven har undersøkt hvor nøyaktig en utviklet matematisk formulering av problemet er til å forutsi flåteetterspørsel under ulike forhold. FSM modellen som har blitt undersøkt her er en forlengelse av en modell som allerede er etablert ved MARFLIX prosjektet. Oppgaven tar utgangspunkt i deep-sea Ro-Ro shipping.

For å teste hvor nøyaktig denne FSM modellen er til å skape en flåte som kan håndtere komplekse ruting-restriksjoner har en deployment modell blitt utviklet. Om resultatene fra modellen er ensartet under ulike tidsrammer, varierende bunkerkostnadene og bruk av kontinuerlig i stedet for heltallige variabler i FSM modellen har også blitt testet.

Et av de viktigste resultatene av arbeidet var at flåten, foreslått av FSM-modellen, ofte er underdimensjonert. Flåtesammensetning problemet er vanligvis betraktet som et strategisk problem, med tidshorisonter opp til flere år. Men forsøk viste at denne modellen er bedre egnet for kortere perioder. Å definere de forskjellige turene foretatt av flåten som kontinuerlige variable vist seg å ha liten innvirkning på flåtens sammensetning, men flåten kunne bli et fartøy fattigere. Metoden viste seg imidlertid å være betydelig raskere enn ved bruk av heltall variabler. Endringer i prisen på drivstoff hadde enorm innvirkning på flåtesammensetningen, og man bør alltid være klar på virkningene av svingninger i drivstoffkostnader har på en flåte. Generelt sett, når prisen økte flåten fikk større og treg dampet en større del av flåten.

Fremtidig arbeid bør rettes mot å forbedre ruting-betingelsene i FSM modellen. I sin nåværende form kan ikke modellen brukes som eneste begrunnelsesgrunnlag når en flåte skal settes sammen. Den kan imidlertid brukes veiledende.

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List of Abbreviations

DNV:	Det Norske Veritas
MARINTEK :	Norwegian Marine Technology Research Institute
NTNU:	Norwegian University of Science and Technology
WWL:	Wallenius Wilhelmsen Logistics
LP:	Linear Programing
DP:	Dynamic Programing
SP:	Set Partitioning
IP :	Integer Programming
MIP:	Mixed Integer Programming

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Chapter 1

Introduction

Maritime transportation an essential part of the society we live in; an estimated 80% of the world's trade volume is transported by sea [1]. The demand of transportation is almost perfectly correlated to the global economic development and productivity. However, since 1980 the world's maritime fleet has grown with approximately 25% and in the same time frame the world productivity has increased with only the half of that [2]. This has led to harder competition between shipping companies, forcing them to operate with decreasing margins, in what already can be called an uncertain market. In addition, there has been change in the political climate (e.g. environmental aspects), and a trend towards structural rationalization can be found; both through horizontal integration and by vertically integrating shipping into terminal operations and hinterland transportation **[3].**

While much of the maritime business environment has changed, the business methods of many shipping companies have not. The maritime industry is quite conservative; low risk family businesses are still the norm. As a result, most companies still highly rely on intuition and qualitative evaluation of experienced analysts when determining their long-term investment strategies as they always have done. Finding the optimal fleet size and mix of ships for future needs is arguably the single most important decision of a ship owner, and the most complex one. In other industries (e.g. air freight, road transportation and train) quantitative methods are applied much more frequently to this problem. When solving a fleet size and mix problem the aim is to determine an optimal fleet for given market situations [4]. The problem is most often connected to adjusting or extending an existing fleet, not building one from scratch.

In the shipping industry it is customary to categorize planning decisions by their time horizon. Strategic planning spans several years, tactical planning cover months while operational planning deal more with the day to day decisions. The fleet size and mix problem is usually defined as a strategic planning decision It is, however, important to take both tactical and operational elements into consideration as the available fleet determines the deployment possibilities, and overall earning potential, in the future [2, 4, 5].

The scientific study of planning decisions in the maritime transportation industry has been lagging behind comparable industries like airfreight and land based transportation.

Christensen at al. [6] point at the relative low visibility, the lack of structure, the market uncertainty, and the long traditions of the industry as possible explanations. In addition, it is hard to convert many of the findings from the other industry into maritime applications. One example of this is the longevity of the ships themselves; a ship has the expected life time of approximately 20 to 30 years, binding up considerable amounts of money. It is estimated that capital costs of a shipping company with a young fleet can account for up to 80% of the running costs [7]. On top of this is the huge variations in vessel value; varying from the scrap metal value of the ship to its weight in gold, in a matter of months, figuratively speaking. In many ways one might say that finding the best fleet composition is finding out how one might utilize the present resources in order to maximize the future earnings and optimize the net present value of the company.

This thesis will address the accuracy of a FSM model already established in the MARFLIX project. The MARFLIX project is a collaboration between NTNU, DNV, MARINTEK and WWL. The mission of the MARFLIX project is to solve the fleet size and mix problem through quantitative methods. The industrial case forming the backdrop of the project is based on the activities of WWL, a shipping operator working with freight of automobiles. This industry segment also forms the basis for this thesis. In this thesis the model has been developed further and tests have been made in order to say something about the quality of the results of the model. However, before the problem can be solved some background information is needed; this is presented in chapter 2. The problem is then described in detail (chapter 3), followed by a review of relevant literature in chapter 4. The different models are then presented and explained in chapter 5, and the computer implementation of them described in chapter 6. Finally, in chapter 7, the results are presented. The thesis is then concluded by some final remarks on the findings and possible future work.

Chapter 2

Background

This chapter contains some background information for the thesis and set the project in its proper context. The chapter starts with an introduction to shipping in general and ends with a closer look into the subsegment that deals with the transportation of cars and associated cargoes. In the introduction some of the unique features of the shipping industry were introduced. In this section a more detailed description of the operational environment of this particular transportation method is presented.

Shipping modes

There are many ways of splitting the shipping industry into segments and categories; one way is to distinguish between the modes of operation of the ships. This division was according to Christiansen et al. [5, 6] first presented by Lawson in 1972. Lawson divides shipping in three general operational profiles: industrial, tramp and liner shipping. It is called industrial shipping when both the ships and the cargo have the same owner. The objective of shipment is transport the cargo at a minimal cost. Tramp shipping is usually compared to the taxi service; following available cargo in the market. While there might be a certain amount of contractual cargo to transport, it also operates the spot market with the objective to maximize profit. Liner shipping companies, on the other hand, operate according to set itineraries and schedules between predefined ports, similar to a bus line. The different operation modes are not mutually exclusive; a ship can easily be operated in different modes, and a shipping company might simultaneously operate its fleet in different ways [5].

The Shipping Market

In order to make rational decisions about fleet composition one must have extensive insight into the market in which it operates. The shipping market is a global and cyclical market driven by *supply and demand*. It is often branded as a perfect market due to the global aspect and the number of competing parties. Stopford [8]describe the shipping market cycle as the combination of three different cycles:

- Long-term cycles are typically triggered by major changes in the maritime transportation industry
- The short-term cycles are governed by changes in the world economy

- Lastly, the cyclical demand and supply of different commodities due to seasonal changes

Demand for maritime services is derived from the demand for goods. The supply, on the other hand, is determined by the available fleet and port capacity, in addition to the accessibility of goods. The shipping freight rates mirror the available transportation tonnage versus freight demand interaction. For example; if the increase in fleet capacity is larger than the change in world GDP the freight rates will drop. If the increase in GDP is larger however, the freight rates rise. The fluctuating freight rates reflect the volatile shipping market. This market is as earlier mentioned cyclical in nature, something that has been tried illustrated in Figure 1. Increasing freight rates results in a higher demand for ships. Excess supply of vessels leads to lower freight rates. In order to restore the balance, ship owners will put some vessels out of operation or demolish old tonnage, leading to a reduced fleet and an increase in freight rates. The process then starts again. Stopford [8] sets the usual shipping cycle to last from four to seven years. These cycles are often possible to predict based on the amount of tonnage coming into the market compared to what is going out.

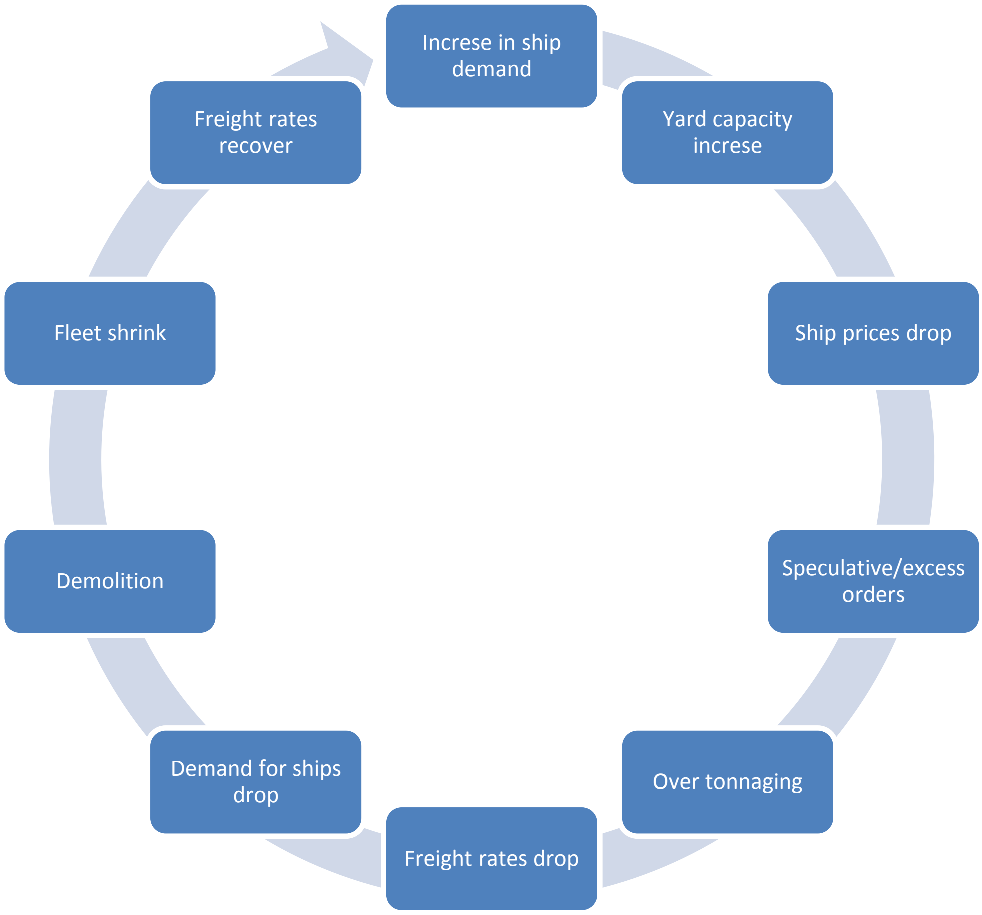

Figure 1: The Shipping Market Cycle

A ship is worth what you can earn with it. This means that the prices of a ship (both newbuilds and second hand vessels) highly depend on the freight rates, in addition to the steel price, following the same fluctuating market cycle. An extreme example of this was seen in

2007/2008 when the demand for shipping services was high and the prices for ships were excessive. When the demand dropped as a result of the credit crunch in the second half of 2008, however, the prices of ships hit the floor.

The ship owners are not the only players in shipping. Ships must be built, financed, insured and pass technical standards. Disputes about liability and contractual disagreements must be settled. Cargo must be loaded and unloaded. The list goes on, but from what is already written the complexity of the industry can be glimpsed.

The world of shipping is divided into several submarkets; categorized after their cargo type. UNCTAD distinguish between oil tankers, bulk carriers, general cargo, container ships and other ships.The different economic markets the different types of vessels operate in can vary quite a lot. For instance, since the 1969's there has been a permanent growth in dry bulk trade but since the supply of new ships have matched the demand there has been quite steady freight rates in this segment, only to increase significantly at the dawn of the new millennium due to the Chinese expansion. Because of this sudden increase in freight rates in this segment the credit crunch hit this market extra hard. The tanker markets are, on the other hand, traditionally much more volatile than dry bulk.

Owning VS Chartering

Instead of owning vessels, shipping operators and cargo owners can lease a vessel, or space on a vessel. This is called chartering. A fleet can consist of both owned vessels and vessels chartered under various charter arrangements. There are three main chartering arrangements; bareboat charter, time charter and voyage charter. In the bareboat charter the charterer rent the ship, usually for many years and all operational costs, maintenance and crew costs are to be paid by the charterer. The time charter can have longer or shorter time frames, and only the operational costs are to be paid by the charterer, the owner provides the crew. On a voyage charter (or spot charter) only the cargo space is rented, usually for a fixed price. For measuring the performance of the fleet over longer periods where there are changes in the fleet's mix of charter types the time charter equivalent (TCE) is used. WWL have most of their fleet on time charter contracts from their parent companies, the fixed cost of the fleet will therefore in this thesis be included in the time charter costs.

Shipment of Cars

Cars, and other motorized vehicles, are high-volume, low-density and high-value cargo that is easily damaged, making transportation a complicated and costly matter with conventional ships [8]. On the other hand, wheeled cargo such as automobiles, trucks, trailers or railroad cars offer the advantage of the ability rolling on and off its transportation carrier, rather than being lifted. To utilize this fact specialized vessels have been constructed to carry these types of cargo. Rather than relying on cranes for loading and on loading of cargo Roll-on/Roll-off vessels are equipped with strong in-built ramps which allows for efficient on- and off-loading by rolling the cargo on or off the vessel [9].

The car carrier industry is by UNCTAD listed as a general cargo segment [1] and consists according to Stopford of 634 ships in 2008, amounting to 9.1 million DWT and with a cargo capacity of approximately three million vehicles [8]. In this segment it is usual for ship operators to have long-term contracts with factories for delivering a percentage of their output to given destinations. Since no specific volumes are specified in the contracts the uncertainty of the shipper in regards to income per trip is high, but the contracts also secures some capital inflow. However, free capacity can also be filled by spot cargo. It is estimated that approximately 85% of the transported volume of WWL is based on long term contracts [10]. The usual length of these contracts is usually three years. However, the time frame could also be shorter, or be as long as five years.

The cargo in this industry segment is usually divided into three types: Auto (dominated by regular cars), Rolling Equipment (e.g. High and Heavy (HH)) and Static Cargo (e.g. Non-Containerized Cargo (NCC)). For transportation of cars the cargo is defined in Car Equivalent Units (CEU) or RT43, where one CEU represents the size of a 1966 Toyota Corona RT43 [9, 10]. The HH cargo can be construction equipment such as bulldozers or tractors for use in agriculture, cargo that because of height or weight need special consideration. NCC cargo on the other hand can be anything from large generators put on multiwheeler trucks to a yacht stored on the top deck of the vessel. In the case of WWL about half the carried cargo fall into the Auto segment, 30% Rolling Equipment and 20% Static Cargo [10].

An efficient car factory can produce a car every 40 seconds, amounting to a total of 2160 cars each day[8]. Storing thousands of cars are not an easy task, and therefore it is preferable to ship them away quite speedily. The largest car carriers can carry about 7000 cars, and can therefore be filled quite fast. As a consequence most car carrier companies operate their fleet according to the liner shipping operation profile, with contracted schedules and itineraries. WWL for example operate their fleet according to 18 different trade routes on fixed schedules[10].

According to Stopford [8] the trade of automobiles and associated cargos amounted to 15 million CEU in 2005, more than the double of transported volume less than a decade before. The biggest trade volumes are transported from Asia to North America and Europe. The industry is to a large extent dominated by eight operators controlling 90% of the transported volume. Of these, WWL is together with their subsidiaries the largest[10].

Chapter 3

Problem Description

In this chapter the problem to be solved will be described in detail, including an outline of the solution method. The reason behind the problem is also discussed.

The **purpose of this work is further develop an existing fleet size and mix model and testing the accuracy with which the result, presented by the model, is at predicting fleet demand under various conditions and premises.** The main focus of the thesis will be connected to the routing of vessels. Therefore, a deployment model has been developed in order to check the reliability of the FSM to construct a fleet that can fulfill its obligations in a more complex deployment setting. In addition, the consistency of the model under different time frames, varying bunker costs and the effects of using continuous instead of integer variables in the FSM will be discussed.

The purpose of the fleet size and mix is to find the optimal fleet composition for a given scenario. It was mentioned in the introduction that these problems usually are categorized as *strategic* problems, whereas routing are considered to be *tactical* problems, based on the length of their planning period.

While FSM- models try to find the optimal number of vessels, and their physical qualities, for a given task, deployment models go more into details around the routing specifics. Routing refers to finding the optimal path to follow**;** the assignment of a sequence of ports to a vessel. In liner shipping it is usual to use the term deployment when considering the routing of vessels, because of the special character of this type of operations. In deployment models the vessels are assigned to predefined routes and often operate them on consecutive trips. This is in contrast to regular routing models where each trip often is operated only once and there is no predefined connection between nodes. In this thesis, however, routing and deployment will be used interchangeably. The term routing will in addition be used whenever a vessel, ship type, is assigned to a specific trade arc, even though the sequence is not established; like in the FSM.

The overlap and codependence between the FSM and deployment is quite clear, and has been pointed at many times in literature **[5, 6, 11]**. The success of the strategic plans depends on future performance, while tactical plans fully rely on the resources made available by past strategic planning decisions. In a maritime setting this means that if routing is not considered, with specific time of arrival and departure, the fleet might end up being under-dimensioned.

Even though the models are quite codependent there are good reasons for not including the same high level of detail in the deployment of vessels in the fleet size and mix problems. The difference in time horizon has been mentioned as one. It takes years to acquire a fleet, and each vessel will operate for decades, and the tactical environment is ever changing. From a strategic view the tactical environment might therefore seem fleeting, and the question is how much weight to give to one operation scenario. Because, even though there are some dangers connected to under-dimensioning the fleet if routing is not included in the FSMP, the danger of over-fitting a fleet for a specific market condition is just as big and disastrous. Another reason for separating the fleet size and mix problem from the routing of the vessels is complexity. In these models there is a limit to the number of unknown factors, just like other equations. The higher the complexity the harder it is to model and even with modern computer technology the computation time of such problems of any relevant size would be too high for any practical use. So, even though the case for including some routing into the fleet size and mix models is good, the case for dividing the task into separate models is also strong. As a compromise some routing is included in the FSMP, but at a level far from what one can find in deployment models.

The basis for the examinations is liner operations connected to the freight of cars and related cargo. In that industry companies like WWL have 85% of their transported volume from long-term contracts **[10].** In these circles one might say that the overlap between strategic and tactical planning are bigger and the combination of methods might prove to be more fruitful, than for companies operating in for example tramp shipping, increasing the importance of the work significantly.

Solution method

The objective of the thesis has now been made clear, but to reach this goal a solution method is needed. For testing model performance, results from the FSM will be compared to those of a deployment model using the same data used in the FSM and the fleet composition found there.

The comparison basis of the two models is first and foremost answering the question of whether or not the vessel compositions found in the FSM trials manage to fulfill its obligations in the deployment model or extra tonnage is necessary. Secondly, is to look at the cost estimates of the different models and the operational profile of the fleet in the deployment model. And thirdly, the routing of the vessels; whether or not the different vessel types operate the same arcs, the same number of times in both models. In addition, a high percentage of idle time and the speed of the vessels indicate the activity level of the fleet.

Before the models used in these trials are presented in chapter 5 a look at previous work is presented in the literature study in the next chapter.

Chapter 4

Literature Study

The main focus of this thesis is to look at the underlying deployment of the ships when trying to solve a fleet size and mix problem. In this chapter a review of relevant literature is presented in order to look at the relevance of this problem, and find impulses into ways of solving it. As with the rest of this thesis the focus of the study is on liner shipping. This literature study has been limited to papers dealing with mathematical formulations of the problem. Simulation based solution method will, for example, not be discussed.

Surveys and General Articles

An good introduction to how operations research is being applied to maritime transportation was published in 2007, written by **Christiansen et al. [6].** The paper looks into all major aspects of how operations research has been applied to maritime transportation applications. The text is written as an introduction to maritime transportation for those already acquainted with operations research and focuses especially on the differences between maritime transportation and other kinds of transportation.

The last decade several articles summing up the previous research into the problems connected to fleet composition, deployment, routing and scheduling have been made. A review of the current status of the scientific study of ship routing and scheduling was done in 2004 by **Christiansen et al. [5].** The study looks at all different planning horizons and the varying operational profiles. One of the findings in this report was the scarcity of research on routing, scheduling and deployment in liner shipping compared to the other operational profiles. It was pointed out that because of the distinct differences between this shipping segment compared to industrial and tramp shipping more research in liner shipping is necessary.

A survey of the industrial aspects of fleet composition and routing research, written by **Hoff et al.** [2]was published in 2010. The article deal with both maritime and road based transportation.

A literature study on the fleet size and mix problem in maritime transportation is made in a still unpublished work by **Pantuso et al**. [11]. The article point out that the appropriate level of detail to apply in these model in regards to the underlying routing of the ships is a subject for future investigation. Uncertainty and non-stationary market status are also pointed out as lacking sufficient attention in the available literature. A simple example of how all these aspects can be included in a model is then presented. The model is to be solved using a multistage stochastic program with recourse.

Author	Year	Article
Christiansen et al.	2004	Ship Routing and Scheduling: Status and Perspectives
Christiansen et al.	2007	Maritime Transportation
Hoff et al.	2010	Industrial Aspects and literature Survey: Fleet Composition and Routing
Pantuso et al.	Not yet published	A Survey on Maritime Fleet Size and Mix Problems

Table 1: Earlier Literature Reviews & General Articles

Scientific Papers

The qualitative study of the fleet sizing problem was started by the pioneering work of **Dantzig and Fulkerson [12],** who in 1954 were the first to optimize a fleet size based on a given demand. The solution was found using the simplex algorithm. The first time the routing of the vehicles (VRP) was included into the FSM (forming the FSMVRP) was done by **Golden et al.** in 1984 [13]**.** These models are not directly related to maritime transportation but are instead formulated as universal models, solvable with given heuristics.

Cho and Perakis [14] presented in 1996 a model that optimizes fleet size and the find optimal routes at minimal costs. The model uses set partitioning where the problem is solved by generating routes for each ship a priori[1], using a path flow method. Two versions of the model is presented; one linear and one formulated as a mixed integer problem. The MIP model introduces the possibility reducing fleet size during the given time frame through laying up ships.

The paper of **Xinlian et al. [15]** from 2000 aims to establish both the optimal ship types to extend a given fleet, when to do this and the optimal deployment of these vessels. The article proposes to solve the problem first for different time periods individually and then bind these together with dynamic programming[2] in order to get the fleet development over several consecutive years. The demand is in this model fixed. A similar multi-period planning problem for long term fleet composition and deployment has been formulated by **Meng & Wang [16]**. The model presented in this article is scenario based, taking some of the uncertainties of future demand into consideration. The MIP model is formulated as a shortest path problem, solved by using branch-and-cut algorithm.

[1] A priori: all possible column vectors are generated in advance with binary variables representing all possible combinations of routes

[2] Dynamic programming is a solution strategy that divides the original problem into several smaller ones. These sub-problems are then solved independently, the relation between the different parts are then used to establish the solution to the original problem. All problems solved using dynamic programming can be written as a shortest path problem in an acyclic network.

A model for fleet deployment in liner shipping was presented by **Perakis and Jaramillo [17]** in 1991. The model was later improved by **Powel and Perakis [18].** While the first model was solved as an LP problem, then rounded of the number of ships allocated to each route, the new model is solved by integer programming and also includes some extensions.

A case study of deployment in liner shipping, written by **Fagerholt et al. [19],** present a fleet deployment model that is solved using a multi-start local search heuristic. The method is industry tested, and has proven to be 2-10% better than results from manual planning for problems with up to 55 vessels and 150 voyages over a half year.

In 1999 **Fagerholt [20]** formulated a model of fleet deployment depicting a liner shipping system outside the coast of Norway. The model use a set partitioning formulation, for generating possible routes a priori dynamic programming is used. The model is solved with the use of a multi-start heuristic. This model was later expanded by **Fagerholt and Lindstad [21]** to include variable speed of the vessels. The goal of this study was to evaluate the supply chain cost connected to reducing the available time for supply vessels to visit offshore oil installations. Six scenarios were tested. The result of the model proved to save 7million USD compared to the estimations done manually.

In order for several Norwegian shipping companies to increase their profitability by combining tonnage a joint fleet composition, routing and scheduling model is formulated by **Sigurd et al. [22]**. Also here the integer problem is formulated as a set partitioning model, formulated by applying the Dantzig-Wolfe decomposition method[3].

Álvarez [23] look at both the routing and deployment of a given fleet of container vessels. To find routes an arc flow formulation is used. While the model does not account for the purchase and sale of vessels the formulation opens for chartering out surplus tonnage capacity. If the number of available vessels proves inadequate a penalty is given. A case study with 120 ports of call is presented, with sensitivity analysis of optimal fleet deployment and routing compared to varying bunker costs. The model is formulated as a MIP multi-commodity flow problem that is solved using a taboo search heuristic.

[3] The formulation of the model constraints of these problems can often be divided into *common constraints* and ship *routing constraints*. Here, common constraints are defined as the cargo constraints in general while the ship routing constraints deal with the individual ships with no fleet interaction. When using the Dantzig-Wolfe decomposition approach the common constraints constitute the master problem, while the ship routing constraints are formulated as a sub-problem for each ship. Because it often is too time consuming to generate all possible schedules it is usual to first solve the LP-relaxation of the restricted master problem in order to restrict the number of possible solutions. The restricted master problem has fewer variables than the original. After solving this problem columns corresponding to ships schedule with positive reduced cost are added to the restricted problem. This way dual value from the solution of the restricted master problem is transferred to the sub-problems. When the sub-problems are solved and new schedules are generated the process starts again. The reoptimization with new columns continues until no column with positive reduced cost exists. It is this way the Dantzig-Wolfe decomposition method is solved when embedded in a branch-and-bound search, or branch-and-price as the case is here.

Author	Year	Major Decision	Method
Dantzig & Fulkerson	1954	Fleet Size	Simplex
Golden et al.	1984	Fleet Size & Routing	Heuristics
Perakis & Jaramillo	1991	Fleet Deployment	LP
Cho & Perakis	1996	Fleet Comp. & Deployment	LP + IP
Powell and Perakis	1997	Deployment	IP
Fagerholt	1999	Fleet Size & Mix	IP + DP (SP)
Fagerholt & Lindstad	2000	Fleet Size & Mix	IP + DP (SP)
Xinlian et al.	2000	Fleet Size & Deployment	LP + DP
Sigurd et al.	2005	Fleet Comp., Routing & Scheduling	Heuristic (DWD)
Fagerholt et al.,	2009	Deployment	MIP + Heuristics
Álvarez	2009	Deployment	MIP + Heuristics
Meng & Wang	2011	Fleet Development. & Deployment	MIP + DP

Table 2: Summary of Literature

Relevance

From the articles that has been treated in this study it is clear that there is a need for more information on the underlying routing and scheduling when considering the fleet size and mix problem in liner shipping. A summary of the articles treated here can be found in Table 2**.**

Most articles presented in this literature study have both strategic and tactical elements. Many of the papers stress the importance of this, none, however, can point at exactly how important or the optimal level of detail; though the paper written by Pantuso et al. [11] brings the subject up as relevant for future research. Some models were too simplistic in the sense they did not allow for recurring visits, other models were for complex to be used in the industrial cases the FSM model this thesis is to look at is intended for. In addition, none of the articles studied here treat ro/ro segment, though most of them are about liner shipping. All models depicting liner shipping describe containerized shipping, where the cargo is to be considered uniform and depicting round-trip trades (all containers must go back to the port of origin). However, the ro/ro industry is far more flexible, as no containers need to be brought back to any depot. Based on the lack of literature in this specific area, and other topics associated with this thesis, the conclusion to be drawn is that more research is needed in this particular field.

Chapter 5

Mathematical Models

In the problem description it was stated that one of the objectives of this thesis is to compare the routing aspect of FSM models and deployment models. In this segment the initial models are presented together with some general information. Summing up the chapter is a comparison of the models.

There are two main ways of incorporating routing into a mathematical model; arc flow model or path flow formulation. The difference between the two is that the arc flow model uses binary variables to state whether ship v travels from i to j, constructing routes. In a path flow model routes are predefined with binary variables telling whether or not the ship traded on that route. The models presented here, both the FSM and the deployment model, use arc flow. This has been done in order make the models as similar as possible, in order to get the best basis of comparison.

Models are formulated to represent the operation environment found in the autoliner industry. The models presented in this chapter are quite simple, if their current state is sufficient will be determined at a later stage.

The fleet size and mix model

According Fagerholt et al. [4] optimization for fleet composition problems are usually solved by using two different approaches:

1. Traditionally it is the IP and MIP approaches that have been used for solving strategic problems. This often leads to challenges in formulating the problem in a manner that is complex enough to imitate reality. The usual solution is to omit many of the routing and scheduling details that make an operation realistic.
2. An alternative is to apply optimization-based iteration methods developed for routing and scheduling.

In this thesis the method first presented, the traditional method, has been applied in order to get a finite answer. To understand the different symbols used in the defining the mathematical model a nomenclature is presented before the actual model:

Sets and indices

V Set of ship types, indexed by v

N Set of nodes, indexed by i and j

N_v Subset of nodes that can be operated by vessel$v$, $N_v \subseteq N$

A Set of arcs connecting nodes (i, j)

A^F Subset of arcs with frequency demand, $A^F \subseteq A$

A^D Subset of arcs with cargo quantity demand, $A^D \subseteq A$

P Set of product classes, indexed by p

S Set of sailing speeds, indexed by s

Parameters

F_{ij} Required number of voyages on arc (i, j)

D_{ijp} Transported cargo demand on arc (i, j) for product class p

K_{vp} Capacity of vessel v for product p

K_v Total capacity of vessel v (for all products)

T_{ijs} The time it takes to travel from node i to j with speed s

C_{vijs} Operational cost for vessel v for one voyage on arc (i, j) at speed level s

N Number of available vessel days

C_v^{TC} Time charter cost for using vessel type v

Variables

x_{vijs} Integer variable giving the number of times vessels type v operate arc (i, j) at speed s

y_{vijp} Transported cargo of product p on vessel v between node i and j

z_v Integer variable equal to the number of vessels of type v

With all sets, indexes, parameters and variables defined the mathematical model can be presented. The different parts are categorized and paired according to function and explained individually.

Objective function

$$\min \sum_{\substack{v\in V \\ (i,j)\in A \\ s\in S}} C_{vijs}\, x_{vijs} + \sum_{v\in V} N C_v^{TC} z_v \tag{5.1}$$

In this model it is assumed that the fleet consists of vessels chartered on long term contracts. The time charter costs are therefore paid for the whole time period. The objective of FSM models is usually to reduce the overall costs. This is done by finding the optimal mix between fixed charter costs and the fluctuating operational costs, like it is done here.

Operations

$v \in V$, $j \in N_v \mid (i,j) \in A$

$$\sum_{\substack{i \in N_v \\ s \in S}} x_{vijs} = \sum_{\substack{i \in N_v \\ s \in S}} x_{vjis} \tag{5.2}$$

In this fleet size and mix model it is of no consequence when a vessel operates an arc, therefore more detailed routing is not needed. This constraint (5.2) merely states that the same number of trips out of a node equals the number of trips into one.

Demand constraints

$(i,j) \in A^D, p \in P$:

$$\sum_{v \in V} y_{vijp} \geq D_{ijp} \tag{5.3}$$

$(i,j) \in A^F$:

$$\sum_{\substack{v \in V \\ s \in S_v}} x_{vijs} \geq F_{ij} \tag{5.4}$$

Constraints (5.3) and (5.4) signify the obligations of the shipping company. In the autoliner industry contracts usually specify some kind of quantity demand (5.3) and/or frequency demand (5.4).

Cargo capacity constraints

$v \in V, (i,j) \in A,\ p \in P$:

$$y_{vijp} \leq \sum_{s \in S} K_{vp} x_{vijs} \tag{5.5}$$

$v \in V, (i,j) \in A$:

$$\sum_{p \in P} y_{vijp} \leq K_v \tag{5.6}$$

The different vessels have various cargo constraints. The amount of cargo that can be transported is both a function of the different kinds of cargo transported (5.5) and the total carrying capacity (5.6). In addition, there is a relationship between transported cargo and sailing (5.5).

Availability

$v \in V$:

$$\sum_{\substack{(i,j) \in A \\ s \in S}} T_{ijs} x_{vijs} \leq N_v\, z_v \tag{5.7}$$

Constraint (5.7) provides the optimal fleet composition for solving the current problem. This is done by ensuring that the number of operation days for each vessel type is lower than the number of available days for that type.

Integer and non-negativity constraints

$v \in V,\ \ (i,j) \in A,\ s \in S_v$:

$$x_{vijs} \geq 0, \text{ and integer} \tag{5.8}$$

$v \in V, (i,j) \in A,$
$p \in P$: $$y_{vijp} \geq 0 \quad (5.9)$$

$v \in V$ $$z_v \geq 0, \text{ and integer} \quad (5.10)$$

The integer and non-negativity constraints secure valid results; one can for example seldom buy a half ship.

This particular model is based upon the FSM model draft established in the MARFLIX project as of **04.11.2011 [24]**. The model has however been strongly revised. For example, the model here is formulated using arc-flow variables, while the original used path-flow; this has been done to improve the basis for comparison with the deployment model presented later in this chapter. In addition, a cargo quantity variable has been added together with associated constraints in order to deal with the carrying capacity of the vessels.

The model doesn't consider the current size and mix of the fleet. One can only assume that since the vessels operate in such a stable market segment (due to the long term contracts), the changes in the fleet are not enormous. However if one had an existing fleet to consider this could easily be put into the mix→ $z_v = z_v^{existing} + z_v^{new}$.

Deployment model

The deployment model is formulated in much the same way as the FSM model; MIP with arc-flow routing. Constraints will only be thoroughly commented where they are different from the FSM model.

Sets and indices

V Set of ships, indexed by v
N Set of nodes, indexed by i and j
N_v Subset of nodes that can be operated by vessel$v$, $N_v \subseteq N$
A Set of arcs connecting nodes (i,j)
A^F Subset of trades with frequency demand, $A^F \subseteq A$
A^D Subset of regions with cargo quantity demand, $A^D \subseteq A$
T Set of time periods, indexed by t
P Set of product classes, indexed by p
S Set of sailing speeds, indexed by s

Parameters

F_{ij} Required number of voyages on arc (i,j)
D_{ijp} Transported cargo demand on arc (i,j) for product class p
K_{vp} Capacity of vessel v for product p
K_v Total capacity of vessel v (for all products)
K_{vp}^S Capacity of spot vessel v for product p
K_v^S Total capacity of vessel v (for all products)
T_{ijs} The time it takes to travel from node i to j with speed s
C_{vtijs} Operational cost for vessel v for one voyage on arc (i,j) at speed level s

Variables

x_{vtijs}	Binary variable stating whether or not vessel v sail the route between i and j with speed level s in time period t
$x_{vto(v)js}$	Binary variable equal to one if vessel v in period t travels from its initial position $o(v)$ to node j at speed s
$x_{vtid(v)s}$	Binary variable equal to one if vessel v in period t travels from node i to final destination $d(v)$ at speed s
y_{vtijp}	Transported cargo of product p on vessel v between nodes i and j in period t
s_{tij}	Integer variable stating how many spot trips taken in period t on arc (i,j)

Objective function

$$\min \sum_{\substack{v\in V\\ t\in T\\ (i,j)\in A\\ s\in S}} C_{vtijs}\, x_{vtijs} \tag{5.11}$$

The fleet is chartered, so the only thing that can be optimized now is the operational costs, as the other costs now can be regarded as fixed. The objective of the model is therefore now defined in order to minimize the operational costs of the fleet while still fulfilling its obligations (5.11).

Continuity and vessel capacity constraints

$$v\in V, t\in T,\ j\in N_v \,|(i,j)\in A: \quad \sum_{\substack{i\in N_v\\ s\in S}} x_{vtjis} \geq \sum_{\substack{i\in N_v \,|\, t>T_{ijs}\\ s\in S}} x_{v(t-T_{ijs})ijs} \tag{5.12}$$

$$v\in V, t=1: \quad \sum_{\substack{j\in N_v\\ s\in S}} x_{vto(v)js} = 1 \tag{5.13}$$

$$v\in V: \quad \sum_{\substack{t\in T\\ i\in N_v\\ s\in S}} x_{vtid(v)s} = 1 \tag{5.14}$$

$$v\in V, t\in T: \quad \sum_{\substack{\tau\epsilon T|t-T_{ijs}<\tau\leq t\\ (i,j)\in A\\ s\in S}} x_{vtijs} = 1 \tag{5.15}$$

To secure model continuity, constraint (5.12) state that the next voyage will start the day after the previous have finished. Because it might be advantageous to have the ships be idle for a while, the ships can wait in port by traveling to the same node it is currently situated in; $T_{ii}=1$. Constraints (5.13) and (5.14) state the voyages of the vessels from their places of origin and their destinations, respectively. These places are assumed known. Constraint (5.15) ensure that each vessel operate no more than one trade in the same time frame.

The level of detail in these constraints is quite a contrast to the one routing restriction found in the FSM model. The reason for this added complexity can be traced to the newly added time aspect.

Demand constraints

$(i,j) \in A^D,$
$p \in P:$
$$\sum_{\substack{v\in V\\ t\in T}} y_{vtijp} \geq D_{ijp} \quad (5.16)$$

$(i,j) \in A^F:$
$$\sum_{\substack{v\in V\\ t\in T\\ s\in S}} x_{vtijs} + s_{tij} \geq F_{ij} \quad (5.17)$$

The demand constraints are here defined in much the same way as in the FSM. The actual demand values however are scaled down to fit the new time frame, and the variables are now also time dependent.

Cargo capacity constraints

$v \in V, t \in T,$
$(i,j) \in A, p \in P:$
$$y_{vtijp} \leq \sum_{s\in S} K_{vp} x_{vtijs} + K_{vp}^S s_{tij} \quad (5.18)$$

$v \in V, t \in T,$
$(i,j) \in A:$
$$\sum_{p\in P} y_{vtijp} \leq K_v x_{vtijs} + K_v^S s_{tvij} \quad (5.19)$$

These constraints are also found in the FSM with the only divergence being the added time dependence of the variables.

Integer and non-negativity constraints

$v \in V, t \in T,$
$(i,j) \in A, s$
$\in S:$
$$x_{vtijs} \in \{0,1\} \quad (5.20)$$

$v \in V, t \in T,$
$j \in N_v, s \in S:$
$$x_{vto(v)js} \in \{0,1\} \quad (5.21)$$

$v \in V, t \in T,$
$i \in N_v, s \in S:$
$$x_{vtid(v)s} \in \{0,1\} \quad (5.22)$$

$t \in T, p \in P,$
$(i,j) \in A:$
$$y_{vtijp} \geq 0 \quad (5.23)$$

$t \in T, (i,j) \in A:$
$$s_{tij} \geq 0 \; and \; integer \quad (5.24)$$

Constraints (5.23)-(5.24) ensure that the variables behave as they are intended to.

In many ways this proposed deployment model is a rewrite of the previous described FSM model. In addition to elements from the FSM model, the deployment model have borrowed components from two articles; Rakke et al.,[25] and Grønhaug and Christiansen [26]

Model comparison

The two models have been crafted in order to fulfill two distinct purposes; the FSM model is to find the optimal fleet composition, and the deployment model is to find the optimal operational pattern of this fleet. And, no matter the similarities, the models are quite clearly very different from each other.

The main difference between the presented models can be explained by one word; time. When planning for tactical situations knowing when things happen, and need to happen, is crucial, while in strategic settings this is of lesser importance. Because of the importance of when events happen the variables are made time dependent and additional constraints are needed. Another major difference connected to time is that in the deployment model vessels can operate outside the given time frame, as long the trip has started before the end of the computation. This cannot be done in the FSM model.

In the deployment model the individual vessels are in focus. The FSM model does, however, not discriminate between the different vessels when assigning the different arcs who are to be operated by which type of vessel. The reason for this assumption simply that there are no vessels yet, the fleet is determined based on operation demand.

In the FSM model no node of origin is defined for the vessels, while in the deployment model there is. However, in the FSM model each ship type must operate as many arcs into a node as out of the node; in practice this means that each type of ship end up in the node they started in. The vessels in the deployment model on the other hand have defined their point of origin, and can end their journey wherever is best for the final solution.

In chapter 7 the result of a wide range of tests made on these models will be presented. There the solution quality of the FSM will be made clear.

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Chapter 6

Computational Study

Because of the complexity of the problems there is no hope of solving these models by hand. The models have therefore been implemented into the computer optimization software FICO™ Xpress Optimization Suite. The programming language the models are written in is called MOSEL. The version used in the development of this thesis is Xpress-IVE Version 1.22.04, Xpress Mosel Version 3.2.3 and Xpress Optimizer Version 21.01.09. It is by the use of Xpress that the tests have been done, as it has dedicated software to solve these kinds of problems at relative high speeds. However, the effectiveness of the software is not the only factor influencing computation time; hardware also matters. The computer used is a Dell Inspiron M301Z, with an AMD Turion™ II Neo K625 Dual-Core Processor 1.50 GHz and 4.00 GB RAM. The operative system used is Vista 7, 64-bit. This is important to have in mind whenever there are references to computation time.

The models have been tested against a variety of different datasets created to imitate, if not recreate, the actual operational conditions found in the autoliner industry. The scenarios tested have been generated by an instance generator made in MATLAB. This program have also dealt with the processing of the data output of the FSM model that was to be used by the deployment model. The MATLAB version used was: Version 7.10.0.499 (R2010a), 64-bit (win64).

How the different models and programs worked together in order to produce the needed model output is illustrated in Figure 2. Here, the main data is first generated by the instance generator created in MATLAB. The data is first in the FSM model, then in the deployment model together with the processed data output of the FSM. Both models produce operation cost estimations and vessel routing data, which form the basis for comparison of the different models.

The model files can be found as appendices to this thesis.

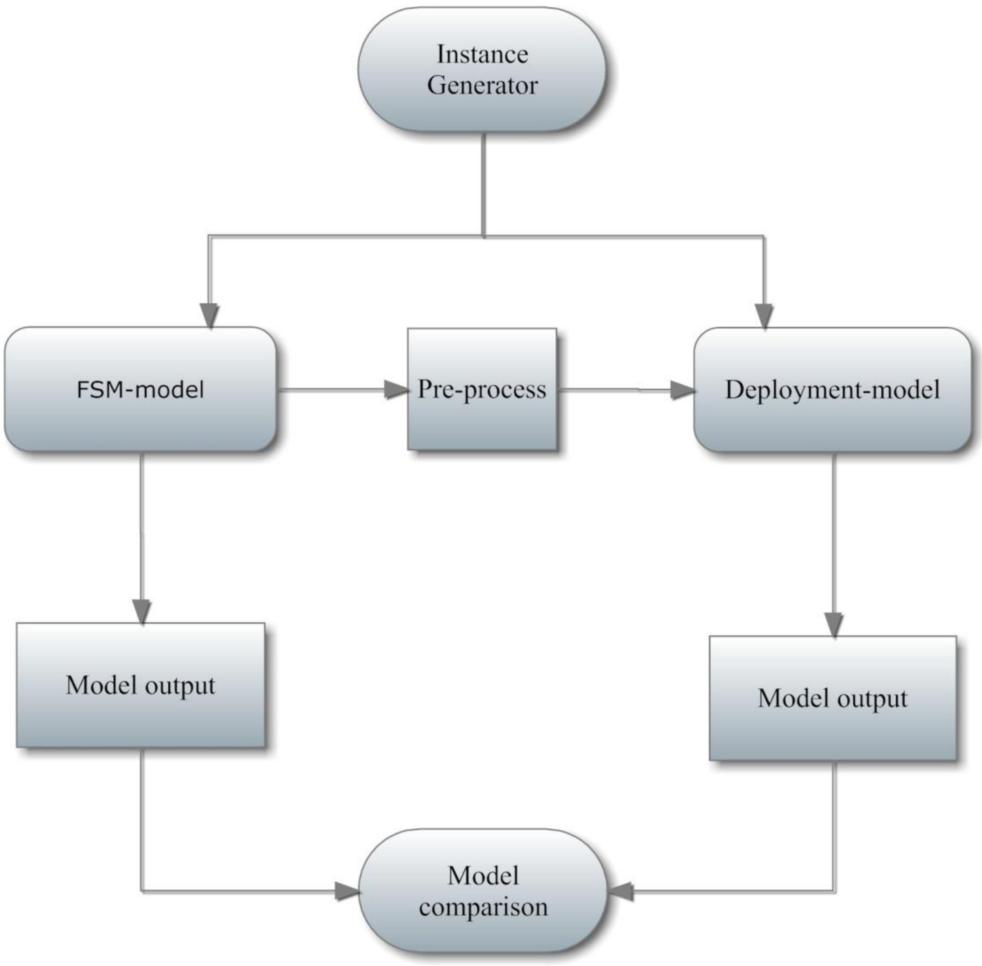

Figure 2: Model Interaction

Scenarios

Earlier in the thesis how the different constraints of the mathematical models represent different industrial aspects found in shipping has been discussed. However, without representative data input the relevance of the models is lost. All data, both the size of the sets and parameter values must somehow be provided. While some of the sets are fixed (or found by the FSM model), most parameters are generated by an instance generator modelled in MATLAB.

In this section a description of how the different pieces of information has been created, or found, and examples on how the data correlates in order to accomplish relevant findings is presented. In addition, how the data relates to the environment it is to represent will be discussed and can in that regard be considered an extension of the model description.

There are several ways to present the data; Fixed and random, sets and parameters, common or individual for the different models. Most of the sets used by the models are shared; Nodes, arcs, vessel types, speed and product types. The deployment model, however, in addition uses the information from the FSM model to create a fixed fleet composition and is defined as a function of time. In the data files nodes, vessel types, speed alternatives and product types are defined by the number of alternatives. The sets are then created and identified by numbers ranging from 1-n. Time is defined the same way, but starts at 0 because of start position and storage. In the FSM model the time horizon is defined by the number of days the vessels are available for operation (N). This value is equal to the number of days in the time set used in deployment. Different runs of the models operate with different time frames, from 60 days to 10 years.

By giving the sets different sizes the complexity of the models are tested. While the reason for giving some sets certain sizes has been based on reality (cargo categories), most set sizes are based on convenience.

Each node in the models represents a region or port. In most of the tests discussed in this thesis has a total of four nodes, resulting in a total of 16 arcs; the paths that bind the nodes together. The largest scenarios studied have eight nodes. Whether or not a vessel can operate a specific trade is randomly decided by the instance generator, in addition to other relevant data like the distance between the different nodes.

In all scenarios there are six alternative vessels that can be chosen for the fleet. Each vessel has a predefined carrying capacity (K, as shown in Table 3), time charter costs (C_v^{TC}) and oil consumption (C) at different speeds **(**Table 4**).** These values are based on the corresponding values of vessels operated by WWL. These values are all constant throughout all the different tests. These vessels represent the breadth of the vessel types used in the industry. In order to get as diversified fleet as possible the time charter cost of the different vessels have been set to be equal. In these studies the operational costs have been of the greatest importance.

Ship type	RTmax	HHmax	NCCmax
LCTC-2 Aniara	7620	36000	5500
LCTC-3 Carmen	7934	36000	16000
LCTC-4 Tugela	8014	38000	23000
PCTC QUS	6300	20000	0
RoRo Mk2	4474	45000	28000
RoRo Mk5	6004	75000	41000
Spot Vessel (PCTC Talia)	6334	21000	0

Table 3: Vessel Carrying Capacity

The spot vessel used in the tests studied in this thesis has the carrying capacity of the PCTC Talia (Table 3). The cost of spot vessels, on the other hand, is not as straight forward. In order to force the deployment model to use the estimated fleet the operational costs of the spot vessels have been set to five times the charter party speed of the Mk2; the most fuel intensive vessel used in this study; more on this in chapter 7.

To limit the complexity of the model, three operating speeds has been considered; 16kn, 18kn and 20kn. These speeds represent slow steaming, charter party and high speed transportation. Even though there usually are several more speed alternatives in realistic conditions it is believed that these three represent the main flexibility of vessels in terms of speed.

Ship type	HFO Consumption				TC Costs
	In Port	Low speed	CP-speed	High speed	
LCTC-2 Aniara	5	42	53	67	23000
LCTC-3 Carmen	5	48	57	68	23000
LCTC-4 Tugela	5	51	58	66	23000
PCTC QUS	6	37	43	49	28000
RoRo Mk2	9	59	72	86	28000
RoRo Mk5	8	51	61	73	33000

Table 4: Fuel Consumption

As is usual in the car freight industry is the **cargo** divided into three categories; automobiles, Rolling Equipment and Static Cargo. The last two categories are sometimes also known as high and heavy (HH) and non-containerized cargo (NCC), respectively.

All the information used by the models is formed as matrixes and arrays. When creating the instance generator, finding the optimal randomness for the creation of a subset, or parameter, was one of the major decisions. Of equal importance was to guarantee that no node was isolated, and no vessel start in a node it cannot start in, etc. The interaction between the different subsets in order to secure the best possible results was time consuming. For example; whether or not there is a frequency demand or a cargo quantity demand has been determined by subsets, but not the number of trips or the size of the demanded quantity. Both demand types is generated based on the time available. A visit once every two weeks is the highest required frequency for a single trade, to limit the number of trades. The demand of cargo is found by summing up the daily production rates. Cars and related goods are usually built for a specific market, and so is the case here; all produced material must be transported. In the cases where $A^F \geq A^D$ total production is defined so that it is equal to, or greater than, the given a given percentage of vessel capacity times the frequency demand. If production rates are not defined by frequency, demand is random based on daily production rates and the number of days in the time horizon.

For more information about how the data has been generated look at the MATLAB files in the appendix.

Xpress models

The computer software FICO™ Xpress Optimization Suite uses a combination of methods for solving the different model tests. First a LP relaxation is found using simplex in the presolve phase. This is followed by root cutting and heuristics, followed by branch-and-bound. For the branch-and-bound an aggressive cutting method was used. Also to speed up the computation the fuel consumption was used for the optimization of the deployment model, instead of the cost of it, in the computations. This has proven to be faster, possibly due to the reduced number of digits.

For the different computations a maximum runtime was set. The length of time varied with the test and complexity of the case that was to be examined. A max time was used because of time limitations.

Chapter 7

Results

The models have been presented, and so have the procedures connected to running the computer representations of the models for varying scenarios. In this chapter the results of the different tests with varying scenarios, time horizons, model variations etc. will be presented. For each of the different tests there are two sub-segments. In the first segment a problem is presented together with a test that might increase some insight into this problem. In the second segment the results of the presented test is discussed.

Test #1: Original models

In this section the results of tests where the models are as they were presented in chapter 5 are studied. The tests consist of four different scenarios. Each scenario is tried at various planning horizons; 60, 120, 180 and 360 days.

FSM model results

In each run of the FSM model a fleet was proposed as optimal for solving a given shipment demand. In addition, an estimate of the cost profile of these operations was given. One could assume that because the only thing that vary in these first test of the different scenarios the needed fleet would be the same for each test; to do twice the work, in twice the time, the same amount of vessels are needed. In Table 5 one can see that this is not the case. The overall trend is that the fleet size decreases with an increase of the time frame, and so does the overall fleet composition.

Scenario	1				2				3				4			
Time	60	120	180	360	60	120	180	360	60	120	180	360	60	120	180	360
Type 1	-	-	-	-	-	-	-	-	0	1	1	1	3	3	2	2
Type 2	-	-	-	-	10	9	9	9	5	4	4	4	3	3	3	3
Type 3	8	7	7	7	-	-	-	-	3	2	2	2	1	1	2	2
Type 4	-	-	-	-	0	1	1	1	-	-	-	-	1	1	0	1
Type 5	-	-	-	-	-	-	-	-	-	-	-	-	3	3	3	2
Type 6	-	-	-	-	3	3	3	3	-	-	-	-	-	-	-	-
Sum	8	7	7	7	13	13	13	13	8	7	7	7	11	11	10	10

*Markings in red represent changes in fleet

Table 5: Fleet Composition

The change in fleet composition for different time horizon can be caused by rationalization. As mentioned in chapters 5 and 6, the demand is defined in two ways; the minimum number of times an arc must be operated, and the minimum transported quantity of a commodity on an arc. Since not all demand is defined by frequency the fleet can utilize the economy of scale in order to deal with the increased demand. Another factor is that with increased time the time margins connected to the activity level of the fleet are increased; the fleet can operate at lower speeds in order to fulfill its obligations or the size can be reduced.

Different fleet composition result in differences in fleet costs and operational patterns. In Table 6 only the operational costs is included, not the total costs, because these costs are the only costs optimized in the deployment model. From the two tables it is clear that with increase in time horizon the fleet uses the advantage of increased margins to lower the overall speed of the fleet, and adjust the fleet for larger quantity demand.

Scenario		60	120	180	360
1	Operational costs	19 263	35 476	50 935	101 869
	Daily operational cost	321	296	283	283
	Slow-steaming	31.8 %	17.5 %	29.3 %	28.4 %
2	Operational costs	31 323	61 534	92 369	180 560
	Daily operational cost	522	513	513	502
	Slow-steaming	37.0 %	35.7 %	41.0 %	42.1 %
3	Operational costs	16 936	30 231	41 770	80 772
	Daily operational cost	282	252	232	224
	Slow-steaming	76.9 %	66.7 %	97.1 %	100.0 %
4	Operational costs	24 818	44 645	67 000	131 727
	Daily operational cost	414	372	372	366
	Slow-steaming	46.9 %	82.8 %	71.4 %	69.5 %

Table 6: FSM Output (1000NOK)

Deployment model results

FSM models are, as previously mentioned, usually used on longer planning horizons. But, one of the goals of this study is to see how results of the FSM stand the test of being applied to a deployment model. For the best possible comparison basis the same time horizons have therefore been used for the two models. The complexity of deployment models makes it difficult to apply them to larger scenarios. An example of this can be found in the fact that the computation tools available for the tests presented here made it impossible to get a feasible integer solution to one of the scenarios for the longest time horizon tested (360 days), Table 7. In these computations the time dependence of the spot trades was removed in order to speed up the solution time.

Scenario		60	120	180	360
	Operational costs	14 906	27 672	39 908	77 139
	Spot Cost	0	0	0	0
	Total	14 906	27 672	39 908	77 139
	Daily operational cost	248	231	222	214
1	Fleet idleness	3.75 %	0.00 %	0.00 %	0.04 %
	Spot trades	0	0	0	0
	Slow-steaming	100 %	95 %	100 %	90 %
	Computation time	1800s	3600s	3600s	7200s
	Gap from best bound sol.	12.05%	3.77 %	2.45 %	1.53 %
	Operational costs	19 289	39 276	64 100	
	Spot	0	0	0	
	Total	19 289	39 276	64 100	
	Daily operational cost	321	327	356	
2	Fleet idleness	12.56%	8.53 %	0.00 %	
	Spot trades	0	0	0	
	Slow-steaming	100 %	100 %	96 %	
	Computation time	1800s	3600s	3600s	
	Gap from best bound sol.	0.31 %	1.06 %	0.99%	
	Operational costs	13 761	28 515	41 442	80 289
	Spot Cost	0	0	0	2 484
	Total	13 761	28 515	41 442	82 873
	Daily operational cost	229	238	230	230
3	Fleet idleness	25.42%	11.79 %	12.30 %	16.75%
	Spot trades	0	0	0	1
	Slow-steaming	100 %	100 %	100 %	98%
	Computation time	1800s	3600s	3600s	7200s
	Gap from best bound sol.	5.78 %	6.99 %	4.81 %	1.70%
	Operational costs	18 401	35 599	55 455	99 114
	Spot Cost	0	0	0	1 932
	Total	18 401	35 599	55 455	101 046
	Daily operational cost	307	297	308	281
4	Fleet idleness	19.67%	15.45 %	5.06 %	28.83%
	Spot trades	0	0	0	1
	Slow-steaming	96 %	96 %	58 %	77.04%
	Computation time	1258s	3600s	3600s	7200s
	Gap from best bound sol.	0.00 %	6.16 %	1.39 %	4.23%

Table 7: Deployment Output (1000NOK)

For all model tests of this size the time it took the FSM model to converge to optimality no more than a few seconds. The deployment on the other hand took much longer. In fact, only a few times did they fully converge, even after running for several hours. As mentioned, one scenario case failed to find a feasible solution at all; the 360 day planning horizon for scenario four. Trials on up to eight hours were tried for this particular case without success. This was probably due to a combination of the size of the test, the largest one tried here, and the lack of sufficient computational power and memory.

As explained in chapter 6, the gap from the best bound solution shown in Table 7 might be a little misleading. This is because of problems with the model connected to spot trades. If the price of the spot vessels are put unnaturally high, instead of using the company's fleet model might put in a spot vessel on a trade because an existing vessel need to take on a ballast trade in order to get in position. As a consequence the spot price has been set five times the operational costs of a vessel in the fleet in order to force the fleet to do as much of the transportation legs as possible. In Table 7, however, the price of the spot trips is set a bit closer to comparable real values.

Model comparison

The model output from the deployment model is much more detailed than what is possible to gather from the FSM model. However, not all the information added in the table for the deployment model is omitted from the FSM table because it can't be found; the reason computation time and the gap from the best bound solution is not included is that all trials have converged completely, and most in less than a second or less. The exception her is the 360 day test for scenario 2; it took 675 seconds to fully converge. The same case scenario was the one that failed to locate a single feasible solution when tested by the deployment model. Computation time is a combination of model complexity, solver efficiency and luck.

The goal of both models is to reduce the costs of the fleet. Therefore the natural starting point for a comparison of the two models is how the operational costs found in the models relate to each other. The results can be found in Figure 3.

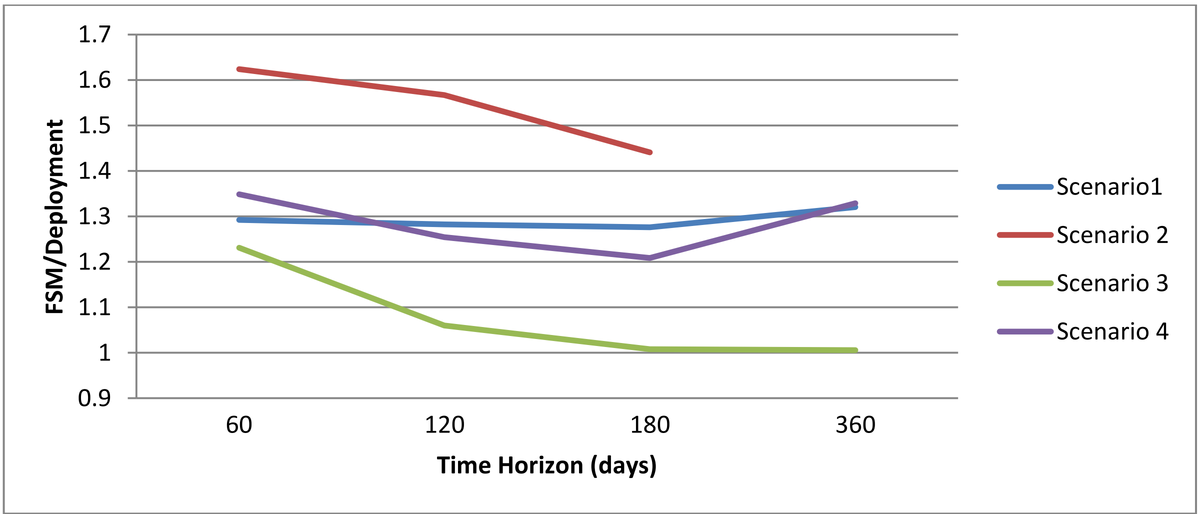

Figure 3: Model Comparison, Operational Cost

In Figure 3 it is easy to see that the cost of the fleet is estimated to be quite a bit higher in the FSM than I the deployment model. The reasons for this difference can be found in two related factors; the distance travelled and the operation speed of the fleet. An example of the routing differences is given in Table 8**.** The example is the results from the 60 day planning case for scenario 4.

Arc	FSM	Deployment	Time of trip*
(1,3)	5	5	1,1,1,1,35
(1,4)	4	0	
(2,3)	4	4	1,1,24,45
(3,1)	4	4	1,35,35,43
(3,2)	4	2	1,23
(3,4)	5	6	1,2,22,22,35,35
(4,1)	5	5	26,43,44,56,56
(4,3)	4	4	1,1,22,43
Total trips	35	30	* deployment

Table 8: Example Routing, Scenario 4 (60 day)

The two models are very different concerning some of the premises for the routing of the vessels, resulting in quite significant routing differences, as can be understood in the variations in the frequency of which the nodes have been visited. One of the reasons of the differences is the starting location of the different vessels. Also, in the FSM model there is no discrimination between the different vessels, the routing is instead based on different ship types. Furthermore, all the different ship types must have as many trips into a node, as out of it, something that might result in unnecessary ballast legs. In the deployment model each vessel is assigned a starting position and the vessels can end up in any given node. This difference in starting and ending conditions possible reduce the number of trips needed.

In the deployment model there is an increase in the length of the planning period, this doesn’t reduce the number of trips but can lower the operational speed of the fleet compared to the FSM model output. However, the FSM model doesn’t discriminate between the different vessels when routing the vessels, reducing the chance of a vessel being unavailable because the vessel in question has served its time. This is especially a problem with the longer time horizons where the added time horizon of the deployment model is negligible compared to the length of the overall planning period, while the extra accumulated time is increasing the efficiency of the fleet in the FSM model. Increasing the speed of the deployed vessels is one possible solution to this problem. But, the voyages included in this study last from 10 to 35 days in charter part speed. The speed alternatives used in this study makes it possible to reduce, or increase, this voyage time by one to four days. If the average voyage lasts 22.5 days, this means that maximum speed must be had on at least five trips to squeeze in the extra trip. Furthermore, the vessel must be located where it is needed at the time, therefore a ballast leg might be necessary or a spot vessel must be put in; see Table 7.

Aside from the difference in routing, Table 8 makes another problem evident. The spread in the trips on the different arcs is not very good. To improve the comparison basis for the FSM model the deployment model must be improved.

Test#2: Operational time spread

In the problem description it was stated that the deployment model was to be used as a reference as to how good the routing had been formulated in the FSM. However, from the data presented in the previous segment of this chapter, it is clear that the routing model itself is not well defined enough to represent the actual transportation environment; the trips on the different arcs are not well enough spread out over the planning horizon. An extension is therefore needed. In addition, further analysis regarding the differences in routing between the models must be done.

There are several ways of eliminating the occurrence of clustered trip intervals in the routing model. By applying inventory constraints one can simulate the cargo production; if a cargo is not produced yet, it cannot be transported. Another way is to split the total planning horizon into time segments based on the minimum frequency a rout must be operated in order to fulfill both frequency demand and quantity demand; much the same way the vessel capacity constraint is defined in regards to sailing time.

Inventory routing

Inventory routing can be defined as the integration of inventory management with the routing of vehicles. If the production of cars is modeled as a continuous process, and the storage capacity in the harbor is used as a maximum constraint this principle can be transferred to fit the model in use. A description of the new parameters, variables and constraints follow. For explanations of the other symbols, see page **14.**

Parameters

P_{tijp} Production in period t of goods in node i made for node j of product class p

$\overline{K_{ijp}}$ Maximum storage capacity for goods to be transported on arc (i,j) of product class p

Q_{ijp} Initial storage of goods to be transported on arc (i,j) of product class p

Variables

q_{tijp} Stored cargo in period t ready for transport on arc (i,j) of product type p

$t \in T, (i,j) \in A, p \in P$: $$q_{tijp} \geq 0 \quad (7.1)$$

Inventory constraints

$t \in T \mid t = 0, (i,j) \in A, p \in P$ $$q_{tijp} = Q_{ijp} \quad (7.2)$$

$t \in T \mid t \geq 1, (i,j) \in A, p \in P$ $$q_{tijp} = P_{tijp} + q_{(t-1)ijp} - \sum_{v \in V} y_{vtijp} \quad (7.3)$$

$t \in T, (i,j) \in A,$
$p \in P$

$$q_{tijp} \leq \overline{K_{ijp}} \tag{7.4}$$

The relation between the storage levels in the previous time period, the daily production and the transported cargo is found in (7.3). This will hopefully result in an even spread in transportation throughout the time frame of the simulation. In this industry it is usual to produce vehicles for a specific region based on the demand there; giving the goods an origin and destination. The storage values at the beginning of the computation are given by constraint (7.2). There is an upper limit on the amount of cargo stored (7.4). Because of the cost of sailing the optimal time of transportation is when each vessel is full, setting the right upper limit for stored cargo is therefore important for the right spread.

Frequency spread

The different rips on each arc can also be spread out by stating that in a given time horizon, individual to that arc, the number of trips on that arc must be equal or more than one. The time horizon will be defied by the length of the model time horizon divided by the minimum number of times the arc must be operated during the computation. Where there is only quantity demand the minimum number of trips is found by using the largest vessel in the study as a reference, example (Table 10). This arc time is the only needed new parameter, and only one additional constraint is needed.

Parameter

T_{ij}^{F} Frequency spread time for arc (i,j)

Frequency spread constraint

$t \in T, (i,j) \in A$:

$$\sum_{\substack{v \in V \\ \tau \epsilon T | t - T_{ij}^{F} < \tau \leq t \\ s \in S}} x_{vtijs} \geq 1 \tag{7.5}$$

This constraint resembles the constraint ensuring each vessel to only operate a single arc for any given time (ref. 5.15). The constraint is here, however, a function of a different time parameter and must be equal or greater than one in any given time period.

Extension alternative comparison

When subjected to the same data that was applied to the models in Test 1, the extended deployment models' result in quite markedly different results. For all tested scenarios, the spread between each required trip was improved significantly as can be seen the example presented in Table 9**.** But, in almost all cases, extra capacity was needed in order to fulfil the new constraints.

	Original		Frequency spread		Inventory routing	
Arcs	No. Trips	Time of trip	No. Trips	Time of trip	No. Trips	Time of trip
(1,3)	5	1,1,1,1,35	5	1,13,25,37,46	5	1,14,27,40,51
(1,4)	0		2	2,5	3	1,1,31,
(2,3)	4	1,1,24,45	5	1,13,28,43,58	6	1,9,20,31,42,53
(3,1)	4	1,35,35,43	4	1,16,31,46	5	1,14,27,40,53
(3,2)	2	1,23	2	1,40	4	1,21,31,56
(3,4)	6	1,2,22,22,35,35	3	20,24,31,	3	20,26,38
(4,1)	5	26,43,44,56,56	4+1	1,13,25,37,49	4+2	1,12,21,34,43,54
(4,3)	4	1,1,22,43	4	1,16,31,43	5	1,7,23,39,55
Sum	30		30		37	

*Markings in red are spot trips

Table 9: Example Routing #2, Scenario 2 (60 day)

Table 9 is an example of the improvement the added extensions have led to in spreading the contracted trips over the entire planning period. Table 10 show how many of the minimum trips needed in this particular case. On a side note, it is clear that the possibility of operating the vessels outside the give time frame is essential in order to get the necessary spread.

Frequency demand	Quantity Demand (CEU)	Minimum Trips
5	23398	5
0	0	0
2	27834	4
4	25452	4
1	6791	1
0	0	0
5	16836	5
4	19873	4

Table 10: Voyage Demand, Scenario 2 (60 day)

For scenario 2 the frequency spread model proved to be the best extension method if the criteria is to minimize the use of spot vessels (Table 9). This is however not all ways the case. Table 11 present another example, scenario 1, where the opposite happens.

	Frequency spread		Inventory routing		Total
Arcs	No. Trips	Time of trip	No. Trips	Time of trip	Demand
(1,2)	4	1,2,17,32	4	1,21,35,47	2
(2,1)	4	1,16,31,46	4	18,33,44,60	4
(2,3)	5	1,16,30,45,60	5	5,9,27,37,51	4
(3,2)	4	1,16,31,46	5	1,1,12,41,50	4
(3,4)	2	1,31	3	6,37,59	2
(4,3)	1+1	1,31	2	28,58	2
Sum	21		23		18

*Markings in red are spot trips

Table 11: Example Routing #3, Scenario 1 (60 day)

Because of the differences in the underlying cause of the spread, there are some variations in output from the two model versions. The extra trips and additional spot vessels lead to higher operational costs compared to the FSM and the original routing model, as seen from Table 12**.** The table shows only the results from the routing examples.

Scenario		FSM	Regular	Freq. Spread	Inventory Routing
1	Operational costs	19 263	14 906	14 758	16 312
	Spot	0	0	1 311	-
	Total	19 263	14906	16 069	16 312
	Daily operational cost	321	248	268	272
	Fleet idleness	0%	4 %	18,75 %	11,46 %
	Spot trades	0	0	1	0
	Slow-steaming	32 %	1	55 %	82.61%
	Computation time	0s	1800s	97s	3600s
	Gap from best bound sol.	0,00 %	12,05 %	0,00 %	20.37%
2	Operational costs	31323	19289	20 596	24 455
	Spot	0	0	1 311	2 622
	Total	31 323	19 289	21 907	27 077
	Daily operational cost	522	321	365	451
	Fleet idleness	0%	9 %	72,41 %	10.64%
	Spot trades	0	0	1	2
	Slow-steaming	37 %	100 %	21,54 %	60%
	Computation time	0	1800s	890s	7200s
	Gap from best bound sol.	0,00 %	0,31 %	0,00 %	3.98%

Table 12: Cost of Routing + Extensions

In order to reduce the chance of the models putting in unnecessary spot vessels on a trade, the price of spot vessels have been set unnaturally high in the calculations, as described in chapter 6. The price gap between the current best optimal solution and the best bound solution might therefore be greater than it might be in reality. The spot price estimations presented in the Table 12, however, is an assumed good approximation.

The instance generator used in establishing the different scenarios randomize the start location for the different vessels. Vessels starting on bulk trades when they are needed elsewhere might have a negative impact on the fleet performance. Therefore it might be interesting to see what happens if this tendency is removed. One must assume that WWL position their fleet better than a random instance generator made in MATLAB. In the two cases tested, the relocation of two vessels the result for the outcome was minimal. Two ballast legs were removed, but the same amount of extra capacity was still needed.

Until now only results of the 60 day time horizon tests have been considered. In the examples given here of the routing for a 60 day time horizon many trips are at the moment of completion en route to their destination port. This means that the ships are not ready for their next trip at the start of the next period. One can therefore ask whether or not the fleet will be able to fulfill the obligations of the fleet in the near future. Tests with longer time horizons than 60 days have therefore been conducted in order to test the two model extensions. The results are negative. With increased time frame the FSM produce smaller fleet recommendations. In addition, the extra time the fleet has available since they can operate outside the given time frame becomes a smaller part of the overall operations. These two factors put together make the need for a lot of additional tonnage needed. This problem is further discussed under test #5 presented later in this chapter, where also two examples of the 120 day scenarios are given; Table 15

For the longer time periods it has proved to be difficult to use the extended model to due to limitations of available computational tools. The frequency spread formulation was possible to use on some of the scenarios in its 180 day planning horizon. The inventory routing formulation proved to be too computer intensive for this and could only be used with some success for scenarios of the size presented here for 120 day horizon. Deployment models are usually constructed for time horizons spanning a few months. These model formulations have proven to fall well into this time frame, larger computational power than what has been available for the author during the writing of this master thesis is however needed to solve problems of industrial size.

The problems connected to applying the fleet proposed by the FSM model into the deployment model is not necessarily only connected to excessively loose routing constraint. The need of spot trade can also be a product of badly defined demand in the studied scenarios. In the container shipping segment, for example, shuttle services is the norm for operation, the reason being that all containers must be transported back to their place of origin. WWL has a few defined shuttle routes **[10],** but most trades are operated by any vessels available at the time. A more balanced demand pattern might remove some of the problems with unwanted spot trips, and might also help the natural spread of the trips.

The preliminary conclusion regarding the accuracy of the FSM in predicting the demand of a fleet is after the two first tests that the FSM model, in its present form, should not be relied upon as the only means for establishing the actual optimal fleet. It can, however, be used as a guidance. Further study is needed.

Test #3: Continuous VS integer variables

Because of the size of real industrial cases, continuous variables are often used instead of integer ones when establishing the company fleet composition. Whether or not this has any effect on the solution quality is therefore an important question. For looking into this, larger scenarios than those that have been treated thus far have been constructed in order to get the best possible comparison basis to real world cases. The tests conducted here have only changed the number of voyages from integer to continuous. In the mathematical model this variable is depicted with an $x_{v(t)ijs}$. The resulting fleet is nonetheless always given as integer.

In Table 13 it is clear that for the larger instances the differences are not that large for the time periods they are intended for. The cost comparison values are based on the data from the 360 planning horizon case with continuous variables. The *I* after the different planning lengths identify the data as being based on integer representations of the problem, while the lack of the *I* indicate continuous variables.

Scenario		60	60I	180	180I	360	360I	1800	1800I	3600	3600I
5	Cost comparison	1.05	1.16	1	1.03	1	1	0.99	0.99	0.99	0.99
	Fleet size	32	36	31	32	30	31	30	30	30	30
	Changes	2	6	1	4	0	5	0	0	0	0
	Run time	1s	1800s	1s	1800s	1s	3600s	1s	3600s	1s	3600s
	Gap	0.0%	0.8%	0.0%	0.6%	0.0%	0.6%	0.0%	0.0%	0.0%	0.1%
6	Cost comparison	1.04	1.11	1	1.04	1	1.01	0.99	0.99	0.99	0.99
	Fleet size	42	47	41	41	40	40	40	40	39	40
	Changes	1	15	1	15	0	8	0	2	1	2
	Run time	0s	842s	0s	1800s	1s	3600s	1s	3600s	0s	3600s
	Gap	0.0%	0.0%	0.0%	1.4%	0.0%	0.6%	0.0%	0.1%	0.0%	0.0%
7	Cost comparison	1.07	1.19	1.02	1.07	1.00	1.02	0.97	0.98	0.97	0.97
	Fleet size	46	50	43	45	42	43	42	42	42	42
	Changes	6	7	1	3	0	5	2	2	2	2
	Run time	1s	1800s	1s	1800s	1s	3600s	1s	3600s	1s	3600s
	Gap	0.0%	0.6%	0.0%	2.2%	0.0%	1.3%	0.0%	0.2%	0.0%	0.1%

Table 13: Continuous VS. Integer Variables

The tests have shown that there are far bigger differences between the results from the shorter time horizons than the longer ones. For example, in scenario 3 the fleet remained unchanged for the 1800 and the 3600 day planning horizon, regardless of whether or not the variable was integer or continuous. The operation costs were however somewhat lower than the reference value, but for the longer time periods one must also remember that the unstable market conditions make the scenario highly speculative and therefore for those cases a higher margins are needed. Similar results have been found for the smaller scenarios, used in tests 1&2.

Test#4: Fuel cost

At the moment this paper is written the cost of fuel is quite high, as of 26th of May 2012 crude oil of Brent quality sold for 106.71$ **[27]** roughly double the price only a decade ago. However, before the financial crisis in 2008 the prices were even higher reaching prices up to145$ per barrel. Similar fluctuating values can be found for the main source of power for marine vessels; heavy fuel oil.

In a previous section of this chapter, the connection between the speed of the vessels and the fleet composition has been discussed. With reduced speed a larger fleet is needed to fulfill the company's obligations in the same timeframe. In recent years much attention has been given to the slow steaming of vessels due to the excess of tonnage in many shipping sectors, and the high fuel prices. Because of the fluctuating market conditions a simple test has been conducted, to find out what effect these price variations have on the FSM model output. In all tests until now the price of fuel has been set to 700NOK, the same value WWL operate with when establishing their fleet. Here, in addition to the regular fuel price both higher and lower fuel prices have been considered. In these tests the difference in fuel cost has been set to be 200NOK (approx. $\pm$30%).

In Table 14, on the next page, the first four scenarios are the regular scenarios studied in tests 1&2. The other three scenarios are the larger ones used in test three. The largest differences are found in the longer instances. For the longer instances it might be argued that, because of the large gap between the present solutions and the best bound one, the findings are speculative. However, the similar findings were found when the scenarios were tested with continuous variables and for the longer time horizons which converged much more successfully. The table shows only the results of the tests conducted with the 360 timeframe.

The results of the tests proved to resemble the predicted outcome; the size of the fleet was in many cases re-sized depending on the fuel prize, in other cases the difference lay mainly in the composition of the fleet. The optimal fleet is found based on finding the lowest overall cost of the fleet, while still fulfilling the company's contracted obligations. When the prices of fuel rise or fall, the operation costs of the fleet is reevaluated against the time charter costs of the vessels. For example, if it is cheaper to use two smaller vessels at low speed, instead of a larger vessel at full throttle this will be the result of the FSM. Because of the economy of scale, and a larger more differentiated fleet, the differences in the fleet composition are greater in the larger scenarios. Because the low average carrying capacity of the generated optimal fleet when the cost of fuel is low the fleet must conduct more trips than when the fleet tries to save money using the economy of scale. The changes in routing were not found in the smaller scenarios. Here, the changes in the fleet were only used in lowering the speed of the fleet. However, in scenario 1 and 4 there were no change in the fleet. Scenario 1 is the smallest one tested, with only 116 trips in total, while scenario 4 the fleet has a relative high percentage of its vessels on slow-steaming. In these cases an added ship might therefor result in high idleness of the fleet, and a reduced fleet might results in an inability to fulfill its obligations.

Considering the longevity of a vessel fluctuation fuel costs should always be considered when acquiring a vessel. The price variations can be huge during the operational life time of a vessel, and one should therefore always be clear on how the vessel performs under different conditions.

The effects of a reduced fleet have been touched upon earlier in the chapter. A smaller fleet has an overall lower performance when implemented into a deployment model due to the reduced flexibility of the fleet. This flexibility is needed because what is optimal in the FSM is not always what's optimal in the more detailed deployment setting, as seen in test #2 when the trips were spread in time. As a result the higher the fuel cost the better the fleet performs when put in a deployment setting.

Scenario		500 NOK/ton	700 NOK/ton	900 NOK/ton
1	Fuel consumption (1000t)	146	146	146
	Slow-steaming	28 %	28 %	28 %
	Fleet Size	7	7	7
	No differences in composition			
2	Fuel consumption (1000t)	275	258	262
	Slow-steaming	8 %	40 %	40 %
	Fleet Size	12	13	13
	Gap (after 2h)	0	0.0008	0.0002
	Major differences in composition			
3	Fuel consumption (1000t)	129	115	115
	Slow-steaming	20 %	100 %	100 %
	Size	6	7	7
	Minor differences in composition			
4	Fuel consumption (1000t)	188	188	188
	Slow-steaming	70 %	70 %	70 %
	Fleet Size	10	10	10
	No differences in composition			
5	Fuel consumption (1000t)	687	663	649
	Slow-steaming	1 %	10%	22 %
	Fleet Size	30	31	32
	Number of Trips	596	593	591
	Gap (after 1h)	0.66 %	0.62 %	0.78 %
	Some difference in fleet composition			
6	Fuel consumption (1000t)	837	821	805
	Slow-steaming	4 %	13 %	26 %
	Fleet Size	39	40	41
	Number of Trips	638	634	629
	Gap (after 1h)	0.47 %	0.66 %	0.70 %
	Some difference in composition			
7	Fuel consumption (1000t)	952	886	886
	Slow-steaming	1 %	20 %	23 %
	Fleet Size	41	43	44
	Number of Trips	763	--	759
	Gap (after 1h)	2.80 %	1.31 %	2.25 %
	Size differences			

Table 14: Effects of Fuel Cost Variations

Test#5: Planning horizons

Until now excuses have been made to test the FSM model for time periods far lower than it has been constructed for. FSM models are however, actually constructed for planning periods spanning up to several years, while the deployment models that fall in the tactical planning horizons that usually only look at weeks and months. Earlier in this chapter the limitations of deployment models for longer time horizon was made evident. The changing FSM output for the different planning horizons, but otherwise similar conditions, has also been established. In addition, when looking into the possibility of using continuous instead of integer variables it was shown that for time horizons ranging from a year and up, the FSM output was fairly constant.

To find out how the FSM model performs in the setting it is constructed for, tests that show how the estimated optimal fleet of a longer time horizon performs when applied to a deployment model with a smaller, tactical, time frame has been conducted. Because of the similarities between the fleet output in the FSM model for the tested scenarios with time frame between 120 and 360, the 60 day planning period was used for the deployment model. The one year time horizon has been used for estimating the fleet. The result of the tests can be seen in Table 15. Here the “regular” run is the results from test 2, the extended model. All cases have used the frequency spread formulation.

Scenario		60 Regular	60 New	120 Regular	120 NEW
1	Fleet idleness	18.75 %	12.62 %	9.76 %	13.96 %
	Spot trades	1	3	7	1
	Slow-steaming	55 %	54.55 %	37.50 %	47.50 %
	Computation time	97s	1800s	3600s	1800s
	Gap	0.00 %	14.47 %	0.46 %	0.97 %
2	Fleet idleness	72.41 %	27.82 %	16.03 %	10.90 %
	Spot trades	1	4	9	4
	Slow-steaming	21.54 %	81.48 %	32.26 %	61.29 %
	Computation time	890s	1800s	3600s	1800s
	Gap	0.00 %	1.24 %	34.42 %	19.42 %
3	Fleet idleness	29.79 %	2.00 %	20.83 %	21.56 %
	Spot trades	1	2	4	1
	Slow-steaming	100 %	73.91 %	69.23 %	100 %
	Computation time	56	1800s	3600s	1800s
	Gap	0.00 %	5.48 %	6.41 %	1.63 %

Table 15: Different Planning Horizons

The generated fleet in scenario 1 is for, the 360 day planning horizon, one vessel poorer than the previously tested 60 day case that is used in the regular run. Scenario 2 has a different fleet composition but the same fleet size, while scenario 3 has both a smaller fleet and a different composition in the 360 day horizon compared to the 60 day. As a curiosity, how the fleet generated by the FSM model for the 60 day planning horizon on a larger case have been tested. The results are also shown in Table 15. The fleet composition made for the smallest scenario cases all showed to have a better performance than the longer ones. One can therefore conclude that the assignment of routes in the FSM model is not good enough. The FSM model only work for shorter time intervals than it is constructed for due to the margins created by simplification of the FSM routing; stating that all nodes must have as many visits in as out of a given ship type. The impact of this simplification is marginalized as the time horizon increase. The FSM model in its present form can therefore not be relied upon as the only means for establishing the actual optimal fleet. It can, however, be used as a guidance.

Chapter 8

Concluding remarks

This paper has looked into how the fleet generated by a fleet size and mix model stands the test of being scrutinized. The usual planning horizons for these kinds of problems often span several years, the FSM model tested in this thesis, however, proved to perform better for shorter instances in regards to routing. When the proposed fleet composition of the FSM model was applied to a deployment model with more complex routing constraints the result of larger scenarios the fleet proved to be undersized. The reasons for this are probably connected to two main modeling factors. The FSM doesn't discriminate between the different vessels when assigning routes, and therefore, the total number of operation days for the different vessels are not considered; only the fleet total. In addition, the FSM model does not consider the spread in time between the different trips, which might result in the occurrence of clustered trip intervals. The undersized fleet resulted in the need of using the spot market for fulfilling the obligations of the fleet in the deployment model. As the time period increased, the proposed fleet shrank, as the time margins for the total fleet increased. This resulted in the fact that the studied FSM model is better on predicting the needed fleet for shorter periods in time than the planning periods these models are actually constructed for.

The costs estimates of the FSM model and the deployment model were also quite different. This is probably due to the fact that the deployment model makes it possible to operate outside the given planning period as long the last trip is started before the end of the time frame. This gives it the opportunity to slow steam much more frequently than the case is for the FSM model. However, this effect is reduced with an increase of the planning period.

The problems connected to applying the fleet proposed by the FSM model into the deployment model are not necessarily only connected to excessively loose routing constraints in the FSMP however. Some of the routing difficulties could also be due to asymmetric demand in the studied scenarios.

When testing the use of continuous variables instead of integer variable for the number of arcs operated in the FSM model, it proved to be of little consequence to the result when establishing the optimal fleet. Both the accuracy of the result compared to the integer solution and the gains connected to time savings increased with the time horizon of the planning problem.

Changing the price of fuel proved to be of significant importance to the proposed FSM model fleet. When the price increased the fleet got larger and slow steamed a larger portion of the fleet, and the opposite was the case when the prices increased. The fleet mix also changed, as the energy effectiveness of the fleet varied in importance.

The FSM model work for shorter time intervals than it is constructed for due to the margins created by simplification of the FSM routing; stating that all nodes must have as many visits in as out of a given ship type. The impact of this simplification is marginalized as the time horizon increase.

The FSM model in its present form can therefore not be relied upon as the only means for establishing the actual optimal fleet. It can however, be used as guidance.

Chapter 9

Future work

Finding better ways to handle routing in FSM models need to be explored. Possible extensions might include adding a safety factor to the existing routing constraint, or putting a maximum number of successive trips before returning to the start node. The last example would possibly replicate the effect found in the smallest scenario cases tested here, were the generated fleet usually managed to fulfill its obligations without the assistance of additional tonnage.

When it comes to testing, and comparing, the FSM model to a deployment model only some of the possible aspects were looked into. In the deployment model it is for example also possible to include the loading and unloading time of each vessel based on the amount of cargo transported. Another complication that could prove to have major importance is the exact itinerary of any predefined scheduled trip, and the increased loads of HH cargos at the end of the month. All these elements are an important part of the operational environment shipping companies operating in the autoliner segment must deal with. In order to be able to say exactly how important routing is in FSM models, all these and more aspects must be included in the comparison deployment model. Therefore one must conclude that more research is needed.

In the continuance of this work more computational power is needed.

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Chapter 10

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Appendices

In this section the models, as they were implemented into FICO™ Xpress Optimization Suite. The instance generators and post-processing models from MATLAB is also included here.

Additional appendices are included in digital form.

Appendix I – FSM-model

```
model Routing
uses "mmxprs"; !gain access to the Xpress-Optimizer solver

options explterm
options noimplicit

parameters
	DataFile = 'DataIG-4(360).txt';
end-parameters


!**********************************************************
!				Sets
!**********************************************************
declarations
	nShipTypes:	integer;
	nNodes:		integer;
	nProdTypes:	integer;
	nSpeeds:	integer;
	nTime:		integer;
	ShipType:	set of integer;
	Node:		set of integer;
	ProdType:	set of integer;
	Speed:		set of integer;
end-declarations

initializations from DataFile
	nShipTypes;
	nNodes;
	nProdTypes;
	nSpeeds;
	nTime;
end-initializations

ShipType:=	1..nShipTypes;
Node:=		1..nNodes;
ProdType:=	1..nProdTypes;
Speed:=		1..nSpeeds;

finalize(ShipType);
finalize(Node);
```

```
finalize(ProdType);
finalize(Speed);

!Arcs and subsets
 declarations
        Arcs:       array(Node,Node)of integer;
        Node_st:    array(ShipType,Node)of integer;
 end-declarations

initializations from DataFile
    Arcs;
    Node_st;
end-initializations

!***********************************************************
!                    Parameters
!***********************************************************
 declarations
        Frequency:       array(Node,Node) of integer;
        Demand:          array(Node,Node,ProdType) of real;
        Capacity:        array(ShipType,ProdType) of real;
        TotCap:          array(ShipType) of real;
        SailTime:        array(Node,Node,Speed) of integer;
        Consumption:     array(ShipType,Node,Node,Speed) of real;
        CharterCost:     array(ShipType) of real;
 end-declarations

 initializations from DataFile
        Frequency;
        Demand;
        Capacity;
        TotCap;
        SailTime;
        Consumption;
        CharterCost;
 end-initializations

!***********************************************************
!                    Variables
!***********************************************************


declarations
    xTrade:     dynamic array(ShipType,Node,Node,Speed)     of mpvar;
```

```
	yCargo:		dynamic array(ShipType,Node,Node,ProdType)	of mpvar;
	zVessels:	dynamic array(ShipType)				of mpvar;
end-declarations

forall	(vv in ShipType,ii in Node, jj in Node,ss in Speed
			| Arcs(ii,jj)=1 and Node_st(vv,ii)=1 and Node_st(vv,jj)=1 ) do
	create(xTrade(vv,ii,jj,ss));
	xTrade(vv,ii,jj,ss) is_integer;
end-do

forall	(vv in ShipType,ii in Node,jj in Node,pp in ProdType | ii<>jj) do
	create(yCargo(vv,ii,jj,pp));
end-do

forall	(vv in ShipType) do
	create(zVessels(vv));
	zVessels(vv) is_integer;
end-do


!**********************************************************
!				Objective Function
!**********************************************************
declarations
	TCCost:			linctr;
	OperationalCost:	linctr;
	TotalCost:		linctr;
end-declarations

TCCost:= sum(vv in ShipType) nTime*CharterCost(vv)*zVessels(vv);

OperationalCost:=sum(vv in ShipType,ii in Node, jj in Node,ss in Speed)
		Consumption(vv,ii,jj,ss)*xTrade(vv,ii,jj,ss)*700;

TotalCost:=TCCost+OperationalCost;


!**********************************************************
!				Constraints
!**********************************************************


declarations
	Continuity:	dynamic array(ShipType,Node)			of linctr;
```

```
    QDemand:      dynamic array(Node,Node,ProdType)                 of linctr;
    FDemand:      dynamic array(Node,Node)                          of linctr;
    ProdCapacity: dynamic array(ShipType,Node,Node,ProdType)        of linctr;
    TotCapacity:  dynamic array(ShipType,Node,Node)                 of linctr;
    ShipAvailab:  dynamic array(ShipType)                           of linctr;
end-declarations

forall (vv in ShipType,jj in Node) do
    Continuity(vv,jj):=
        sum(ii in Node, ss in Speed) xTrade(vv,jj,ii,ss)=
        sum(ii in Node, ss in Speed) xTrade(vv,ii,jj,ss);
end-do

forall (ii in Node,jj in Node,pp in ProdType) do
    QDemand(ii,jj,pp):=
        sum(vv in ShipType)
            yCargo(vv,ii,jj,pp)>= Demand(ii,jj,pp) ;
end-do

forall (ii in Node,jj in Node) do
    FDemand(ii,jj):=
        sum(vv in ShipType,ss in Speed)
            xTrade(vv,ii,jj,ss)>= Frequency(ii,jj);
end-do


forall (vv in ShipType,ii in Node,jj in Node,pp in ProdType) do
    ProdCapacity(vv,ii,jj,pp):=
        yCargo(vv,ii,jj,pp)<=
        sum(ss in Speed)Capacity(vv,pp)*xTrade(vv,ii,jj,ss);
end-do

forall (vv in ShipType,ii in Node,jj in Node) do
    TotCapacity(vv,ii,jj):=
        sum(pp in ProdType)yCargo(vv,ii,jj,pp)<=
        sum(ss in Speed) TotCap(vv)*xTrade(vv,ii,jj,ss) ;
end-do

forall (vv in ShipType) do
    ShipAvailab(vv):=
        sum(ii in Node, jj in Node,ss in Speed)
        SailTime(ii,jj,ss)*xTrade(vv,ii,jj,ss)<=
        nTime*zVessels(vv);
end-do
```

```
!**********************************************************
!                              End
!**********************************************************
setparam('xprs_verbose',true);
setparam('xprs_maxtime',-7200);
minimize(TotalCost);

fopen('FSM-Output.txt',F_OUTPUT);
writeln('nVessels : ',sum(vv in ShipType) getsol(zVessels(vv)));
writeln;
writeln('AvailVessels: [');
forall (vv in ShipType)do
        writeln('                ', getsol(zVessels(vv) ));
end-do
writeln('                       ]');
fclose(F_OUTPUT);

end-model
```

Appendix II – Deployment model

```
model FSMmodel
uses "mmxprs"; !gain access to the Xpress-Optimizer solver

options explterm
options noimplicit

parameters
	DataFile = 'DataIG-new3(120).txt';
	DataFile2 = 'RoutingData-new3.txt';
end-parameters


!**********************************************************
!                          Sets
!**********************************************************
declarations
	nShipTypes:	integer;
	nNodes:		integer;
	nProdTypes:	integer;
	nSpeeds:	integer;
	nTime:		integer;
	ShipType:	set of integer;
	Node:		set of integer;
	ProdType:	set of integer;
	Speed:		set of integer;
	Time:		set of integer;
	nVessels:	integer;
	Vessel:		set of integer;
end-declarations

initializations from DataFile
	nShipTypes;
	nNodes;
	nProdTypes;
	nSpeeds;
	nTime;
end-initializations

initializations from DataFile2
	nVessels;
end-initializations


ShipType:=	1..nShipTypes;
Node   :=	1..nNodes;
ProdType:=	1..nProdTypes;
Speed  :=	1..nSpeeds;
Time   :=	0..nTime;
```

```
Vessel :=        1..nVessels;

finalize(ShipType);
finalize(Node);
finalize(ProdType);
finalize(Speed);
finalize(Time);

!Arcs and subsets
 declarations
                Start:          array(Vessel,Node)of integer;
                Fleet:          array(ShipType,Vessel)of integer;
                Arcs:           array(Node,Node)of integer;
                Node_v:         array(Vessel,Node)of integer;
                Node_st:        array(ShipType,Node)of integer;
 end-declarations

initializations from DataFile
        Arcs;
        Node_st;
end-initializations

initializations from DataFile2
                Start;
                Fleet;
                Node_v;
end-initializations


!************************************************************
!                                       Parameters
!************************************************************
 declarations
                Frequency:              array(Node,Node) of integer;
                Demand:                         array(Node,Node,ProdType) of real;
                CapacityD:              array(Vessel,ProdType) of real;
                TotCapD:                array(Vessel) of real;
                SailTime:               array(Node,Node,Speed) of integer;
                ConsumptionD:           array(Vessel,Node,Node,Speed) of real;
                Production:             array(Node,Node,ProdType) of real;
                StorageCap:             array(Node,Node) of real;
                StartStorage:   array(Node,Node,ProdType) of real;

                CostS:                  array(Node,Node) of real;
                CapacityS:              array(ProdType) of real;
                FSpread:                array(Node,Node) of real;
 end-declarations

 initializations from DataFile
                Frequency;
```

```
        Demand;
        SailTime;
        Production;
        StorageCap;
        StartStorage;

        CostS;
        CapacityS;
        FSpread;

 end-initializations

 initializations from DataFile2
        CapacityD;
        TotCapD;
        ConsumptionD;

 end-initializations

!**********************************************************
!                    Variables
!**********************************************************


declarations
    xTrade:      dynamic array(Vessel,Time,Node,Node,Speed)       of mpvar;
    yCargo:      dynamic array(Vessel,Time,Node,Node,ProdType)    of mpvar;
    qStorage:    dynamic array(Time,Node,Node,ProdType)           of mpvar;
    Spot:        dynamic array(Time,Node,Node)                    of mpvar;
    vesselTotal: dynamic array(Vessel)                            of mpvar;
    TotSpot:                                                      mpvar;
end-declarations

forall(v in Vessel)do
    create(vesselTotal(v));
    vesselTotal(v) is_integer;
end-do


forall  (ll in ShipType,vv in Vessel,tt in Time,ii in Node, jj in Node,ss in Speed
             | Arcs(ii,jj)=1 and Node_v(vv,ii)=1 and Node_v(vv,jj)=1) do
    create(xTrade(vv,tt,ii,jj,ss));
    xTrade(vv,tt,ii,jj,ss) is_binary;
end-do

forall  (vv in Vessel,tt in Time,ii in Node,jj in Node,pp in ProdType | ii<>jj) do
    create(yCargo(vv,tt,ii,jj,pp));
end-do

forall  (tt in Time,ii in Node,jj in Node,pp in ProdType) do
```

```
        create(qStorage(tt,ii,jj,pp));
end-do!

forall  (tt in Time, ii in Node, jj in Node | Arcs(ii,jj)=1  and tt<>0) do
        create(Spot(tt,ii,jj));
        Spot(tt,ii,jj) is_integer;
end-do

forall(vv in Vessel)do
        vesselTotal(vv)=sum(tt in Time, ii in Node, jj in Node, ss in Speed | Arcs(ii,jj)=1 and
Node_v(vv,ii)=1 and Node_v(vv,jj)=1)xTrade(vv,tt,ii,jj,ss);
end-do

TotSpot is_integer;

!**********************************************************
!                               Objective Function
!**********************************************************

declarations
        sailingCost:        linctr;
        spotCost:                linctr;
        TotalCost:               linctr;
end-declarations

sailingCost:= sum(vv in Vessel,tt in Time,ii in Node, jj in Node,ss in Speed)
                ConsumptionD(vv,ii,jj,ss)*xTrade(vv,tt,ii,jj,ss);
spotCost:=sum(tt in Time, ii in Node, jj in Node)CostS(ii,jj)*Spot(tt,ii,jj);

!spotCost:=sum(tt in Time, ii in Node, jj in Node,ss in Speed |
ss=2)SailTime(ii,jj,ss)*Spot(tt,ii,jj)*(70*7+200);

TotalCost:=sailingCost+spotCost;

!**********************************************************
!                               Constraints
!**********************************************************


declarations
        Continuity:         dynamic array(Vessel,Time,Node)
                of linctr;
        VoyageTime:         dynamic array(Vessel,Time)
                        of linctr;
        QDemand:            dynamic array(Node,Node,ProdType)                of linctr;
        FDemand:            dynamic array(Node,Node)                         of linctr;
        ProdCapacity:       dynamic array(Vessel,Time,Node,Node,ProdType) of linctr;
        TotCapacity:        dynamic array(Vessel,Time,Node,Node)             of linctr;
        InitialStorage:     dynamic array(Time,Node,Node,ProdType)           of linctr;
        Storage:            dynamic array(Time,Node,Node,ProdType)           of linctr;
```

```
	StorageK:		dynamic array(Time,Node,Node)			of linctr;
	FrequencySpread:	dynamic array(Time,Node,Node)			of linctr;
end-declarations

forall (vv in Vessel,tt in Time, ii in Node | tt <= 1 and Start(vv,ii)=1) do
	Continuity(vv,tt,ii):=
		sum(jj in Node, ss in Speed) xTrade(vv,tt,ii,jj,ss)=1;
end-do

forall (vv in Vessel,tt in Time,jj in Node |  tt>1) do
	Continuity(vv,tt,jj):=
		sum(ii in Node, ss in Speed) xTrade(vv,tt,jj,ii,ss)=
		sum(ii in Node, ss in Speed | tt>SailTime(ii,jj,ss))
			xTrade(vv,tt-SailTime(ii,jj,ss),ii,jj,ss);
end-do

forall (vv in Vessel,tt in Time) do
	VoyageTime(vv,tt):=
		sum(tau in Time, ii in Node,jj in Node, ss in Speed
			| tt-SailTime(ii,jj,ss)<tau and tau<=tt)
		xTrade(vv,tau,ii,jj,ss)=1;
end-do

forall (ii in Node,jj in Node,pp in ProdType) do
	QDemand(ii,jj,pp):=
		sum(vv in Vessel,tt in Time| tt>=1)
			yCargo(vv,tt,ii,jj,pp)>= Demand(ii,jj,pp) ;
end-do

forall (ii in Node,jj in Node) do
	FDemand(ii,jj):=
		sum(vv in Vessel,tt in Time,ss in Speed | tt>=1)
			xTrade(vv,tt,ii,jj,ss)+sum(tt in Time) Spot(tt,ii,jj)>= Frequency(ii,jj);
end-do

forall (vv in Vessel,tt in Time,ii in Node,jj in Node,pp in ProdType) do
	ProdCapacity(vv,tt,ii,jj,pp):=
		yCargo(vv,tt,ii,jj,pp)<=
		CapacityD(vv,pp)*(sum(ss in
Speed)xTrade(vv,tt,ii,jj,ss))+CapacityS(pp)*Spot(tt,ii,jj); !
end-do

forall (vv in Vessel,tt in Time,ii in Node,jj in Node) do
	TotCapacity(vv,tt,ii,jj):=
		sum(pp in ProdType)yCargo(vv,tt,ii,jj,pp)<=
		TotCapD(vv)*(sum(ss in Speed)xTrade(vv,tt,ii,jj,ss))+6334*Spot(tt,ii,jj); !
end-do


(!forall (tt in Time,ii in Node,jj in Node,pp in ProdType | tt=0) do
```

```
    InitialStorage(tt,ii,jj,pp):=
        qStorage(tt,ii,jj,pp)=StartStorage(ii,jj,pp);
end-do

forall (tt in Time,ii in Node,jj in Node,pp in ProdType | tt>=1) do
    Storage(tt,ii,jj,pp):=
        qStorage(tt,ii,jj,pp)=
        Production(ii,jj,pp)+qStorage(tt-1,ii,jj,pp)-
        sum(vv in Vessel) yCargo(vv,tt,ii,jj,pp);
end-do

forall (tt in Time,ii in Node,jj in Node | ii<>jj) do
    StorageK(tt,ii,jj):=
        sum(pp in ProdType) qStorage(tt,ii,jj,pp)<=StorageCap(ii,jj);
end-do!)

forall (tt in Time, ii in Node, jj in Node | FSpread(ii,jj)>=1 and tt<>0) do
    FrequencySpread(tt,ii,jj):=
        sum(tau in Time | tt-FSpread(ii,jj)<tau and tau<=tt) (sum(vv in Vessel, ss in
Speed)
        xTrade(vv,tau,ii,jj,ss)+ Spot(tau,ii,jj))>=1;
end-do!)

TotSpot = sum(tt in Time,ii in Node, jj in Node      | Arcs(ii,jj)=1 )Spot(tt,ii,jj);
!***********************************************************
!                                                   End
!***********************************************************
setparam('xprs_verbose',true);      !     Enable message printing
setparam('xprs_maxtime',-1800);     !     Max run time

forall(v in Vessel)do
    setmipdir(vesselTotal(v),XPRS_PR,10);
end-do!)

!Set a directive on a variable or SOS, XPRS_PR   100 is a priority (1 is highest, 1000 lowest)
setmipdir(TotSpot,XPRS_PR,10);
        !
setparam('xprs_cutstrategy',3);     !Aggressive cut strategy.

minimize(TotalCost);
end-model
```

Appendix III– MATLAB file (MAIN)

```
%function instance_generator
clc
clear all
close all

%Sets
    nShipTypes=6;
    nTime=3600;
    nNodes=4;
    nSpeeds=3;
    nProdTypes=3;

    %Subsets

    Arcs = zeros(nNodes,nNodes);
    for i = 1:nNodes
        for j = 1:nNodes
            if i == j
                Arcs(i,j) = 1;
            else
                Arcs(i,j) = floor(rand()/3+0.9);
            end
        end
    end

    for i = 1:nNodes
        for j = 1:nNodes
            if Arcs(i,j)==0;
                Arcs(j,i) = 0;
            end
        end
    end
Length = nNodes*nNodes;
    FArcs = zeros(nNodes,nNodes)
    DArcs = zeros(nNodes,nNodes)
    LArcs=zeros(Length,1);
    LFArcs=zeros(Length,1);
    LDArcs=zeros(Length,1);
temp=0;
    for i = 1:nNodes
        for j = 1:nNodes
            if i == j
                FArcs(i,j) = 0;
                DArcs(i,j) = 0;
            else
                FArcs(i,j) = round(rand()+0.15)*Arcs(i,j);
                DArcs(i,j) = round(rand()+0.2)*Arcs(i,j);
            end
            temp=temp+1;
            LArcs(temp,1)=Arcs(i,j);
            LFArcs(temp,1)=FArcs(i,j);
            LDArcs(temp,1)=DArcs(i,j);
        end
    end

  [ Node_st ] = VesselNode();
```

```
%Parameters

    %Given Capacity
    Capacity    =[  7620    3600    550
            7934    3600    1600
            8014    3800    2300
            6300    2000    0
            4474    4500    2800
            6004    7500    4100    ] ;
            %HH and NCC valus are based on a hight of 10m...



    TotCap      =[  8000    8500    9000    7000    4500    6000    ] ;
            %Estimates for everything exept Mk vessels




    %SailTime
    SailTable = zeros(nNodes,nNodes);
    SailTime = zeros(Length,nSpeeds);

    for i = 1:nNodes
        for j = i:nNodes
             number = (rand/1.6+0.3)*15000;

            if i == j
                SailTable(i,j) = 1;
            else
                SailTable(i,j) = number;
                SailTable(j,i) = number;
            end
        end
    end


    Length2=Length*nShipTypes;

    Consumption1=zeros(Length,nSpeeds);

        temp = 0;
    for i = 1:nNodes
       for j = 1:nNodes
            temp = temp + 1;
            SailTime(temp,1) = ceil(SailTable(i,j)/(16*24));
            SailTime(temp,2) = ceil(SailTable(i,j)/(18*24));
            SailTime(temp,3) = ceil(SailTable(i,j)/(20*24));
       end
    end


ConsumptionOp=[ 42.2    53.3    67.3
                48.2    57.1    67.7
                50.5    57.9    66.3
                36.8    42.5    49.2
                59.0    71.9    86.4
                50.6    60.6    72.6    ];
```

```
ConsumptionPort=[   5    5    5    6.1      8.5      7.5 ]';

counter=0;
  for i = 1:Length
      for j=1:nSpeeds

          if i == 1 || i == 6 || i == 11 || i == 16
              Consumption1(i,j)=ConsumptionPort(1);
              Consumption2(i,j)=ConsumptionPort(2);
              Consumption3(i,j)=ConsumptionPort(3);
              Consumption4(i,j)=ConsumptionPort(4);
              Consumption5(i,j)=ConsumptionPort(5);
              Consumption6(i,j)=ConsumptionPort(6);
          else
              Consumption1(i,j)  = SailTime(i,j)*ConsumptionOp(1,j);
              Consumption2(i,j)  = SailTime(i,j)*ConsumptionOp(2,j);
              Consumption3(i,j)  = SailTime(i,j)*ConsumptionOp(3,j);
              Consumption4(i,j)  = SailTime(i,j)*ConsumptionOp(4,j);
              Consumption5(i,j)  = SailTime(i,j)*ConsumptionOp(5,j);
              Consumption6(i,j)  = SailTime(i,j)*ConsumptionOp(6,j);
          end

      end
  end
  %Consumption=(Length2,nSpeeds);

Consumption=[Consumption1;Consumption2;Consumption3;Consumption4;Consumptio
n5;Consumption6];
  %Current cost of HFO= 140 EUR/ton
CostS = zeros(Length,1);
CostS = 71.9*5*ceil(SailTable/(18*24))
CapacityS = [6334   2100    0];
TotCapS = [6334];

      %Frequency
    Fdemand=zeros(Length,1);
    temp=0;
    for i = 1:nNodes;
        for j = 1:nNodes
            if i==j
            Frequency(i,j)=0;
            else
            Frequency(i,j)=ceil((rand()/14)*nTime)*FArcs(i,j);
            end
        temp = temp + 1;
        Fdemand(temp,1)=Frequency(i,j);
        end
    end


    TotProd=zeros(Length,1);
    for i=1:Length
        if LFArcs(i)>=LDArcs(i)
            TotProd(i)=(Fdemand(i)*4200)/nTime+(550*LFArcs(i)-
(Fdemand(i)*4200)/nTime)*rand;
        else
            TotProd(i)=round(rand*400)*LDArcs(i);
        end
    end
```

```
TotProd

Production = rand(Length,nProdTypes);        % create random matrix of size
N x N
sP = sum(Production,2);                       % Sum over each row

for i = 1:Length
 Production(i,:) = (Production(i,:) / sP(i))*TotProd(i);
end

Demand=Production*nTime;

    %Storage capacity
    StorageCap = zeros(Length,1);
    for i = 1:Length
        StorageCap(i)=6000+(16000-6000).*rand;
    end

    %Size of start storage
    StartStorage = zeros(Length,nProdTypes);
    temp = 0;
    for i = 1:nNodes
        for j = 1:nNodes
            temp = temp + 1;
               if i==j
                   StartStorage(temp,1)=0;
                   StartStorage(temp,2)=0;
                   StartStorage(temp,3)=0;
               else
                    StartStorage(temp,1) = Arcs(i,j)*1500;
                    StartStorage(temp,2) = Arcs(i,j)*1500;
                    StartStorage(temp,3) = Arcs(i,j)*1500;
               end
        end
    end


    CharterCost=[23000   23000   23000   28000   28000   33000   ];



    %Write to file
fid=fopen('DataIG.txt','wt');

    fprintf(fid,'!Sets \n');
    fprintf(fid,'nShipTypes :');
        fprintf(fid,'%1.0f \n',nShipTypes);
    fprintf(fid,'nTime :');
        fprintf(fid,'%1.0f\n',nTime);
    fprintf(fid,'nNodes :');
        fprintf(fid,'%1.0f\n',nNodes);
    fprintf(fid,'nSpeeds : ');
        fprintf(fid,'%1.0f\n',nSpeeds);
    fprintf(fid,'nProdTypes :');
        fprintf(fid,'%1.0f \n \n',nProdTypes);

    fprintf(fid,'!Subsets \n');
    fprintf(fid,'Arcs :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f %4.0f\n',Arcs');
```

```
        fprintf(fid,'   ]\n\n');
    fprintf(fid,'Node_st :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f %4.0f\n',Node_st');
        fprintf(fid,'   ]\n\n');

    fprintf(fid,'!Parameters \n');
    fprintf(fid,'SailTime :[\n');
        fprintf(fid,'%14.0f %6.0f %6.0f\n',SailTime');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'Consumption :[\n');
        fprintf(fid,'%14.1f %10.1f %10.1f\n',Consumption');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'Frequency :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f %4.0f\n',Frequency');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'Demand :[\n');
        fprintf(fid,'%14.0f %6.0f %6.0f\n',Demand');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'Production :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f\n',Production');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'StorageCap :[\n');
        fprintf(fid,'%14.0f\n',StorageCap');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'StartStorage :[\n');
        fprintf(fid,'%14.0f %6.0f %6.0f\n',StartStorage');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'Capacity :[\n');
        fprintf(fid,'%14.0f %6.0f %6.0f\n',Capacity');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'TotCap :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f %4.0f %4.0f %4.0f\n',TotCap');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'CharterCost :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f %4.0f %4.0f %4.0f\n',CharterCost');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'CostS :[\n');
        fprintf(fid,'%14.0f\n',CostS');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'CapacityS :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f\n',CapacityS');
        fprintf(fid,'                                     ]\n\n');
    fprintf(fid,'TotCapS :[\n');
        fprintf(fid,'%14.0f\n',TotCapS');
        fprintf(fid,'                                     ]\n\n');
fclose(fid);
```

Appendix IV– MATLAB file 2(Ship-type/node compatability)

```
function [ Node_st ] = VesselNode()
clc
clear all
nRows = 6;          % Row size of matrix
nColumns = 4;       % Column size of matrix
minZeroes = 1;      % Constraint 1 (for columns)
minRowSum = 2;      % Constraint 2 (for rows)
%

function vector = make_column
vector = [false(minZeroes,1); true(nRows-minZeroes,1)];  % Create vector
  [vector,maxLength] = randomize_column(vector);         % Randomize order
end

function [vector,maxLength] = randomize_column(vector)
vector = vector(randperm(nRows));          % Randomize order
  edges = diff([false; vector; false]);    % Find rising and falling edges
  maxLength = max(find(edges == -1)-find(edges == 1));  % Find longest
% sequence of ones
end

Node_st = false(nRows,nColumns);    % Initialize matrix
for iColumn = 1:nColumns,
  Node_st(:,iColumn) = make_column; % Create each column
end

rowSum = sum(Node_st,2);

while any(rowSum < minRowSum),          % Loop while constraint 2 is not met
  [minValue,rowIndex] = min(rowSum);      % Find row with lowest sum
  zeroIndex = find(~Node_st(rowIndex,:)); % Find zeroes in that row
  randIndex = round(1+rand.*(numel(zeroIndex)-1));
  columnIndex = zeroIndex(randIndex);     % Choose a zero at random
  column = Node_st(:,columnIndex);
  while ~column(rowIndex),                % Loop until zero changes to one
    column = make_column;                 % Make new column vector
  end
  Node_st(:,columnIndex) = column;        % Update binary matrix
  rowSum = sum(Node_st,2);                % Update row sum vector
end
Node_st
end
```

Appendix V– MATLAB file 3(Fleet processing)

```
clc
clear all
close all

fid=fopen('FSM-Output-1(360).txt','rt');
for i=1:3,    fgetl(fid), end;
AvailableFleet=fscanf(  fid,  '%g',   [1, 6]  )'

fid2=fopen('DataIG-1(360).txt','rt');
for i=1:16,    fgetl(fid2), end;
Node_st=fscanf(  fid2,  '%g',   [4, 6]  )'

nVessels=sum(AvailableFleet);
nShipTypes=6;
nNodes=4;

Fleet2=zeros(nShipTypes,nVessels);
for i=1:nShipTypes
    if i==1
        temp=ones(1,AvailableFleet(i));
        Fleet2(1,1:length(temp))=temp;
    end
    temp=ones(1,AvailableFleet(i));
    if i>1
        Fleet2(i,sum(AvailableFleet(1:i-
1))+1:sum(AvailableFleet(1:i)))=temp;
        temp=0;
    end
end


fclose(fid);
Start=zeros(nShipTypes,nNodes);
Fleet2
%Node_st
AvailableFleet


rowEndVals = cumsum(AvailableFleet);
totalRows = rowEndVals(end);
totalCols = size(Node_st,2);

Node_v = zeros(totalRows, totalCols);

prevRowEnd = 0;

for i = 1:length(AvailableFleet)
    thisRowStart = prevRowEnd + 1;
    Node_v(thisRowStart:rowEndVals(i),:) = ...
    repmat(Node_st(i,:), AvailableFleet(i), 1);
    prevRowEnd = rowEndVals(i);
end

%Node_v
Start = zeros(nVessels,nNodes);
```

```
for i = 1:sum(nVessels)
    for j = 1:nNodes
        if Node_v(i,j)==1;
            Start(i,j) = rand;
        else
            Start(i,j) = 0;
        end
    end
end
B=(max(Start'))';
C=Start;

for i = 1:sum(nVessels)
    for j = 1:nNodes
        if C(i,j)==max(B(i));
            Start(i,j) = 1;
        else
            Start(i,j) = 0;
        end
    end
end
%Start
max(Start)

Consumption =[
           5.0        5.0        5.0
        1012.8     1119.3     1278.7
         675.2      746.2      874.9
        1308.2     1492.4     1682.5
        1012.8     1119.3     1278.7
           5.0        5.0        5.0
         801.8      906.1     1076.8
         759.6      852.8     1009.5
         675.2      746.2      874.9
         801.8      906.1     1076.8
           5.0        5.0        5.0
         590.8      692.9      807.6
        1308.2     1492.4     1682.5
         759.6      852.8     1009.5
         590.8      692.9      807.6
           5.0        5.0        5.0
           5.0        5.0        5.0
        1156.8     1199.1     1286.3
         771.2      799.4      880.1
        1494.2     1598.8     1692.5
        1156.8     1199.1     1286.3
           5.0        5.0        5.0
         915.8      970.7     1083.2
         867.6      913.6     1015.5
         771.2      799.4      880.1
         915.8      970.7     1083.2
           5.0        5.0        5.0
         674.8      742.3      812.4
        1494.2     1598.8     1692.5
         867.6      913.6     1015.5
         674.8      742.3      812.4
           5.0        5.0        5.0
           5.0        5.0        5.0
        1212.0     1215.9     1259.7
         808.0      810.6      861.9
```

1565.5	1621.2	1657.5
1212.0	1215.9	1259.7
5.0	5.0	5.0
959.5	984.3	1060.8
909.0	926.4	994.5
808.0	810.6	861.9
959.5	984.3	1060.8
5.0	5.0	5.0
707.0	752.7	795.6
1565.5	1621.2	1657.5
909.0	926.4	994.5
707.0	752.7	795.6
5.0	5.0	5.0
6.1	6.1	6.1
883.2	892.5	934.8
588.8	595.0	639.6
1140.8	1190.0	1230.0
883.2	892.5	934.8
6.1	6.1	6.1
699.2	722.5	787.2
662.4	680.0	738.0
588.8	595.0	639.6
699.2	722.5	787.2
6.1	6.1	6.1
515.2	552.5	590.4
1140.8	1190.0	1230.0
662.4	680.0	738.0
515.2	552.5	590.4
6.1	6.1	6.1
8.5	8.5	8.5
1416.0	1509.9	1641.6
944.0	1006.6	1123.2
1829.0	2013.2	2160.0
1416.0	1509.9	1641.6
8.5	8.5	8.5
1121.0	1222.3	1382.4
1062.0	1150.4	1296.0
944.0	1006.6	1123.2
1121.0	1222.3	1382.4
8.5	8.5	8.5
826.0	934.7	1036.8
1829.0	2013.2	2160.0
1062.0	1150.4	1296.0
826.0	934.7	1036.8
8.5	8.5	8.5
7.5	7.5	7.5
1214.4	1272.6	1379.4
809.6	848.4	943.8
1568.6	1696.8	1815.0
1214.4	1272.6	1379.4
7.5	7.5	7.5
961.4	1030.2	1161.6
910.8	969.6	1089.0
809.6	848.4	943.8
961.4	1030.2	1161.6
7.5	7.5	7.5
708.4	787.8	871.2
1568.6	1696.8	1815.0
910.8	969.6	1089.0
708.4	787.8	871.2
7.5	7.5	7.5

```
                                     ];

rowEndValsCon = cumsum(AvailableFleet)*16;
totalRowsCon = rowEndValsCon(end);
totalColsCon = size(Consumption,2);

ConsumptionD = zeros(totalRowsCon, totalColsCon);

prevRowEnd = 0;

temp=1;
for i = 1:length(AvailableFleet)
    thisRowStart = prevRowEnd + 1;
    ConsumptionD(thisRowStart:rowEndValsCon(i),:) = ...
    repmat(Consumption(temp:temp+15,:), AvailableFleet(i), 1);
    prevRowEnd = rowEndValsCon(i);
    temp=temp+16;
end

Capacity =[
          7620   3600    550
          7934   3600   1600
          8014   3800   2300
          6300   2000      0
          4474   4500   2800
          6004   7500   4100
                                     ];

rowEndVals = cumsum(AvailableFleet);
totalRowsCap = rowEndVals(end);
totalColsCap = size(Capacity,2)

CapacityD = zeros(totalRowsCap, totalColsCap);

prevRowEnd = 0;

for i = 1:length(AvailableFleet)
    thisRowStart = prevRowEnd + 1;
    CapacityD(thisRowStart:rowEndVals(i),:) = ...
    repmat(Capacity(i,:), AvailableFleet(i), 1);
    prevRowEnd = rowEndVals(i);
end

TotCap = [8000 8500 9000 7000 4500 6000]'

rowEndVals = cumsum(AvailableFleet);
totalRowsTotCap = rowEndVals(end);
totalColsTotCap = size(TotCap,2);

TotCapD = zeros(totalRowsTotCap, totalColsTotCap)
prevRowEnd = 0;
for i = 1:length(AvailableFleet)
    thisRowStart = prevRowEnd + 1;
    TotCapD(thisRowStart:rowEndVals(i),:) = ...
    repmat(TotCap(i,:), AvailableFleet(i), 1);
    prevRowEnd = rowEndVals(i);
end

fid=fopen('RoutingData.txt','wt');
```

```
    fprintf(fid,'nVessels :');
        fprintf(fid,'%1.0f \n',nVessels);

    fprintf(fid,'Fleet :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f %4.0f\n',Fleet2');
        fprintf(fid,'    ]\n\n');
    fprintf(fid,'Start :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f %4.0f\n',Start');
        fprintf(fid,'    ]\n\n');
    fprintf(fid,'Node_v :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f %4.0f\n',Node_v');
        fprintf(fid,'    ]\n\n');
    fprintf(fid,'ConsumptionD :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f %4.0f\n',ConsumptionD');
        fprintf(fid,'    ]\n\n');
    fprintf(fid,'CapacityD :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f %4.0f\n',CapacityD');
        fprintf(fid,'    ]\n\n');
    fprintf(fid,'TotCapD :[\n');
        fprintf(fid,'%14.0f %4.0f %4.0f %4.0f\n',TotCapD');
        fprintf(fid,'    ]\n\n');

 fclose(fid);
```