Analysis of voyage optimization benefits for different shipping stakeholders

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Improving energy efficiency and reducing greenhouse gas emissions in shipping have been central objectives in the development of sustainable shipping. The way how ships are operated has a noteworthy impact on the overall energy efficiency and produced emissions. Voyage optimization processes aim to improve the operational efficiency of a ship by optimizing route and speed profiles and consequently bring economic benefit to the shipping stakeholders.

The central subject of this thesis is a case study where the overall benefits of voyage optimization for a fleet of a specific shipowner are evaluated. The study utilizes the operational Automatic Identification System data of 49 Medium Range tankers between January 2018 and March 2019 in ship performance simulations where different voyage optimization strategies are implemented. The objective in the case study is to assess the potential of improvement in the fleet energy efficiency and how the implementation of voyage optimization processes would affect the overall economics of the shipowner. The results of the case study show that the potential in fuel saving and emission reduction can be 11.5 to 28% depending on the optimization strategy. For the shipowner economics the consequential reduction in fuel cost would result in approximately 7.2 to 17.8% increase in the average daily revenue performance of the fleet.

Several stakeholders are typically involved in the shipping process which makes the implementation of voyage optimization difficult. The discussion part of the thesis focuses on the approaches how to share the benefits from voyage optimization in a way that all stakeholders are motivated to change the operational processes. The key factor would be a creation of benefit distribution scheme where the monetary benefits from the voyage optimization are shared between the ship operator and the charterer. Moreover, a successful implementation of voyage optimization would require changes in port operation scheduling, real-time information sharing and reliable estimations on energy saving in ship operations.

**Keywords:** Voyage optimization, Ship performance analysis, Automatic Identification System, Energy efficiency
Preface

This master’s thesis is completed as a part of Nordic Master in Maritime Engineering double degree program. The thesis is submitted to two universities; the Technical University of Denmark (DTU) and Aalto University, Finland.

The supervisors of the thesis are associate professor Ulrik Dam Nielsen from the DTU Department of Mechanical Engineering, Section of Fluid Mechanics, Coastal and Maritime Engineering and professor Pentti Kujala from Aalto University, Department of Mechanical Engineering, Marine and Arctic Technology. The thesis was written in a co-operation with Finnish ship design and operation software house NAPA. The academic advisor from NAPA is Pekka Pakkanen, the director of development in NAPA Shipping Solutions.

In Helsinki, July 12th, 2019

Miika-Matti Ahokas
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Moreover, I would like to thank my friends and fellow students for the journey during the master’s studies. Without your support, I would not be able to overcome all the challenges encountered during these two years.

Finally, the greatest thanks go to my newborn daughter for enchanting me during the final stages of this project and to my wife, Heini, for the whole-hearted support and cheer during this process.

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The research is funded by Finnish ship design and operation software house NAPA. NAPA provided the tools and access to the data utilized in the research process. The methods used in the thesis case study are not tied to NAPA or its products and the results can be obtained by other means as well.
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#### Abbreviations

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<tr>
<td><strong>AIS</strong></td>
<td>Automatic Identification System</td>
</tr>
<tr>
<td><strong>EEDI</strong></td>
<td>Energy Efficiency Design Index</td>
</tr>
<tr>
<td><strong>EEOI</strong></td>
<td>Energy Efficiency Operational Indicator</td>
</tr>
<tr>
<td><strong>ETA</strong></td>
<td>Estimated Time of Arrival</td>
</tr>
<tr>
<td><strong>HFO</strong></td>
<td>Heavy fuel oil</td>
</tr>
<tr>
<td><strong>IMO</strong></td>
<td>International Maritime Organization</td>
</tr>
<tr>
<td><strong>ITTC</strong></td>
<td>International Towing Tank Conference</td>
</tr>
<tr>
<td><strong>MGO</strong></td>
<td>Marine gas oil</td>
</tr>
<tr>
<td><strong>MMSI</strong></td>
<td>Maritime Mobile Service Identity</td>
</tr>
<tr>
<td><strong>MR</strong></td>
<td>Medium Range tanker</td>
</tr>
<tr>
<td><strong>NAPAVO</strong></td>
<td>NAPA Voyage Optimization</td>
</tr>
<tr>
<td><strong>RPM</strong></td>
<td>Revolutions per minute</td>
</tr>
<tr>
<td><strong>RTA</strong></td>
<td>Required Time of Arrival</td>
</tr>
<tr>
<td><strong>SEEMP</strong></td>
<td>Ship Energy Efficiency Management Plan</td>
</tr>
<tr>
<td><strong>SFOC</strong></td>
<td>Specific fuel oil consumption</td>
</tr>
<tr>
<td><strong>SOLAS</strong></td>
<td>Safety of Life at Sea</td>
</tr>
<tr>
<td><strong>SSW</strong></td>
<td>DTU Ship Simulation Workbench</td>
</tr>
<tr>
<td><strong>STM</strong></td>
<td>Sea Traffic Management</td>
</tr>
<tr>
<td><strong>TCE</strong></td>
<td>Time Charter Equivalent</td>
</tr>
<tr>
<td><strong>VLCC</strong></td>
<td>Very Large Crude Carrier</td>
</tr>
<tr>
<td><strong>VTS</strong></td>
<td>Vessel Traffic Service</td>
</tr>
</tbody>
</table>
Roman symbols

\( A_F \) ship wind area
\( B \) breadth
\( C_b \) block coefficient
\( C_b \) midship section coefficient
\( C_p \) prismatic coefficient
\( C_{wp} \) waterplane area coefficient
\( C_X \) wind resistance coefficient
\( D \) propeller diameter
\( DWT \) ship deadweight
\( EAR \) propeller expanded area ratio
\( g \) acceleration due to gravity
\( H_s \) significant wave height
\( h \) water depth
\( K_t \) propeller thrust coefficient
\( K_Q \) propeller torque coefficient
\( L_{PP} \) length between perpendiculares
\( L_{WL} \) waterline length
\( LOA \) length overall
\( MCR \) maximum continous rating
\( M_{FC} \) fuel consumption mass
\( P \) engine power
\( P_D \) delivered power
\( P_E \) effective power
\( PL \) ship payload
\( PoD \) propeller pitch/diameter ratio
\( R \) resistance
\( S \) wetted surface area
\( T \) draught
\( T_d \) design draught
\( T_P \) wave period
\( t \) thrust deduction
\( V \) velocity
\( w \) wake fraction
\( Z \) number of propeller blades
Greek symbols

\( \eta_H \)  hull efficiency
\( \eta_0 \)  propeller open water efficiency
\( \eta_{RR} \)  relative rotative efficiency
\( \eta_{trans} \)  transmission efficiency
\( \rho \)  sea water density
1 Introduction

Reducing the emissions in shipping is a common goal for all stakeholders involved in the shipping process. Development of the Energy Efficiency Operational Indicator (EEOI) and the Ship Energy Efficiency Management Plan (SEEMP) by IMO urges to improve energy efficiency not only by the installation of more energy efficient machinery and equipment, but also saving energy by operations (IMO 2009). However, the contractual mesh between the shipping stakeholders is complicated, thus leading to situations where some stakeholders may have incentives for inefficient operation. As an example of this, a ship operator may arrive to a busy harbor at an inefficient speed just to wait to unload anchored for several days or weeks while receiving compensation (demurrage) from a charterer. Typically, the demurrage rate is higher than the extra fuel cost which brings an incentive for the ship operator to arrive to the harbour as early as possible (IMO 2009).

The key objective of the voyage optimization processes is to enhance the ship’s operational performance towards energy efficient shipping. In recent years, several studies discussing the ship voyage optimization problem have been published. For instance, studies by Lu et al. (2015) and Chang et al. (2013) employ different voyage optimization strategies such as finding the shortest route, avoiding bad weather and utilizing strong ocean currents to reduce the fuel consumption and shipborne emissions on specific ships and voyages. Another study by Jia et al. (2017) estimates the fuel consumption and emission reduction in a global context by optimizing ship speed to meet the ETA just in time (Just-in-Time arrival). These studies, among others, conclude that implementation of voyage optimization processes have a noteworthy benefit on ship’s energy efficiency.

While earlier research on voyage optimization focus mainly on energy efficiency on voyage and ship level, the objective of this thesis is to study what are the overall benefits of voyage optimization for a fleet of a specific shipowner. The research problem can be expressed by the following research questions:

1. What are the energy efficiency, monetary and safety benefits for voyage optimization for a fleet of specific shipowner?
2. How to share the monetary benefits to different shipping stakeholders, so that there is motivation to change operational processes?

The scope of this thesis is limited to consider Medium Range tanker (45 000 - 55 000 DWT) voyages operated under a voyage charter party. For understanding the big picture of shipping processes, the first part of the thesis discusses the role of shipping stakeholders, operational processes, contractual terms used in shipping and the present situation of benefit sharing between different shipping stakeholders. The aim is to respond to the first research question by determining the expected benefits of voyage optimization to the stakeholders. The problem of conflicting incentives in operational processes and the present situation of monetary benefit sharing are exemplified by hypothetical operational scenarios. While the energy saving and emission reduction is the starting point of the voyage optimization, the consequential benefits e.g. reduction in fuel costs and improved safety are discussed as well. Particularly, the importance of these benefits is reviewed for different shipping stakeholders.

The second part of the thesis covers the case study where the supposed fuel saving and CO$_2$ reduction by voyage optimization processes is assessed. The case study uses the operational Automatic Identification System-data of 49 Medium Range tankers collected between January 2018 and March 2019. All ships are operated by the same shipowner, allowing an overview on the performance of
the majority of the company fleet. The ship performance simulations were performed with NAPA Voyage Optimization tool by utilizing operational AIS-data, weather data, nautical charts and a ship performance model. The simulations of actual voyages were then compared with optimized voyages which utilize different voyage optimization strategies. The performance calculation methods and data-flow of the optimization are presented in the outline. Supplementary simulations of selected voyages were performed with DTU Ship Simulation Workbench tool and the results were compared with actual performance records from noon reports.

The third part of the thesis reflects on the first part and the analysis of the case study to discuss the encounter of the expected benefits and optimization. The aim is to respond to the second research question by defining possible changes in contractual terms in order that they motivate both stakeholders. A simple voyage cashflow calculation is included to express in which level the shipping costs could be reduced on a yearly basis on a fleet level.
2 Shipping process

The shipping industry is one of the most important global industry networks connecting several stakeholders from shipbuilders to ship operators, and eventually to ship scrappers. Due to its global position, the shipping industry is highly affected by global market cycles. The universal shipping industry can be divided into four separate markets (Stopford, 2009):

1. Freight market
2. Newbuilding market
3. Sale and purchase market
4. Demolition market

The analysis in this thesis is focused on the freight market and to the stakeholders involved in sea transport. For simplicity, the sea transportation process in the freight market is referred hereinafter to as shipping process and the stakeholders in the freight market is referred to as shipping stakeholders.

2.1 Stakeholders in the freight market

In general, many different players are involved in the shipping process. Figure 1 illustrates the simplified connection between different stakeholders described in the master’s thesis by Järvenpää (2016). Typically, individual contracts are agreed with two stakeholders only, which makes the general view of the shipping process complicated (IMO, 2009b).

The two key stakeholders in shipping are the charterer and the ship operator which conclude the charter-party to be followed in operation. Charterer is the stakeholder arranging the carriage of cargo. The ship operator is the stakeholder responsible for the operation of the ship and often the ship operator is also the stakeholder who owns the ship. A broker is an individual player whose task is to communicate between the cargo owner and shipowner and find ships for the cargoes when a shipping contract is about to be negotiated. Since the voyage optimization is affected mainly by the charter party between the charterer and the shipowner, the following subsections concentrate on the roles of these stakeholders.
2.1.1 Charterer

Charterer is the company who arranges the carriage of cargo by a ship owned by them or hiring a ship. Depending on the charter party, the charterer either hires a ship with a fixed daily or monthly price (time charter), or fixed price per ton of cargo transported (voyage charter). Different types of charter contracts are described further in section 2.2.1.

2.1.2 Shipowner

Shipowner is the company or individual who owns the ship. The shipowner may operate their own ships or hire ships to a dedicated ship operator company. Generally, the shipowner is responsible for all shipping related costs, however, under different charter-party arrangements the voyage and operating related costs may be shared differently between the shipowner, operator and charterer.

2.2 Contracts and clauses used in shipping process

The shipping contracts and clauses are intended to conclude the terms used in the shipping process between the charterer and the shipowner. The following subsections concentrate on the types of charter parties and additional clauses used to elaborate the shipping contract.

2.2.1 Charter parties

A charter party is the main shipping contract between the charterer and the shipowner. Several types of charter parties exist for different types of operation. The scope in the case study in section 6 focuses exclusively on voyage charter. Thus, the further description of shipping process focuses mainly on voyage charter.

Voyage charter

In a voyage charter, the freight is determined with a fixed price per ton of cargo transported. The voyage charter is typically used in tanker and bulk shipping where homogeneous goods are transported in large quantities. Generally all voyage-related costs are paid by the shipowner (Stopford, 2009). A typical scenario of the voyage charter is, for instance, when a cargo owner has a need to transport petroleum products from port A to port B. The cargo owner contacts a broker who finds an available shipowner with a suitable ship and timetable to complete the voyage. The terms for operation will be set out in a charter party. If the operation is completed within the terms agreed, the process is complete. However, if the voyage is not completed within the terms agreed in the charter party, a claim can be raised by either stakeholder. For example, the shipowner is entitled to raise a claim for demurrage if ship's laytime at port exceeds the limit stated in the charter party. Respectively, the charterer is entitled to dispatch if the ship spends less time at port than required in the charter party. Clauses where these claims are defined are further discussed in section 2.2.2.

Time charter

In time charter, the operational control of the ship is handed over to the charterer with a fixed daily or monthly price. In this arrangement, the shipowner pays the operating and capital costs of the ship and the charterer is responsible of voyage and cargo related costs such as fuel, port charges and loading/discharging fees. (Stopford, 2009).

Bare boat charter
In bare boat charter, only the ship is chartered to a third party who manages the complete freight operation by organizing the crew and paying the operating and voyage costs. (Stopford, 2009)

**Contract of affreightment**

Contract of affreightment is typically used on long-term chartering and it can be described as a single contract for multiple voyage charters. The contract can be concluded, for example, for a certain period or certain amount of cargo, and the rate can be set by tons of cargo transported or number of voyages completed. (Järvenpää, 2016).

### 2.2.2 Clauses

Additional clauses are used together with a charter party, to set the detailed terms and the modus operandi in specific occasions. The key clauses in the context of this study are described in the following.

**Laytime**

Laytime is the agreed period of time for the loading/discharge operation at the port.

**Laycan**

Laycan is the time period between the earliest and the latest occasion when the ship can commence the loading/discharge operation.

**Demurrage**

Demurrage is a compensation paid to the shipowner for the delay in loading/discharge operation for which he is not responsible (Stopford, 2009). For example, a loaded ship may arrive to a port by the time agreed in the charter party, but due to a congestion in the port the ship cannot be received for a discharge within the laycan agreed in the charter party. Therefore, the shipowner receives a demurrage from the charterer for each extra day spent in operation.

**Dispatch**

Dispatch is the compensation paid for the charterer if the loading/discharge operation is completed in less time than the laytime allows. The rate is typically half of the rate of demurrage (Schofield, 1997).

**Notice of Readiness**

The shipowner sends notice of readiness (NOR) to the charterer when the ship is ready for loading/discharge. Typically, at the moment when Notice of Readiness is announced, the laytime comes into effect. To announce a valid NOR, the ship needs to be arrived at the port and physically ready for loading/port operations. (Laajarinne, 2014).

**Virtual Arrival**

The virtual arrival clause is intended to enable speed adjustment and later arrival time than the ETA agreed in the charter party, if there is a known delay in the arrival port. The aim of virtual arrival is to reduce waiting times at port and allow ships to utilize the extra time at voyage instead and,
thereby, receive savings in fuel consumption. The virtual arrival clause may include reduction in the
demurrage rate to share the financial benefits between the shipowner and charterer.

2.3 Shipping costs in voyage charter

The shipping costs can vary broadly in the course of time due to changes in fuel oil prices, the state
of global economy, the way shipping company is managed etc. Therefore, each individual cost in
shipping process should be considered as a variable. Stopford (2009) has analyzed the share of major
costs of running a 10-year old capesize bulk carrier under the Liberian flag at 2005 prices. General
overview of the cost share-out is presented in fig. 2. The shipping market is extremely fluctuating
and the share-out depends also e.g. on the type of cargo, ship type and size category etc. Therefore,
the diagram is later used only as a rough guide in the estimation of reduction in shipping costs by
implementation of voyage optimization.

![Figure 2 – General share-out of shipping costs. Redrawn. (Stopford, 2009)](image)

According to Stopford (2009), the shipping costs can be categorized into four main groups – operating
costs, periodic maintenance, voyage costs and capital costs. Additionally, the shipping costs include
cargo-handling costs which is omitted in fig. 2 due to its inaccuracy.

The economy of shipping is dependent on the relationship between freight cost and ship size. There-
fore, a suitable way to measure the total cost of shipping process is the unit cost, where the cost is
determined per unit transportable (Stopford, 2009):

\[
C_{tm} = \frac{OC_{tm} + PM_{tm} + VC_{tm} + CHC_{tm} + K_{tm}}{DWT_{tm}}
\]  

(2.1)

where:
\[ C \text{ is the cost per dwt per annum} \]

\[ OC \text{ is the operating cost per annum} \]

\[ PM \text{ is the periodic maintenance per annum} \]

\[ VC \text{ is the voyage cost per annum} \]

\[ CHC \text{ is the cargo handling cost per annum} \]

\[ K \text{ is the capital cost per annum} \]

\[ DWT \text{ is the ship deadweight} \]

Subscript \( t \) stands for the year and \( m \) for the ship number of the fleet.

In a voyage charter the revenue depends on the quantity and the rate paid per unit of the cargo. For example, in a case of product tankers, the cargo capacity is typically between 30 000 - 120 000 dwt which is considerably lower compared to VLCC tankers with capacity over 200 000 dwt. However, the rate paid per cargo unit in refined petroleum products is higher compared to crude oil which makes the business cost-effective.

### 2.3.1 Voyage costs

Voyage costs incorporates the variable costs of operating a ship. The share of voyage costs is defined elaborately in charter-party. Generally, under voyage charter all voyage related costs are paid by the shipowner, except in the under of demurrage or dispatch claims where costs may be shared in different ways. Voyage costs include port charges, loading/discharging, cleaning holds, cargo claims, canal transit dues and bunker fuel. The principal components in voyage cost calculation are presented in eq. (2.2) (Stopford, 2009).

\[ VC_{tm} = FC_{tm} + PD_{tm} + TP_{tm} + CD_{tm} \]  \hspace{1cm} (2.2)

where:

- \( VC \) is the voyage costs
- \( FC \) is the fuel costs for main and auxiliary engines
- \( PM \) is Port and light dues
- \( TP \) is tug and pilotage costs
- \( CD \) is canal dues

**Fuel costs**

Fuel costs is the largest variable in voyage related costs. As the power to move the ship increases by the cubic of the speed, the fuel consumption is assumed to increase proportionally. A commonly used fuel consumption cubic rule is presented in eq. (2.3) (Stopford, 2009).

\[ F = F^* \left( \frac{S}{S^*} \right)^3 \]  \hspace{1cm} (2.3)

where:
In laden voyages, the operating speed is agreed in the voyage charter party. The ballast voyages are sailed without a contract, hence the ship operator can choose a suitable operating speed to reach the next loading port. In both cases it is beneficial to operate with as slow speed as possible to minimize the fuel costs. However, the prevailing market situation is the crucial factor which dictates the final operating speed. For example, if the freight market is increasing during ballast voyage, there is no reason to speed up to arrive the loading port. On the contrary, when the freight market is decreasing, it is important to arrive the loading port before the cargo rates decrease significantly. Furthermore, in ballast voyages it is important for the ship operator not to miss the time period for laycan and losing the cargo by arriving late to the loading port.

**2.3.2 Operating costs**

Operating costs represents the fixed cost of operating a ship. Operating costs include crew wages, provisions, repairs and maintenance, stores and supplies, lubricating oil, water, insurance and overheads. In voyage charter, the operating costs are covered by the shipowner.

Principal components of operating costs are (Stopford, 2009):

\[ OC_{im} = M_{im} + ST_{im} + MN_{im} + I_{im} + AD_{im} \]  \hspace{1cm} (2.4)

where:

- \( OC \) is the operating costs
- \( M \) is the manning cost
- \( ST \) is the storage cost
- \( MN \) is the routine repair and maintenance cost
- \( I \) is the insurance cost
- \( AD \) is the administration cost

The way how a ship is used in daily operations covered by voyage costs has an impact on the operating costs as well. For example, reduction in fuel costs may have a consequential cut in lubricant consumption and less frequent repairs and maintenance.

**2.3.3 Cargo handling costs**

Cargo handling costs consist from the sum of loading and discharge related costs and the cost of any claims arisen related to cargo handling, e.g. demurrage. The principal components of cargo handling costs are presented in eq. (2.5) (Stopford, 2009):

\[ CHC_{im} = L_{im} + DIS_{im} + CL_{im} \]  \hspace{1cm} (2.5)

where:
Typically cargo related costs under a voyage charter party are paid by the charterer, except the cargo handling costs (Stopford, 2009). Cargo handling costs vary largely depending on the cargo type and is therefore not included in the example calculation.

### 2.3.4 Capital costs
The characteristics defining the capital costs of a ship differ completely from the voyage costs, operating costs and cargo handling costs which have a direct effect on the physical operation of the ship. In general, the capital costs consist of the initial purchase of the ship, the capital repayment for the investors and the cash received from the sale of the ship. (Stopford, 2009).

### 2.4 Voyage cashflow
This section covers the description of voyage cashflow calculation based on the voyage cashflow analysis introduced by Stopford (2009). The voyage cashflow calculation is later implemented in section 8.3 when the influence of voyage optimization on shipping company economics is estimated.

#### 2.4.1 Freight rate
Freight rate is the negotiated rate per unit of cargo paid between named ports. The freight rate mechanism in the freight market functions by shipowners and shippers negotiating a certain freight rate which reflects on the current freight market situation. For instance, if there are plenty of ships operating in the market, the freight rate is low and contrary if there are too few ships operating in the market, the freight rate is high. (Stopford, 2009).

#### 2.4.2 Time-Charter Equivalent
Typically the shipowners measure the daily revenue performance of a ship by using the Time-Charter Equivalent. Time-Charter Equivalent is calculated by subtracting the voyage costs and operating costs from the total freight earnings over the time period spent for the delivery.

$$\text{TCE/day} = \frac{\text{Freight earnings} - \text{Voyage costs} - \text{Operating costs}}{\text{Number of days}}$$  \hfill (2.6)

The number of days is determined as the time between the ship leaving port after discharge of previous cargo until the discharge of current cargo. Slower speed yields to a longer time spent at sea and lowers the Time-Charter Equivalent. Therefore, the speed should be reduced only in cases when the savings in fuel costs exceeds the reduction of TCE caused by the increase in voyage duration. (Hellenic Shipping News Worldwide, 2015)
2.5 Hypothetical scenarios of voyage charter

The focus when determining the expected benefits is targeted on the voyage charter contract. The benefits are simplest to be defined when cargo is fully loaded at point A and fully unloaded at point B. The unbalance in benefit sharing in shipping operations can be clarified by hypothetical example scenarios described by the following. The fuel consumption and CO₂ emission estimations were calculated by using NAPA Voyage Optimization tool.

2.5.1 Scenario I - Operation with original ETA

A 55 000 dwt sized product tanker is steaming from Houston, USA to Marseilles, France. Charterer has concluded with ship operator to ship 50 000 tons of petroleum products with voyage charter agreement. The ship is in full laden condition and it will be fully discharged in the destination. The route distance is approximately 5 500 nautical miles and with a constant speed of 12 knots the duration of the voyage will be approximately 19.5 days. According to the voyage charter agreement, fuel expenses are paid by the ship operator. The voyage is optimized for just-in-time arrival 20 days after the departure. The planned route is visualized as waypoints in Figure 3 below.

![Figure 3 – Planned route a.k.a voyage itinerary.](image)

After 10 days of steaming according to the original voyage itinerary, port authorities at Marseilles announce that due to shortage in storage tank space at the port, the 50 000 tons of petroleum products can not be unloaded from the ship until five days after the original ETA. The Ship master decides to proceed with original ETA and the ship arrives at port after 20 days from the departure. The ship is anchored near the port to wait for the port authority’s permission to maneuver to the berth. After the five days of wait, the ship is maneuvered to the berth for discharge. According to the voyage charter agreement, the charterer is bound to compensate the ship operator 18 000 $ demurrage rate per day for the time which could have been utilized in other operations if the ship was discharged according to the original agreement. The total fuel consumption in this route is 390 tons of HFO based on the performance calculation with NAPA Voyage Optimization tool. With a bunker price of 400 $/ton the total cost of fuel per voyage would be 156 000 $. However, by reducing average steaming speed to 8 knots for the remaining voyage, the ship would arrive just-in-time to the port for discharge. The calculated total fuel consumption would be then 340 tons. Therefore, the cost of bunker would be...
By receiving 18,000 $ of demurrage each day spent at anchor, the ship operator would gain 90,000 $ in total during the five days of wait. If the demurrage is used straight to compensate the fuel costs, the monetary benefits for the ship operator would be:

**Table 1 – Fuel cost calculation with initial ETA.**

<table>
<thead>
<tr>
<th>Voyage sailed in 20 days:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunker paid by the ship operator</td>
<td>156,000 $</td>
</tr>
<tr>
<td>Total demurrage received</td>
<td>90,500 $</td>
</tr>
<tr>
<td>Residue of bunker cost after demurrage</td>
<td>66,000 $</td>
</tr>
</tbody>
</table>

Therefore, the percentual saving compared to voyage sailed in 25 days in fuel cost is 51% for operating inefficiently. This comparison assumes that any demurrage is not paid during the extra five days spent en route when speed is reduced after 10 days. The 20-day voyage produces 15 % more CO₂ emissions compared to the 25-day voyage. Summary of the scenario is included in fig. 4.

**Figure 4 – Summary of the scenario.**

**Benefits of the scenario**

The benefits for the scenario focuses on the ship operator which receives demurrage from waiting at the anchor. Typically, the demurrage rate is higher than the expenses of fuel cost when steaming efficiently, so the ship operator has incentive to operate inefficiently. Additionally, the ship operator could have time for maintenance jobs etc. while at anchor.

**Disadvantages of the scenario**

The disadvantages of the scenario fall upon the charterer since they are bound to pay demurrage to the ship operator for the delay in port. General disadvantages are more emissions in total and emissions.
produced in port areas. Generally it can be also discovered that the benefits are not in balance between stakeholders.

### 2.5.2 Scenario II - Just-in-time operation and implementation of Virtual Arrival

The starting point of this scenario is same as in previous scenario above. The arrival port has implemented a queue system to schedule the berthing instead of first-come first-served berthing policy. After 10 days of steaming, the port authorities at Marseilles announce about five-day delay in port operations. The ship master acts immediately and contacts charterer representative to deliberate about the delay. The charterer and ship operator agree to enter Virtual Arrival agreement for the remaining voyage. A new Required Time of Arrival is agreed between the charterer and ship operator 25 days after the departure. The agreement to undertake Virtual Arrival is implemented by using charter party clause which binds the charterer to compensate the extra five days used on voyage by paying 75% of the demurrage rate to the ship operator.

The ship operator reduces the voyage speed and new voyage itinerary is made to meet the Required Time of Arrival. The ship operator has assessed the ship’s performance and fuel consumption to ensure that the speed reduction is reasonable.

The ship is acknowledged as “virtually arrived” at Marseilles port 20 days after the departure of the ship while, in reality, the ship is still en route. Five days later there is space in storage tank and the ship is arrived at the port accordingly to the Required Time of Arrival and berthed for discharge. The total calculated fuel consumption by steaming with average speed of 8 knots for the remaining 15 days would be 340 tons. The ship operator receives 75% of the demurrage rate for each extra day spent en route. The monetary benefits for the ship operator would then be:

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunker paid by the ship operator</td>
<td>136 000 $</td>
</tr>
<tr>
<td>Total demurrage received</td>
<td>67 500 $</td>
</tr>
<tr>
<td>Residue of bunker cost after demurrage</td>
<td>68 500 $</td>
</tr>
</tbody>
</table>

Table 2 – Fuel cost calculation with implementation of Virtual Arrival.

Therefore, the shipowner saves 50% in the fuel costs by operating efficiently and the CO₂ emissions are 15% less compared to the 20-day voyage. Additionally, the demurrage which charterer is bound to pay is 25% less than in previous scenario. The monetary benefit for ship operator is 3.5% less compared to the previous scenario but yields to more efficient operation and balanced benefits between both stakeholders. Summary of just-in-time operation with Virtual Arrival is presented in fig. 5.
Benefits of the scenario

Distinguishable benefit for the charterer, compared to the previous scenario, is the reduction in demurrage rate paid to the ship operator for the delay. Furthermore, the ship operator has an incentive to operate efficiently, since the energy saving and reduction of emissions is cost effective. The reduction of speed yields to improved safety and less congestion at port areas. Reduction in crew fatigue is also conceivable benefit.

In general, the share of benefits is more balanced than in previous scenario. Less emissions are produced especially in port areas when implementing just-in-time arrival.
3 Ship energy efficiency

The *Third IMO GHG study 2014* has estimated that shipping produces 2.2% of anthropogenic CO\(_2\) emissions (IMO, 2015b). In recent years, the shipborne emissions have become more and more controlled by regulative measures such as Energy Efficiency Design Index for newbuildings and Ship Energy Management Plan set by International Maritime Organization. This chapter concerns the technical requirements to improve ship energy efficiency and the improvement in energy efficiency by operations.

### 3.1 MARPOL

The International Convention for the Prevention of Pollution from Ships (MARPOL) is a convention developed to protect the pollution of marine environment by shipborne pollutants. The convention was approved by IMO in 1973 and came into force in 1983. Today, the convention consists of six annexes, and the latest amendment *Annex VI – Prevention of air pollution from ships* and its regulations considering ship energy efficiency are discussed in the following.

#### 3.1.1 EEDI

Energy efficiency index for newbuildings came into effect as an amendment under the regulation of MARPOL Annex VI Chapter 4 in July 2011 (IMO, 2011). The purpose of EEDI is to ensure that energy efficiency of newbuild ships is in an appropriate level. In practice this would result as installation of more energy efficient appliances and adjustments in design principles to improve the technical abilities towards energy efficient operations. The EEDI measures energy efficiency by dividing the CO\(_2\) emissions produced with the tonne-mile transport work done. The condition to fulfill the energy efficiency requirements is to satisfy the minimum energy efficiency level for specific ship type and size category. Therefore, the EEDI is more a measure of CO\(_2\) emissions rather than a direct indicator of actual energy efficiency. In simple terms, the EEDI can be represented by eq. (3.1) (IMO, 2016a).

\[
EEDI = \frac{\text{CO}_2 \text{ emission}}{\text{transport work}}
\]

(3.1)

The actions to improve EEDI in newbuildings can be for instance hull optimization, propeller optimization, adjustment of design speed, usage of energy saving devices and installation of energy efficient machinery.

#### 3.1.2 SEEMP

The MARPOL regulation on Ship Energy Efficiency Management Plan entered into force on January 1st 2013 and it requires all ships of more than 400 gross tonnage to carry a ship specific Ship Energy Efficiency Management Plan. The main purpose of the SEEMP is to create a mechanism for shipowners to monitor and improve the operational efficiency of a ship. The framework when developing ship specific SEEMP can be realized by four steps: planning, implementation, monitoring, and self-evaluation and improvement (IMO, 2016a). In this manner the SEEMP could be developed by improving the performance continuously.
3.1.3 EEOI

The Energy efficiency operational indicator is a optional monitoring index to measure the operational energy efficiency of a specific ship. The EEOI may be used as an index when monitoring the execution of SEEMP. The voyage specific EEOI is calculated as:

\[
EEOI = \frac{\sum_j FC_j \cdot C_{Fj}}{m_{cargo} \cdot D}
\]  

(3.2)

The ship specific average EEOI for the period under review is calculated as:

\[
EEOI_{\text{average}} = \frac{\sum_i \sum_j (FC_{ij} \cdot C_{Fj})}{\sum_i (m_{cargo,i} \cdot D_i)}
\]  

(3.3)

where:

- \( i \) is the voyage number
- \( j \) is the fuel type
- \( FC_{ij} \) is the mass of consumed fuel \( j \) during a voyage \( i \)
- \( C_{Fj} \) is the fuel mass to CO\(_2\) mass conversion factor for fuel \( j \)
- \( m_{cargo} \) is the cargo carried (tonnes), work done (number of TEU or passengers) or gross tonnes for passenger ships
- \( D \) is the distance in nautical miles corresponding to the cargo carried or work done. (IMO, 2009a)

While EEOI can be a suitable indicator to measure the produced greenhouse gases in ship operations, the EEOI has drawn criticism for being imprecise when presenting the ship’s energy efficiency. According to Bimco (2017), "Operational efficiency indices, such as the IMO Energy Efficiency Operational Indicator, are overly simplistic or even misleading on an individual ship basis and should, therefore, not be considered for regulatory purposes". The problems of EEDI’s inaccuracy are mainly due to unavoidable situations of bad weather conditions and ballast voyages which decrease the EEOI value (Psaraftis, 2019).

3.2 Operational efficiency

All ships are capable of improving their energy efficiency by saving energy at the operational stage. However, new ships which are designed to fulfill the EEDI requirements may have more potential and flexibility to accomplish operational improvements for instance with flexibility in speed adjustment and using energy saving devices. The scope when discussing the ways to improve ship’s operational efficiency is limited to reductions in ship’s speed (Slow steaming), reducing the time spent on waiting at the port (just-in-time arrival) and voyage optimization by weather routing. While energy management in auxiliary systems supporting the machinery functioning and sustaining the crew has potential in improving the total operational efficiency as well, the subject is left out of the scope in this thesis.
3.2.1 Slow steaming

As described in section 2.3.1, a reduction in operational speed can decrease the fuel consumption significantly. Slow steaming refers to operating ship at a significantly lower speed than the design speed. The general definition of slow steaming is when main engine’s load is less than 60% of the maximum continuous rating (MCR) (IMO, 2016b). The crucial factor of a ship’s ability for slow steaming is the main engine’s capability to run at low loads. From the increasing trend of slow steaming, the engine manufacturers have developed slow steaming upgrade kits to allow main engines to be run at lower loads (Wiesmann, 2010).

When considering slow steaming in the context of the complete shipping process, several benefits and disadvantages can be found. Table 3 summarizes the benefits and disadvantages from the perspective of the ship operator and charterer when operating under voyage charter party, and from an environmental perspective as well (IMO, 2016b).

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Benefits</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship operator</td>
<td>Lower fuel consumption per voyage</td>
<td>Higher auxiliaries working hours per voyage</td>
</tr>
<tr>
<td></td>
<td>Lower average engine load</td>
<td>Higher maintenance costs due to operation at low loads</td>
</tr>
<tr>
<td></td>
<td>Lower lubricating oil consumption</td>
<td>More tendency to hull fouling</td>
</tr>
<tr>
<td>Charterer</td>
<td>-</td>
<td>Longer delivery time of cargo</td>
</tr>
<tr>
<td>Environment</td>
<td>Lower NOx emissions</td>
<td>Higher CO impact</td>
</tr>
<tr>
<td></td>
<td>Lower CO2 emissions</td>
<td>Higher particulate matter concentration</td>
</tr>
<tr>
<td></td>
<td>Lower SOx emissions</td>
<td>Higher sludge</td>
</tr>
</tbody>
</table>

As summarized in table 3, slow steaming has numerous benefits for the ship operator but also consequential disadvantages from slow steaming such as higher maintenance costs which diminish the monetary benefits of the ship operator. When operating under a voyage charter party, the charterer has no benefit from slow steaming – instead the operator needs to tolerate from longer delivery time of cargo. From an environmental point of view slow steaming reduces the production of GHG emissions, but increases the impact of carbon monoxide and PM concentration. Slow steaming also increases the amount of sludge oil due to the poor combustion by the operating the main engine at low loads.

3.2.2 Just-in-Time operation

The origin of the just-in-time operation concept comes from the manufacturing industry where inventory levels associated costs are aimed to minimize by manufacturing products based on demand. In shipping operations, this philosophy is applied by reducing the unnecessary waiting time at the arrival port. The concept of just-in-time operation brings the savings in fuel consumption from the speed reduction similarly as in slow steaming. However, just-in-time operation differs from slow steaming as the objective of just-in-time operation is to carefully adjust the speed within the voyage constraints to meet the time of arrival just in time, rather than drastically decreasing the operating speed and resulting later arrival time.

As discussed in section 2.1, the shipping process is influenced by many factors which are based on the demand of different shipping stakeholders. Current practices and charter party constraints in shipping
industry are still encouraging ship operator to schedule their ships to arrive to the port as early as possible. Additionally, the slotting issue in ports complicates the scheduling if berth or storage space is not available. These circumstances create barriers against the successful implementation of just-in-time operation.
4 Voyage optimization

The traditional way of planning ship routes in the past has relied mainly on avoiding bad weather (Chen, 2013). However, voyage planning by focusing only on weather forecast has limitations on optimizing efficient ship performance and the reliability of weather forecast decreases as the time period of the forecast increases. A more advanced voyage optimization technology aims to take into account the optimal routing, speed adjustment and port scheduling to reduce emissions produced by shipping. Furthermore, a sophisticated voyage optimization takes into account the ship motions and responses to enhance operational safety. A recent research, such as Jia et al. (2017) and Lu et al. (2015), has showed that there is potential to improve ship’s operational performance and reduce shipborne emissions by the implementation of voyage optimization technology.

4.1 Motivation for voyage optimization

The voyage can be optimized by various objectives. Such objectives are for instance, minimizing fuel consumption, emissions or voyage time and maintaining ship safety, cargo safety and comfort onboard. Often there can be several objectives to be optimized, but balancing between different objectives can be problematic since improving one objective may reduce the other (Lu et al., 2015). Typically, the prioritized objective is minimizing the voyage time or fuel consumption. The prioritized objectives may vary between different shipping stakeholders. Generally, the stakeholder who pays for the fuel is interested in minimizing the fuel consumption. The charterer is typically interested in cargo safety and minimizing the voyage time, allowing for faster cargo transport. An example of different voyage optimization objectives and their importance for different shipping stakeholders are evaluated by the author in table 4.

Table 4 – Example on the prioritization of voyage optimization objectives under voyage charter party.

<table>
<thead>
<tr>
<th>Priority</th>
<th>Charterer</th>
<th>Operator</th>
<th>Onboard crew</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cargo safety</td>
<td>Ship safety</td>
<td>Ship safety</td>
</tr>
<tr>
<td>2.</td>
<td>Voyage time</td>
<td>Cargo safety</td>
<td>Cargo safety</td>
</tr>
<tr>
<td>3.</td>
<td>Emissions</td>
<td>Fuel consumption</td>
<td>Comfort onboard</td>
</tr>
</tbody>
</table>

In some ship performance optimization cases, shipping stakeholders could achieve benefits in environmental, monetary and safety related terms by prioritizing just one objective. For example, optimizing for minimum fuel consumption enhances the ship energy efficiency and reduces the shipborne emissions. The consequential speed slow-down can enhance the ship safety and comfort onboard by reducing risk of excessive ship motions, propeller racing or slamming in heavy weather.

4.1.1 Fuel consumption

Because of the cubic relationship between the speed and fuel consumption introduced in section 2.3.1, speed adjustment during voyage may have a notable effect on total fuel consumption. A research of Lu et al. (2015) estimated the potential for fuel saving on a Pacific-crossing voyage by optimizing four different routes with the lowest Beaufort Number, shortest distance, lowest fuel consumption and a route with the most head sea and bow sea. All routes used the same departure and arrival time, loading condition and fixed average speed. The results were then compared to an actual route sailed as recorded in the noon report. The results showed an average fuel saving potential of 10% compared
to the recorded route. Since the reduction in fuel consumption has a consequential effect on reducing the emissions and bunker cost, the result is remarkable in both environmental and monetary terms.

The research by Jia et al. (2017) uses speed optimization and implementation of just-in-time operation in the assessment of potential reduction in fuel consumption and emissions. The hypothesis in the research is that if the waiting time at the arrival port could be minimized and the ship can be berthed at short notice after her arrival, the voyage can be sailed with a slower average speed and the savings in fuel consumption and emissions arise from the impact of speed reduction. The research evaluates 5066 voyages operated by 483 Very Large Crude Oil Carriers. The results show that if 50% of the assessed waiting time at port could be reduced, the average port time saved is 37 hours and the average fuel consumption saving is 12.5% per voyage. Therefore, optimal port scheduling could benefit the stakeholder who pays the fuel bill and helps to avoid congestion at the port areas.

4.1.2 Emissions

When estimating the EEOI described in section 3.1.3, the prioritized objective is the reduction of shipborne emissions. The reduction of emissions is also the key objective in a global scale since emissions have an impact on environmental sustainability. Because the emissions produced is directly dependent to the amount of fuel burned, prioritizing minimum fuel consumption or minimum emissions always avail one another.

IMO has committed to reduce the total annual greenhouse gas emissions at least 50% by the year 2050 compared to 2008 (IMO, 2018). The research by Jia et al. (2017) assess that if only 50% of the estimated waiting time at the port could be avoided in the operation of VLCC tankers, the consequential speed slow-down yields to an average reduction of 422 tons of CO₂ emissions per voyage. Relatively, this would be 12.5% of all the emissions produced in VLCC operations. Therefore, the implementation of just-in-time operation could be one potential solution towards the IMO’s 2050 strategy.

4.1.3 Weather awareness

The most important environmental factors related to ship performance and safety are surface wind and waves. Wind and waves induce additional resistance on ship motion and can expose the ship to excessive motions. The inaccuracy of weather forecasts makes the prediction of the impact of wind and waves on ship performance difficult. However, the prediction has become more reliable during the past decades by the improved weather and wave models as the quality of satellite generated wave data and ocean-wave prediction models have increased. (Sen and Padhy, 2015)

The weather awareness in the voyage optimization process aids in the decision whether to avoid a certain route due to bad weather conditions or to avoid excess ship motion in waves by voluntary speed reduction. Considering ship safety, hazards such as parametric resonance, propeller racing, slamming or shipping of green water should be avoided. (Chen, 2013)

A research by Chang et al. (2013) studies the utilization of strong ocean currents in route planning. The object in the study is to use favourable ocean currents to reduce fuel consumption and voyage time. With the information on ocean currents, the currents following the route direction could be used as an advantage and the currents opposite the route direction can be avoided. The study focuses on voyages sailed with super-slow steaming, i.e. speed of approximately 12 knots, at Kuroshio region in East Asia. In the conclusion of the research Chang et al. state that utilizing the favourable effect
of Kurushio current could theoretically save 1-8% in voyage time on a example route from Taipei to Tokyo. Alternatively, by avoiding unfavourable currents on the opposite route could theoretically save 5-7% in voyage time.

4.2 Voyage planning

In general, voyage planning consists of ship scheduling, passage planning and ensuring optimum ship performance. Figure 6 illustrates an example of the workflow on voyage planning between shipping stakeholders under voyage charter.

![Voyage planning workflow](image)

Figure 6 – Voyage planning workflow in voyage charter operations.

As described in section 2, the starting point in all operations is that there is a demand for transportation. For example, the cargo owner needs to transport petroleum products from port A to port B. The cargo owner contacts a shipowner with a suitable ship and timetable to complete the voyage. The voyage is operated under a voyage charter and the cargo owner pays a fixed rate per ton of cargo for the complete transport service. Therefore, the voyage planning remains solely as the ship operator’s task in voyage charter operations.

Initial voyage planning may be done in co-operation with the ship operator’s on-shore planners and the crew onboard. However, the proper passage planning is done onboard, typically by the second officer or the captain. The passage plan should include information, for instance, on course and speed alterations, potential hazards and restricted water depth areas along the route (IMO, 1999). Voyage optimization services enter into the voyage planning at this stage, since the resources for estimating the optimum ship performance and proper weather routing onboard may be limited. After the voyage is initiated, operator and cargo owner monitor the voyage during its execution, for example by receiving noon reports or using AIS-tracking service. When the ship has reached the arrival port and the voyage is complete, voyage reports will be prepared as agreed in the voyage charter party.
4.2.1 Voyage scheduling

Voyage scheduling can be a complex exercise in the terms of both ship and port operations. Some shipowners run their operations on a liner shipping service where one or more ships sail on a fixed route, departing and arriving to port at regular intervals. In such operations keeping the schedule is essential for maintaining efficient operation. Breskin (2018). The contrary to liner shipping service is the so called tramp shipping service. Ships operated under the tramp shipping market do not operate on a regular schedule or routes. Tramp shipping operations are typically run under voyage charter and the preference in such operation is to minimize the time spent in ballast. Operating under a voyage charter is more flexible in a sense that the charter party applies to a single voyage. However, the tramp shipping markets can be highly complex and scheduling operations based on the demand for tramp shipping services can be troublesome.

The physical limits of the ports and the difference in port operation customs around the world complicate the voyage scheduling further. For example, low tide, local holidays, the capacity of cargo handling gear and berthing queue policy can cause unforeseen delays in port operations if these issues are not taken into consideration when scheduling the voyage (Breskin, 2018). The uncertainties in port operations and the prevailing first-come first-served berthing policy impede especially the implementation of just-in-time operation strategy.

In tramp operations, the objectives in voyage scheduling depend on the current market situation. In ballast voyages, when the ship is empty of cargo and she is sailing to the next loading port, the fluctuation of the market plays a major part when deciding the operation speed. For example, when the market is increasing there is no special reason to rush to the next port. However, when the market is falling, it is important to arrive to the loading port before the cargo price decreases significantly. Furthermore, the ship operators do not want to take the risk of losing cargo by arriving to the loading port at the end of the laycan. In laden voyages, when the ship is carrying cargo and the schedule is already agreed in the charter party, the situation is more stable and the operation speed can be more carefully adjusted to meet the Just-in-Time ETA. Therefore, it can be stated that the room for optimization falls upon mainly on laden voyages.

4.2.2 Passage planning

The IMO Guidelines for voyage planning (IMO, 1999) presents four main stages in the process of passage planning: appraisal, planning, execution and monitoring.

The Appraisal stage should take all voyage relevant information into consideration, such as seaworthiness of the ship, operational limitations, potential risks along the route and characteristics of the cargo.

The planning stage involves detailed planning of the passage from berth A to berth B, including the areas where the presence of a pilot is required. Voyage optimization services may be used at this stage to estimate an optimal route in terms of fuel consumption, voyage time, ship and cargo safety, or comfort onboard.

In the execution stage, the voyage is executed in accordance with the passage plan.

In the monitoring stage, the progress of the voyage is closely monitored. Any changes made to the passage plan should be clearly marked and recorded.
4.2.3 Voyage optimization algorithms

To include the weather awareness and the desired optimization objective in the voyage planning, sophisticated methods are required to find the best route available. A study by Walther, Rizvanolli, Wendebourg and Jahn (2016) focuses on the different state-of-the-art methods to model the weather routing problem and the algorithms to obtain the optimal route. To model the weather routing problem, the research highlights the approaches where the problem is considered as a constrained graph problem, a constrained nonlinear optimization problem or as a combination of both. Based on the formulation of the optimization problem, different methods are then used to solve it. The highlighted methods are Dijkstra’s algorithm, dynamic programming and optimal control methods, isochrone methods and iterative approaches. In the conclusion, Walther et al. (2016) state that the methods to be used strongly depend on the requirements of optimization objectives. For example, the Dijkstra’s algorithm can lead to accurate results, but it is best suitable for short route calculations due to a relatively long computation time. Therefore, for reliable results it should be carefully considered what type of methods are used to optimize a specific objective, but also consider the computational effort.

4.2.4 Voyage data sharing

To overcome the problems in voyage planning and scheduling, the sharing of voyage information is a necessity between different stakeholders such as the ship operator, charterer and port authorities. Information sharing among stakeholders increases transparency in shipping market. Better cooperation and communication can lead to "smarter shipping" and the information could be used, for instance, to predict port congestion. A good example of the benefits in information sharing can be found from the aviation transportation where Air Traffic Management principles have been used to redesign routes by optimizing the use of airspace and calculating the most efficient route. (Jia et al., 2017).

4.3 Voyage optimization strategies

The implementation of voyage optimization strategies can be exemplified by continuing with the hypothetical scenarios introduced in section 2.5. Similar optimization scenarios will be used later in the case study simulations described in section 7. The starting point in the analysis of voyage optimization benefits is to compare the original sailed voyage with scenarios where different voyage optimization strategies are implemented.

4.3.1 Voyage as sailed

This scenario can be considered similar to the Hypothetical scenario I introduced in section 2.5.1, where the ship operated with the original passage plan and arrived to the port five days in advance to wait for the berthing. The route distance, average speed, fuel consumption, CO₂ emissions and the realized weather conditions enroute will be used as reference points in comparison of the voyage optimization strategies.

Starting point of the case study is to simulate several previous sailed voyages by utilizing AIS data points from the route, generic ship model and past weather data. The simulation gives output for time and distance sailed, speed, fuel consumption and produced CO₂ emissions. In executable simulations, it is essential to identify whether the ship has anchored near the port to wait her turn for berthing or sailed straight to the berth for discharge. Typically ship operators will arrive port as soon as possible...
within the contractual limits to avoid any due dispatch penalties (IMO, 2016b). Therefore, in most cases there is some time spent at anchor anyway if there is congestion at the port or port is not ready.

4.3.2 Route as sailed and optimized speed with just-in-time ETA

This scenario can be considered similar to the Hypothetical scenario II introduced in section 2.5.2, where the ship followed the original route, but the arrival time was adjusted to meet the Required Time of Arrival which was set five days later than the original ETA. This yielded to a significant reduction in fuel consumption and shipborne emissions.

The simulation in the case study utilizes the Required Time of Arrival to calculate the optimal speed along the route to obtain lowest fuel consumption and CO\(_2\) emissions. In the case study, the time adjustments between the original ETA and RTA are expected to be much shorter compared to the two hypothetical scenarios.

4.3.3 Optimized route and speed with just-in-time ETA

The simulation utilizes the same Required Time of Arrival as in the previous scenario, but it includes weather routing methods in the calculation of the optimal route and speed along the voyage to obtain the lowest fuel consumption and CO\(_2\) emissions. A visualization of optimized routes in NAPA Voyage Optimization-tool is presented in Figure 7.

![Figure 7](image)

Figure 7 – Visualization of optimized routes in NAPA Voyage Optimization.

4.4 Expected benefits of voyage optimization

When comparing the results of previous voyage optimization scenarios, the hypothesis is that Optimized route and speed with just-in-time ETA strategy will have the lowest fuel consumption. However, the result is dependent on the original optimization methods used when the actual voyage was sailed. The shipowner may also have a good reason to utilize the time spent at anchor, e.g. maintenance work, when early arrival to the port is justifiable. Moreover, the ship cannot be operated too slow for long time due to increased maintenance costs and longer run of auxiliaries.
Weather routing can be implemented also without involvement of port authorities. Therefore, in analysis of the results, the benefits by using the just-in-time ETA and weather routing will be separated. Weather optimization brings benefits mainly to the ship operator while just-in-time optimization brings monetary benefits to the charterer and produces less emissions at the port.

4.4.1 Just-in-Time operation and re-scheduling during voyage

Benefits of implementing just-in-time operation to avoid congestion at port was discussed in example scenarios in section 2.5.1 and section 2.5.2. Just-in-time operation can also utilize weather routing to gain the benefits and improve safe operation.

4.4.2 Weather routing

The benefits when implementing Weather routing focus mainly to the ship operator. The economical benefit is reduction in fuel costs by optimizing the route for minimum energy consumption. The reduction of emissions is a consequence from reduction of fuel consumption. Mutual benefit for the ship operator and charterer is the lower risk of cargo damage or loss. Other safety aspects are lower risk of ship damage, less heavy rolling or other motions and increase of crew well-being.
5 Automatic Identification System

Shipborne Automatic Identification System (later referred to as AIS) is primarily used for transferring ship identification and tracing information for the ships nearby and shore-based Vessel Traffic Service (VTS) centers. IMO requires AIS transponders to be fitted in ships of 300 gross tons or above engaged on international voyages, cargo ships of 500 gross tons or above not engaged on international voyages and in all passenger ships. The initial objectives of AIS is to avoid collisions and enhance operational safety by providing supplementary information together with navigational systems. (IMO, 2015a). General description of shipborne AIS usage is presented in Figure 8.

![Figure 8 – Shipborne AIS system overview.](image)

Primarily ships share AIS information via dedicated VHF radio channels. In busy traffic areas, the information is shared also with a local VTS center. VTS centers may send additional information to ships, such as local navigational warnings, traffic management information and port information. (IMO, 2015a). Along with enhanced situation awareness, information sent by AIS can be used in many other applications, such as in search and rescue operations or analyzing vessel performance.

5.1 AIS broadcast information

The information sent by Automatic Identification System is categorized into three different types; static information, dynamic information, and voyage-related information. Details of the sent information are presented in table 5. Static information is entered to the AIS system on the installation and will be changed only if the properties are changed, for example, if the name of the ship changes. Apart from ship’s navigational status (i.e. at anchor, underway by engines, etc.) all dynamic information is updated automatically from the sensors connected to AIS system. Voyage-related information is entered manually to the system and may be updated during the voyage. (IMO, 2015a).
Table 5 – Information sent by ship with the AIS (IMO, 2015a).

<table>
<thead>
<tr>
<th>Static</th>
<th>Dynamic</th>
<th>Voyage related</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMSI</td>
<td>Ship’s position with accuracy indication and integrity status</td>
<td>Ship’s draught</td>
</tr>
<tr>
<td>Call sign &amp; name</td>
<td>Time in UTC</td>
<td>Hazardous cargo (type)</td>
</tr>
<tr>
<td>IMO number</td>
<td>Course over ground</td>
<td>Destination and ETA</td>
</tr>
<tr>
<td>Length and beam</td>
<td>Speed over ground</td>
<td>Route plan (optional)</td>
</tr>
<tr>
<td>Type of ship</td>
<td>Navigational status</td>
<td></td>
</tr>
<tr>
<td>Location of position-fixing antenna on the ship</td>
<td>Heading &amp; Angle of heel (optional)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pitch and roll (optional)</td>
<td></td>
</tr>
</tbody>
</table>

The MMSI (Maritime Mobile Service Identity) is a unique data broadcast identification number which is input manually. Occasionally, some ships may mistakenly share their MMSI with another ships which causes errors in their position and possibly very unrealistic transitions on a map (Wu et al., 2017).

Additionally, the ship can send short safety-related messages addressed either to a specified destination or all ships in the area. The content of these messages should relate to the safety of navigation, e.g. an iceberg sighted. The message should be kept at short as possible for clarity reasons. (IMO, 2015a).

According to the IMO (2015a) guidelines for the onboard use of AIS systems, the automatic reporting interval for AIS information depends on the information type. Static and voyage-related information should be updated every six minutes and on request. Dynamic information reporting interval is dependant on ship’s speed and course alteration from two to twelve seconds according to table 6. When the ship is at anchor, the reporting interval of three minutes is required. Safety-related text messages are sent only if necessary.

Table 6 – Dynamic information reporting interval (IMO, 2015a).

<table>
<thead>
<tr>
<th>Ship speed</th>
<th>Reporting interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship at anchor or moored and not moving faster than 3 knots</td>
<td>3 min</td>
</tr>
<tr>
<td>Ship at anchor or moored and moving faster than 3 knots</td>
<td>10 s</td>
</tr>
<tr>
<td>0-14 knots</td>
<td>10 s</td>
</tr>
<tr>
<td>0-14 knots and changing course</td>
<td>3.5 s</td>
</tr>
<tr>
<td>14-23 knots</td>
<td>6 s</td>
</tr>
<tr>
<td>14-23 knots and changing course</td>
<td>2 s</td>
</tr>
<tr>
<td>&gt;23 knots</td>
<td>2 s</td>
</tr>
<tr>
<td>&gt;23 knots and changing course</td>
<td>2 s</td>
</tr>
</tbody>
</table>

5.2 Voyage simulation utilizing AIS data

For utilizing AIS data points to create simulations of ship operations, the data needs to be stored. Many organizations and private sector companies such as HELCOM (governmental) and VesselTracker
(private) provide access for real-time AIS data and also collect and store historical AIS data. The typical coverage range of onboard transceivers is between 15 to 20 nautical miles and for extending the range, onshore AIS stations and satellite receivers are used. Typical coverage for onshore AIS station is 40 nautical miles and satellite receiver can cover a range of 1000 nautical miles. (Tu et al., 2018)

Unfortunately, the quality of stored AIS data does usually not come with such integrity as described in table 6. A typical reason for this could be an absence of a data transmission link at the open sea (Jaskolski, 2017). The data providers may also choose to use a lower time stamp resolution for data storage. Apart from the resolution, the data may include some erroneous entries as well, for example, the speed over ground entries may include extremely large or negative values (Tu et al., 2018).

The historical AIS data used in the case study is requested from various commercial providers. Access to the data is provided by NAPA. The data is collected with terrestrial and satellite receivers. This increases the data accuracy and integrity compared to using only either method. Overview of AIS data collecting and storing is presented in Figure 9.

The key information for the case study are ship’s IMO number, ship’s position, time, speed over ground, navigational status, draught and destination. In sake of efficient data extracting, it is important to manage with as little information as possible. Therefore, some of the information can be left out in the data extracting process from the provider and filled in later by other means. For example, the IMO number identifies the ship in question and the call sign and relevant static information can then be determined by using web services such as IHS Maritime Portal.
5.3 AIS data processing

The raw AIS data requires careful filtering and processing in order to analyze the voyage specific information and to eventually simulate the ship’s performance during the voyage. For the evaluation in the case study, the following steps are required to obtain voyage specific information by AIS data processing:

1. Identify portcalls
2. Filter out short voyages
3. Filter out voyages with bad AIS data resolution
4. Identify ship’s loading condition
5. Identify time spent at anchorage
6. Estimate ship payload

The following subsections cover the details about these AIS data processing steps.

5.3.1 Portcall identification

The portcall identification i.e. when the ship has arrived to the port area is used to divide the AIS data into individual voyages. The general method to split the AIS data to individual voyages can be performed with an algorithm which uses the AIS information on speed and distance to the closest port as the input. An overview of the portcall identification algorithm is presented on the loop flowchart in Figure 10.

![Flowchart of the portcall identification algorithm.](image)

The voyage ends when the two conditions in ship’s speed and the proximity to the nearest port are fulfilled. The information on existing ports is fetched from the port information database. The conditions when starting the next voyage are that the next departure port is the same as the previous arrival port. Respectively, the speed when the ship is not longer stationary needs to exceed the set
stationary threshold value. The portcall identification algorithm and port information database used in the case study simulations are provided by NAPA.

### 5.3.2 Data filtering

AIS data from voyages with a duration of less than 24 hours were filtered out, because short voyages were considered to be insignificant in the context of the case study. Typically, short voyages do not have noteworthy room for optimization and some of the short voyages may result from false triggered portcall identifications if ship is slowly manoeuvring between terminals in centralized port areas such as Singapore.

As stated above, the quality of raw AIS data depends on the data provider and the proximity of AIS data capturing transceivers and stations. Figure 11 illustrates the issue of bad AIS data point resolution, where the missing data causes the connection between datapoints to egregiously cross large land areas.

![Unrealistic voyages with bad AIS data point resolution.](image)

Especially the South China Sea and the Bay of Bengal are problematic areas in terms of AIS data quality as seen in Figure 11. The data resolution at open sea is poor in many occasions and good quality resolution is observed only near coastal areas. Unrealistic voyage data can also be detected from extremely straight connections between datapoints in open sea. The land crossing voyages and voyages with clearly unrealistic routes were filtered out by comparing the distance of the AIS-based route with the shortest route from NAPA Voyage Optimization route library. All AIS-based routes with distance less than 0.9 times the shortest route from the route library were eventually filtered out. NAPA route library uses the typical sailed routes as the basis of the shortest possible route, thus the factor of 0.9 was carefully adjusted to include the AIS-based routes which are slightly shorter than the shortest route from NAPA route library.

### 5.3.3 Draught separation

The ship’s loading condition, i.e. whether the ship is in ballast or laden condition can be determined by a draught ratio which is the ratio between observed draught and the design draught (Jia et al., 2017). Typically in tanker operations, it can be assumed that the ship does not receive any backhaul cargo in the discharge port (Stopford, 2009). Therefore, approximately half of the voyages are considered
to be operated in laden condition and half in ballast condition. However, when considering product tanker operations, it may be profitable enough to sail with part laden condition, instead of fully laden condition.

The AIS-reported draught of the ships considered in the case study varies from 4.5 to 13.1 meters. Once again, it should be acknowledged that the draught is reported to the AIS system by the deck officer and it may be incorrect. The draught ratio limit was set that voyages with a draught ratio <70% were considered as ballast voyages. An example of draught separation is shown in Figure 12.

![Figure 12](image_url) – Example of draught separation histogram.

The distribution between the ballast and laden voyages in Figure 12 supports the assumption that half of the voyages are sailed in laden and the other half in ballast condition. However, in the case of product tankers, in a draught of 8.8 meters some cargo may still be carried between close ports.

### 5.3.4 Ship payload

Information on ship payload, i.e. how much cargo the ship is carrying, is typically not publicly available. Jia, Prakash and Smith (2019) show that the AIS-reported draught can be used as a reasonable estimation of ship’s payload.

Variable lightweight model (Jia, Prakash and Smith, 2019):

\[
PL = C_B L_{pp} B \rho T - C_B d L_{pp} B \rho T_d + DWT
\]

(5.1)

where:

- \(PL\) is the ship payload in tons
- \(C_B\) is the ship block coefficient during operation
- \(L_{pp}\) is the ship length between perpendiculars
$B$ is the ship breadth
$ho$ is the sea water density
$T$ is the ship draught during operation
$C_{Bd}$ is the ship design block coefficient
$T_d$ is the ship design draught
$DWT$ is the ship deadweight in tons

Ship block coefficient during operation can be approximated with the prevailing draught according to MAN (2011):

$$C_B = 1 - (1 - C_{Bd}) \left( \frac{T_d}{T} \right)^{1/3}$$ (5.2)

The ship payload estimation is later used when calculating the Energy Efficiency Operational Index for the case study fleet.

5.3.5 Anchorage identification

The portcall identification algorithm introduced in section 5.3.1 identifies clearly the moment when the ship is stationary in the port area. However, the algorithm does not provide detailed information between the time from arrival to the next departure. Therefore, a more precise method is needed to identify the possible waiting time spent at anchorage before the ship enters to the berth for discharge.

A practical way to identify the anchorage time is to define port specific anchoring areas as a subset of individual ports in port database by using geospatial analysis techniques. The ship can be considered in anchorage when the ship is stationary inside the anchoring area. Some ports, such as Singapore, define their anchoring areas precisely as sections for different ship categories and closely manage the ships in anchorage (Maritime and Port Authority of Singapore, 2019). Therefore, in the analysis of AIS data, the preferable way is to define the anchoring areas as polygons instead of circle with specific radius.

The identification of individual anchorages in the case study was done manually for the 50 most visited ports. The anchoring areas were defined in this case by observing the coordinate points of AIS data with a geospatial analysis tool QGIS. A ship in anchorage is required to have a certain scope in the anchor cable length. The scope is defined by the ratio of the length of cable to the depth of water and the ratio ranges typically from 6 to 10 (IACS, 2017). This scope allows ship to have a slow circular motion while in anchorage which is shown as a circular patterns when the AIS data coordinates are plotted on a map. The anchoring areas can be then manually defined by framing the circular patterns in specific area as visualized in Figure 13. The AIS data points inside this polygon are used to create a sub-time series and when the following conditions are fulfilled, the ship can be identified as anchored with a fair degree of certainty: (Holmslykke, 2019)

1. The ship is identified as arrived
2. The particular AIS datapoint is included in the anchorage sub-time series
3. The ship is stationary, i.e. the speed over ground is less than 2 m/s
A more sophisticated way to obtain the anchoring areas would be to automate the process by using big data methods to track precise ship movements in port areas in order to create the polygons defining the anchoring areas. However, a development in this kind of approach requires substantial effort and it is left out from the scope of this thesis.

Figure 13 – Identifying the anchorings with geospatial mapping tool.
6 Performance calculation

This section covers the methods how ship’s performance can be simulated by using ship performance model, weather data, depth data and sea-going voyage data. In the case study, a set of realized voyages are simulated by using NAPA Voyage Optimization tool (hereinafter referred to as NAPA VO). Additionally, a set of selected voyages are simulated with a DTU Ship Simulation Workbench tool (hereinafter referred to as SSW) and the results are compared to the actual values based on noon reports. Flow chart of the performance calculation is presented in Figure 14.

The NAPA VO includes performance models of 55 000 ships in their database. The data sources for depth data and nowcast weather data are integrated to the system, thus in the context of this thesis only the sea-going voyage data is needed to be input by using the information from AIS-data to recreate the sailed voyages. The simulations are run for three different voyage optimization scenarios as described in section 4.3.

In SSW, the ship model is created from the user defined ship details. The weather data used in the SSW simulations is extracted from the NAPA VO results, thus the weather conditions are similar in both cases. In SSW simulations no optimization is applied, thus the simulation is done for the Voyage as sailed scenario only. The results of these selected voyages are then compared with the NAPA VO results and the actual voyage information based on noon reports in section 8.4.

6.1 Acknowledgement of the case company

The fleet used in the case study is medium range product tankers of Danish shipowner TORM A/S. The decision is justified by the good availability of AIS data and comprehensive fleet of 51 MR vessels. In this study the voyages of 49 ships are analyzed. The displayed information of the ships is publicly accessible and the publication of the results presented later on the thesis is accepted by the shipowner. Additional information of shipowner and the fleet operations was collected by interviews with the company representatives (Holmslykke, 2019). When performing Voyage as Sailed simulations, it should be noted that TORM A/S focuses already in voyage optimization by using Ship Performance Optimization System (SPOS) onboard their ships to perform weather routing.
6.1.1 Ships

The ships used in the case study are 49 Medium Range tankers (45 000 – 55 000 DWT). For representational purposes, the ships are categorized into 15 ship groups so that all sister ships belong to the same group. The ship groups are identified with the IMO number of the first ship in the group. The main dimensions of each ship group are presented in table 7. Although the ships in the same group are sister ships to each other, some of the dimensions may vary slightly. In these situations the value of first ship in the group is displayed in the table. Full list with all individual ship information is included in the appendix A. The information on ship main dimensions is collected from IHS Maritime Portal.

<table>
<thead>
<tr>
<th>Ship IMO</th>
<th>no. of ships</th>
<th>DWT</th>
<th>L&lt;sub&gt;pp&lt;/sub&gt;</th>
<th>B</th>
<th>T&lt;sub&gt;d&lt;/sub&gt;</th>
<th>C&lt;sub&gt;bd&lt;/sub&gt;</th>
</tr>
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<tbody>
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<td>51.371</td>
<td>174.0</td>
<td>32.2</td>
<td>13.1</td>
<td>0.838</td>
</tr>
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<td>9465992</td>
<td>11</td>
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<td>176.0</td>
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<td>32.2</td>
<td>12.2</td>
<td>0.822</td>
</tr>
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<td>173.9</td>
<td>32.2</td>
<td>12.2</td>
<td>0.822</td>
</tr>
<tr>
<td>9262091</td>
<td>1</td>
<td>45.999</td>
<td>173.9</td>
<td>32.2</td>
<td>12.1</td>
<td>0.820</td>
</tr>
<tr>
<td>9215103</td>
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<td>45.999</td>
<td>173.9</td>
<td>32.2</td>
<td>12.1</td>
<td>0.820</td>
</tr>
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<td>9172193</td>
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<td>171.0</td>
<td>32.2</td>
<td>12.2</td>
<td>0.814</td>
</tr>
</tbody>
</table>

6.2 Ship performance model

The ship performance model in Napa VO is combined from the ship specific data and generic models, such as propeller model, resistance curves and wind coefficients to create enhanced digital model. The main dimensions and the ship type are considered when defining a resistance model for specific hull types by applying generic resistance curves for the hull type calculated by Holtrop & Mennen method. Generic models are also utilized in the creation of propeller model, SFOC curve and wind-force coefficients for specific ship type which are then scaled from the basis of ship main dimensions. The process of ship performance model creation is described in Figure 15.
The ship model creation in SSW follows similar procedure as described in Figure 15. Instead of generic models, in SSW the models are defined in more detail by the user. Therefore, much more details about the ship are needed to be known or estimated when creating the ship performance model.

### 6.2.1 Hull resistance model

When ship is traveling through calm water it experiences a resistance to its forward motion. This resistance can be divided into two components: frictional resistance and wave-making resistance. The frictional resistance takes into account the phenomena when ship drags water along the hull due to the boundary layer developed on the wetted hull when the ship traveling through water. The wave-making resistance occurs as the hull generates waves when traveling through a body of water. These waves travel with the same speed as the ship. Frictional resistance and wave-making resistance occur simultaneously and they physically interact with each other. However, in practice the most useful approach is to consider both phenomena separately. In slow speeds the frictional resistance has more significant effect to the total hull resistance, but as the speed increases the wave-making resistance becomes dominant. (Larsson, 2010), (Matusiak, 2010).

A well-known approach to approximate hull resistance is the statistical method originally introduced by Holtrop and Mennen (1982) where the total resistance is calculated by using basic hull dimensions. The method is developed through a regression analysis based on model experiments and full-scale data. The total stillwater resistance in Holtrop & Mennen method is subdivided into following components (Holtrop and Mennen, 1982):

![Figure 15 – Ship performance model creation. Redrawn. (Napa, 2019).](image-url)
\[ R_{\text{still}} = R_F(1 + k_1) + R_{\text{APP}} + R_W + R_B + R_{TR} + R_A \] (6.1)

where:

- \( R_{\text{still}} \) is the total stillwater resistance of the hull
- \( R_F \) is the frictional resistance according to the ITTC 1957 formula
- \( 1 + k_1 \) is the form factor describing the viscous resistance of the hull form in relation to \( R_F \)
- \( R_{\text{APP}} \) is the resistance of appendages
- \( R_W \) is the wave-making and wave-breaking resistance
- \( R_B \) is the additional pressure resistance of bulbous bow near the water surface
- \( R_{TR} \) is the additional pressure resistance of immersed transom stern
- \( R_A \) is the model ship correlation resistance

The total stillwater resistance of the ship depends on the ship’s loading condition. Greater draught increases the wetted surface area and displacement of the ship, yielding to a greater frictional and wave-making resistance. Generally, the ship is encountering greater stillwater resistance in laden condition where draught is greater than in ballast condition.

6.2.2 Wave added resistance

The waves induce the ship to experience added resistance when passing through the water. The wave added resistance can be separated into short wave and long wave-induced resistance. The short waves induce resistance as the waves reflect from the moving hull. The long waves induce the ship to experience heave and pitch motions which dissipate the kinetic energy of forward moving ship. Heave and pitch motions force the hull to generate additional short waves which interfere with long waves, increasing the total wave added resistance. Ship particulars, such as length, beam, draft, and speed together with wave characteristics, such as significant waveheight, wave period and wave direction have an effect on the magnitude of wave added resistance. (Arribas, 2007). A method to calculate wave added resistance in Napa VO is based on the so-called radiated energy method introduced by Gerritsma and Beukelman (1972). The method utilizes strip theory to determine the resistance force.

6.2.3 Wind resistance

In addition to the stillwater resistance and wave added resistance, the ship experiences a resistance due to air movement above the waterline. Especially ships with big superstructures have a large wind area which has significant effect on wind added resistance. Along with ship particulars, wave added resistance is dependant on wind characteristics, such as speed and direction. The ITTC (2014) recommended procedures and guidelines proposes wind resistance to be calculated as:

\[ R_{\text{wind}} = \frac{1}{2} \rho_{\text{air}} V_{\text{air}}^2 C_X(\psi) A_F \] (6.2)

where:

- \( R_{\text{wind}} \) is the wind force in Newtons
- \( \rho_{\text{air}} \) is the density of air in \( \text{kg/m}^3 \)
\( V_{air} \) is the wind speed in m/s
\( C_X \) is the wind resistance coefficient respect to the wind direction
\( \psi \) is the relative wind direction; 0 being heading wind
\( A_F \) is the wind area of the ship exposed to the wind in m\(^2\)

### 6.2.4 Shallow water resistance

In shallow water areas the flow under the ship’s keel and sea bottom is restricted. This increases the rate of water flow which induces increase in resistance. A method developed by Lackenby (1963) is proposed to correct speed loss due to effect of shallow water resistance:

\[
\frac{\Delta V_S}{V_S} = 0.1224 \left( \frac{A_M}{h^2} - 0.05 \right) + 1.0 - \left( \tanh \left( \frac{gh}{V_S^2} \right) \right)^{\frac{1}{2}}
\]  

(6.3)

where:

- \( V_S \) is the ship speed
- \( \Delta V_S \) is the loss of ship speed due to shallow water
- \( A_M \) is the midship section area under water
- \( h \) is the water depth
- \( g \) is the acceleration due to gravity

### 6.2.5 Propeller model and propulsion coefficients

Propeller design is one of the key elements when optimizing ship’s technical performance. The propeller design is affected by various phenomena, such as water flow generated by hull into the propeller field and the water flow out of the propeller which generates the forward thrust. Properties such as wake fraction coefficient \(( \omega)\) and thrust deduction coefficient \(( \omega)\) describe the flow into the propeller. Torque coefficient \(( K_Q)\), thrust coefficient \(( K_T)\) and propeller advance ratio \(( J)\) describe the propellers performance in generating thrust.

### 6.2.6 Propulsion power

The effective power assumes that all the energy can be utilized to push the ship trough the water without any propulsive losses. Therefore, the effective power is calculated simply by:

\[
P_E = R_{total} \cdot V
\]

(6.4)

where:

- \( P_E \) is the effective power of the ship
- \( R_{total} \) is the total resistance experienced by the ship
- \( V \) is the velocity of the ship

The ship model in NAPA VO includes a 10% increase in total resistance due to the hull fouling. Additional 15% sea margin is applied as well to provide allowance for significant increase in added
resistance.

The actual delivered power is the power measured at the propeller shaft. The delivered power takes into account the hull, propeller, propulsion and transmission efficiencies. The delivered power is calculated by:

\[
P_D = \frac{P_E}{\eta_H \eta_0 \eta_{RR} \eta_{trans}}
\]  

where:

- \(P_D\) is the delivered power of the ship
- \(P_E\) is the effective power of the ship
- \(\eta_H\) is the hull efficiency
- \(\eta_0\) is the propeller open water efficiency
- \(\eta_{RR}\) is the relative rotative efficiency
- \(\eta_{trans}\) is the transmission efficiency

Propeller open water efficiency is the ratio of thrust power to the power absorbed by the rotating propeller without the hull affecting to the propeller inflow. When the hull interferes the inflow to the propeller, the flow becomes rotational. The relative-rotative efficiency takes account the change of efficiency due to the rotational flow. The transmission efficiency takes account the energy losses due to shaft alignment and friction in shaft bearings. If the shaft and engine are coupled with a gearbox, the transmission efficiency takes account the gearbox efficiency as well.

### 6.2.7 Fuel consumption

The eq. (6.5) to calculate the delivered power is equivalent to the power measured at the propeller shaft. The fuel consumption calculation in eq. (6.6) calculates the fuel oil consumption per voyage by using the Specific Fuel Oil Consumption curve (SFOC). The SFOC indicates the fuel oil consumption in kg/kWh in specific power rating. Therefore, the energy losses in the main engine engine are taken account within the SFOC rate.

\[
M_{FC} = \frac{\sum P_{Dk} \cdot SFOC_k \cdot \Delta T_k}{1000 \cdot 1000}
\]  

where:

- \(M_{FC}\) is the mass of the fuel burned in tons
- \(k\) is the leg number
- \(P_D\) is the delivered power in Watts
- \(SFOC_{ME}\) is the specific fuel oil consumption value of the main engine in kg/kWh
- \(\Delta T\) is the time period of prevailing \(P_D\) value in hours

The fuel consumption per voyage consist from the summation of fuel consumption per each voyage leg. The principle of voyage legs is described further in section 6.5.
6.2.8 Emissions

The production of shipborne emissions is proportional to the amount of fuel burned. The amount of produced emissions can be evaluated by using emission coefficients for each fuel type. The values of the constants depend on various circumstances such as the fuel quality and engine conditions. The emission coefficients used in the simulations are based on the results of the third IMO GHG study and are shown in table 8.

Table 8 – Emission factors of major shipborne emissions (IMO, 2015b).

<table>
<thead>
<tr>
<th></th>
<th>Marine HFO [g/g fuel]</th>
<th>Marine MDO [g/g fuel]</th>
<th>Marine LNG [g/g fuel]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>3.114</td>
<td>3.206</td>
<td>2.750</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.00006</td>
<td>0.00006</td>
<td>0.05120</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.00016</td>
<td>0.00015</td>
<td>0.00011</td>
</tr>
</tbody>
</table>

6.3 Sea-going voyage data

The AIS data utilized for the route-based simulations in NAPA VO are ship IMO number and the latitude and longitude coordinates with corresponding timestamp to identify the waypoints of the ship. Additionally, draught information is utilized to obtain the total resistance of the ship in prevailing situation. The information on water depth data and land areas are extracted from nautical charts. The raw AIS data of the 49 ships between the time period of 15 months processed in the case study, includes approximately 4.5 million individual AIS datapoints. Figure 16 illustrates all the voyages sailed by TORM MR tankers from January 2018 to end of March 2019.

Figure 16 – All available AIS data of Torm ships from January 2018 to the end of March 2019.
6.4 Weather data

Nowcast weather data is utilized in simulations to estimate the wave added resistance, resistance due to wind and effect of sea currents. Also, in the case of weather routing, the weather data is used to calculate the optimum voyage including the positive influence of weather. The weather data used in the performance calculations includes entities for significant waveheight, wave zero-crossing period, wave direction, wind speed, wind direction, sea current direction and sea current speed. The weather data provider in Napa VO is TideTech.

The sea current data uses entities for current speed and current direction. Wave components are separated into wind waves and swells. Both wave types have individual entities for significant wave height, wave zero-crossing period and wave direction for each data point. The wind data uses entities for wind speed and wind direction.

6.5 Output

The output results will be calculated for the three scenarios described in section 4.3. The results in simulations return waypoints based on the AIS coordinates with corresponding timestamps. For each waypoint, the nowcast weather data is extracted from the weather data provider. The extracted data for the waypoints include values for the wind speed and direction, significant waveheight, wave direction, sea current speed, sea current direction. Water depth is extracted from nautical charts.

The adjacent waypoints are connected to each other with legs which follow the great circle. Each leg includes calculated results for leg distance, speed over ground, propeller rpm, propulsion power, fuel consumption and CO\textsubscript{2} emissions. The total fuel consumption and CO\textsubscript{2} emissions per voyage are summed from the leg values. Additionally, the results output the histogram of Beaufort distribution during the voyage. Visualization of waypoints and legs in NAPA VO is presented in Figure 17.

![Figure 17](image)

Figure 17 – Visualization of waypoints and legs in NAPA VO staging platform.
are presented along with surrounding weather information such as wind barbs and the different areas of significant waveheight. The output results in the case study are analyzed and visualized with MATLAB.
7 Simulations

Because the operational details in different voyages can differ considerably, a set of assumptions is needed to be made to ensure comparable results. For example, in reality different fuel types and qualities are used and the draught can change during the voyage. The assumptions in all the simulated voyages are the following:

1. Only the main engine fuel consumption is considered.
2. The fuel used in all the ships is Heavy Fuel Oil.
3. All the time spent in anchorage is considered as excess time.
4. Voyages before and after canal crossing are treated as individual voyages.
5. Voyages are sailed with a constant draught from departure to arrival.

When estimating the excess time on the voyage, it was assumed that all the time spent at anchorage is spare time which could be utilized to extend the time spent for steaming. However, some ports, such as Fujairah in United Arab Emirates and Lagos in Nigeria, use ship-to-ship cargo exchange operations and offshore loading/discharge stations, when the loading/discharge operations can be done at anchorage instead of mooring the ship at berth (Holmslykke, 2019). These kind of operations cannot be identified by the methods used to identify the anchorage as described in section 5.3.5.

7.1 Simulation methods

Voyage simulations based on actual routes are simulated with the performance calculation model developed by NAPA. For comparison of different simulation methods, additional simulations are performed on selected voyages with DTU’s Ship Simulation Workbench-tool (Taskar, 2019). The performance calculation methods for each performance parameter are summarized in table 9.
Table 9 – Calculation methods for ship performance parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>NAPA Voyage Optimization</th>
<th>DTU Ship Simulation Workbench</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm water resistance</td>
<td>Tuned Holtrop &amp; Mennen method-based generic resistance curve</td>
<td>Methods can be chosen from:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Holtrop &amp; Mennen</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Hollenbach</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Guldhammer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- user specified</td>
</tr>
<tr>
<td>Wave added resistance</td>
<td>Gerritsma &amp; Beukelman method-based generic wave added resistance</td>
<td></td>
</tr>
<tr>
<td>Wind resistance</td>
<td>Ship type specific wind coefficients</td>
<td>ITTC method</td>
</tr>
<tr>
<td>Shallow water resistance</td>
<td>Lackenby’s method-based</td>
<td></td>
</tr>
<tr>
<td>Propeller model</td>
<td>Generic propeller model based on regression analysis</td>
<td></td>
</tr>
<tr>
<td>Propulsion coefficients</td>
<td>Ship type specific coefficients scaled based on vessel dimensions</td>
<td></td>
</tr>
<tr>
<td>Engine properties</td>
<td>Installed engine power MCR from ship database</td>
<td></td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>Generic SFOC curves for different engine types</td>
<td></td>
</tr>
</tbody>
</table>

Methods can be chosen from:
- Holtrop & Mennen
- Hollenbach
- Guldhammer
- user specified

In the simulations run with NAPA VO the corresponding ship model is fetched automatically based on the IMO number. In SSW simulations, the user defines the calculation methods for different ship performance parameters and the ship model is created based on the input values defined by user.

7.1.1 NAPA Voyage Optimization

The simulations calculated with NAPA VO were performed by calling the NAPA Voyage Optimization API programmatically by using MATLAB. The raw AIS data was first split into individual voyages by using the portcall identification algorithm introduced in section 5.3.1. The three different simulation scenarios require different input attributes as described in table 10.

Table 10 – The input attributes for different simulation scenarios in NAPA VO.

<table>
<thead>
<tr>
<th>Voyage as sailed</th>
<th>Just-in-Time Arrival</th>
<th>Weather Routing &amp; Just-in-Time Arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMO number</td>
<td>IMO number</td>
<td>IMO number</td>
</tr>
<tr>
<td>Coordinates</td>
<td>Voyage start time</td>
<td>Departure coordinates</td>
</tr>
<tr>
<td>Draught</td>
<td>Draught</td>
<td>Arrival coordinates</td>
</tr>
<tr>
<td>Timestamps</td>
<td>Operation method:</td>
<td>Operation method:</td>
</tr>
<tr>
<td></td>
<td>- Constant speed over ground</td>
<td>- Constant speed over ground</td>
</tr>
<tr>
<td></td>
<td>- Constant propeller rpm</td>
<td>- Constant propeller rpm</td>
</tr>
<tr>
<td></td>
<td>- Arrival time</td>
<td>- Arrival time</td>
</tr>
</tbody>
</table>
In *Just-in-Time Arrival* and *Weather Routing & Just-in-Time Arrival*-simulations the operation method can be chosen from constant speed over ground, constant propeller rpm and specific arrival time. In both simulations, the operation method was chosen as specific arrival time. The operation method with specific arrival time uses constant rpm with a varying speed profile when calculating the required time of arrival.

### 7.1.2 DTU Ship Simulation Workbench

Simulations with DTU Ship Simulation Workbench tool were performed for four selected voyages. The filtered AIS data and weather data for the selected voyages were exported directly to a csv-file in Ship Simulation Workbench compatible format. The resolution of data points was slightly reduced in order to successfully run the simulations in SSW. Contrary to NAPA VO simulations, simulations in SSW do not include the effect of sea currents. Table 11 presents the selected methods to calculate the ship resistance in SSW simulations.

**Table 11 – Resistance calculation methods used in DTU Ship Simulation Workbench model.**

<table>
<thead>
<tr>
<th>Resistance component</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm water resistance</td>
<td>Guldhammer</td>
</tr>
<tr>
<td>Wave added resistance</td>
<td>DTU-method</td>
</tr>
<tr>
<td>Wind resistance</td>
<td>ITTC-method</td>
</tr>
<tr>
<td>Shallow water resistance</td>
<td>Lackenby</td>
</tr>
</tbody>
</table>

The required information to perform the resistance calculation with the selected methods are tabulated in table 12.
Table 12 – The user defined parameters used in DTU Ship Simulation Workbench model for the ship IMO 9392470.

<table>
<thead>
<tr>
<th>Hull</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>174.5</td>
</tr>
<tr>
<td>LOA</td>
<td>181.99</td>
</tr>
<tr>
<td>T</td>
<td>12.0</td>
</tr>
<tr>
<td>Cm</td>
<td>0.99</td>
</tr>
<tr>
<td>Cwp</td>
<td>0.915</td>
</tr>
<tr>
<td>S</td>
<td>8412.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Propeller</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>6.64</td>
</tr>
<tr>
<td>PoD</td>
<td>0.658</td>
</tr>
<tr>
<td>rpm_{design}</td>
<td>113</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Propulsion</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>w</td>
<td>0.31</td>
</tr>
<tr>
<td>t</td>
<td>0.21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Engine</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{MCR}</td>
<td>11620</td>
</tr>
<tr>
<td>gear_ratio</td>
<td>1</td>
</tr>
</tbody>
</table>

The ship main dimensions and engine details in table 12 are collected from IHS Maritime Portal. The propulsion details are estimations based on the NAPA VO model. The propeller diameter is an estimation based on design draught and the propeller model is based standard B-series propeller calculated automatically in SSW by using the propeller diameter and number of propeller blades. Gear ratio is set as 1, since the main engine is assumed to have a straight shaft coupling to the propeller.

7.2 Voyage as sailed

An example of Voyage as Sailed simulations is presented based on the results of ship IMO 9392470. Figure 18 illustrates all the voyages the ship has sailed between January 2018 and end of March 2019. The visualization and analysis of the voyages is done in MATLAB.
To ensure valid results, the data filtering methods described in section 5.3.2 were applied. The filtering of simulation results was executed with the following conditions:

1. Voyages with duration less than 24 hours were removed
2. Voyages with total distance less than 90% of the shortest calculated distance were removed

The total number of voyages for ship 9392470 decreased from 96 to 46 after the filtering process. The remaining voyages were then simulated and the results were imported to MATLAB for analysis. Descriptive statistics of the valid voyages are presented in table 13.

Table 13 – Descriptive statistics of the voyages of ship 9392470.

<table>
<thead>
<tr>
<th>No. of voyages: 46</th>
<th>Duration [h]</th>
<th>HFO daily [t]</th>
<th>CO₂ daily [t]</th>
<th>Avg. speed [kn]</th>
<th>Port time [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>149.7</td>
<td>21.7</td>
<td>67.6</td>
<td>10.4</td>
<td>50.5</td>
</tr>
<tr>
<td>Median</td>
<td>124.2</td>
<td>23.0</td>
<td>71.6</td>
<td>11.1</td>
<td>38.0</td>
</tr>
<tr>
<td>Min</td>
<td>28.0</td>
<td>4.0</td>
<td>12.5</td>
<td>3.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Max</td>
<td>471.8</td>
<td>31.1</td>
<td>96.8</td>
<td>12.8</td>
<td>299.5</td>
</tr>
</tbody>
</table>

Figure 19 shows the relationships between fuel consumption, sailing time and average speed.
From the fitted curves in Figure 19 it can be observed that the relationship between fuel consumption and sailing time have linear correlation whereas daily fuel consumption and average speed follow third order polynomial curve.

7.3 Just-in-Time Arrival

The Just-in-Time Arrival optimization strategy utilizes the actual route sailed with an adjustment of arrival time to minimize the time spent at the port area. Therefore, the ship can sail straight to the berth for the discharge. The potential savings in fuel consumption are received from the lower average sailing speed and engine loading compared to the voyage as sailed. The adjustment in arrival time is obtained by adding the excess time spent in anchorage to the original arrival time as described in section 5.3.5. To perform the just-in-time arrival simulations the following assumptions were made:

1. The voyage is sailed with constant rpm to meet the required time of arrival.
2. The voyage speed is not limited by any regional restrictions.
3. All arrival ports utilize the scheduled queue system.
4. All arrival ports have time slot available for the just-in-time arrival.
5. All the ships are capable for slow steaming with minimum of 6 knots.
6. All the time spent in anchor has been excess time, i.e. no loading or discharge has been performed in anchorage.

The inputs to run just-in-time arrival simulations as described in table 10 are route coordinates, voyage start time, ship draught, and the chosen operation method is voyage arrival time. Based on the interviews with Holmslykke (2019) all ships in the case study are capable to slow steam with minimum speed of 6 knots. For maintaining the minimum speed of 6 knots in all the voyages, the voyage as sailed simulations with the average speed under 6 knots were assumed to arrive the port with an average speed of 6 knots and then wait the rest of the excess time at port. In these cases the required arrival time was first obtained by running the simulations with the speed over ground operation method set to 6 knots. The simulations were then run again by using the corresponding arrival time with constant rpm to get the final results.
7.3.1 Overview of speed optimization algorithm

To meet the required arrival time the voyage is sailed with a constant rpm. Therefore, the speed profile of the ship varies along the route from the effect of added resistance due to waves, wind, currents and shallow water. In general, the required arrival time with a constant rpm is obtained with an iterative process where several options of constant rpm value are calculated and the most suitable to meet the arrival time is selected.

7.4 Weather optimization

The weather optimized voyages with Just-in-Time Arrival were performed with the same assumptions as described in section 7.3. The input information for Weather Routed voyages as described in table 10 are departure coordinates, arrival coordinates and the chosen operation method is voyage arrival time. Voyages which initially had slower average speed than 6 knots were operated with constant speed over ground set as 6 knots.

7.4.1 Overview of the weather optimization algorithm

The weather routing algorithm in NAPA VO is based on graph optimization algorithm. The objective is to find the route which fulfills the given ETA at lowest fuel consumption. The network of the possible routes is based on navigational chart data and weather routing is utilized in areas where navigation is not restricted. In practice, this would mean restricted areas in nautical charts such as shallow areas or fixed traffic lanes in busy traffic areas.
8 Analysis of the results

Total number of voyages simulated with NAPA VO is 1768, where 927 were laden and 840 were ballast voyages. The results were calculated for two scenarios – one where only the laden voyages were optimized and other where laden and ballast voyages were optimized. The two cases are examined separately in the following subsections. The fuel consumption in with different voyage simulation scenarios are compared by plotting the fuel consumption in relation to sailing time. Descriptive statistics are used to express the reduction in CO$_2$ emissions and fuel consumption and in the consequential savings in fuel cost. The cost of the bunker is estimated by using the global 20 ports average between January 2018 and end of March 2019, which is 430.5 USD for high sulfur IFO380 fuel oil (Ship and Bunker, 2019).

8.1 Optimization of laden voyages

Table 14 shows the total duration, fuel consumption, emissions, port time and bunker cost per ship when the laden voyages are optimized during the period under review. Furthermore, the savings in fuel consumption and cost, and the reduction in emissions and excess port time are shown for different voyage optimization strategies. The sum represents the results for the entire fleet and the remainder are obtained from the ship specific results. The optimization results of laden voyages are presented in its entirety in appendix B.

<table>
<thead>
<tr>
<th>Voyage as Sailed</th>
<th>Duration [h]</th>
<th>Fuel consumption [t]</th>
<th>CO$_2$ [t]</th>
<th>Port time [h]</th>
<th>Bunker cost [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>306 851.9</td>
<td>196 776.9</td>
<td>612 763.2</td>
<td>119 469.2</td>
<td>84 909 227.3</td>
</tr>
<tr>
<td>Mean</td>
<td>6 262.3</td>
<td>4 015.9</td>
<td>12 505.4</td>
<td>2 438.1</td>
<td>1 732 841.4</td>
</tr>
<tr>
<td>Median</td>
<td>6 174.5</td>
<td>3 834.9</td>
<td>11 941.8</td>
<td>2 365.2</td>
<td>1 654 744.6</td>
</tr>
<tr>
<td>Min</td>
<td>4 594.8</td>
<td>2 067.6</td>
<td>6 438.4</td>
<td>1 269.5</td>
<td>892 160.4</td>
</tr>
<tr>
<td>Max</td>
<td>8 526.4</td>
<td>6 218.3</td>
<td>19 363.8</td>
<td>3 990.8</td>
<td>2 683 194.7</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>779.2</td>
<td>958.0</td>
<td>2 983.2</td>
<td>609.6</td>
<td>413 374.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>22 539.0</td>
<td>70 146.2</td>
<td>25 355.3</td>
<td>9 725 576.8</td>
</tr>
<tr>
<td>Mean</td>
<td>460.0</td>
<td>1 431.6</td>
<td>517.5</td>
<td>198 481.2</td>
</tr>
<tr>
<td>Median</td>
<td>449.7</td>
<td>1 399.7</td>
<td>464.5</td>
<td>194 049.3</td>
</tr>
<tr>
<td>Min</td>
<td>138.1</td>
<td>429.2</td>
<td>0.0</td>
<td>59 584.7</td>
</tr>
<tr>
<td>Max</td>
<td>841.7</td>
<td>2 619.0</td>
<td>1 721.6</td>
<td>363 206.3</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>179.4</td>
<td>558.4</td>
<td>412.2</td>
<td>77 398.4</td>
</tr>
</tbody>
</table>
### Just-in-Time arrival & Weather Routing

<table>
<thead>
<tr>
<th></th>
<th>Fuel saving [t]</th>
<th>CO₂ reduction [t]</th>
<th>Bunker cost saving [USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sum</strong></td>
<td>32 315.4</td>
<td>100 596.2</td>
<td>13 944 099.8</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>659.5</td>
<td>2 053.0</td>
<td>284 573.5</td>
</tr>
<tr>
<td><strong>Median</strong></td>
<td>654.9</td>
<td>2 038.4</td>
<td>282 572.3</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>246.9</td>
<td>768.3</td>
<td>106 553.5</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>1 048.0</td>
<td>3 262.4</td>
<td>452 205.9</td>
</tr>
<tr>
<td><strong>Std. Dev</strong></td>
<td>209.6</td>
<td>652.4</td>
<td>90 424.7</td>
</tr>
</tbody>
</table>

For the fleet of 49 ships the total saving in fuel costs by using just-in-time arrival is over 9.7 million USD or 11.5%. The total saving in port time for the fleet is 25 355 hours or approximately 1 056 days if all the waiting time at anchorage can be minimized. On average, each ship has stayed approximately 21.5 days at anchorage during the 15-month period. However, significant differences can be observed between different ships as one ship did not get any port time saving and maximum saving was approximately 71.7 days with a standard deviation of 17.2 days.

The total saving in fleet fuel costs by using just-in-time arrival and weather routing is 13.9 million USD or 16.4%. The total saving in port time is the same as in just-in-time arrival scenario. By using weather routing services, the savings compared to just-in-time arrival alone is 4.9 percentage units greater, thus the weather routing alone has a potential to achieve significant savings.

In Figure 20 the fuel consumption and the sailing time of all simulated voyages are plotted. Reference lines for each simulation scenarios are used to represent the change in fuel consumption when the sailing time increases. In the right hand side plot, the change in Energy Efficiency Operational Indicator is shown in different simulation scenarios.

![Figure 20](image)

**Figure 20** – Visual representation of fuel consumption and EEOI.

The average reduction in EEOI compared to Voyage as Sailed scenario is 10.3 % by using just-in-time arrival strategy. When weather routing is added, the reduction is 9.7%. The result is a good example of the inconsistent nature of the EEOI as discussed in section 3.1.3 when simulations with weather...
routing have remarkably lower fuel consumption, but higher average EEOI value because the total distance sailed is longer.

8.2 Optimization of all voyages

Table 15 shows a summary of the results when the laden and ballast voyages are optimized. The optimization results of laden and ballast voyages are presented in its entirety in appendix C.

Table 15 – Optimization results per ship.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>306 851.9</td>
<td>196 776.9</td>
<td>612 763.2</td>
<td>119 469.2</td>
<td>84 909 227.3</td>
</tr>
<tr>
<td>Mean</td>
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<td>2 438.1</td>
<td>1 732 841.4</td>
</tr>
<tr>
<td>Median</td>
<td>6 174.5</td>
<td>3 834.9</td>
<td>11 941.8</td>
<td>2 365.2</td>
<td>1 654 744.6</td>
</tr>
<tr>
<td>Min</td>
<td>4 594.8</td>
<td>2 067.6</td>
<td>6 438.4</td>
<td>1 269.5</td>
<td>892 160.4</td>
</tr>
<tr>
<td>Max</td>
<td>8 526.4</td>
<td>6 218.3</td>
<td>19 363.8</td>
<td>3 990.8</td>
<td>2 683 194.7</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>779.2</td>
<td>958.0</td>
<td>2 983.2</td>
<td>609.6</td>
<td>413 374.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>36 464.4</td>
<td>113 489.4</td>
<td>38 049.0</td>
<td>15 734 377.2</td>
</tr>
<tr>
<td>Mean</td>
<td>744.2</td>
<td>2 316.1</td>
<td>776.5</td>
<td>321 109.7</td>
</tr>
<tr>
<td>Median</td>
<td>758.9</td>
<td>2 361.3</td>
<td>687.3</td>
<td>327 468.1</td>
</tr>
<tr>
<td>Min</td>
<td>319.6</td>
<td>994.0</td>
<td>83.3</td>
<td>137 886.5</td>
</tr>
<tr>
<td>Max</td>
<td>1 213.0</td>
<td>3 776.2</td>
<td>2 297.0</td>
<td>523 412.5</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>218.7</td>
<td>680.9</td>
<td>494.5</td>
<td>94 361.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>55 115.7</td>
<td>171 579.1</td>
<td>23 782 409.9</td>
</tr>
<tr>
<td>Mean</td>
<td>1 124.8</td>
<td>3 501.6</td>
<td>485 355.3</td>
</tr>
<tr>
<td>Median</td>
<td>1 095.4</td>
<td>3 410.4</td>
<td>472 669.0</td>
</tr>
<tr>
<td>Min</td>
<td>582.5</td>
<td>1 813.2</td>
<td>251 352.5</td>
</tr>
<tr>
<td>Max</td>
<td>1 797.1</td>
<td>5 594.8</td>
<td>775 453.0</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>296.3</td>
<td>922.5</td>
<td>127 858.3</td>
</tr>
</tbody>
</table>

The total saving in fuel costs for the fleet by using just-in-time arrival is 15.7 million USD or 18.5%. The total saving in port time when the waiting time in ballast voyages is added is 38 049 hours or approximately 1 585 days if all the waiting time at anchorage can be minimized. Therefore, if just-in-time arrival can be implemented in ballast voyages as well, the increase in total port time saving is 33% compared to the previous scenario where only laden voyages were optimized. On average, each ship has stayed approximately 32 days at anchorage during the 15-month period. The differences between different ships vary from the minimum being approximately 3.5 days and maximum 96.7 days with a standard deviation of 25.4 days.
The total saving in fuel costs by using just-in-time arrival and weather routing is 23.8 million USD or 28.0%. The difference when weather routing is added is 9.5 percentage units compared to the just-in-time arrival alone. Figure 21 presents the relationship of fuel consumption and sailing time, and the change in EEOI when both laden and ballast voyages are optimized.

![Figure 21](image)

Figure 21 – Visual representation of fuel consumption and EEOI.

The average reduction in EEOI compared to Voyage as Sailed scenario is 17.5% by using just-in-time arrival strategy. When weather routing is added, the reduction is 16.9%. As in previous scenario, the EEOI has lower average value for simulation results with higher fuel consumption. For comparison, UMAS (2016) evaluates the EEOI value index reduction of MR tankers between 11-54% in speed range of 12 to 6 knots compared to the 12.8 knots baseline when only speed is reduced. The results in this study fall within this estimation range.

### 8.3 Voyage cashflow estimation

The shipping cost in voyage charter were discussed in section 2.3 and the principles of voyage cashflow estimation was reviewed in section 2.4. The change in voyage cashflow is presented as a change in Time Charter Equivalent and the results should be considered as a very rough estimation. The TCE of Torm MR fleet for the 15-month period under review is presented in Figure 22.
The average TCE for Torm MR tankers for the period under review is 10,525 USD per day. The freight earnings are estimated directly by using the fleet average TCE, voyage costs, operating costs and voyage duration. Figure 23 shows the change in fleet average TCE value when different voyage optimization strategies are implemented. Ship specific values of the voyage cashflow estimation are included in appendix B and appendix C.

The increase in average TCE value when only laden voyages are optimized is 7.2% with just-in-time arrival and 10.4% when weather routing is added. Respectively, when laden and ballast voyages are optimized, the increase in average TCE value is 11.9% with just-in-time arrival and 17.8% when weather routing is added.

### 8.4 Comparison of selected voyages

This section shows the results of the simulations done in NAPA Voyage Optimization and DTU Ship Simulation Workbench for selected voyages. The results are compared with the actual voyage information based on noon reports provided by Torm. In total, four voyages were simulated with both
simulation tools. The selected voyages are Eastbound Atlantic crossing, Westbound Atlantic crossing, Eastbound Pacific crossing and Southbound Philippine Sea crossing. All voyages were sailed by a different ship. Figure 24 visualizes the routes of the selected voyages.

![Figure 24 – Route visualizations of example voyages.](image)

All selected voyages were sailed in laden condition and the simulations were run with an assumption that the fuel used was high sulphur Heavy Fuel Oil with a lower calorific value of 42.7 MJ/kg. According to the noon reports, in Emission Control Areas such as coast of United States, the ships have steamed by using Marine Gas Oil instead of Heavy Fuel Oil. In such cases a conversion factor of 1.06 has been used to convert the energy content of MGO to correspond the energy content of HFO (Brynolf, Andersson and Fridell, 2011).

8.4.1 Voyage 1 - Eastbound Atlantic crossing

Voyage 1 was sailed from the North side of Panama Canal to Rotterdam between February and March 2018 by a ship with IMO 9304590. The voyage details are shown in table 16.

<table>
<thead>
<tr>
<th>Voyage 1 - Eastbound Atlantic crossing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship</td>
<td>9304590</td>
</tr>
<tr>
<td>Departure</td>
<td>North Panama Canal (PAN)</td>
</tr>
<tr>
<td>Distance</td>
<td>4,896 NM</td>
</tr>
<tr>
<td>Draught</td>
<td>10.7 m</td>
</tr>
<tr>
<td>Arrival</td>
<td>Rotterdam (NLD)</td>
</tr>
<tr>
<td>Duration</td>
<td>423 h</td>
</tr>
</tbody>
</table>

The results from both simulations and the actual values from the noon report are presented in table 17. The percentual difference between simulations and noon report values is included in the right column next to the calculated value.
Table 17 – Voyage 1 comparison statistics.

<table>
<thead>
<tr>
<th></th>
<th>Noon Report</th>
<th>Napa VO</th>
<th>VO difference</th>
<th>SSW</th>
<th>SSW difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption [t]</td>
<td>422.5</td>
<td>379.7</td>
<td>-10.1%</td>
<td>324.7</td>
<td>-23.1%</td>
</tr>
<tr>
<td>Rpm avg.</td>
<td>101.8</td>
<td>85.4</td>
<td>-16.1%</td>
<td>91.6</td>
<td>-10.0%</td>
</tr>
<tr>
<td>Power avg. [kW]</td>
<td>4 944</td>
<td>4 580</td>
<td>-7.4%</td>
<td>4 353</td>
<td>-12.0%</td>
</tr>
</tbody>
</table>

The most significant difference between NAPA VO and Noon Report values is in the average rpm, NAPA VO value being 16.1% lower. The most significant difference between SSW is the 23.1% lower fuel consumption in SSW value. Figure 25 shows the time series of speed over ground, propeller rpm, propulsion power and fuel consumption.

![Figure 25](image_url) - Voyage 1 speed over ground, propeller rpm, propulsion power and fuel consumption.

The fuel consumption time series shows a distinct peak in NAPA VO value as the speed over ground decreases the same time. This is most likely due to a bad weather conditions when a voluntary speed loss is introduced. The plots of SSW simulation follow the speed profile and do not point out the similar peak in the fuel consumption. Figure 26 shows the simulation histograms of propeller rpm, propulsion power and Beaufort distribution during the voyage.

![Figure 26](image_url) - Voyage 1 propeller rpm, propulsion power and Beaufort distribution histograms.
The Beaufort scale in Figure 26 shows that the ship has encountered a broad scale of weather conditions and Beaufort number 7 has been the most prevalent condition. In the definition of Beaufort scale the number 7 represents a wind speed between 13.9 and 17.1 m/s and significant waveheight between 4.0 and 5.5 meters (WMO, 2012).

8.4.2 Voyage 2 - Westbound Atlantic crossing

Voyage 2 was sailed from IJmuiden to the North side of Panama Canal between August and September 2018 by a ship with IMO 9392470. The voyage details are shown in table 18.

Table 18 – Voyage 2 details.

<table>
<thead>
<tr>
<th>Voyage 2 - Westbound Atlantic crossing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship</td>
<td>9392470</td>
</tr>
<tr>
<td>Draught</td>
<td>10.0 m</td>
</tr>
<tr>
<td>Departure IJmuiden (NDL)</td>
<td>Arrival North Panama Canal (PAN)</td>
</tr>
<tr>
<td>Distance 4 878 NM</td>
<td>Duration 465 h</td>
</tr>
</tbody>
</table>

The results from both simulations and the actual values from the noon report are presented in table 19. The percentual difference between simulations and noon report values is included in the right column next to the calculated value.

Table 19 – Voyage 2 comparison statistics.

<table>
<thead>
<tr>
<th>Noon Report</th>
<th>Napa VO</th>
<th>VO difference</th>
<th>SSW</th>
<th>SSW difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption [t]</td>
<td>295.4</td>
<td>328.7</td>
<td>11.3%</td>
<td>231.4</td>
</tr>
<tr>
<td>Rpm avg.</td>
<td>92.0</td>
<td>80.2</td>
<td>-12.8%</td>
<td>79.5</td>
</tr>
<tr>
<td>Power avg. [kW]</td>
<td>3 177</td>
<td>4 088</td>
<td>27.8%</td>
<td>2778</td>
</tr>
</tbody>
</table>

The difference in fuel consumption between NAPA VO and the Noon Report is 11.3% whereas the fuel consumption in SSW is 21.7% lower than in Noon Report. Figure 27 shows the time series of speed over ground, propeller rpm, propulsion power and fuel consumption.
The propeller rpm, propulsion power and fuel consumption follow a similar pattern between NAPA VO and SSW simulations, but the propulsion power has higher magnitude in NAPA VO simulation. Since the speed profile used in both simulations is the same, the total resistance in NAPA VO model is higher compared to the SSW model, resulting higher average propulsion power. Figure 28 shows the simulation histograms of propeller rpm, propulsion power and Beaufort distribution during the voyage.

The propeller rpm is close to each other in both simulations. However, the propulsion power is higher in NAPA VO simulations as discussed before. The weather conditions vary from Beaufort scale 1 to 6 which could be described as good weather conditions in the Atlantic Ocean between August and September.

### 8.4.3 Voyage 3 - Eastbound Pacific crossing

Voyage 3 was sailed from the Yosu to Rosarito in September 2018 by a ship with IMO 9250490. The voyage details are shown in table 20.
Table 20 – Voyage 3 details.

<table>
<thead>
<tr>
<th>Voyage 3 - Eastbound Pacific crossing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship 9250490</td>
</tr>
<tr>
<td>Departure Yosu (KOR)</td>
</tr>
<tr>
<td>Distance 5 444 NM</td>
</tr>
</tbody>
</table>

The results from both simulations and the actual values from the noon report are presented in table 21.

Table 21 – Voyage 3 comparison statistics.

<table>
<thead>
<tr>
<th>Noon Report</th>
<th>Napa VO</th>
<th>VO difference</th>
<th>SSW</th>
<th>SSW difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption [t]</td>
<td>346.8</td>
<td>348.3</td>
<td>0.4%</td>
<td>328.8</td>
</tr>
<tr>
<td>Rpm avg.</td>
<td>98.1</td>
<td>103.4</td>
<td>5.1%</td>
<td>88.7</td>
</tr>
<tr>
<td>Power avg. [kW]</td>
<td>2 847</td>
<td>4 059</td>
<td>29.9%</td>
<td>3 923</td>
</tr>
</tbody>
</table>

As seen from table 21, the fuel consumption calculated with NAPA VO is nearly the same as the actual fuel consumption from the Noon Report, but the average power is significantly larger in NAPA VO. Similar results are found between the SSW simulations and the noon report. Figure 29 shows the time series of speed over ground, propeller rpm, propulsion power and fuel consumption.

Figure 29 – Voyage 3 speed over ground, propeller rpm, propulsion power and fuel consumption.

Figure 29 shows that the most significant difference between the two simulations is the magnitude in propeller rpm. Compared to the values from Noon Report, the propeller model in NAPA VO is more accurate than the propeller model in SSW.
Figure 30 shows the simulation histograms of propeller rpm, propulsion power and Beaufort distribution during the voyage.

![Simulation histograms](image)

**Figure 30** – Voyage 3 propeller rpm, propulsion power and Beaufort distribution histograms.

Figure 30 shows that the difference in propeller rpm is distinct, but the results in propulsion power are close to each other. The prevalent Beaufort number is 3 and overall the weather can be described as a good weather conditions in the Pacific Ocean in September.

### 8.4.4 Voyage 4 - Southbound Philippine Sea crossing

Voyage 4 was sailed from Ulsan to Brisbane in March 2019 by a ship with IMO 9465980. The voyage details are shown in table 22.

<table>
<thead>
<tr>
<th>Voyage 4 - Southbound Philippine Sea crossing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship</td>
</tr>
<tr>
<td>Departure</td>
</tr>
<tr>
<td>Arrival</td>
</tr>
<tr>
<td>Distance</td>
</tr>
<tr>
<td>Duration</td>
</tr>
</tbody>
</table>

The results from both simulations and the actual values from the noon report are presented in table 23.

<table>
<thead>
<tr>
<th>Noon Report</th>
<th>Napa VO</th>
<th>VO difference</th>
<th>SSW</th>
<th>SSW difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption [t]</td>
<td>397.1</td>
<td>332.8</td>
<td>-16.2%</td>
<td>363.4</td>
</tr>
<tr>
<td>Rpm avg.</td>
<td>116.4</td>
<td>91.4</td>
<td>-27.3%</td>
<td>107.0</td>
</tr>
<tr>
<td>Power avg. [kW]</td>
<td>5 999</td>
<td>4 931</td>
<td>-21.6%</td>
<td>6 848</td>
</tr>
</tbody>
</table>

Figure 31 shows the time series of speed over ground, propeller rpm, propulsion power and fuel consumption.
Figure 31 – Voyage 4 speed over ground, propeller rpm, propulsion power and fuel consumption.

Figure 32 shows the simulation histograms of propeller rpm, propulsion power and Beaufort distribution during the voyage.

Figure 32 shows that the propeller rpm and propulsion power is higher in SSW simulation. The SSW simulation results are also closer to the actual values from Noon Report. The Beaufort distribution varies from 0 to 6, number 4 being the prevalent value.
9 Benefit sharing

This section discusses the overall benefits from the implementation of voyage optimization and the possible solutions to share the monetary benefits to different shipping stakeholders. The material is collected qualitatively by interviewing experts from Torm A/S and from STM Validation Project.

According to Siwe (2019) the three conditions to successfully implement just-in-time operation are:

1. Scheduling of port operations
2. Real-time information sharing on the arrival time
3. Reliable estimations on energy saving from just-in-time operation

The greatest barrier preventing the implementation of just-in-time arrival operation is the first-come, first-served policy used by some of the global ports. If the ship would arrive to a port where this policy is used later than than the original ETA, she will lose her place in the queue. This can lead to a situation where no excess time is saved and future operations will be adjourned. Therefore, the basis of implementation of just-in-time arrival operations is to change the first-come, first-served habit in individual ports. The situation can be problematic even in ports where time slots for port operations are scheduled well beforehand. The contract determining the port operations and schedule is typically agreed between the charterer and port, so the ship operator does not have control when negotiating the change in arrival time. Therefore, the motivation to negotiate about change in arrival time should come from the charterer’s side.

The ship performance prediction has an important role when estimating the energy saving from just-in-time operation. It is important that the voyage optimization service provider is an independent player so that the results are not biased by either stakeholders involved in the shipping process. Reliable estimations would require reliable weather forecasts and reliable performance calculation methods.

9.1 Voyage optimization benefits for shipping stakeholders

The benefits from the implementation of voyage optimization are reviewed separately as benefits from just-in-time operation and benefits from weather routing.

9.1.1 Benefits from Just-in-Time operation

Ship operator

The most significant benefit for the ship operator when operating under a voyage charter party is the reduction in bunker costs and emissions. The estimation in case study shows a reduction in bunker costs up to 18.5% if all the voyages can be operated with just-in-time arrival strategy. Overall, the slower speed can lead to improved safety and increase crew well-being as the ship is less likely to be exposed to excessive motions.

Charterer

When operating under a voyage charter party, the charterer has no noteworthy monetary benefit when implementing just-in-time operation, unless the ship operator and charterer agree to share the
monetary benefits acquired from the reduction in bunker cost. The charterer should have motivation to propose a suitable benefit sharing scheme, since under a voyage charter party, it is for them the only way to gain monetary benefit from just-in-time operation. When considering safety, the improved cargo safety can be considered as a benefit for the charterer as well when there is lower risk for cargo damage or loss.

Port

The direct benefit from just-in-time operation for ports is that there are less emissions produced at port areas from running auxiliaries at anchorage. Sharing of reliable information on arrival times could help ports to schedule port stays more carefully which can help to reduce the congestion in ports by having fewer ships at same time in the area.

9.1.2 Benefits from Weather routing

Ship operator

With reliable weather routing, ship operators can perform voyage optimization with a desired optimization objectives. In the case study where minimizing fuel costs was the primary objective, the reduction in bunker cost shows up to 28% when weather routing is combined with just-in-time operation. Weather awareness can help improving operational safety when excessive motions can be predicted in bad weather conditions. Furthermore, weather awareness helps to ensure the crew well-being and lowers the risk of cargo damage and loss.

Charterer

The benefit of weather routing for the charterer is the lower risk of cargo damage or loss. If charterers are able to negotiate lower insurance costs, because the ship operator is using weather routing services, the charterer could achieve monetary benefit as well.

Port

Reliable weather routing services can lead to more accurate information on arrival times. With more accurate arrival information, the port schedule management could be done more carefully, resulting in shorter waiting times.

9.2 Possible solutions for benefit share

International shipping association BIMCO has developed charter party clauses such as Virtual arrival clause for voyage charter parties and Sea Traffic Management clause for voyage charter parties to share the benefits between different shipping stakeholders. The clauses and their characteristics for ship operator and charterer are summarized in table 24.
Table 24 – Comparison of BIMCO voyage charter clauses (BIMCO, 2019a).

<table>
<thead>
<tr>
<th>BIMCO clause</th>
<th>Charterer</th>
<th>Ship operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual arrival clause</td>
<td>- Gives the right to request operator to adjust ship’s speed to meet the specified time of arrival &lt;br&gt; - Compensates the additional time used on the sea voyage with an agreed demurrage rate (If there is no agreement, default 50% of the initial demurrage rate shall apply)</td>
<td>- Entitled to refuse charterer’s request if it e.g. might compromise vessel’s safety &lt;br&gt; - Receives savings from lower bunker costs and receives demurrage from the charterer</td>
</tr>
<tr>
<td>STM clause</td>
<td>- Shall do the utmost to obtain and share information about ship’s arrival time &lt;br&gt; - Gives the right to request operator to adjust ship’s speed to meet the specified time of arrival &lt;br&gt; - Compensates the additional time used on the sea voyage with an agreed demurrage rate (If there is no agreement, default 50% of the initial demurrage rate shall apply)</td>
<td>- Shall do the utmost to obtain and share information about ship’s arrival time &lt;br&gt; - Receives savings from lower bunker costs and receives demurrage from the charterer</td>
</tr>
</tbody>
</table>

In BIMCO Sea Traffic Management (STM) clause, the key element is the communication and information sharing between the charterer and the ship operator as it is described in BIMCO (2019b): "The Sea Traffic Management system is designed to contribute to a safer, more efficient and environmentally friendlier maritime sector through the development and use of information shared between different stakeholders". Otherwise, the features of the STM clause follow the features with BIMCO Virtual Arrival clause.

9.2.1 Implementation of Virtual Arrival policy

The BIMCO Virtual Arrival Clause for voyage charter parties gives a right for the charterer to request an adjustment to ship’s speed in order to meet the ETA just in time. The default rate in the reduction in demurrage is 50% but the actual rate can be negotiated between the ship operator and charterer. The amount of extra time be also agreed by both stakeholders. The role of third party weather routing providers, such as NAPA, increases in this kind of situations where the amount of extra time is needed to be assessed.

In the case study there was no information about the situations where demurrage claims were risen. Hypothetically, if all voyages in the case study where excess port time was observed were cases where demurrage claims were risen, the total demurrage received from the charterer would have been approximately 28.5 million USD. If Virtual Arrival clause with the default 50% reduction in demurrage rate was used in these cases, the combined saving in bunker cost and received demurrage would have been approximately 28.2 million USD. The calculation is shown in table 25.
In the calculation shown in table 25, even the default share of 50% reduction in demurrage rate comes close to the demurrage received in a case where no optimization was implemented. Therefore, by negotiating the demurrage reduction to satisfy both stakeholders, the benefits from the implementation of Virtual Arrival would be more balanced.

9.2.2 Sharing the saving in bunker cost

Other alternative would be not to reduce the demurrage rate, but instead to share the savings directly from saved bunker costs between the ship operator and the charterer. If we follow the same hypothesis as before, the monetary benefit for both stakeholders would be approximately 7 million USD. If the savings were directly used to compensate the demurrage paid by the charterer, the reduction in demurrage costs for the operator would be 29%. The calculation is shown in table 26.

From the ship operator’s point of view, this procedure would be more cost effective, whereas the charterer can gain more benefit from the previous scenario, when there is a reduction in demurrage rate. This procedure would require a reliable estimation of the saving potential when the arrival time is changed. Therefore, services from an independent voyage optimization service provider would be recommended in the calculation of the bunker saving potential.

9.3 Contractual changes for benefit share

The Virtual Arrival is not widely used by the shipping companies. According to Krzynski (2019) there are two types of reasons for the hesitance: one concerning the legal aspects and other concerning the operational aspects when implementing virtual arrival. The legal aspects may prevent the ship operator for agreeing virtual arrival contract, because arriving late might rise delay claims from the charterer or other third party stakeholders. To protect ship operators against third party claims when implementing virtual arrival, the legal aspects in the virtual arrival clause should override the ship operator’s obligations to the third parties. When considering the operational aspects, the main reason for the hesitance may be that the clauses which allow the implementation of virtual arrival are built
on trust. Both stakeholders need to trust each other in order to arrange a benefit distribution scheme which benefits both stakeholders. As voyage charters are sailed typically on a short term basis, there is no possibility to create trustworthy relationships. (Siwe, 2019).

The advantage of benefit sharing with a reduction in demurrage rate is that the savings are not based directly on an estimate of potential savings in bunker cost. The ship operator and charterer have, therefore, more room to negotiate a reasonable reduction in the reduction in demurrage rate without involvement of third party service provider estimating the saving potential in the bunker. The most cost effective model for benefit sharing for the ship operator would be by simply sharing the savings in bunker cost between the charterer. However, this would require involvement of a reliable service provider to estimate the saving potential.

The international regulations on shipping should have amendments to ensure that ship operators share their voyage plans with a relevant trusted parties. In practice, this could be enforced by adding amendments to the SOLAS and IMO regulation related to voyage planning (Singhota, 2019). For example, SOLAS Chapter V - Regulation 34 states:"Prior proceeding to sea, the master shall ensure that the intended voyage has been planned (IMO, 2014)." However, currently the voyage plan is kept as ship operator’s own information, although, the technology to share the information with trusted parties exists.

To get all global ports to change from first-come, first-served policy to a scheduled port operations a change in local customs and operation models is required. This may be the hardest barrier to overturn when trying to change the current habits in shipping to allow more efficient operations. Nevertheless, information sharing and more transparent shipping operations could change the habits in shipping in a right direction. According to Siwe (2019), for authorities such as Vessel Traffic Services the implementation of STM would be the biggest turning point since the implementation of AIS – with the AIS the authorities became aware of the name of the ship and by the implementation of STM the authorities will become aware of the intentions of the ship. Especially, a change of course in some major global ports could have a knock-on effect on changing the habits globally.
10 Discussion and conclusions

The first part of this thesis introduced the big picture of shipping processes by discussing the role of shipping stakeholders, operational processes and contractual terms used in shipping. The present situation of benefit sharing and the problem of conflicting incentives between shipping stakeholders were exemplified through hypothetical operational scenarios. The aspects of voyage optimization in terms of passage planning and voyage scheduling were introduced together with different voyage optimization strategies.

In the second part, voyage simulations were successfully run by using a ship performance model, weather data, sea-going voyage data and data from nautical charts. Different methods to estimate total ship resistance and to create sub-models, such as propeller model and wind model, were introduced. Simulations were run for 1767 voyages sailed by 49 ships with three different simulation scenarios by using NAPA Voyage Optimization-tool with ship performance models integrated in NAPA system. Additionally, four selected voyages were simulated by using DTU Ship Simulation Workbench tool by using the same weather data and sea-going voyage data as in simulations performed with Napa Voyage Optimization. In this case, the ship performance models were created by the user entered parameters. The simulation results of selected voyages from both simulation tools were then compared with actual values from Noon Reports.

The results from the case study shows a 11.5% reduction in emissions and bunker cost when just-in-time arrival is implemented to laden voyages. When weather routing is applied to these voyages, the reduction increases to 16.4%. The room for optimization focuses mainly on laden voyages, because there are less uncertainties when the details on the voyage schedule are determined in the charter party. When both, the laden and ballast voyages are optimized with just-in-time arrival, the reduction in bunker cost and emissions are 18.5%. When weather routing is applied, the reduction increases to 28.0%. However, to obtain savings of such magnitude in tramp shipping can be extremely difficult and requires accurate prediction of the market development and the demand for transportation.

The result comparison on selected voyages showed relative difference from 0.4 to 16.2% in fuel consumption between NAPA Voyage Optimization simulations and values from Noon Reports. For simulations ran with DTU Ship Simulation Workbench, the relative difference in fuel consumption varied from 5.2 to 23.1%. Therefore, there is room for further validation in the ship performance calculation to achieve more accurate results. However, for approximate ship performance models, the results do not seem overly alarming and the accuracy in the ship performance model can be enhanced by using additional data sources, such as noon reports and automation measurements onboard.

The overall benefits of voyage optimization are related to lower emissions, lower bunker cost, improved safety and less congestion in the port areas. For the ship operator, the major benefit when operating under a voyage charter party is the reduction in bunker costs and emissions. The charterer can benefit from voyage optimization if the savings can be shared e.g. by entering the virtual arrival clause or by using other benefit distribution scheme. The benefits for ports are less emissions produced in the port area and less congestion. The accurate information on ship arrival times can benefit the port time scheduling.

The successful implementation of voyage optimization in a global scale requires a change in the prevailing habit of first-come, first-served policy. Reliable estimations on energy saving and real-time information on arrival times are considered as the key factors towards the change. However, when
the voyage plan is done by using a reliable weather routing service, the ship operator can achieve significant savings without changes in the contracts between different shipping stakeholders.

10.1 Further studies

Based on the amount of recent publications, the voyage optimization and ship performance analysis are prevalent subjects in current marine technology research. Several subjects outside the scope of this thesis have potential to improve the results in ship performance analysis.

Further validation in ship performance models can be done, for example, by using additional data sources and big data methods. The enhanced models would increase the accuracy of the results and provide more reliable performance predictions. Especially, detailed information on hull fouling can increase the accuracy of the resistance model. Furthermore, the anchoring identification described in section 5.3.5 can be automated, increasing the accuracy of extra time spent in anchorage. The information of ports utilizing ship to ship loading/discharge integrated in the port database would improve the overall reliability of the excess time estimation further.
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