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Analysing Emission Reducing Measures for Shuttle Tankers Based on Autonomous Identification System Data

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Preface

This master thesis is the final work of the Master of Science degree in Marine Technology at the Norwegian University of Science and Technology in Trondheim. The work has been conducted during the spring of 2017, and corresponds to 30 ECTS. The topic of the thesis is shuttle tanker operations and the use of Automatic Identification System (AIS) data to analyse ship operations.

The work has been challenging, and there have been several people that I would like to thank for their help. First, I would like to thank my supervisor, Professor Bjørn Egil Asbjørnslett. He has been helpful in formulating the topic and scope of the thesis, and has given me valuable advice and guidance throughout the semester.

I would also like to thank Geir Almås and the rest of the staff at Teekay in Stavanger for their help and advice. I highly appreciate that I got the opportunity to visit them in Stavanger to get an insight into their work. I would like to thank Stian Aamodt from the Norwegian Coastal Administration for access to AIS data.

Last, but not least, I would like to thank my family, girlfriend and office mates for their vital support throughout the semester.

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Abstract

Many of the oil installations on the Norwegian Continental Shelf are dependent on shuttle tankers transporting the produced oil to shore. Shuttle tanker operations contribute to considerable emissions of volatile organic compounds (VOC). VOC is oil vapor that is mainly produced during offloading of oil between the offshore storage facility and the shuttle tanker. VOC is harmful to human and animal life and contributes to greenhouse gas emissions. It is possible to recover the VOC and utilise it as fuel for the shuttle tankers. VOC recovery and utilisation reduces environmental harmful emissions and reduces the overall fuel consumption.

Automatic Identification System (AIS) data is analysed in order to find an operational profile for the shuttle tankers. AIS is a global collision avoidance system mandatory on all larger vessels. The AIS provide information about the vessel such as position, speed and identification. The operational profile is used to assess the effect of implementing VOC recovery and utilisation as fuel for shuttle tankers operating on the Norwegian Continental Shelf.

The AIS data consists of 33 shuttle tankers with over 1.8 million individual AIS messages. In order to reduce the scope and complexity of the analysis, only four shuttle tankers are included in the analysis. First, a heuristic analysis of the four vessels is conducted to find an operational profile. Thereafter, a detailed analysis of one vessel for a 23 day period is conducted in order to assess the quality of the heuristic method.

The results show that the heuristic approach is a sufficient method for analysing large amounts of data. The average operational profile for the analysed shuttle tankers is notable close to expected outcome. However, a detailed analysis points out certain flaws in the heuristic analysis that show significant changes for the 23 day period.

Average operational profile from the heuristic method

Offloading Operation [%]	**Transit Ballast** [%]	**Transit Laden** [%]	**Waiting** [%]	**Port** [%]
18.75	36.17	23.75	8.02	13.31

There is a considerable VOC reduction potential. Assuming a recovery rate of 100% of the VOC emissions, the shuttle tankers can save fuel corresponding to 27-70 of hours of transit per offloading operation.

Sammendrag

Mange av olje-installasjonene på den norske kontinentalsokkelen er avhengig av bøyelastere for å frakte den produserte oljen til land. Aktiviteten til bøyelasterne bidrar i betydelig grad til utslipp av flyktige organiske forbindelser ("volatile organic compounds" - VOC). VOC er oljedamp som stort sett blir produsert i løpet av lossingen av olje mellom offshore lagringsanlegg og bøyelastere. VOC er skadelig for mennesker og dyr og bidrar til utslipp av drivhusgasser. Det er mulig å gjenvinne VOC og bruke dette til drivstoff for bøyelasterne. Gjenvinning og bruk av VOC reduserer miljøskadelige utslipp og reduserer det totale drivstofforbruket.

Data fra "Automatic Identification System" (AIS) er analysert for å finne en operasjonsprofil for bøyelastere. AIS er et globalt system for å unngå skipskollisjoner og er påbudt på alle større fartøyer. AIS gir informasjon om fartøyet slik som posisjon, fart og identifikasjon. Operasjonsprofilen brukes for å vurdere effekten av å implementere VOC gjenvinning til utnyttelse som brennstoff for bøyelastere som opererer på norsk kontinentalsokkel.

AIS dataen består av 33 bøyelastere med over 1.8 millioner individuelle AIS meldinger. For å redusere omfanget og kompleksiteten av analysene, er bare fire bøyelastere inkludert i analysen. Først er det gjennomført en heuristisk analyse av de fire fartøyene for å finne en operasjonsprofil. Deretter er det gjennomført en detaljert analyse av ett fartøy i løpet av en 23 dagers periode for å vurdere kvaliteten av den heuristiske metoden.

Resultatene viser at den heuristiske tilnærmingen er en tilstrekkelig metode for å analysere store menger data. Den gjennomsnittlige operasjonsprofilen for de analyserte bøyelasterne er tett opp til forventet resultat. Den detaljerte analysen viser imidlertid enkelte feil i den heuristiske analysen som gir signifikante endringer i løpet av perioden på 23 dager.

Gjennomsnittlig opererasjonsprofil fra heuristisk metodeg

Offloading Operation [%]	**Transit Ballast** [%]	**Transit Laden** [%]	**Waiting** [%]	**Port** [%]
18.75	36.17	23.75	8.02	13.31

Det er et betydelig potensial i å redusere utslipp av VOC. Forutsatt en gjenvinning av VOC utslipp på 100 %, kan bøyelasterne spare drivstoff som svarer til titalls timer i transittid i lastet tilstand.

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Acronyms

AIS Automatic Identification System.

bbl barrel.

BLS Bow Loading System.

CALM Catenary Anchor Leg Mooring.

CO_2 carbon dioxide.

COG Course Over Ground.

DP Dynamic Positioning.

DWT deadweight tonnes.

ERRV Emergency Response and Rescue Vessel.

ESD Emergency Shut Down.

ETA Estimated Time of Arrival.

FFI Forsvarets Forsknisngsinstitutt.

FPSO floating, production, storage and offloading.

FSO floating, storage and offloading.

HFO Heavy Fuel Oil.

IEA International Energy Agency.

IMO International Maritime Organization.

ISS International Space Station.

ITU International Telecommunication Union.

LNG Liquefied Natural Gas.

LOA Length Overall.

MDO Marine Diesel Oil.

MMSI Maritime Mobile Service Identities.

NCA Norwegian Coastal Administration.

NCS Norwegian Continental Shelf.

NO_x nitrogen oxides.

NORAIS Norwegian Automatic Identification System.

OLS Offshore Loading System.

SO_x sulfur oxides.

SOG Speed Over Ground.

SOLAS Safety of Life at Sea.

UCL University College London.

UTC Coordinated Universal Time.

VHF Very High Frequency.

VLCC Very Large Crude Carrier.

VOC Volatile Organic Compounds.

WGS World Geodetic System.

Chapter 1

Introduction

1.1 Background

A significant part of the oil production on the Norwegian Continental Shelf (NCS) is transported by shuttle tankers. At certain oilfield developments it is not practicable to install oil pipelines to shore, and shuttle tanker transportation is the only method of transportation. Shuttle tankers are specialized oil takers that load produced oil offshore and transport it to onshore terminals and refineries. They are usually equipped with a Dynamic Positioning (DP) system for sufficient position keeping during offloading operations.

Shuttle tankers are one of the major contributors of Volatile Organic Compounds (VOC) emissions in Norway (Martens et al., 2001). VOC is a mixture of different hydrocarbon compounds that are harmful to the environment and contribute to greenhouse gas emissions. VOC are produced mainly during loading and offloading of oil, but can also be produced during transit. Recovery and utilization of VOC as fuel has the potential to significantly reduce the overall emissions from shuttle tankers. Fuel efficiency and emission reduction is increasingly becoming a major aspect of offshore operations.

Analysing shuttle tanker operations with a focus on emission reducing measures requires an understanding of how a shuttle tanker operates. Large scale monitoring of Automatic Identification System (AIS) data has become available after AIS receivers have been deployed on satellites recent years. AIS provides information about operational aspects of ships, such as position and speed. AIS data analyses can provide useful information for understanding how a ship operates and contribute to establish an operational profile for a vessel.

1.2 Motivation

As emission reducing measures and cost effectiveness has become a higher priority for petroleum activities the recent years, there has been aimed attention on potential improvements in shuttle tanker activities. In order to assess the effect of design and equipment changes, the operation itself must be understood. Operational profiles provide information about what types of operations the vessel participates in, and how the machinery system operates during the different types of activities. Analysing the operations of shuttle tankers and creating operational profiles for the vessels can be used as a foundation for further investigation on technological improvements.

Generally, it can be difficult and time consuming to obtain operational profiles, and ship owners may be protective of operational data. Operational profiles do not necessary give the total picture of the operation for a vessel. In recent years, global monitoring of AIS data has become available, which gives the opportunity to investigate vessel operations.

1.3 Objective and Scope

The objective of this thesis is to create a heuristic method for analysing AIS data to create operational profiles for shuttle tankers. The AIS data will cover shuttle tanker traffic in Norwegian waters over a period of one year. First, a general operational profile will be created focusing on a few shuttle tankers and their operations over a period of one year. The analysis will consist of a heuristic method for determining the operational modes that constitutes the operational profile for the vessel. Thereafter, one of the shuttle tankers will be analysed in detail over a shorter period of time. The operation profiles from the two analyses will be compared to evaluate the quality and accuracy of the heuristic analysis of large amounts of AIS data. The results from the AIS analysis and the following operational profile will be used support an analysis of the effect of VOC recovery and utilisation as fuel for shuttle tanker operations on the NCS

The aims of the thesis is to give an understanding of shuttle tanker operations on the Norwegian Continental Shelf, and establish a method for analysing AIS data to find and assure the quality of operational profiles for shuttle tankers. The operational profile will be used as a groundwork for investigating the suitability of utilizing emission reducing features.

1.4 Literature Review

This chapter presents the literature study conducted to find relevant and state of the art literature for the topics of the thesis. First, research on satellite monitoring of AIS data is presented. Next, relevant literature and studies on shuttle tanker operations and VOC recovery and utilisation technology is presented.

Global monitoring of AIS is a relatively new concept and still under development. There have been several studies on detection and evaluation of AIS data. In Norway, the Norwegian Defence Research Establishment (Forsvarets Forskningsinstitutt - FFI) has been central in the development of AIS monitoring by satellite AIS receivers. Wahl et al. (2005), Eriksen et al. (2010) and Skauen (2016) are all studies on satellite AIS monitoring that are organised by FFI. They provide an understanding of the AIS system, and how to interpret and analyse AIS data. The study by Wahl et al. (2005) presented early on the potential for AIS monitoring from small satellites. In 2010, two satellite AIS receivers were deployed, and the study Eriksen et al. (2010) presents the results from the first months of operation. The study presents several possibilities for studying ship operations using AIS data and the challenges and limitations of analysing AIS data. The quality and probability of detecting AIS signals by satellite receivers is investigated in the study by Skauen (2016). The study presents four methods of improving the AIS monitoring performance; improving algorithms, multiple/better antennas, adding satellites or focussing on the space based AIS channels (Skauen, 2016).

The third International Maritime Organization (IMO) Greenhouse Gas study is a collaborative study led by the University College London (UCL) (Smith et al., 2015). It investigates global emissions of greenhouse gasses from ship traffic between 2007 and 2012, as well as estimations of future scenarios for ship traffic emissions. The aim is to update the second IMO Greenhouse Gas study from 2009, (Buhaug et al., 2009), using new and improved methods. The study uses two different approaches for emission estimations, a top-down method where the estimations are based on fuel consumption statistics from the International Energy Agency (IEA), and a bottom-up method where the estimations are based on ship activity observations from satellite AIS coverage. The second study from 2009 utilised a limited sample of AIS data from land based receivers that were not able to detect AIS messages far from shore. By utilising AIS data from satellite receivers, the third IMO Greenhouse Gas study was able to improve the method. The emissions are estimated by combining the AIS data with ship technical data from the IHS Fairplay database. The results show that the total emissions from maritime transport in 2012 was 950 tonnes CO_2, which corresponds to

2.7% of global CO_2 emissions. Although this is a reduction from the 2007 emission estimates, the predicted future scenarios are similar to the second IMO Greenhouse Gas study with an increase of 50% to 250% in the period up to 2050.

Emission reduction is becoming an important aspect in ship design and maritime operations. Shuttle tankers contribute to large emissions of VOC. The amount emitted can be reduced by recovering the VOC and utilising it as fuel. MAN (1998) presents a study on VOC utilising systems for shuttle tankers and Very Large Crude Carriers (VLCCs). The study shows that in some cases a VOC recovery system can reduce the fuel oil consumption by 90% by replacing it with VOC, and in addition a considerable reduction of sulfur oxides (SO_x) and nitrogen oxides (NO_x) emissions. This represent a reduction in fuel costs and environmental harmful emissions. MAN (1998) presents a case study for a shuttle tanker transporting oil from Statfjord to Rotterdam. Based on the operational profile of this operation, the study shows that the investment cost of a VOC utilisation system will have a payback time of 3.5 to 5.2 years.

Melhus et al. (2002) presents in a Phd thesis an analysis of VOC combustion in diesel engines. An experiment is conducted where a rapid compression machine is redesigned to use VOC. The result of the experiment shows that the heavier condensed components from the VOC is suitable for a traditional diesel scheme. Lighter VOC components, mainly methane and ethane, are more complicated to recover and store and are therefore normally not utilised in VOC recovery. Hansen et al. (2010) presents a study on VOC emissions reducing measures. The drop line system KVOC, increased cargo tank pressure and re-absorption are presented as efficient and cost effective measures that reduce the overall VOC emissions from shuttle tanker activities. The three measures can potentially reduce the VOC emitted by 60-70%.

1.5 Structure of the Report

The rest of this thesis consists of seven chapters that are arranged in the following way:

- Chapter 2 presents an introduction of shuttle tankers and offshore offloading operations on the NCS. The offloading operations are described from the perspective of the shuttle tanker, and the offloading methods in focus are the ones that are common on the NCS, tandem and Offshore Loading System (OLS) buoy offloading. Further, the operational modes that constitute the complete operation of a shuttle tanker are presented.

- Chapter 3 presents the theory and application of AIS and the use of AIS receivers installed on satellites for global AIS monitoring.

- Chapter 4 presents the methodology of the AIS data analysis. The methods for investigating the ship operations and determining operational modes are described.

- Chapter 5 presents the challenges of VOC emissions from shuttle tanker operations. The chapter presents several VOC emission reducing measures and the potential of utilising VOC as fuel.

- Chapter 6 Presents the results from the AIS data analysis and the effects of implementing the emission reducing measures presented in chapter 5.

- Chapter 7 presents a discussion of the analysis and the results obtained.

- In Chapter 8 a conclusion is reached, and a recommendation for further work on the topic is presented.

Chapter 2

Shuttle Tanker Operations

This chapter presents characteristics and operations of a shuttle tanker. The thesis is limited to the NCS, hence only shuttle tanker operations in this area are included. Chapter 2.1 presents the basics of shuttle tankers, while chapter 2.2 presents floating, production, storage and offloading (FPSO)s. In chapter 2.3, offshore offloading operations are presented, with a focus on tandem offloading and offloading from an OLS.

2.1 Shuttle Tankers

Offshore installations that are not connected with pipelines to shore are dependent on shuttle tankers to transport the oil. A stable oil production is dependent on the storage condition. If the storage tanks are full the production must stop. An unplanned shut-down of production is expensive and is avoided if possible. This entails that the operability of the shuttle tankers is an important aspect of the production. To maintain a steady production, the shuttle takers must offload on a regular basis, but environmental conditions and technical complications may cause delays and impact on the oil production. At many of the locations on the NCS, the environmental conditions are harsh and demanding. The shuttle tankers that are operating at these locations are among the most advanced vessels in their segment.

Shuttle tankers vary in size, but the ships that operate on the Norwegian Coastal Administration (NCA) are usually in the size range of 100,000 to 150,000 deadweight tonnes (DWT), with a pump capacity of 8,000-15,000 m^3/h. Shuttle tankers are usually equipped with a DP system to ensure position keeping and maneuvering capabilities during offloading operations and a Bow Loading System (BLS) for loading and offloading.

The main guideline for shuttle tanker operations on NCS is the NOROG 140 guideline developed by Norwegian Oil and Gas in cooperation with operators on the NCS (Norsk Olje og Gass, 2015). The guideline provides recommended operational and technical requirements to ensure safe loading operations. The operators on the NCS have guidelines for offloading operation procedures. The guidelines by Statoil that are used in this thesis only comprise the fields operated by Statoil. Other fields may have different procedures.

2.2 Floating, Production, Storage and Offloading Units

FPSO's have been present in the North Sea since 1986, and today, there are more than 100 units in operation worldwide (Vinnem et al., 2015). Most FPSO's are ship shaped and either converted oil tankers or new-built constructions. Deciding between new-build and conversion is usually based on the lifetime and the environmental impacts of the oilfield. If the lifetime exceeds 20 years, a new-build FPSO is usually preferred (Paik, 2007). The hull of the FPSO is able to store the produced oil, and the largest FPSO's have a storage capacity of over 2 million barrel (bbl). The selection of development concepts are based on several aspects such as environment, water depth, production capacity, distance to shore and distance to existing infrastructure (Paik, 2007). FPSO's are suitable for developments that are far from shore and existing infrastructure. Shuttle tanker transportation is often a less costly method than to install pipelines. Small oilfields with a short lifetime are suited for FPSO developments. They can rather easily be decommissioned and moved to other locations for reuse of the installation Paik (2007). The mobility of a FPSO construction is also advantageous at locations where rapid disconnections are required, e.g. due to icebergs.

There are several different FPSO mooring methods. In areas with milder environmental conditions and benign waters, spread mooring is a suitable method (Paik, 2007). A spread-moored FPSO has a fixed position and is not able to adjust position or to disconnect. The FPSO is moored to the seabed with several mooring lines, and does not have thruster systems for position keeping (Zhao and Vinnem, 2016). For areas that are more exposed to harsh environmental conditions a single point mooring system is more suitable. A FPSO can be equipped with either an internal or external turret, which the risers and mooring lines are attached to. A turret mooring enables the FPSO to rotate and weathervane to keep a position facing the most dominant weather conditions.

2.3 Offshore Loading

Offshore loading is the most crucial part of shuttle tanker operations. It is performed either directly from a storage facility or via a loading buoy. Direct offloading is conducted from a FPSO unit or a floating, storage and offloading (FSO) unit. There are two main mooring configurations for offshore offloading between a FPSO or FSO and a shuttle tanker: side-by-side and tandem. During a side-by-side configuration the two vessels are positioned parallel and close to each other, while during a tandem offloading operation the shuttle tanker is positioned a certain distance behind the FPSO. An offloading buoy system is connected to a storage facility and can either be fixed to the seabed, floating or submerged.

Offloading between an offshore storage facility and a shuttle tanker can be performed via a loading buoy. The buoy is equipped with a swivel that enables the shuttle tanker to weathervane around the buoy (Lamb, 2003). One of the advantage of buoy offloading concepts is that the distance between the oil installation and the shuttle tanker is increased, thus reducing the risk of collisions.

Catenary Anchor Leg Mooring (CALM) is a much used concept for buoy loading. The buoy is a single point mooring system moored to the seabed with anchor legs, with the risers attached to the underside of the buoy (Lamb, 2003). The difference in wave response between the CALM system and the shuttle tanker reduces the operability of the offloading system (Lamb, 2003). Submerged loading buoys have similar features to the CALM system, but the buoy is submerged at a certain depth. OLS is a submerged loading buoy system installed on the Statfjord and Gullfaks oilfields in the North Sea. A similar system is also installed on the Draugen oilfield.

2.3.1 Tandem Offloading

Tandem offloading is the method most practised in the North Sea (Chen, 2003), hence it is the FPSO-shuttle tanker transfer method in focus in this thesis. The method is proven to be more advantageous at withstanding harsh environmental conditions and in performing fast disconnections (Motta et al., 2011) (Wang et al., 2010). The duration of an offloading operation is dependent on storage capacity and pumping rate, but is usually in the range of roughly 24 hours (Chen, 2003).

During a tandem offloading operation, the shuttle tanker is positioned behind and connected to the FPSO with a loading hose and a hawser. The shuttle tanker must maintain its position in order to keep a safe distance. This can be performed either by DP (by DP mode) or by maintaining an astern thrust such that the hawser is in tension (taut hawser mode). DP mode is beneficial in harsh environments, hence it is the dominant method on the NCS (Chen, 2003). On the NCS DP class 2 is recommended (Statoil, 2017). DP class 2 requires full redundancy of the system, i.e. if one system fails, the other one automatically takes over. During an offloading operation the FPSO is positioned with the bow towards the direction of the most dominant environmental conditions with the connected shuttle tanker a certain distance behind in a sheltered position. Figure 2.1 illustrates a tandem offshore offloading configuration between a turret moored FPSO and a shuttle tanker.

Figure 2.1: Tandem offloading configuration between a turret moored floating, production, storage and offloading (FPSO) and a shuttle tanker (Paik, 2007)

Offshore offloading is the main purpose and the most crucial part of shuttle tanker operations. The shuttle tanker must operate in harsh and challenging conditions, and since the oil production is reliant on regular offloading it is essential that the shuttle tankers have a high operability. The operation consists of several stages that have a set of operational requirements. Chen (2003) presents a breakdown of the operation into five stages that comprises the complete operation: approach, connection, offloading, disconnection and departure. The description of the tandem offloading procedure is obtained from the operational guidelines for tandem operations on the NCS by Statoil (Statoil, 2017).

Approach

In advance of arriving within a 10 nautical mile zone of the installation, the vessel must report the Estimated Time of Arrival (ETA) and receive a confirmation that the installation is ready for oil offloading. The initiation of the operation requires acceptable visibility (Chen, 2003).The visibility can be interrupted by e.g. fog, but this is not any major issue on the NCS. If the operation is cancelled the shuttle tanker must move to a waiting position.

As the shuttle tanker approaches 3 nautical miles of the installation the speed has to be reduced to below 5 knots. When it reaches a distance of 900 m the shuttle tanker must stop and switch to DP manoeuvring, before it continues to a 500 m distance which is the safety zone for the installation. During the manoeuvring from the 900 m to the safety zone, the speed cannot exceed 1.2 knots. When the shuttle tanker reaches the safety zone, the speed is further reduced to a maximum speed of 0.6 knots. This speed is maintained until the shuttle tanker reaches a distance of 150 m from the installation and stops to initiate the connection phase (Statoil, 2017).

Connection

When the shuttle tanker has arrived at the installation it will connect to the hawser and loading hose via the BLS. First, a running line is shot from the installation over to the shuttle tanker. The running line is attached to a messenger line which again is attached to the hawser. After the hawser is attached, the loading hose is connected.

Usually the wind conditions require the FPSO or FSO to weathervane with the bow towards the dominant wind direction, and the shuttle tanker positioned behind the stern. The environmental requirements for connection are presented in table 2.1. The requirements are from the guidelines for tandem offloading operations on the NCS by Statoil (Statoil, 2017).

Table 2.1: Environmental requirements for connection between installation and shuttle tanker in tandem mode (Statoil, 2017)

Parameter	**Value**
Significant wave height [m]	4.5
Maximum wave height [m]	7.5
Maximum wave period [seconds]	15
Maximum Wind Speed [knots]	32
Minimum Visibility [m]	500

Offloading

After the safety measures and test are completed, the loading can begin. During the offloading phase the shuttle tanker is in DP-mode while the oil is transferred to the storage tank. The duration varies, but is usually 20-30 hours. During the entire offloading phase the systems and the nearby surroundings are monitored. The loading rate is continuously monitored for sudden changes that could be caused by an oil leakage. The nearby surroundings are monitored for visible oil spills (Statoil, 2017). If the weather conditions aggravate and reach beyond acceptable limits, a leakage is detected or a system failure occurs, the shuttle tanker must cancel the operation and disconnect. The environmental criteria for offloading is presented in table 2.2

Table 2.2: Environmental requirements for offloading between oil installation and shuttle tanker in tandem mode (Statoil, 2017)

Parameter	**Value**
Significant wave height	5.5
Maximum wave height [m]	9.0
Maximum wave period [seconds]	15
Maximum Wind Speed [knots]	38
Minimum Visibility	Stern of the oil installation visible from the shuttle tanker

While the shuttle tanker is loading oil, it has to maintain a position within certain limitations. These limitations vary slightly between the installations, but are in the same size range. The tandem offloading guideline by Statoil presents these requirements for the FPSOs and FSOs that they operate on the NCS (Statoil, 2017). When a parameter exceeds the limitations the Emergency Shut Down (ESD) system is activated. The system consists of the classes, ESD class one and ESD class two. The ESD class one procedure includes a shut-down of the pumps and shutting the valves. The same procedure is carried out for ESD class two, but the shuttle tanker will disconnect from the installation (Statoil, 2017).

At the Norne FPSO, the shuttle tanker must maintain a position of 80-100 m behind the stern of the FPSO. If this distance exceeds 120 m or becomes closer than 75 m, the ESD class one is activated. If the distance exceeds 130 m or becomes closer than 65 m, ESD class two is activated. The shuttle tanker must also maintain a position within an angle of +/- 40° from the hawser connection point. ESD class one is activated if this limit is exceeded. If the angle exceeds an angle of +/- 50°, ESD class two is activated. Figure 2.2 illustrates the positional limitations for position keeping during offloading.

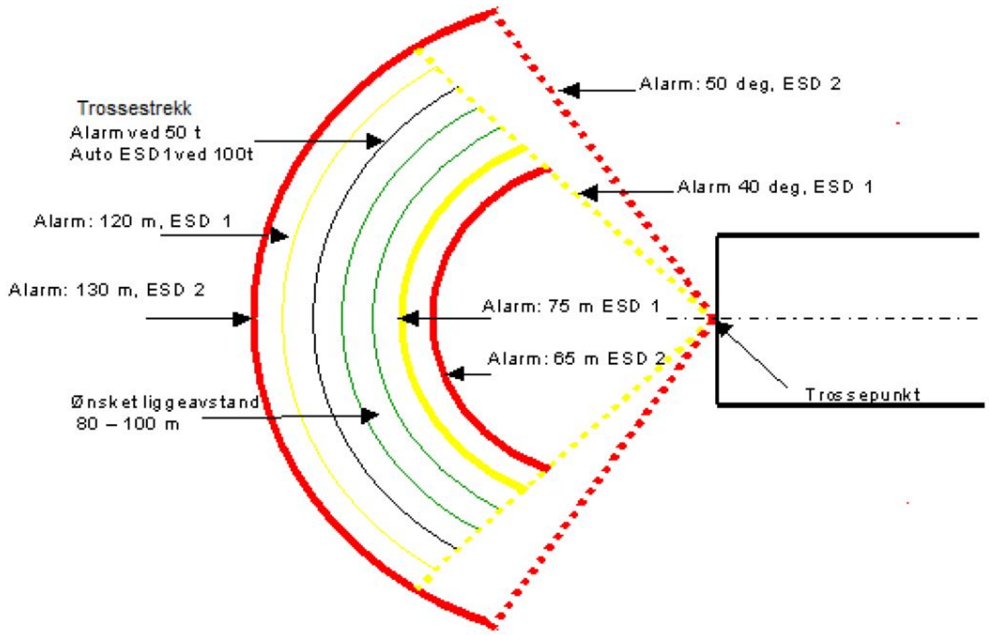


Figure 2.2: Limitations for position keeping during offloading operations between a floating, production, storage and offloading (FPSO) system/ floating, storage and offloading (FSO) system and a shuttle tanker (Statoil, 2017).

Disconnection
When the loading of oil is completed, the disconnection phase is initiated. Valves are closed, equipment is rinsed free of oil and the hawser and hose is transferred back to the installation.

Departure
When the disconnection is completed the shuttle tanker departs from the installation. At the start of the departure, the shuttle tanker backs away while in DP mode until it reaches an acceptable limit and switches to manual manoeuvring. The course is set for planned route and the shuttle tanker departs for a destination to unload the cargo.

2.3.2 Offshore Loading System (OLS)

OLS is a submerged buoy loading concept in use at the Statfjord and Gullfaks oilfields in the North Sea. The buoy is connected to pipelines from the storage facility on the oil installations on the fields. A loading hose is connected to the submerged buoy in one end and a messenger line in the other end. The messenger line is connected to a pick-up buoy on the surface that enables the messenger line to be picked up and transferred to the shuttle tanker.

The description of the OLS offloading procedure is obtained from the offloading procedure guidelines for OLS offloading on the NCS by Statoil (Olsen and Lindman, 2015).

Approach

The approach phase is similar to the approach phase for tandem operations presented in chapter 2.3.1. The safety zone for the OLS is a 500 m radius from the buoy centre. Before entering the safety zone, the shuttle tanker must conduct safety procedures and clarify with the installation that it is ready for offloading. At 900 m from the buoy, the shuttle tanker switches to DP manoeuvring and proceeds at a maximum speed of 1.2 knots. When it enters the safety zone, the speed is further reduced to 0.6 knots before stopping at 250 m from the buoy to initiate the connection phase (Olsen and Lindman, 2015).

Connection

Support from the Emergency Response and Rescue Vessel (ERRV) at the current installation is needed for the connection phase. The ERRV is responsible for picking up the messenger line and shooting it to the bow of the shuttle tanker. When the messenger line is picked up by the shuttle tanker, it manoeuvres at a slow speed towards a 70 m distance from the buoy position. When it reaches this destination it is set in weathervane mode before the messenger line is pulled inn and the loading hose is connected (Olsen and Lindman, 2015). The environmental requirements for the connection phase are identical to the requirements for tandem connection, see table 2.1.

Offloading

When all safety procedures and test are done, the loading can start. The environmental requirements are similar to the requirements for tandem offloading, see table 2.1. The only difference is that there are normally no visibility restrictions. During the offloading, the flow is continuously monitored for sudden changes. Nearby surroundings are monitored for visible leakages and oil spills.

While the offloading phase is ongoing, the shuttle tanker must maintain a position within certain limitations. The limitations are identical at Statfjord and Gullfaks. The shuttle tanker should maintain a 60 m - 80 m distance from the buoy position. If it becomes closer than 30 m, the ESD class one is activated, while ESD class two is activated if it becomes closer than 20 m. The distance cannot exceed 92 m or the ESD class one is activated. If it exceeds 114 m the ESD class two is activated (Olsen and Lindman, 2015). Figure 2.3 illustrates the different positional requirements during OLS offloading.

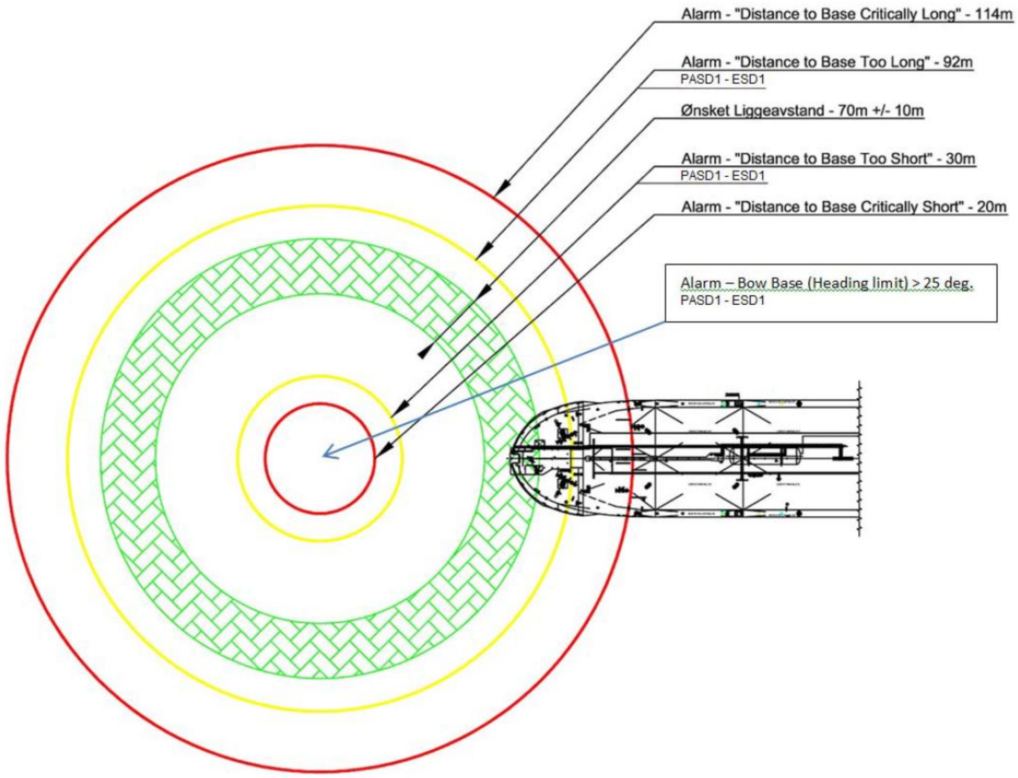


Figure 2.3: Limitations for position keeping during offloading from an Offshore Loading System (OLS) (Olsen and Lindman, 2015).

Disconnection

When the offloading phase is completed, the disconnection phase is initiated. First, equipment is rinsed. Thereafter, the loading hose is disconnected and the shuttle tanker backs away at a slow speed while releasing the messenger line.

Departure

When the messenger line is detached and the shuttle tanker is out of the safety zone, it switches to manual manoeuvring and departs for an unloading destination.

2.4 Operational Profile

The operational profile for a ship is an overview of the specific time usage and engine output for the operation of a ship. It usually comprises one year of operation. The operational profile is used to optimize the machinery arrangement for ships under development, such that it complies with the technical and operational requirements. It can also be used by ship owners to estimate fuel costs, and to identify possibilities of improvement of operation. An operational profile is based on operational data of existing ships within the same segment. It can either be general for a fleet, for a specific type of vessels or for a single vessel. The operational profile is divided into operational modes that represent a specific operation and engine output. An operational mode is presented as proportion of time it is in use, and the average use of engine power during that time.

MAN (1998) presents an operational profile for a general shuttle tanker operating in the North Sea. The Operational profile is divided into four operational modes. Table 2.3 presents the operational modes and the distribution of time and propulsion power for each mode presented by MAN (1998).

Table 2.3: General shuttel tanker operational profile (MAN, 1998)

Operational mode	**Days per year**		**Hours/trip [h]**
	Days	**Proportion [%]**	
Offloading at oilfield	65	18	20
Voyage to port	117	32	36
Unloading at port	65	18	20
Voyage to oilfield	117	32	36

The operational profile presented in table 2.3 represents a typical round-trip pattern for a shuttle tanker offloading at the Statfjord oilfield and unloading in Rotterdam (MAN, 1998). For other oilfields and sailing patterns, the operational profile might be different. Shuttle tankers do not necessary only load oil at one specific oilfield or unload at one specific terminal.

2.4.1 Shuttle Tanker Operational Modes

The operational modes should represent specific operations that differ from each other. The operational modes presented in this chapter are defined by the author of this thesis as a suitable subdivision of shuttle tanker operations on the NCS.

Transit

The transit phase is often the major operational mode for a ship. For a shuttle tanker, the transit mode can be divided into two phases: transit in ballast condition and transit in laden condition. These operational phases can again be divided according to specific vessel speeds, e.g. maximum speed and average speed. During this operational mode the DP system is inactive. The main engines provide propulsion power, and there is not need for much electric power production.

Offshore Loading

In chapter 2.3 a breakdown of the offloading operation is presented. A common feature for the offloading phases is that the shuttle tanker is utilizing DP for the majority of the time. Of the five phases presented in chapter 2.3, it is the offloading phase that is the major part of the whole offloading operation. The power output for this mode is relatively high, because of all the different systems that are active during the offloading operation. DP class two is required on the NCS.

Waiting

If the environmental conditions are beyond the acceptable limit of operation, the shuttle tanker has to wait until the conditions improve. The waiting position is required to be a minimum of 10 nautical miles from the closest offshore installation (Statoil, 2017). While the shuttle tanker is waiting it is usually stationary and operating on DP. The waiting phase happens either before the shuttle tanker connects, or if it has to disconnect due to unacceptable conditions or system failures.

At Port

When the shuttle tanker is at port it is either discharging oil, or loading fuel and preparing for departure. At port the shuttle tanker does not use the main engines, but the auxiliary engines must provide sufficient electric power to run the systems in use during unloading.

Idle

When the shuttle tanker is in idle mode it is waiting to start on a new offloading mission. Sometime a new mission is not available directly after discharge, and the shuttle tanker must wait. While it is waiting, the shuttle tanker can either be in port or anchored close to shore.

Chapter 3

Automatic Identification System (AIS)

This chapter is an introduction to AIS. The chapter presents the theory of AIS used in this thesis. Chapter 3.1 presents the AIS system. In chapter 3.2 space based AIS is presented, with a focus on Norwegian projects and developments.

3.1 Introduction to AIS

AIS is a worldwide collision avoidance and monitoring systems for ship traffic. All ships equipped with AIS send out and receive AIS message signals through Very High Frequency (VHF) radio transmissions. There are in total 27 messages in the AIS signal, consisting of a combination of static, dynamic and voyage related data (Eriksen et al., 2010) (Skauen, 2016). The Safety of Life at Sea (SOLAS) convention from IMO requires that all ships engaged in international voyages and over 300 gross tonnes, all ships not engaged in international voyages but over 500 gross tonnes and all passenger ships irrespective of size shall be equipped with Class A AIS equipment (IMO, 1974). There are two types of AIS equipment, the main type, Class A, and a simpler and less costly type, Class B (Xiao et al., 2015). The Class B equipment is used by smaller vessels that are less than 300 tons, e.g. fishing vessels, and is not mandatory (Eriksen et al., 2010).

The different message types are transmitted with certain reporting intervals. Static data, such as vessel identification and specifications, has a reporting interval of 6 minutes. Dynamic data has a reporting interval of 2-10 seconds depending on speed and course change, while at anchor or moored condition it has a reporting interval of 3 minutes (ITU, 2014). There are four broadcast channels operating on different frequencies for transmitting AIS messages, the nominal channels AIS1 and AIS2 and the two long range channels AIS3 and AIS4 (ITU, 2014).

The AIS system is described in detail by the International Telecommunication Union (ITU) (ITU, 2014). Among the 27 message types, the messages 1-5 and 27 are of special interest in this thesis. Message type 1-4 transmit dynamic messages, where message 1-3 are position reports by mobile shipborne equipment, and message 4 is a base station report transmitted with a minimum reporting interval of 10 seconds (ITU, 2014). Message type 5 contains static and voyage related data. The long range channels are intended for message type 27 which transmits a reduced message similar to messages 1-3 (ITU, 2014). The long range broadcast message has a transmission interval of 3 minutes (ITU, 2014). Alternating between the two channels implies that a message is broadcast every 6th minute for each channel. Table 3.1 presents the most common parameters for the AIS messages described. The table is based on the message description by ITU (2014).

AIS signals can be detected by land base stations located at strategic positions along the coastline. While ship-to-ship transmissions have a range of approximately 20 nautical miles, a land base station is able to detect AIS transmissions from a distance of up to 60 nautical miles, or 110 km (Eriksen et al., 2010). Land-to-ship signals have an extended range, due to the elevated location of the land base station (Høye et al., 2008).

Table 3.1: Most relevant Automatic Identification System (AIS) parameters (ITU, 2014)

Parameter	**Description**	**Message type:**
Maritime Mobile Service Identities (MMSI)	Unique identifier for each AIS transmitter	All message types
Navigational Status	15 different signals that describes the navigational status of the vessel, e.g. at anchor, moored, sailing	1,2,3,27
Speed Over Ground (SOG)	Current speed of the vessel	1,2,3,27
Latitude & longitude	The current position at time of transmission	1,2,3,4,27
Course Over Ground (COG)	Course given in degrees (0-359)	1,2,3,27
True heading	Degrees (0-359)	1,2,3
Coordinated Universal Time (UTC)	year, month, day, hour, minute, second	1,2,3,4
Time Stamp	UTC second when the report was generated	1,2,3
IMO Number	Vessel identification number by IMO	5
Name	Registered name of the vessel	5
type of ship & cargo type	Number that indicates the type of ship and a number that indicates cargo type	5
Overall dimensions	4 numbers that specifies the dimensions of the ship	5
Estimated Time of Arrival (ETA)	Estimated time of arrival for set destination	5
Destination	Maximum 20 characters string specifying the destination of the ship	5

3.2 Space Based Automatic Identification System

Land based stations do not have sufficient range for large scale monitoring of AIS transmissions. Since the mid 2000s, there has been projects dedicated to satellite based AIS monitoring. In 2010, two AIS receivers were deployed into space by a Norwegian collaboration; the Norwegian Automatic Identification System (NORAIS) receiver installed on the International Space Station (ISS) and the AISSAT-1 nano-satellite (Eriksen et al., 2010). A copy of the AISSAT-1 satellite, AISSAT-2, was launched in 2014 to increase the AIS monitoring capability, extend the coverage and work as an in-orbit spare for AISSAT-1 (Skauen, 2016). Both AISSAT satellites follow a polar orbit with a total of 15 daily orbits. AIS messages that are received by the AISSAT satellites are forwarded to the Svalbard ground station, before they are further forwarded to the NCA and the Forsvarets Forsknisngsinstitutt (FFI) (Skauen, 2016). In 2015, the NORAIS receiver was replaced with a more advanced version with improved algorithms. While the AISSAT satellites operate on the nominal AIS channels AIS1 and AIS2, the new NORAIS receiver operates on all four channels (Skauen, 2016). In July 2017, the third generation AISSAT satellite (AISSAT-3) was launched into orbit.

According to a study by Eriksen et al. (2010), there are several problems with a space based AIS receiver. Firstly, the decoding of the signals was troublesome due to weaker signals and multiple signals received simultaneously. Secondly, the area covered is large and the number of transmitted messages might be high in dense traffic areas. The study by Skauen (2016) investigated possible improvements for the tracking capability of AIS signals. The study presents four improvement methods: improving algorithms, multiple or better antennas, adding satellites or focusing on the space AIS channels. Skauen (2016) presents the probability of detection by the space based AIS systems AISSAT and NORAIS. Figure 3.1 and 3.2, presented by Skauen (2016), illustrates the cumulative probability of re-detection of a detected vessel within 24 hours for the AISSAT satellites and the NORAIS receiver, respectively. The AISSAT receiver probability illustrated in figure 3.1 is based on the nominal AIS channels, while the NORAIS receiver probability is based on the space AIS channels.

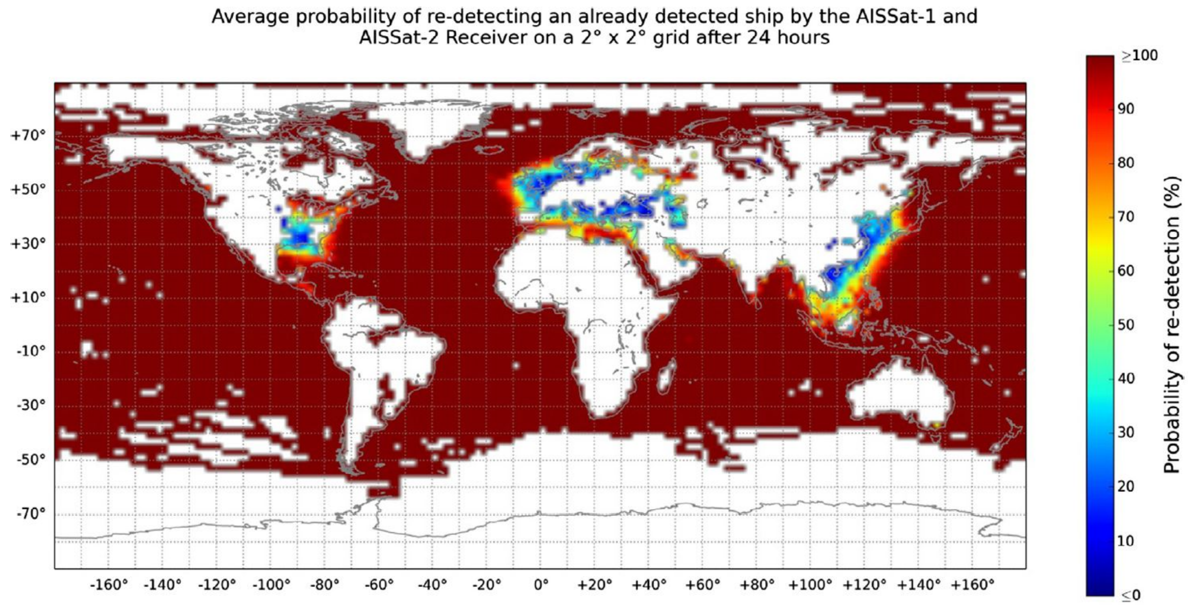


Figure 3.1: Cumulative probability of re-detection within 24 hours for AISSAT-1 and AISSAT-2 combined (Skauen, 2016)

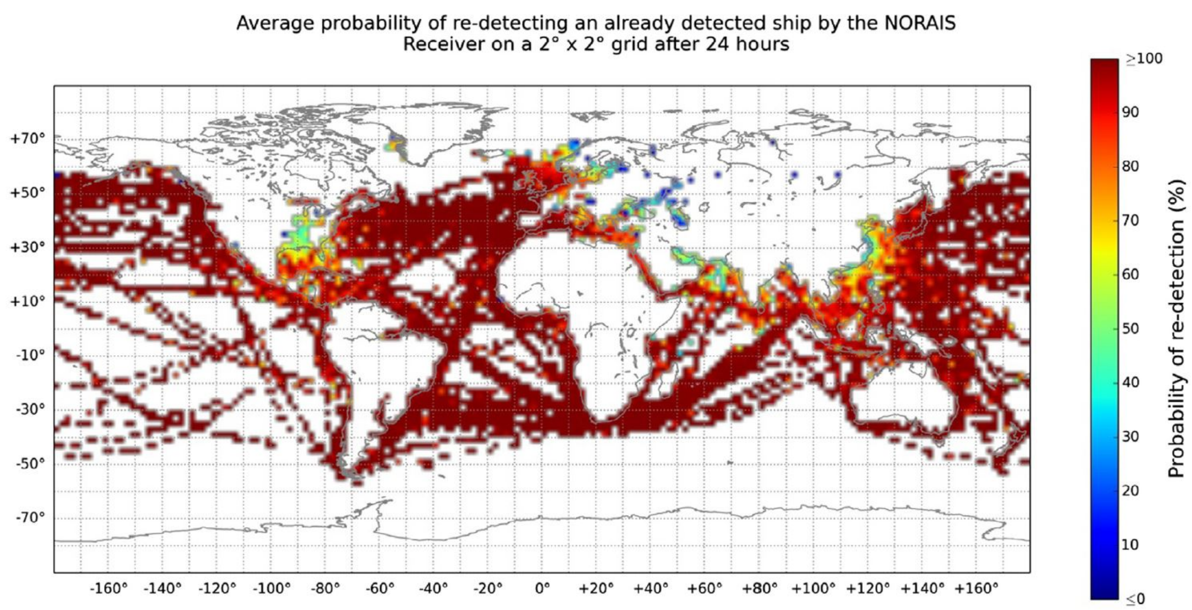


Figure 3.2: Cumulative probability of re-detection within 24 hours for NORAIS operating on space Automatic Identification System (AIS) channels (Skauen, 2016)

In figure 3.1 it can be seen that the probability of re-detection within 24 hours for the AISSAT receivers is low for some locations with a high density of ship traffic, like the North Sea. This is because the dense ship traffic causes co-channel interference and land-based signal interference (Skauen, 2016). The NORAIS receiver has a higher probability for some of the dense traffic areas, as it can be seen in figure 3.2. There are several aspects that explain this difference. The orbits of the AISSAT and NORAIS receivers are different. The NORAIS receiver is able to detect AIS signals between approximately 70° S and 70° N, while the AISSAT receivers cover larger areas including areas closer to the poles. The lower orbit of the ISS results in a smaller field of view. The orbital differences result in a better coverage for the NORAIS receiver for some of the dense traffic areas, while it has a poor or non-existing coverage of extreme northern and southern latitudes (Skauen, 2016).

Chapter 4

Automatic Identification System Data Analysis

This chapter presents the AIS analysis. Chapter 4.1 presents the AIS data obtained from the NCA and the parameters included in the analysis. The data is evaluated for further use in the analysis in chapter 4.2. The heuristics for for categorizing, evaluating and analysing the data using Matlab is presented in chapter 4.3.

4.1 AIS Data From the Norwegian Coastal Administration

The AIS data that is sent to NCA is stored in the database ”Havbase”. The databse presents sailed distances and emissions for specific vessel segments. The database combines standard AIS data with information such as machinery type, fuel type and vessel size from the IHS Fairplay ship registries to estimate fuel consumption, emissions and distance sailed (Askildsen, 2016). NCA have granted axes to raw-data for specific AIS data of shuttle tanker traffic over a period of one year. The data consists of approximately 1.8 million AIS messages that each consists of 14 data points. Of the 14 different data points, only 10 are included in the analysis, see table 4.1.

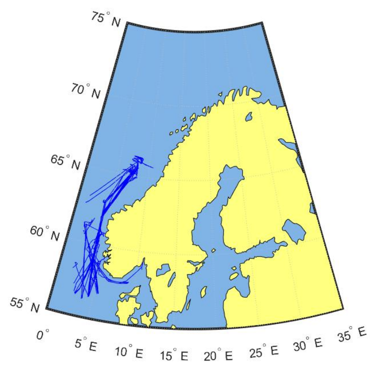
Some of the raw data is not necessary to include in the analysis. By excluding data, the computational time and the complexity of the analysis is reduced. There are no other ship types than shuttle tankers included in the obtained data, hence it is not necessary to include the vessel type information. The size group does not give enough information about the specific size and dimensions of each individual ship. The size and dimensions of the ships will be found and included in the analysis, and it is not necessary to include the size group data. The area data category does not provide detailed information about the specific area from where the message was transmitted. As the analysis will assess the positional data in detail, it is not expedient to include the area data from the dataset in the analysis. The last data point that is excluded from the analysis is the geom4326 label. The latitude and longitude data provides sufficient positional data. Table 4.1 presents the data that is included or not included from the AIS messages.

Table 4.1: Automatic Identification System (AIS) data and estimated fuel consumption and emissions data from the Norwegian Coastal Administration (NCA)

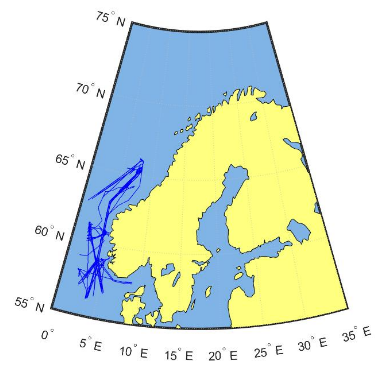
Data	**Included/not included**
MMSI	Included
IMO number	Included
Vessel name	Included
Date and time	Included
Fuel consumption	Included
CO_2 emission	Included
Distance sailed	Included
Time to next recorded message	Included
Vessel type	Not included
Size group	Not included
Area	Not included
Latitude	Included
Longitude	Included
geom4326	Not included

NCA provided specific data for shuttle tanker traffic in Norwegian waters for the whole year of 2016. The data contains AIS recordings approximately every 6^{th} minute for each vessel. Occasionally the time between the AIS messages is longer, but the frequency of longer time periods between the received messages occurring is relatively low. The time period of 6 minutes applies for all types of data. The 6 minute interval was chosen to limit the data size, while still being applicable for analysing ship operations. Although the majority of the signals have a 6 minute interval, messages with both higher and lower intervals regularly appear.

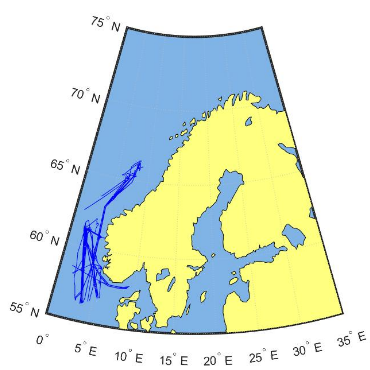
The AIS data is limited to Norwegian waters, hence there are missing signals whenever the vessel has sailed out of this area. This area limitation was implemented to prevent large data files with excessive information, which would make an analysis rather complex and time consuming. The positional data for four of the shuttle tankers detected can be seen in Figure 4.1. In the figure, a line is drawn between each position for a vessel in consecutive order according to time.



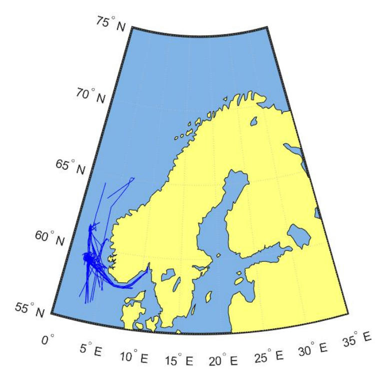
(a) Shuttle Tanker 1



(b) Shuttle Tanker 2



(c) Shuttle Tanker 3



(d) Shuttle Tanker 4

Figure 4.1: Positional data for the Norwegian Continental Shelf (NCS) plotted for each shuttle tanker over a time period of one year.

4.2 Data Categorization and Evaluation

The raw-data is obtained as all AIS signals recorded on a monthly basis. In order to analyse the data it had to be categorized. The first step was to decompose the data and arrange it for each specific ship. Altogether, there were 33 shuttle tankers registered in Norwegian waters in 2016. Some were only in Norwegian waters for a short period of time, and where probably only in transit mode for the series of recorded AIS messages. These shuttle tankers were not relevant for the analysis and were excluded for further analysis.

Due to the amount of data and similarity of the different vessels, the number of ships included in the analysis was reduced to four. The four vessels that were chosen are presented in table 4.2. The vessels were chosen due to a combination of amount of suitable and certain data, and the suitability for comparing size differences.

Table 4.2: Shuttle Tankers included in the analysis

Vessel ID	**Year built**	**LOA [m]**	**DWT**	**AIS message signals**
ST 1	2010	248.56	106,000	61,004
ST 2	2011	248.56	106,000	47,287
ST 3	2011	284.95	149,999	56,988
ST 4	2013	257.26	111,634	78,332

LOA = Length Overall

None of the AIS data included transmissions for a whole consecutive year without disruptions. Some of the data was missing, probably due to undetected signals or errors in the database, but mainly data is lost because the vessels left Norwegian waters. The four vessels missed in total approximately 179, 223, 196 and 95 days, respectively. A major part of the operation is missing. This is the result of the compromise that was done to reduce the amount of data.

Some of the AIS messages does only have a time stamp and position recorded. The rest of the information for the received message is missing. For these messages it is assumed that the shuttle tanker has the same speed, fuel consumption and CO_2 emission as the previous AIS message. This assumption increases the total time of operational data by only 21, 6, 24 and 11 hours, respectively.

4.3 Operational Mode Heuristics

The first step of the AIS analysis is to determine the different operational modes for the vessels. The operation is subdivided into categories that have a set of parametric criteria that distinguish them from each other. The criteria is determined based mainly on position and speed. For this thesis the four main categories of operational modes are: offloading, port, transit and waiting. The specific criteria for each operational mode is described in chapter

4.3.1 to 4.3.3.

4.3.1 Offshore Offloading Operational Mode

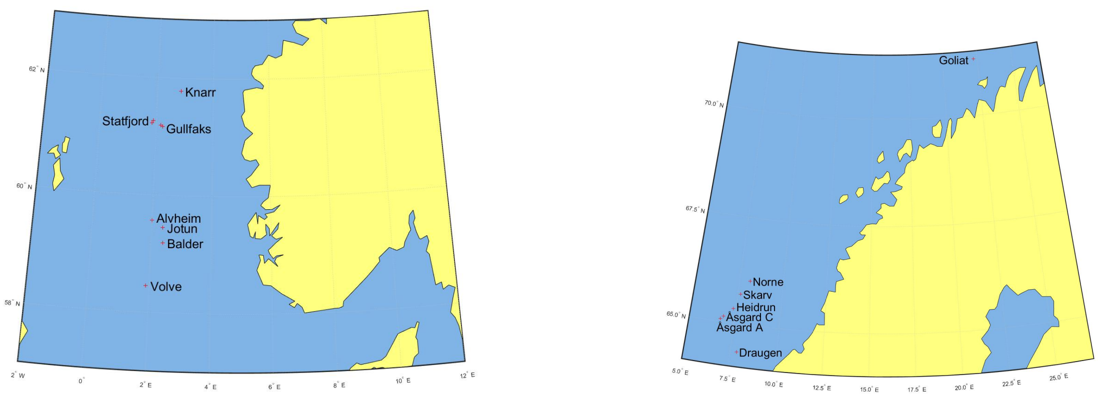
The main criterion for the offloading operation is the proximity to an oil installation or loading buoy. When the vessel is within a certain radius of an oil installation, and has an approximate stationary position, the vessel is most likely loading oil at that installation. If the shuttle tanker is close to the installation and has a noticeable speed it is either approaching or departing from the installation.

On the NCS there were in total 14 installations that were dependent on shuttle tankers to transport the produced oil in 2016. Today, there are currently three oil installations that offload oil via submerged loading buoys and ten that offload directly from a FPSO or FSO. The Gullfaks and Statfjord installations have two OLS loading buoys each. The Volve and Jotun oilfields were shut down in 2016, in September and December, respectively (Norwegian Petroleum Directorate, 2017). They are included in the analysis due to the fact that the AIS data obtained is from the same year as they were shut down. The Jotun FPSO is still active today, producing oil from other nearby oilfields (Norwegian Petroleum Directorate, 2017). The installations that are implemented in the analysis are listed in table 4.3.

Table 4.3: List of Installations on the Norwegian Continental Shelf reliant on shuttle tanker transportation of oil.

Installation	Type	Area
Alvheim	FPSO	North Sea
Balder	FPSO	North Sea
Draugen	LB	Norwegian Sea
Goliat	FPSO	Barents Sea
Gullfaks	LB	North Sea
Heidrun	FSO	Norwegian Sea
Jotun[1]	FPSO	North Sea
Knarr	FPSO	North Sea
Norne	FPSO	Norwegian Sea
Skarv	FPSO	Norwegian Sea
Statfjord	LB	North Sea
Åsgard A	FPSO	Norwegian Sea
Åsgard C	FSO	Norwegian Sea
Volve[1]	FSO	North Sea

The installations are mainly located in the North Sea and the Norwegian Sea, with one exception, Goliat, which is located in the Barents Sea. The North Sea and the Norwegian sea are separated at 61° N, and the Norwegian Sea and the Barents Sea is separated at 71° N. The locations of the installations are illustrated in figure 4.2.



(a) Installations located in the North Sea

(b) Installations located in the Norwegian Sea and the Barents Sea

Figure 4.2: Installations on the Norwegian Continental Shelf.

The positions for the installations operated by Statoil were obtained from the tandem offloading and OLS offloading procedure guidelines (Statoil, 2017) (Olsen and Lindman, 2015). The positions for the remaining installations were obtained from the AIS monitoring website Marine Traffic (Marine Traffic, 2017). Marine Traffic is a user based website, and the accuracy and reliability of the positions are uncertain. To verify the positional accuracy, the positions specified in the Statoil offloading guidelines and the positions specified by Marine Traffic are compared, see table 4.4. The AIS coordinates that are obtained from Marine Traffic are continuously updated. The coordinates are obtained July 11, and there might be small changes in position since that day. The position of Åsgard A was not accessible from Marine Traffick and is not included in the comparison.

[1]Shut down in 2016

Table 4.4: Comparison of positions from Marine Traffic and Statoils offloading procedure guidelines (Statoil, 2017) (Olsen and Lindman, 2015).

Installation	**Statoil Guidelines**		**Marine Traffic**		**Distance [m]**
	Latitude	**Longitude**	**Latitude**	**Longitude**	
Gullfaks OLS 1	61.19109	2.155825	61.1911111	2.1558333	2
Gullfaks OLS 2	61.16675	2.228	61.1672222	2.2297222	107
Heidrun FPSO	65.3446	7.365002	65.3433333	7.3638889	150
Norne FPSO	66.02657	8.086884	66.0269444	8.0866667	43
Statfjord OLS A	61.2632	1.885278	61.2636111	1.8872222	114
Statfjord OLS B	61.22401	1.836883	61.2244444	1.8386111	105
Åsgard C FSO	65.12967	6.8615	65.1311111	6.8638889	196

The distance is calculated by the Matlab function, *distance()*, that calculates the distance between two points on a sphere or ellipsoid. The function needs a reference sphere or ellipsoid to calculate the distance precisely. The earth is an ellipsoid and the radius at sea level is not constant at all latitudes. Matlab has several reference ellipsoids included in the program, and the one used in the distance calculations in this thesis is the reference ellipsoid created with the current World Geodetic System (WGS), WGS84.

As the distance offset is ranging from 2 m to 200 m, it is assumed that the coordinates provided by Marine Traffic have a margin of error within this range. In order to analyse the correct location for offloading operations, a small area surrounding the installation is determined as the offloading area. The area is set to a radius of 1.5 km from the position of the installation. The distance is set to avoid overlaps between installations close to each other, but at the same time avoiding shuttle tankers in transit that never approach for offloading. The distance between the loading buoys at Gullfaks is approximately 4.7 km, and the distance between the two loading buoys at Statfjord is approximately 5 km.

The AIS messages that are transmitted during offloading operations have to be extracted from the dataset of all AIS messages from the shuttle tanker. First, the algorithm reads through the whole set of recorded messages. For each message, the distance between the position transmitted and all 14 installations is calculated. If the distance is less than 1.5 km, the AIS message is stored together with a notification of installation and the distance to the installation for the current message. The Matlab script can be found in appendix D.

The AIS messages that are extracted are not necessary corresponding to the shuttle tanker performing offloading operations. As described in chapter 2.3.1, the shuttle tanker will switch to DP manoeuvring at a distance of 900 m from the installation, and within the safety zone of 500 m the speed is maximum 0.6 knots. Therefore, all the extracted data has to be analysed once more to find which messages that corresponds to the shuttle tanker being in transit mode, rather than offloading. To find these messages, the extracted data is read through, and if the speed of the shuttle tanker is higher than 0.6 knots, the message is categorised as transit mode.

The proximity to the installation and low speed does not necessary mean that the shuttle tanker is offloading oil. It can either be approaching, connecting, disconnecting or departing. To simplify the analysis these four phases are regarded as ”offloading operation” for the operational profile.

4.3.2 Port

Shuttle tankers are regularly in port to unload oil. A method for finding the AIS messages that are transmitted from a port location is to measure the distance from the location of the shuttle tanker and the shoreline. All AIS message locations that are within a certain distance of a coastline point can be extracted for further analysis. For each shuttle tanker location, the distance has to be calculated for each coordinate that make up the complete shoreline. This entails that the amount of coordinate points affects the computational time.

Matlab has a set of coordinates that are used to make map projections. The map projection of Scandinavia, 55° N to 75° N and 0° to 35° E, consists of 340 coordinates. The coordinates do not create a detailed map projection, but a small number of coordinates reduces the computational time. There are in total 243,611 AIS messages transmitted by the four vessels, which results in over 82 million computations. The distance criteria set for extracting the AIS message data point must ensure that there are no blind spots along the coast. In figure 4.3 a map projection of the 340 coordinates that constitutes the coastline is presented. The arrow points out the most remote coordinate point which has the closest coordinate approximately 56 km away. To ensure that there are no blind spots along the coastline the distance criteria can be set as half of the longest distance between neighbouring coordinates. Setting the distance criteria as half of this distance will ensure that the area covered by each coordinate will overlap with the area covered by surrounding coordinates.

A matlab script searches through all the positional data for a vessel and measures the distance to the closest point along the coastline. The matlab script is presented in appendix D. A distance of 30 km is chosen as a limit of being ”close to shore”, and all AIS recordings that are within this limit is stored for further analysis. The computational time for this analysis is more than 12 hours, thus to make more accurate distance measurements by obtaining more coordinate points for the coastline would give a noticeable increase in computational time, without necessary achieving more accurate results.

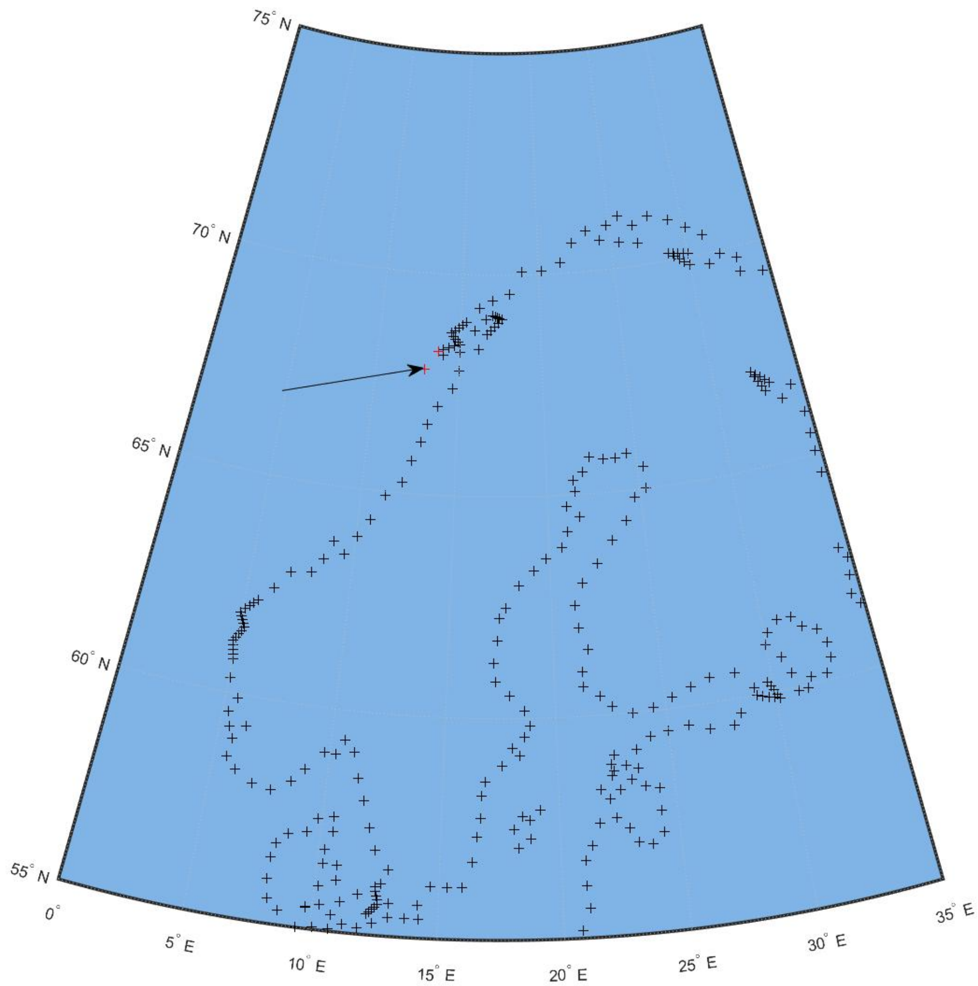


Figure 4.3: Map projection of the coordinates included in the mapping function in Matlab

The next step is to analyse the filtrated data to find AIS recordings when the vessel is virtually at a full stop. A Matlab script labels all AIS recordings that comply with the proximity to shore and has a speed below 0.5 knots as a port position. AIS messages that comply with these criteria are labelled ”port”. If the speed is above 0.5 knots, the AIS message is labelled ”Transit”.

4.3.3 Transit & Waiting

If the AIS recording did not comply with the conditions that are mentioned in chapter 4.3.1 and 4.3.2, it means that the vessel is neither close to shore or close to an installation. At this stage, the vessel is in open waters and is most likely in transit, but only if it has a noticeable speed. The Matlab script, which can be found in appendix D, searches through the remaining AIS data and labels all AIS transmissions with a speed above 1.0 knots as ”transit” mode. All remaining AIS transmissions with a speed below 1.0 knots are labelled as ”waiting” mode.

While the shuttle tanker is in transit or waiting mode it is either sailing to an installation in ballast loading condition or sailing to port in laden loading condition. In order to determine which of the two loading conditions the shuttle tanker is in at any time, the complete set of AIS data has to be analysed. The two operation modes that impact the loading condition are port and offloading. A Matlab script, which can be found in appendix D, reads through the complete set of AIS data. Whenever the operational mode is ”port” the loading condition is set as ”ballast”, while if it is ”Offloading operation” the loading condition is set as ”laden”. This ensures that all AIS messages being next after will be labelled as the current loading condition.

A problem that occurs for the method to determine the loading condition is the situation when the shuttle tanker sails out of Norwegian waters. There is no data for what the shuttle tankers have done during the missing time intervals. If the shuttle tanker leaves in laden condition and is absent from Norwegian waters for more than 48 hours, it is assumed to unload the oil at a terminal outside Norwegian waters. The first AIS transmission received after it left Norwegian water is therefore labelled as ballast loading condition. The following AIS messages are labelled ”ballast” until the shuttle tanker performs an offloading operation.

Chapter 5

Emission Reduction from Shuttle Tanker Operations

Shuttle tanker operations on the NCS contribute to emissions of VOC. VOC is evaporated oil consisting of hydrocarbons such as methane and propane. The oil evaporates mainly during loading and unloading of oil, but VOC can also evaporate during sailing. Reducing VOC emissions has environmental benefits and can potentially be utilised as fuel. Some of the VOC reacts with sunlight and creates ozone. Ozone is harmful to humans and the environment, and is linked to several health problems. Methane is a component of VOC which is a greenhouse gas that contributes to global warming. The global warming potential for methane is 21 times higher than CO_2. Due to the negative consequences of VOC emissions, measures to reduce the VOC emissions from shuttle tanker operations have been initiated. The VOC emissions do also represent a major energy loss. This chapter presents measures that can reduce the emissions of VOC and how it can be utilised as fuel.

5.1 Volatile Organic Compounds (VOC) Recovery and Utilization

Oil vapours are explosive. To maintain safe conditions, the storage tanks are filled with inert gas. The inert gas consists mainly of nitrogen (83%), CO_2 and oxygen (MAN, 1998). The level of oxygen must be kept below 8% to prevent formation of explosive gasses. As the storage tanks are filled with inert gas and VOC, the internal pressure increases. The pressure inside the storage tanks should be kept at about 1.1 bar. In order to keep the pressure at acceptable levels, the mixture of inert gas and VOC must be discharged. The fraction of hydrocarbon gasses in the discharged gas is expressed as ALFA, see equation 5.1. At the start of the loading process the hydrocarbon gas content is approximately 20%. As the storage tanks are filled the fraction rises to about 70% when the loading is complete. These numbers are for the Statfjord field, and other fields may have different characteristics (Melhus et al., 2002) (MAN, 1998). Figure 5.1 illustrates the change in relative VOC content in the discharged gas. The illustration is based on a similar figure from MAN (1998).

$$ALFA = \frac{\text{Hydrocarbon volume}}{\text{Total gas release volume}} \tag{5.1}$$

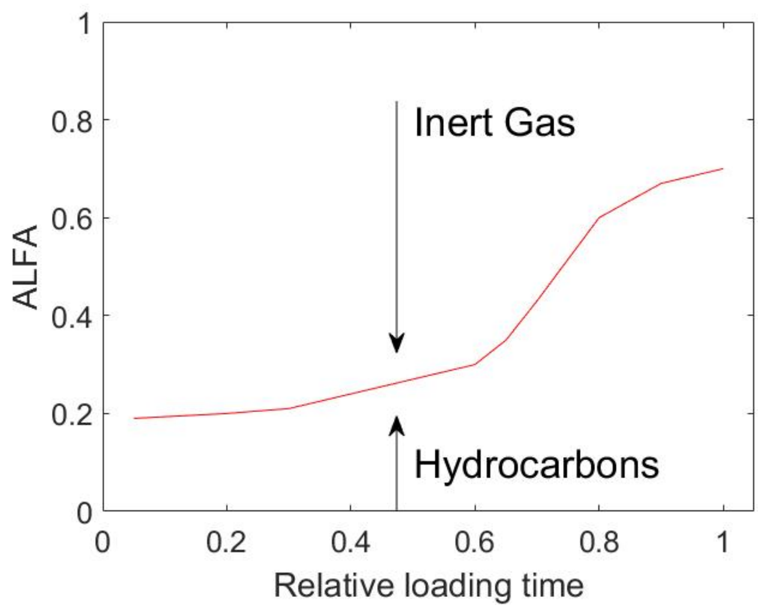


Figure 5.1: Fraction of VOC content in the discharged gas during loading

The released VOC represents a significant energy potential. For a round-trip from Mongstad to Gullfaks, measurements by Statoil show that the energy potential for the produced VOC is comparable to total fuel consumption for the round-trip (MAN, 1998). Utilising VOC as fuel has many benefits. The total emissions and fuel consumption is reduced. The reduction of fuel consumption reduces operating costs. Additionally, VOC is a cleaner fuel than Heavy Fuel Oil (HFO) (MAN, 1998).

5.1.1 Volatile Organic Compounds (VOC) Emission Reduction Technology

As VOC reduction has become a high priority for shuttle tanker operators, there have been several reduction methods developed the last 10-15 years. The earliest conventional VOC utilisation systems uses condensation to separate the heavier hydrocarbons from the VOC (MAN, 1998). Figure 5.2 illustrates the basic components of a VOC condensation system. When the VOC gas is released from the storage tanks it is compressed, dried and cooled. The liquefied hydrocarbons are then sent to a storage tank. In the earlier condensation systems, the light hydrocarbons (methane and ethane) are discharged to the atmosphere (MAN, 1998). The VOC may contain CO_2 and water. In order to remove the water, the VOC gas must be dehydrated below freezing point (Oldervik et al., 2001). The CO_2 must be removed for using cooling temperatures below -80° C (Oldervik et al., 2001).

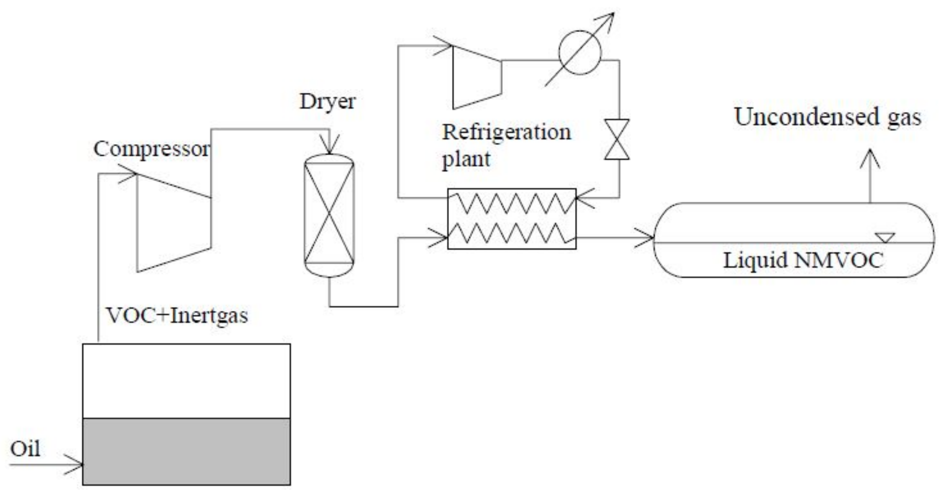


Figure 5.2: Volatile Organic Compounds (VOC) condensation system (Oldervik et al., 2001).

Today, there are several possible VOC reducing measures. Hansen et al. (2010) presents three methods that are simpler and less costly than a condensation system:

Increasing cargo tank pressure

Increasing the pressure inside the crude oil storage tanks has a beneficial impact on VOC emissions. A pressure increase by 0.5-0.6 bar can reduce emissions by the magnitude of 50-78% (Hansen et al., 2010). Increased pressure in the tanks require reinforcement of the tanks. Although the strengthening of the cargo tanks leads to an increase in steel weight, the overall increase is limited (Hansen et al., 2010).

Absorber

The absorption system is in use during transit in laden condition. The system pumps oil through an absorber where the emitted VOC is mixed with crude oil and pumps it back to the bottom of the cargo tanks. The hydrostatic pressure causes the VOC to be absorbed in to the oil. The remaining inert gas continues to rise through the oil and to the surface. The absorption system is independent from other VOC reducing systems and is only in use when the storage tanks are full during transit.

KVOC

The KVOC system is developed by Knutsen OAS Shipping AS, and is installed on several of the shuttle tankers operating on the NCS (IPIECA, 2013). The concept is a drop line with an increased diameter compared to conventional drop lines. The increased diameter reduces the under-pressure that occurs in the drop line. By reducing the under-pressure, there is less VOC released from the oil (Hansen et al., 2010) . The increase in diameter also enables gas to flow up the column of the drop line, rather than flowing into the storage tanks (Knutsen OAS Shipping, 2017).

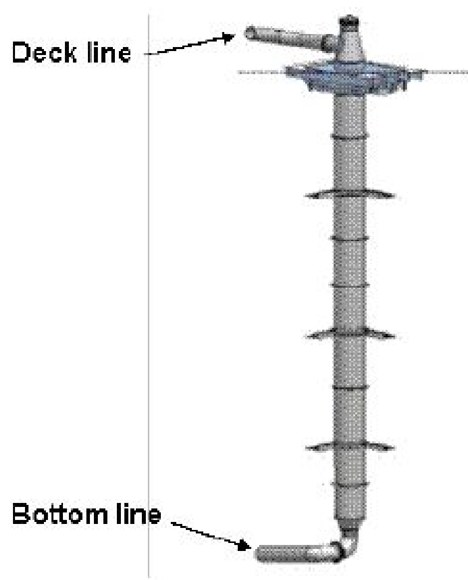


Figure 5.3: KVOC drop line system for Volatile Organic Compounds (VOC) reduction (Hansen et al., 2010)

The KVOC system and increasing tank pressure are passive methods and have a small power requirement. Together with the absorption system, the three systems are able to reduce VOC emissions by 60-70% (Hansen et al., 2010). Although the methods are effective, there are still a remaining part of the VOC that is emitted to the atmosphere.

5.1.2 Methane Recovery

Recovery of the lightest hydrocarbons from the VOC is the most challenging aspect of VOC recovery. Methane and ethane, which are the main components of Liquefied Natural Gas (LNG) requires a temperature of -162°C to be liquefied. Liquefaction and storage of the gas requires much energy, and the potential benefit of recovering and storing the components might be limited.

An alternative method to venting the light components into the atmosphere is to feed the gas directly to a power generating module (Wärtsillä, 2015). By utilising the methane and ethane part of the VOC after the heavier components are liquefied, close to 100% of the VOC is recovered. The power that is generated from the light components can be used to power the systems that require electric power during the offloading operation. As batteries are becoming more relevant in ship designs, there might be a potential for installing batteries and recharge them with the electric power generated.

5.2 Effect of Implementing Volatile Organic Compounds (VOC) Utilisation

The composition of the VOC varies between the different oilfields. The fraction of light components may vary from only a small amount to over 50% of the total VOC. The VOC content does also vary with the age of the oilfield (MAN, 1998). In this thesis the VOC characteristics of the Statfjord oilfield presented by MAN (1998) is used. The VOC content emitted from the oil during loading vary, but can be as high as 2.8 kg per tonne of loaded oil (in harsh conditions) (Wärtsillä, 2015). In order to find an estimate for average VOC emissions, the study by Martens et al. (2001) is used. The study presents a simulation of VOC emissions when loading oil at the Statfjord field. The simulation case has the following underlying conditions:

- Oil loading rate: 2.2 m^3/s

- Loading time: 17.4 hours
- Total non methane VOC: 192,823 kg (Inert gas not included)

Given a constant loading rate and an assumed oil density of 860 kg/m^3, the total amount of loaded oil is estimated to be:

$$17.4\,[h] * 2.2\,[m^3/s] * 0.860\,[tonne/m^3] * 3600\,[s/h] = 118,500\,[tonne]$$

Around the time this study was conducted (2001), the VOC composition from the oil produced at Statfjord consisted of approximately 95% non methane VOC (MAN, 1998). With this taken into account, the total amount of VOC emitted is approximately 203 tonnes. . The average rate of VOC emitted is then estimated to be:

$$\frac{203,000\,[\text{kg VOC}]}{118,500\,[\text{tonne oil}]} = 1.71\,[\text{kg VOC/tonne oil}]$$

The specific energy of the VOC depends on the composition. The VOC composition from the Statfjord field is presented in table 5.1 (MAN, 1998) (Melhus et al., 2002). The average specific energy for the emitted VOC is approximately 46 MJ/kg. In comparison, the specific energy is 42.9 MJ/kg for HFO and 45,7 for Marine Diesel Oil (MDO) (Wattum and Erikstad, 2012).

Table 5.1: Composition of the Volatile Organic Compounds (VOC) emitted from the Statfjord Oilfield (Melhus et al., 2002)

Component	**Fraction [%]**	**Specific energy [MJ/kg]**
Methane	6	50
Ethane	16	48
Propane	37	47.2
i-Butane	6	46.9
n-Butane	18	47.7
i-Pentane	4	38.8
n-Pentane	5	40.4
Higher alkanes	8	36.4

The carbon content of a fuel composition is independent from engine type (Smith et al., 2015). It is determined by the carbon content of the hydrocarbons that constitute the fuel. The carbon content of HFO, MDO and LNG is presented in table 5.2

Table 5.2: CO_2 content in common fuel compositions (Smith et al., 2015)

Fuel type	**CO_2 content [tonne/tonne fuel]**
HFO	3.114
MDO	3.206
LNG	2.750

Chapter 6

Results

6.1 Heuristic AIS Analysis Results

The first part of the analysis was to determine the proportion of time the shuttle tankers were in the different operational modes. Concerning the general modes offloading operation, transit, port and waiting, the majority of the operational time for the vessels was in transit mode, with an average of 59%. The results for all four vessels analysed are presented in table 6.1.

Table 6.1: Operational profile from the heuristic method

Vessel	**Offloading Operation** [%]	**Transit** [%]		**Waiting** [%]	**Port** [%]
		Ballast	**Laden**		
Shuttle tanker 1	16.92	46.65	26.07	2.76	7.60
Shuttle tanker 2	17.47	40.17	18.84	11.05	12.46
Shuttle tanker 3	24.73	34.23	22.01	6.20	12.82
Shuttle tanker 4	15.87	23.64	28.08	12.05	20.36
Average	18.75	36.17	23.75	8.02	13.31

The total time of operational data for each shuttle tanker is approximately 4496, 3427, 4087 and 6509 hours, respectively. In table 6.2 to 6.5, the fuel consumption and CO_2 emissions are presented. Each table presents both the total fuel consumption and CO_2 emissions and the rate of consumption and emissions for each operational mode. The average rate of CO_2 emissions are presented in table 6.6.

Table 6.2: Fuel consumption and CO_2 emissions for shuttle tanker 1

Operational Mode	**Fuel Consumption**		**CO_2 Emissions**	
	Total [tonnes]	**Consumption rate [tonnes/h]**	**Total [tonnes]**	**Emission rate [tonnes/h]**
Offloading Operation	779	1.025	2,473	3.251
Transit Laden	2,693	1.284	8,596	4.098
Transit Ballast	2,217	1.891	7,081	6.042
Waiting	54	0.436	172	1.384
Port	355	1.041	1,128	3.303

Table 6.3: Fuel consumption and CO_2 emissions for shuttle tanker 2

Operational Mode	**Fuel Consumption**		**CO_2 Emissions**	
	Total [tonnes]	**Consumption rate [tonnes/h]**	**Total [tonnes]**	**Emission rate [tonnes/h]**
Offloading Operation	609	1.017	1,932	3.27
Transit Laden	2,468	1.793	7,883	5.726
Transit Ballast	1,318	2.041	4,211	6.521
Waiting	289	0.764	918	2.425
Port	446	1.041	1,411	3.304

Table 6.4: Fuel consumption and CO_2 emissions for shuttle tanker 3

Operational Mode	**Fuel Consumption**		**CO_2 Emissions**	
	Total [tonnes]	**Consumption rate [tonnes/h]**	**Total [tonnes]**	**Emission rate [tonnes/h]**
Offloading Operation	341	0.337	1,083	1.071
Transit Laden	1,390	0.993	4,444	3.176
Transit Ballast	1,372	1.526	4.388	4.879
Waiting	41	0.162	130	0.514
Port	179	0.342	569	1.086

Table 6.5: Fuel consumption and CO_2 emissions for shuttle tanker 4

Operational Mode	**Fuel Consumption**		**CO_2 Emissions**	
	Total [tonnes]	**Consumption rate [tonnes/h]**	**Total [tonnes]**	**Emission rate [tonnes/h]**
Offloading Operation	1,142	1.105	3,623	3.503
Transit Laden	2,067	1.344	6,597	4.288
Transit Ballast	2,346	1.282	7,478	4.092
Waiting	412	0.525	1,308	1.667
Port	1,538	1.160	4,879	3.681

Table 6.6: Average rate of CO_2 emissions

Vessel	**Offloading operation**	**Transit Laden**	**Transit Ballast**	**Waiting**	**Port**	**Average**
	[tonne CO_2/tonne fuel]					
Shuttle tanker 1	3.172	3.192	3.195	3.174	3.173	3.181
Shuttle tanker 2	3.215	3.194	3.195	3.174	3.174	3.190
Shuttle tanker 3	2.895	3.199	3.197	3.173	3.175	3.128
Shuttle tanker 4	3.170	3.190	3.191	3.175	3.175	3.180

6.2 Case - 23 Days of Operation

The amount of data is too large to analyse all the data in detail for all four vessels. In order to acquire a more detailed assessment of the results, the operations during a specific time period for one vessel are analysed. The vessel chosen for this assessment is shuttle tanker 4, since it is the only one that has data for a longer time period without any interruptions or significant amounts of missing data. The time period consists of approximately 540 hours, or close to 23 days. The period is chosen because of few and short intervals of missing AIS data. The longest time period between the AIS messages for this specific time period is approximately 7 hours. The majority of the time intervals between the AIS transmissions for the 23 days was 6 minutes.

6.2.1 Assessment of Each Day of Operation

In order to assess the operation of the shuttle tanker for the time period chosen, the AIS data is analysed in detail for each day. The following chapter presents the sailing pattern and operations for the shuttle tanker. The results from this assessment is used to create a new operational profile for the shuttle tanker.

Day 1

The first AIS message on the first day is received at 00:03:29. The location of the signal is 59.3265N 10.5153E, which corresponds to the terminal at Slagentangen in the Oslofjord. Figure 6.1 illustrates the exact location of the coordinates. The figure is created using Google maps.

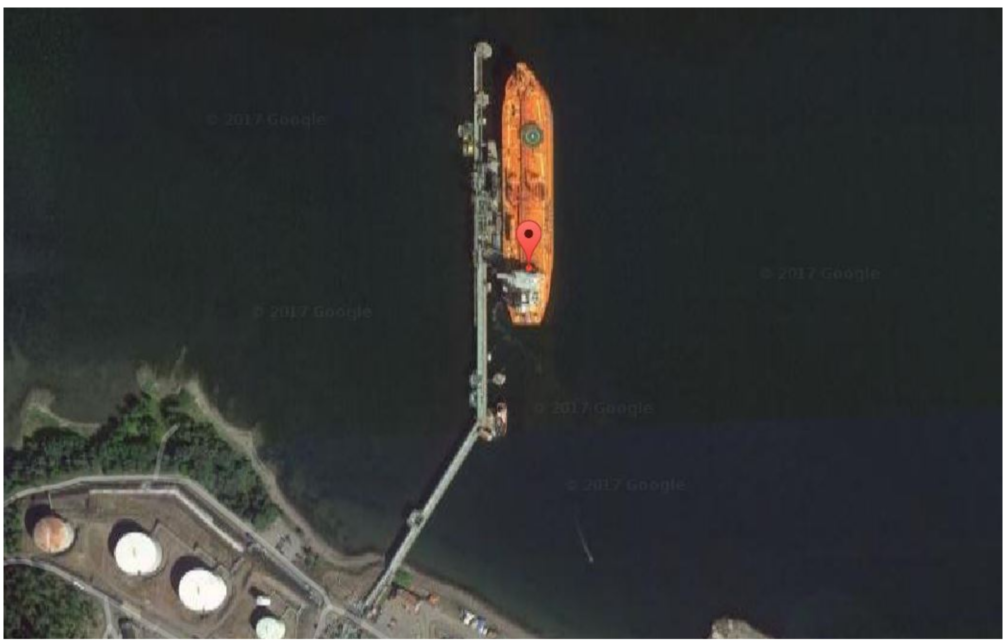


Figure 6.1: Initial position of the shuttle tanker on day 1

This position is maintained until the shuttle tanker departs at 13:22. The remaining part of the day it sails along the coast of southern Norway with an average speed of 9.8 knots. As the shuttle tanker departed from an oil terminal, it is reason to assume that the shuttle tanker has empty cargo tanks and is in ballast mode.

Day 2

The first AIS transmission received next day is at 03:23. During the next 24 hours the shuttle tanker remains in transit with an average speed of 8.8 knots.

Day 3

At 03:52 on the third day, 38 hours since it departed from Slagentangen, the shuttle tanker reaches within a 1.5 km radius of the Balder FPSO. Since it departed from Slagentangen, it has sailed a distance of 50.66 nautical miles with an average speed of 8.8 knots, see figure 6.2.

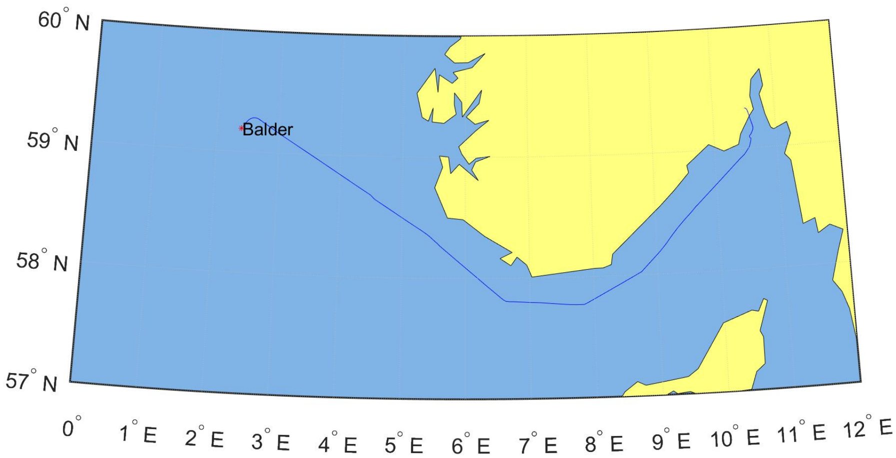


Figure 6.2: Route sailed between day 1 and day 3

The shuttle tanker remains in the 1.5 km zone of the installation for approximately 13 hours. During this time period, the shuttle goes through the operational phases that are described in chapter 2.3.1. Figure 6.3 presents the position of the vessel for the time it is within the 1.5 km zone. It can be seen in the figure that the shuttle tanker maintains a certain distance from the installation and a safe angle to the hawser connection point.

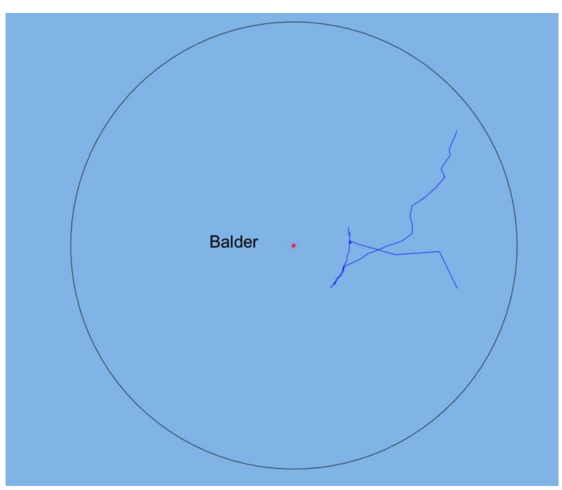


Figure 6.3: Shuttle tanker positions within 1.5 km of the Balder intstallation

The speed and distance to the installation provides information about which procedure that is ongoing. Figure 6.4 presents the distance to the installation and the speed of the shuttle tanker during the time period the shuttle tanker is within the 1.5 km zone. For the first two hours the shuttle tanker approaches the installation at a low speed. At about 1.1 km and 0.8 km from the installation, the shuttle tanker stops for a short period before it continues the approach. After about 2.3 hours, the distance stops to decrease at a distance from the installation of approximately 380 m. At the same time the speed of the shuttle tanker drops to an almost full stop. The distance and the low speed is maintained for 10.3 hours before the speed and distance rapidly increases and the shuttle tanker departs.

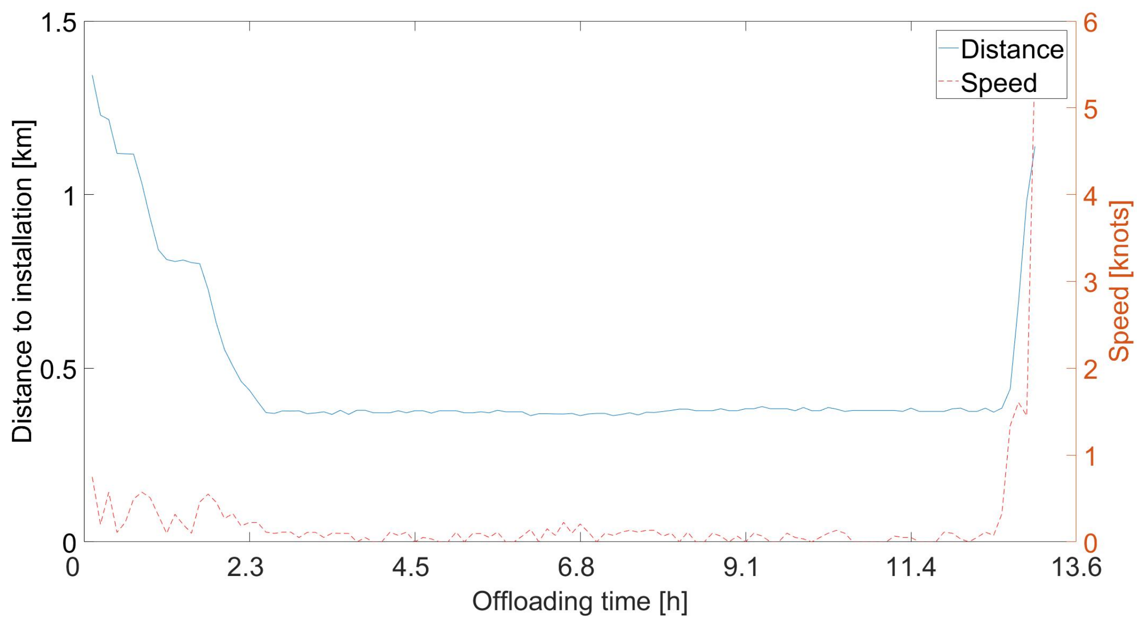


Figure 6.4: Shuttle tanker speed and distance to the installation during offloading on day 3

The shuttle tanker leaves the 1.5 km zone at 16:55. The remaining time of the day it sails in an eastern direction with an average speed of 2.4 knots.

Day 4 - 7

The next two days, day 4 and 5, the shuttle tanker sails in an eastern direction with a speed below 1 knots. On day 6, it continues on this course and speed for 12 hours, until it turns around 180° at 14:17, and heads towards the Balder installation, which it departed from three days ago. The remaining day the shuttle tanker maintains the same course with an average speed of 2.9 knots. At day 7, the shuttle tanker continues towards the Balder installation at an average speed of 4.7 knots, and at 03:41 it reaches within 1.5 km of the installation. The route of the shuttle tanker for the days described is presented in figure 6.5. The numbers along the path of the vessel indicates the last AIS message received at that day.

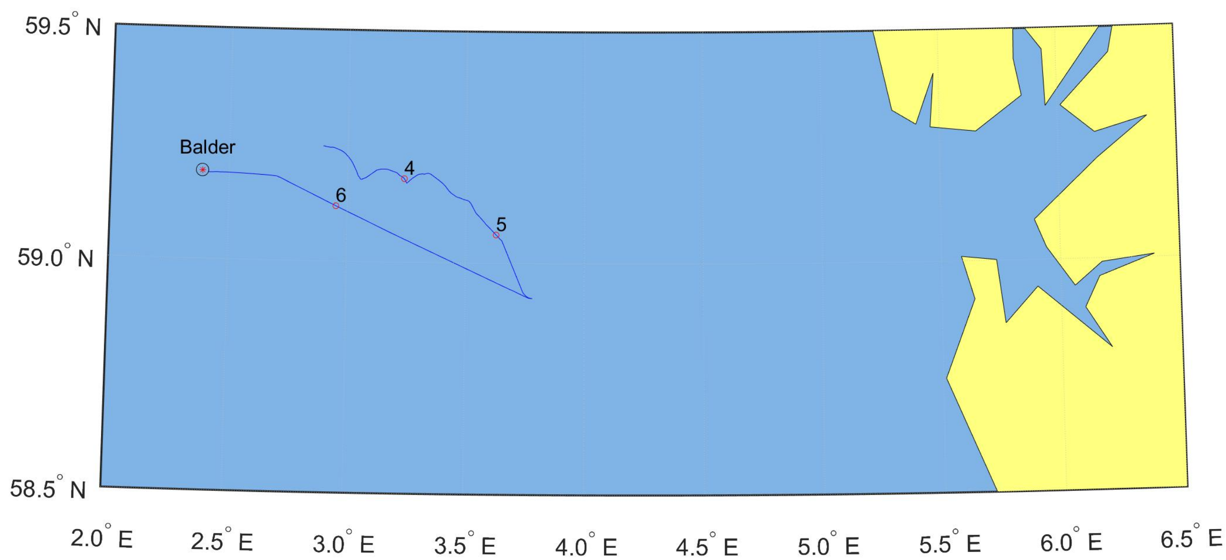


Figure 6.5: Route sailed by the shuttle tanker for day 4, 5, 6 and 7.

The shuttle tanker is located within the 1.5 km zone for about 13 hours while it performs offloading operations. The first 2.4 hours, the shuttle tanker is approaching and connecting before it loads oil for 10.4 hours. After 12.8 hours it disconnects and departs from the installation. A plot of distance and speed during the offloading operation can be found in appendix B. After the offloading operation the shuttle tanker sails in an eastern course with an average speed of 6.1 knots.

Day 8

The next day the shuttle tanker continues in the same direction for approximately 10 hours, before it turns around and sails back in the direction of the Balder installation. The last received AIS message is at 17:51. No AIS messages are received before the next day. The average sailing speed for Day 8 is 4.2 knots.

Day 9-10

An AIS message is received at 01:00 the following day. The shuttle tanker remains in the same course and speed as the previous day, until it reaches the 1.5 km zone of Balder after roughly 10 hours. The shuttle tanker remains at this installation the next 20 hours. Figure 6.6 presents the distance from the installation and speed of the shuttle tanker during that time. The distance at where the shuttle tanker most probably is offloading oil, is not reached before eight hours after the shuttle tanker reached the 1.5 km zone.

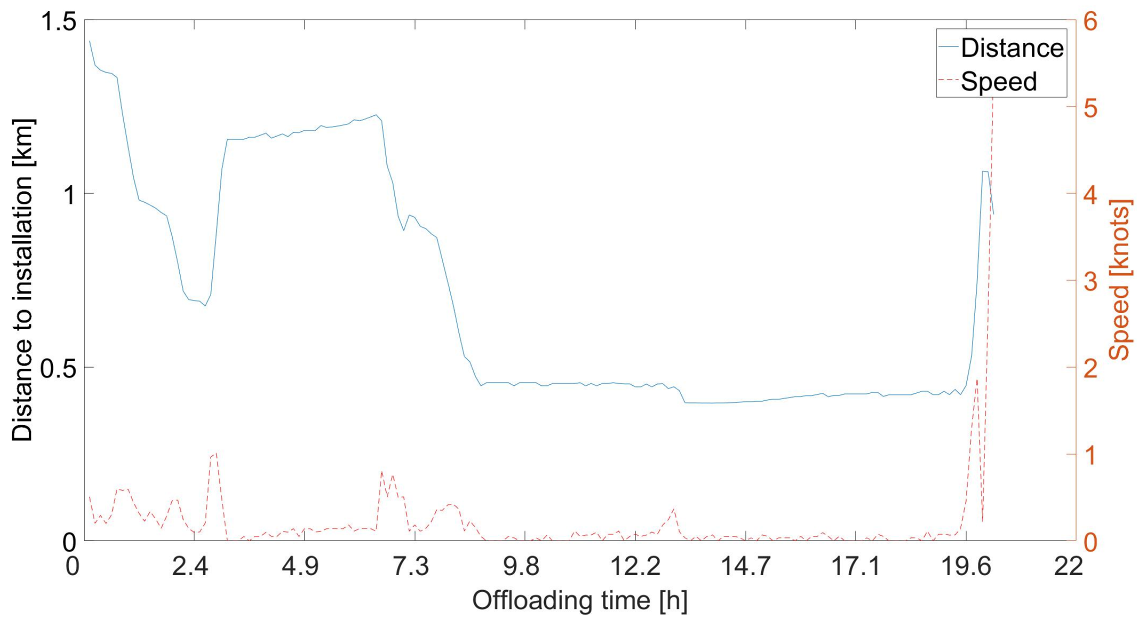


Figure 6.6: Shuttle tanker speed and distance to the installation during offloading on day 9 and 10

When the offloading operation is completed the next day it departs from the installation at 06:30. The remaining day the shuttle tanker sails in a south-eastern direction at an average speed of 11.9 knots.

Day 11-12

The shuttle tanker continues on the same course, before it enters the Oslofjord, and reaches the terminal at Slagentangen at 12:15. It remains at this location until 16:20 the next day, when it departs and heads for the North Sea. During the seven and half hours it sails it has an average speed of 12 knots.

Day 13-14

The course of the shuttle tanker continues along the southern coast of Norway and heads for the North Sea. The shuttle tanker is in transit the whole day covering approximately 173 nautical miles, which entails an average speed of 7.2 knots. The next day it continues towards the Balder installation. The last AIS message is received at 22:24 from a location approximately 12 km from the Balder installation.

Day 15

The shuttle tanker reaches the 1.5 km zone of the installation a few minutes after midnight. It remains within the 1.5 km zone for about 15 hours. A plot of the distance and speed of the shuttle tanker can be found in appendix B. The first 1.7 hours the shuttle tanker approaches and connects. The loading of oil takes approximately 13.2 hours. At 15:30 the shuttle tanker leaves the 1.5 km zone, and sails first westwards, before it turns and continues straight north. The last AIS message is received at 22:25. Since the shuttle tanker departed from Balder it has sailed 25 nautical miles with an average speed of 3 knots.

Day 16

At 03:59, the shuttle tanker reaches the 1.5 km zone of the Jotun Installation. The previous four hours the shuttle tanker has sailed 12.7 nautical miles which implies an average speed of 3.2 knots. The next 10.5 hours, the shuttle tanker performs offloading operations. The first 1.9 hours it approaches the installation at a slow speed before connecting and the offloading begins. The loading of oil takes approximately 8.2 hours. At 14:29, the shuttle tanker sails out from the 1.5 km zone and continues sailing in a south-eastern direction with an average speed of 6.3 knots.

Day 17-20

The first seven hours of the day, the shuttle tanker sails in a south-eastern direction. At 07:21 it stops at a position approximately 8.5 km from shore and 15 km from Stavanger. During the first 7 hours the shuttle tanker had an average speed of 5.7 knots. The rest of the day it maintains the same position close to shore. The shuttle tanker remains in this position for almost three whole days. At 04:38 on day 20, the shuttle tanker departs from the location, 60 hours since it arrived on day 17. The remaining time of the day the shuttle tanker sails in a north-western direction towards the Balder installation with an average speed of 5.2 knots

Day 21-23

The shuttle tanker continues to approach the Balder installation, and at 16:13 on day 21 it reaches the 1.5 km zone of the installation. On the way to the installation the shuttle tanker takes a few detours before it finally approaches the installation. For the first 16 hours of day 21, the shuttle tanker has an average speed of 1.7 knots. The duration of the offloading operation is approximately 17.6 hours. The first two hours the shuttle tanker approaches the installation and connects. The duration of the oil offloading is approximately 15 hours. At 07:00 on Day 22, the shuttle tanker sails out of the 1.5 zone of the Balder installation. 28.5 hours later, 11:30 the next day, the shuttle tanker arrives at the terminal at Slagentangen. The shuttle tanker had an average speed of 11.9 knots for the voyage from Balder to Slagentangen.

6.2.2 Summary of Case Results

In the time period analysed, there is one part that points out to be wrongly assessed by the heuristic method. This is the part from Day 17 to day 20 where the shuttle tanker remains at the same location for approximately 70 hours. The shuttle tanker is regarded as being in port for the entire period of 70 hours. This is wrong, as it can clearly be seen on a plot of the position that it is in open waters, manoeuvring at slow speeds, ref appendix C. By applying the correct categorisation for the discovered error, a more accurate operational profile can be determined for the specific period analysed. In table 6.7, a comparison between the operational profile determined by the heuristic method and by the detail analysis is presented.

Table 6.7: Comparison of results from heuristic method and detail analysis

Analysis	**Offloading Operation** [%]	**Transit** [%]		**Waiting** [%]	**Port** [%]
		Ballast	**Laden**		
Heuristic (23 days)	15.85	19.61	25.94	16.11	22.49
Heuristic (271 days)	15.87	23.64	28.08	12.05	20.36
Detailed (23 days)	15.85	19.61	25.94	28.86	9.74

A second issue that is discovered in the detailed assessment is the determination of the phases in the offloading operation. In figure 6.4 and figure 6.6 it can be seen that when the shuttle tanker approaches it rarely reaches a speed above 0.6 knots. This causes the heuristic method to determine the approach as offloading although the shuttle tanker is manoeuvring. In figure 6.6 it can be seen that the shuttle tanker stops approaching and backs away before it stops and keeps this position for about three hours. The actual offloading does not start until eight hours after it reached within 1.5 km from the installation.

Based on this discovery the offloading operations for the case are analysed in detail. Table 6.8 presents the distribution af operations for the six times the shuttle tanker arrived at an installation and offloaded oil.

Table 6.8: Distribution of the different phases of Offloading operations

Installation	**Duration [h]**				
	Total	**Approach**	**Waiting [h]**	**Loading**	**Departure**
Balder	13.06	2.13	0	10.38	0.55
Balder	13.37	2.33	0	10.41	0.63
Balder	20.18	4.02	3.26	12.29	0.61
Balder	15.42	1.62	0	13.22	0.58
Jotun	10.49	2.44	0	7.44	0.61
Balder	17.64	2.12	0	14.91	0.61

6.3 Utilisation of Volatile Organic Compounds (VOC) Emissions

The storage capacity of the shuttle tankers is unknown, but by knowing the DWT of the vessel it is possible to assume a storage capacity. An assumption is made that the storage capacity corresponds to 85% of the DWT of the vessels. The storage capacities of the vessels are presented in table 6.9. In chapter 5.2 it was estimated that the Statfjord oilfield has an average rate of VOC emission of 1.7 kg VOC per tonne offloaded oil. The amount of recovered VOC, assuming a 100% recovery rate is presented in table 6.9. The specific energy density of fuel compositions is presented in chapter 5.2. Assuming that HFO is the fuel used by the shuttle tankers there is a potential of saving 1.07 tonnes of HFO per tonne of recovered VOC. MDO and VOC have approximately the same energy density.

Table 6.9: Fuel reduction by recovering Volatile Organic Compounds (VOC) and utilising it as fuel

Vessel	85% of DWT		Produced VOC	Potential Fuel saved	
				HFO	MDO
	[tonnes]	[m^3]	[tonnes]	[tonnes]	[tonnes]
Shuttle tanker 1	90,100	104,750	153.2	163.9	153.2
Shuttle tanker 2	90,100	104,750	153.2	163.9	153.2
Shuttle tanker 3	127,500	148,250	216.7	231.9	216.7
Shuttle tanker 4	94,889	110,300	161.3	172.6	161.3

The potential for fuel saving is based on 100% VOC emissions, without any VOC reducing measures. With a KVOC system, increased storage tank pressure and absorption the VOC emissions can be reduced with as much as 70%. Most shuttle tankers operating on the NCS have probably installed VOC reducing technology. Given that the shuttle tankers reduce the VOC emissions with 70%, the fuel saved is reduced with the same factor.

The results presented in table 6.8 show that for the specific offloading operations, the loading phase constitutes approximately 77% of the time the shuttle tanker is within the 1.5 km zone of an installation. The average duration the shuttle tankers are within the 1.5 km zone of an installation is 25.2, 25.5, 24.3 and 14.63 hours, respectively. Assuming that 77% of the offloading operation time is actual offloading, the average loading time is 19.4, 19.6, 18,7 and 11.2 hours.

The VOC that is used as an example in the analysis has a low methane concentration. Therefore, most of the components are less uncomplicated to liquefy and store. Since the ratio of hydrocarbons in the VOC increases as the storage tanks fill up, it is assumed that the liquefied VOC is utilised during transit in laden condition, after it has finished offloading. The average fuel consumption for the shuttle tankers is presented in table 6.2 to 6.5. In laden condition they have an average fuel consumption of 1.284, 1.793, 0.993 and 1.344 tonnes/h, respectively. The rate of CO_2 emitted per tonne of fuel is presented in table 6.6. The emission rates for the transit modes resemble the theoretical CO_2 emission rate for MDO. Assuming that the shuttle tankers use MDO as fuel, have a 70% VOC emission reduction and recover 100% of the emitted VOC, the recovered VOC would correspond to fuel for 38, 27, 70 and 38 hours of transit in laden condition.

Chapter 7

Discussion

AIS data Analysis
The results show that a heuristic analysis is a good method of analysing shuttle tanker operations to create operational profiles. The detailed analysis show some important deviations from the heuristic analysis, but overall the results seem confident.

The resemblance of the average operational profile obtained from the heuristic analysis to the operational profile presented by MAN (1998) (table 2.3) is of interest. The calculated average proportion of time in transit is 59.92%, which is remarkably close to the 60% presented by MAN (1998). Moreover, the offloading operation is within the same proportion as the proposed operational profile presented by MAN (1998). Although there is a variance between the individual operational profiles, it is an interesting result. It shows that the heuristic approach to a certain extent is precise, and that the criteria implemented in the algorithm are applicable.

The specific operational profile for each vessel shows a noticeable variance between the vessels. There are several aspects that can influence the operational profiles. First, the amount of missing data will have an impact on the analysis results. The proportion of time in different operational modes is not measured when the shuttle tankers leave Norwegian waters. Most likely the shuttle tanker is either in transit or unloading in a port. The relative time in port is noticeable higher for shuttle tanker 3. Shuttle tanker 3 has the smallest amount of missing data. This could mean that the three other shuttle tankers more often sail out of Norwegian waters to unload the oil, and consequently not recorded in the present data. Taking this into account, the operational profile for shuttle tanker 3 might give the most accurate representation of shuttle tanker operations on the NCS.

In the detailed analysis, one noticeable error for the heuristic approach was observed. The heuristic analysis will characterise shuttle tankers with a low speed close to shore as being in port. In the detailed analysis is was discovered that this had a significant impact on the operational profile for the time period that is analysed. The issue is corrected by changing the operational mode for this time period from ”port” to ”waiting”. By changing the characterisation of the AIS messages, the proportion of time in port is halved and the proportion of time in waiting is consequently doubled, see table 6.7.

VOC reduction and Utilisation

The carbon content of MDO is 3,206 kg CO_2 per tonne MDO. The average CO_2 emission for the shuttle tankers analysed is 3,169 kg per tonne fuel, hence the assumption that the shuttle tankers are using MDO as fuel is reasonable. It is worth noting that the rate of CO_2 emission drops from 3.17-3.19 CO_2 per tonne fuel to 2.9 CO_2 per tonne fuel. Compared to the theoretical CO_2 content per tonne fuel, this looks like a switch from MDO to LNG. This could imply that the shuttle tanker utilises the lighter components from the emitted VOC directly to auxiliary engines that provide electric power to the DP system. The lighter components of VOC consists mainly of methane which is the main component of LNG.

It should be remarked that the rate of fuel consumption and CO_2 emissions for shuttle tanker 3 is significantly less than for the other three vessels. This is contradictory to the fact that it is the largest vessel. It is not known why these results are obtained. The analysis did not detect any clear evidence that could describe this irregularity. Assuming that the results presented in table 6.4 are not correct, the potential profit of VOC reduction will be different from the estimation presented in chapter 6.3.

The results in chapter 6.3 presents the amount of transit hours the recovered VOC represent. The estimation relies on the assumption that the energy conversion efficiency for the engine system using MDO and the system utilising VOC are the same. It is also assumed that the recovery rate is 100%. In reality, a 100% recovery rate might be difficult to achieve. The energy needed to recover and store VOC is not assessed in the analysis. The analysis only assess the potential fuel savings for replacing bunker fuel with VOC. Due to this fact, the fuel saving potential will not be as high as the results show.

The VOC composition used in the analysis is based on the VOC composition of the Statfjord oilfield. The methane constitutes a small part of the composition. At other oilfields the proportion of methane might be much higher.

Quality of the Analysis

The data analysed in this thesis is AIS data from shuttle tankers in Norwegian waters over a period on one year. The data contains 33 individual MMSI numbers. It is not known if all the shuttle tankers located in Norwegian waters in 2016 are included in the data. There might have been shuttle tankers that were categorized as regular crude oil tankers or other vessel types, and therefore were not included in the data received. This does not have any impact on the analysis, as the data had to be limited in order to obtain an accurate analysis of the AIS data.

Some of the data do not have any valid information for emissions, speed and distance. It is assumed that these AIS messages holds the same emission rate, fuel consumption and speed as the previous AIS signal received. Based on the AIS data that is available, the probability of a sudden change in these parameters is extremely low. The amount of estimated data constitutes somewhere between 0.1% and 0.6% of the total amount of data for the four analysed vessels. Even if the assumed values for the parameters are wrong, it will not give any major impact on the results.

Obtaining AIS data for areas outside Norwegian waters would increase the quality of the analysis and certainty of the results, but the computational time would increase. The computational time of the heuristic analysis algorithm has been a challenge. The choice of limiting the analysis to four vessels was mainly based on this aspect. There might be potential improvements for the algorithm that can reduce the computational time. Since algorithm improvements was not within the scope of this thesis, improving the efficiency of the algorithm was a low priority during the work on this thesis.

Chapter 8

Conclusion

The overall aim of this thesis has been to determine how shuttle tanker operate by analysing AIS data and creating operational profiles based on the analysis. The operational profiles have been used as a groundwork for determining the effect of VOC recovery and utilisation.

AIS data for shuttle tankers operating in Norwegian waters was obtained from the NCA. First, a heuristic analysis of the AIS data was created. The heuristic analysis shows that it is possible to obtain an adequate representation of shuttle tanker operations based on a few criteria for for the operational modes. The operational profiles for the analysed shuttle tankers show that there is a certain variance between the vessels, but the average results show a close resemblance to the expected outcome.

In order to evaluate the results from the heuristic analysis, a limited time period for one shuttle tanker was analysed. Approximately 23 days were analysed and the results show that the heuristic method has noticeable flaws in the algorithm. The issue is that the algorithm characterises the shuttle tanker as being in port, when it is actually at a full stop close to shore. For the specific time period analysed in detail, this had a significant impact on the operational profile.

Estimations show that there is a great potential for VOC utilisation for the shuttle tankers. An optimistic estimate, assuming a 100% VOC recovery rate, shows that the recovered VOC has a potential energy output comparable to the energy needed for 27 to 70 hours of transit.

The analyses conducted in this thesis show that AIS data provide significant value to analyse ship operations and creating operational profiles. Although the AIS data was limited both geographically and for a certain vessel type, it constitutes vast amounts of data. A heuristic analysis is a suitable approach for analysing such large amounts of data.

8.1 Further Work

A clear weakness of the analysis is the amount of missing AIS data. For further work on this topic, the analysis should be conducted for global AIS data, or at least for an area covering most of northern Europe. Furthermore, more shuttle tankers should be included for the heuristic analysis. The choice of only including four vessels was based on the computational time of the algorithms. Potential efficiency improvements for the algorithm could enable an increase in data analysed without increasing the computational time.

The fuel consumption and CO_2 emissions are estimations included in the data. The quality and accuracy of these estimations are uncertain. A quality assurance analysis of these parameters would provide additional confidence of the analysis.

The coverage of AIS is rapidly improving and new and improved AIS data will be available the years to come. It will be interesting to perform the same analyses in a few years time, when the AISSAT-3 satellite has been in use and provided additional and improved coverage of AIS signals.

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Appendix A

Project description

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

Master THESIS IN MARINE TECHNOLOGY

Spring 2017

Stud.techn. Håvard Langdalen

Analysing Emission Reducing Measures for Shuttle Tankers Based on Autonomous Identification System Data

Background

Shuttle tankers transporting oil from installations on the Norwegian Continental Shelf are responsible for a large amount of the volatile organic compounds (VOC) emissions in Norwegian waters. Emission reducing measures are requested by the industry and society. Recovery of VOC and utilization as fuel has the potential to reduce the carbon footprint and environmentally harmful emissions.

In order to assess the effect of introducing VOC reducing measures, operational profiles for the shuttle tankers have to be determined. Automatic Identification System (AIS) data provides important information about operational data, such as position, speed, and heading. All ships with a certain size are required to transmit AIS signals. AIS messages, which are detected by land stations and satellites, provide significant information that can contribute to an understanding of shuttle tanker operations and the creation of an operational profile.

Objective

The main objective of this thesis is to identify the possibility of analysing large scale AIS data to create operational profiles for shuttle tankers. The Operational profiles will be used as a framework for assessing the effect of VOC recovery and utilisation.

Scope of Work

The candidate shall/is recommended to cover the following tasks in the project thesis:

1. Review and document previous work and publications on related topics, and present an introduction to shuttle tanker operations and AIS.

2. Categorize and evaluate AIS data for shuttle tanker traffic in Norwegian waters. The AIS data analysis will consist of two stages. First, a heuristic approach will be created for analysing extensive amounts of data. Secondly, a limited time period for a specific number of ships will be analysed in detail in order to evaluate the quality and precision of the heuristic approach.

3. Analyse the effects of VOC recovery on shuttle tankers based on the findings from the AIS analysis.

4. Discuss the results and the methods that are used in the thesis, and reach a conclusion and a recommendation for further work.

Supervisor:
Bjørn Egil Asbjørnslett

Deadline: 31.07.2017

Appendix B

Offloading Operation Plots

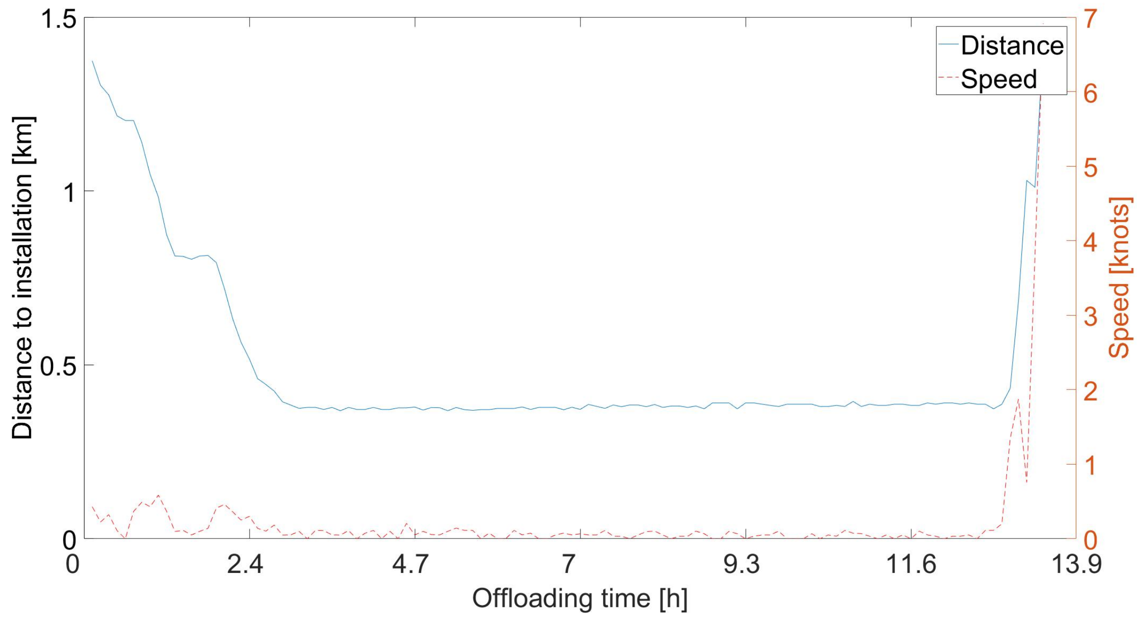


Figure B.1: Offloading Operation - Day 7

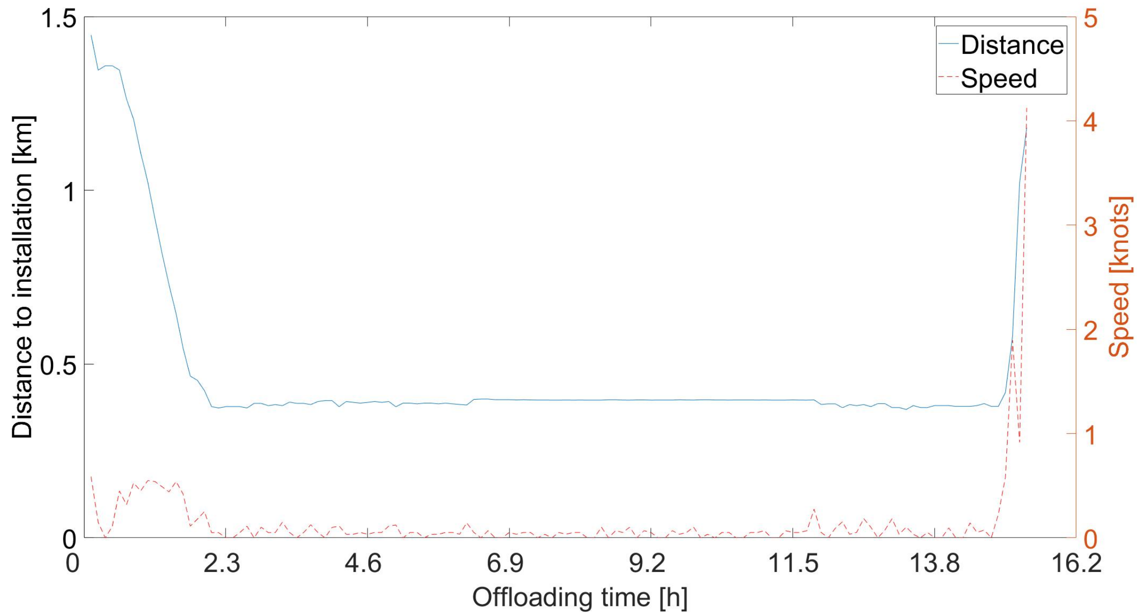


Figure B.2: Offloading Operation - Day 15

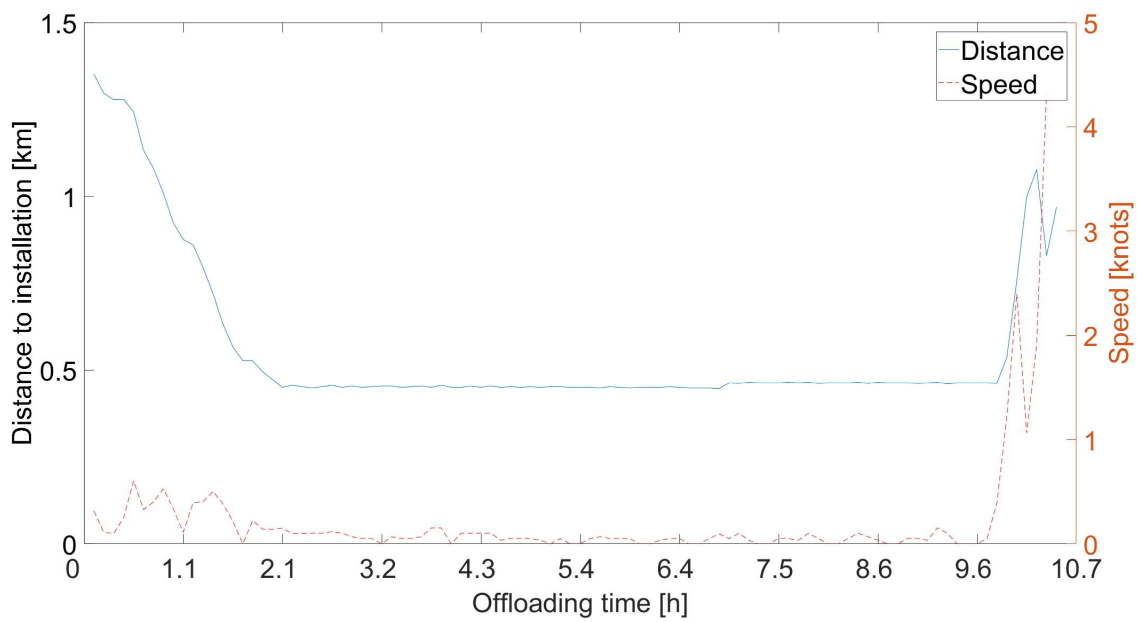


Figure B.3: Offloading Operation - Day 16

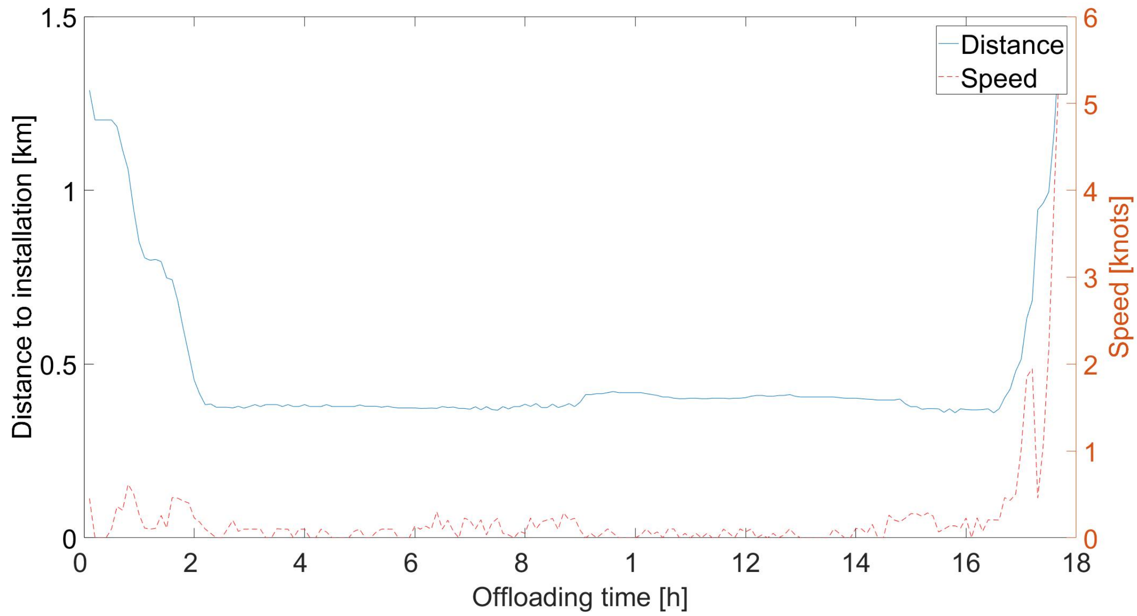
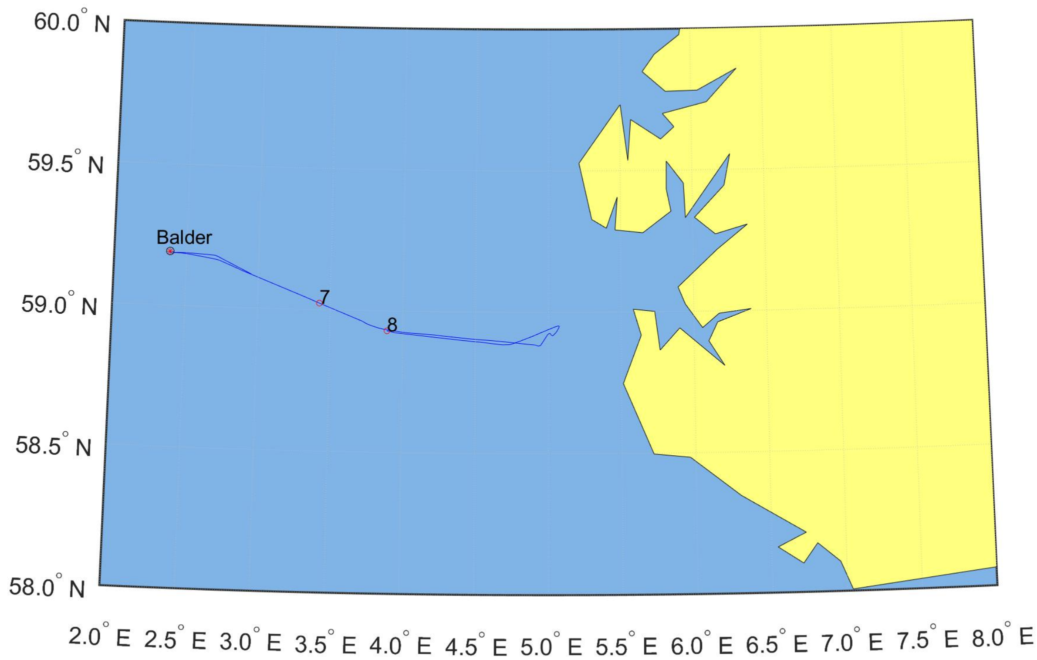


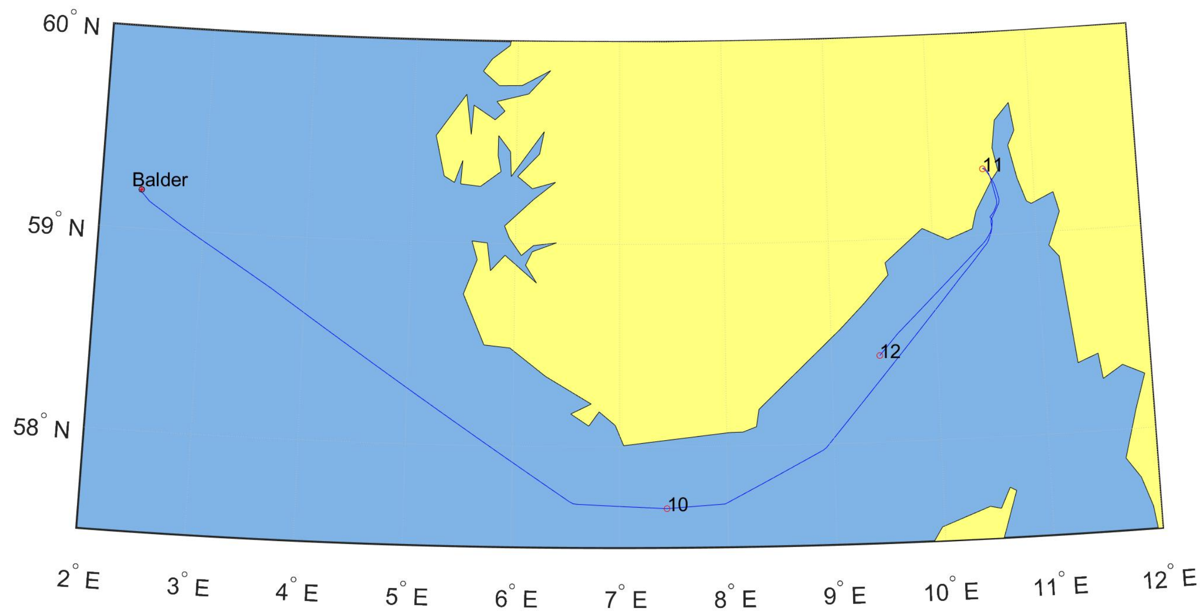
Figure B.4: Offloading Operation - Day 22

Appendix C

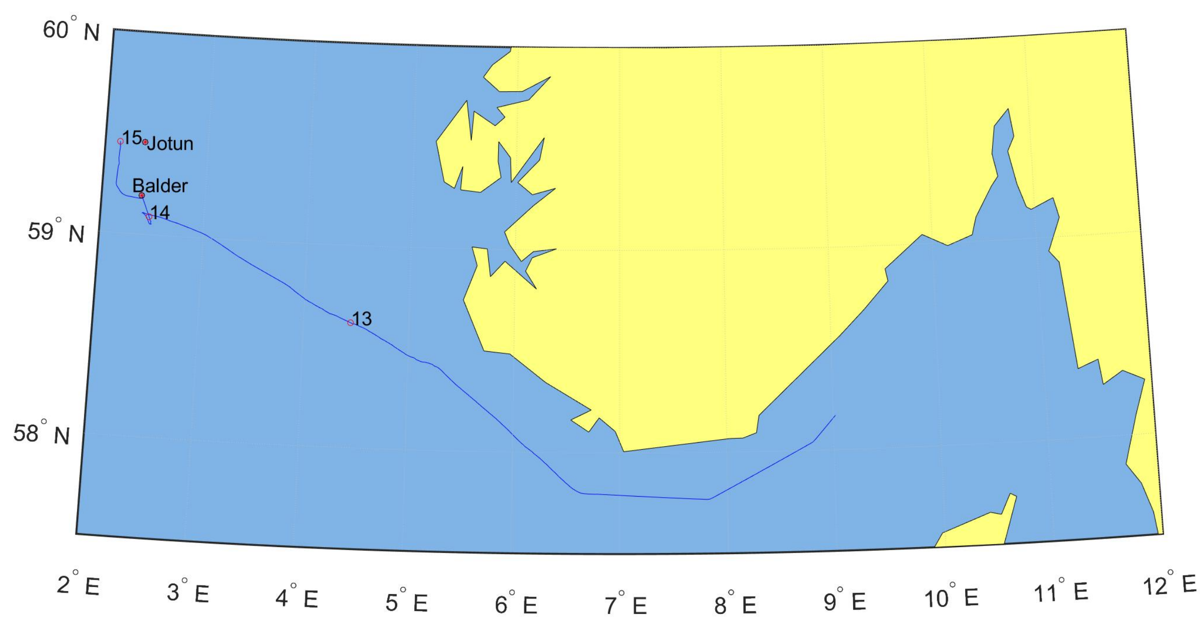
Shuttle Tanker Position Plots



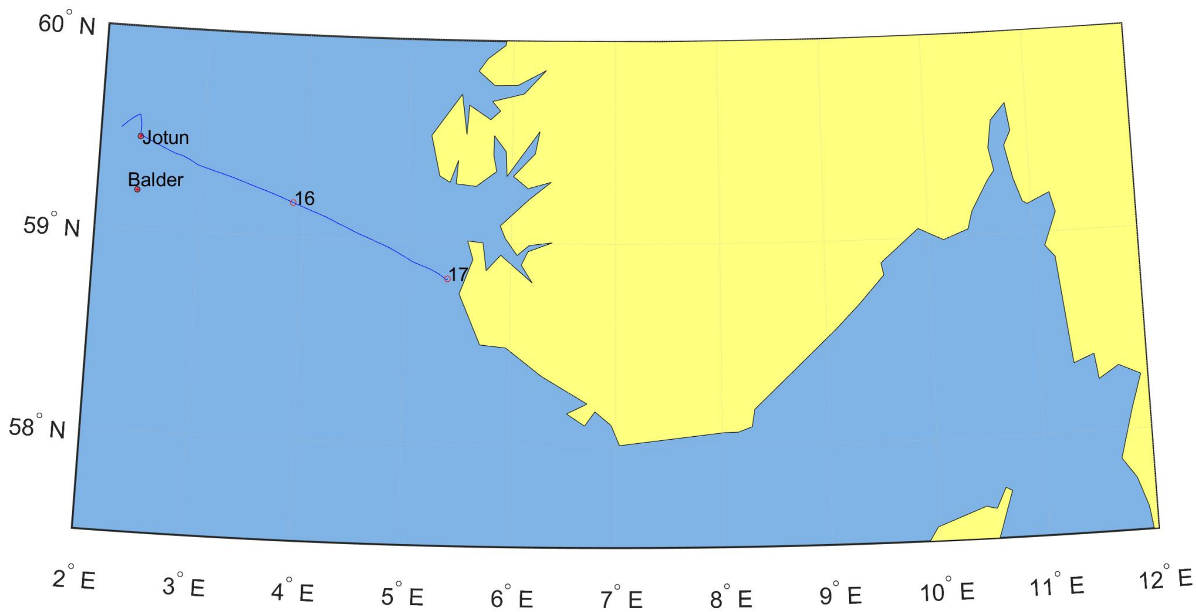
Route sailed by the shuttle tanker for day 7 and 8



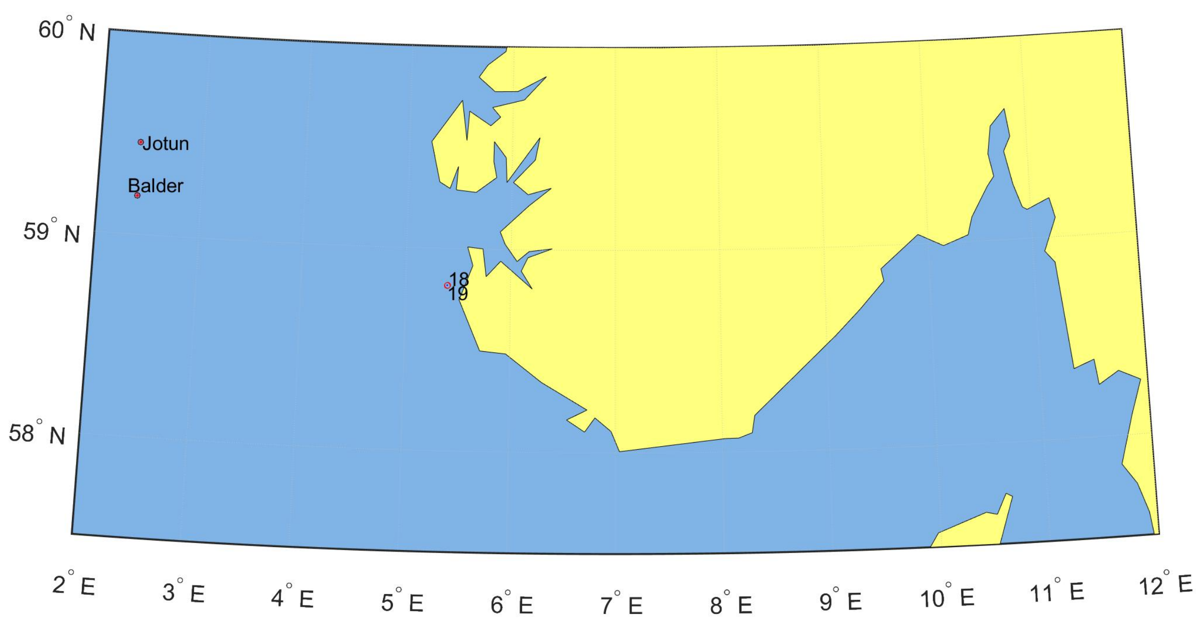
Route sailed by the shuttle tanker for day 10, 11 and 12



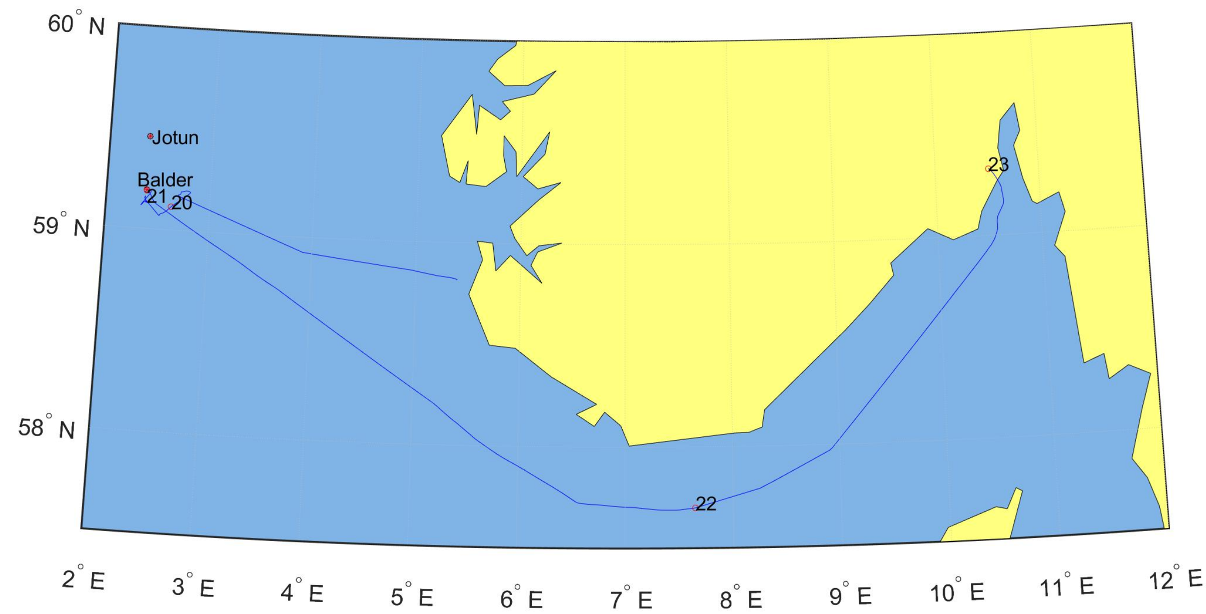
Route sailed by the shuttle tanker for day 13, 14 and 15



Route sailed by the shuttle tanker for day 16 and 17



Route sailed by the shuttle tanker for day 18 and 19



Route sailed by the shuttle tanker for day 20, 21, 22 and 23

Appendix D

Matlab Script

Sorting vessels - vesselsort.m

```
%                          VESSEL SORT

% This script sorts the data into specific data sets for each shuttle ...
    tanker
%
% The script generates a table "res2" which includes the all the results




clear all
tic

%% Import data from text file.

% Auto-generated by MATLAB on 2017/04/25 19:30:41

% Copyright 2014 The MathWorks, Inc.
% Automating File Import
% Select folder containing data interactively

L = 0;

Location =  'C:\Users\langd\Documents\Master\';
% Identify where to search for files
% Store the name of all .xls files as a vector D
```

```
D = dir([Location, '\*.csv']);
% Extract the file names
filenames = {D(:).name}.';



for y = 1:length(filenames)


%% Initialize variables.
filename = filenames{y};
delimiter = ';';
startRow = 2;

%% Format for each line of text:
formatSpec = '%f%f%q%q%f%f%f%f%q%f%f%f%f%q%[^\n\r]';

%% Open the text file.
fileID = fopen([Location '\' filename],'r');

%% Read columns of data according to the format.
% This call is based on the structure of the file used to generate this
% code. If an error occurs for a different file, try regenerating the code
% from the Import Tool.
dataArray = textscan(fileID, formatSpec, 'Delimiter', delimiter, ...
    'EmptyValue',NaN,'HeaderLines' ,startRow-1, 'ReturnOnError', false, ...
    'EndOfLine', '\r\n');

%% Close the text file.
fclose(fileID);

%% Create output variable
shuttletankers = table(dataArray{1:end-1}, 'VariableNames', ...
    {'mmsi','imonumber','vesselname','date_time_utc','fuelconsumption',...
'co2emission','utseilt_dist_nm','sec_nextpoint','15_lloydstypename',...
'sizegroupgrosston','utredningsomraadeid','long','lat','geom4326'});

%% Finds all unique vessels
%% 'imonumber' can be changed to 'mmsi'

A = unique(shuttletankers(:,2));
vesselid = A{1:size(A,1),{'imonumber'}};
imonumber = shuttletankers{1:size(shuttletankers,1),{'imonumber'}};

```

```
for i = 1:size(vesselid,1)
res{i + L,1} = vesselid(i);
res{i + L,2}  = shuttletankers(shuttletankers.imonumber == vesselid(i),:);
end
L = L + size(vesselid,1);

for k =1:size(res,1)
T(k,1) = res{k,1};
end

vessels = unique(T);
numberofvessels = size(vessels,1);
end

%%
%% Sort the data according to time
for ii = 1:numberofvessels

waitbar(ii/numberofvessels)

%% Finds all the data positions for a vessel
pos = [find(T(:)== vessels(ii))];
res2(ii).results=[];
for j=1:size(pos,1)
res2(ii).results = [res2(ii).results; res{pos(j),2}];
end

%% Sort table according to time
res2(ii).results = sortrows(res2(ii).results,4);
res2(ii).name = res2(ii).results{1,3};


newtable = res2(ii).results;

%% Calculate fuel consumption, CO2 emissions and Speed (per minute)

for p = 0:2:4
for jj = 1:size(newtable,1)
Z(jj,1) = newtable{jj,5+p}/(newtable{jj,8+(p/2)}/60);
end

Z = array2table(Z);

newtable = [newtable(:,1:5+p) Z newtable(:,(6+p):(14+(p/2)))];
```

```
if p == 0
newtable.Properties.VariableNames{6 + p} = 'fuelpermin';
elseif p == 2
newtable.Properties.VariableNames{6 + p} = 'CO2permin';
elseif p == 4
newtable.Properties.VariableNames{6 + p} = 'distpermin';
end

Z = [];
end

res2(ii).results = newtable;
end


%% Initial Operationa mode set to blank = ''
for d = 1:size(res2,2)
for s = 1:size(res2(d).results,1)
res2(d).PosInfo(s).Operation = '';
end
end

%% Estimate parameters for missing AIS data

elip = referenceEllipsoid('earth');
totalNANtime = 0;
for i = 1:size(res2,2)


for j = 1:size(res2(i).results,1)
if isnan(table2array(res2(i).results(j,11))) %if the time until next ...
    message is missing


%% calculate the time between NAN message and next message
res2(i).results(j,11) = ...
    {seconds(datetime(table2array(res2(i).results((j+1),4)))...
- datetime(table2array(res2(i).results((j),4))))};

%% Assume same speed and emissions as last message
res2(i).results(j,10) = res2(i).results(j-1,10);
res2(i).results(j,9) = {table2array(res2(i).results(j,11))*...
table2array(res2(i).results(j,10))/60};
```

```

%% CO2 emisssions
res2(i).results(j,8) =  res2(i).results(j-1,8);
res2(i).results(j,7) = {table2array(res2(i).results(j,11))*...
table2array(res2(i).results(j,8))/60};

%% Fuel consumption
res2(i).results(j,6) =  res2(i).results(j-1,6);
res2(i).results(j,5) = {table2array(res2(i).results(j,11))*...
table2array(res2(i).results(j,6))/60};

end
end
end

toc
```

Offloading Operations - offloading.m

```

%%  Offloading Operation data extraction
%% This script extracts the AIS messages that correspond to offloading ...
    operations

%% Import installation data from spreadsheet
% Script for importing data from the following spreadsheet:
%
%    Workbook: C:\Users\langd\Documents\Skole\Master\Data - ...
    Kystverket\FPSO_Norge.xlsx
%    Worksheet: Ark1
%
% To extend the code for use with different selected data or a different
% spreadsheet, generate a function instead of a script.

% Auto-generated by MATLAB on 2017/05/10 19:29:57

%% Import the data
[¬, ¬, raw] = xlsread('C:\Users\langd\Documents\Master\FPSO_Norge.xlsx',...
'Ark1','A1:C17');
raw(cellfun(@(x) ¬isempty(x) && isnumeric(x) && isnan(x),raw)) = {''};
```

```
cellVectors = raw(2:end,1);
raw = raw(2:end,[2,3]);

%% Create output variable
data = reshape([raw{:}],size(raw));

%% Create table
FPSO = table;

%% Allocate imported array to column variable names
FPSO.FPSO = cellVectors(:,1);
FPSO.lat = data(:,1);
FPSO.long = data(:,2);

%% Referance elipsoid for distance calculations
elip = referenceEllipsoid('earth');
coordinates2 = [FPSO.lat FPSO.long];
%%
for i = 1:size(res2,2)

tab = 1;
res2(i).approach15=table;


for y = 1:size(res2(i).results,1)

%% Measure the distance between the AIS message and the installations
%% Calculate distance and note which installation, and which AIS message

for k = 1:size(FPSO,1)

%% If it is within 1.5km of an installation
if distance(coordinates2(k,1),coordinates2(k,2),...
table2array(res2(i).results(y,16)),...
table2array(res2(i).results(y,15)),elip)/1000

res2(i).approach15(tab,:) = [res2(i).results(y,4:11)...
res2(i).results(y,15:16) array2table(distance(coordinates2(k,1),...
coordinates2(k,2),table2array(res2(i).results(y,16)),...
table2array(res2(i).results(y,15)),elip)/1000) FPSO.FPSO(k) {y}];

tab = tab + 1;
end
end
```

```
tab = size(res2(i).approach15,1) + 1;
end


%% Apply headers
if isempty(res2(i).approach15) == 0
res2(i).approach15.Properties.VariableNames{11} = 'Dist_to_inst';
res2(i).approach15.Properties.VariableNames{12} = 'Installation';
res2(i).approach15.Properties.VariableNames{13} = 'dataposition';

end
end

%% Sorts the offloading operations data into seperate tables
%% for each specific offloading operation.

for i = 1:size(res2,2)

counter = 1;
FPSOcounter = 0;


for j = 1:size(res2(i).approach15,1)
name = cell2mat(table2array(res2(i).approach15(j,12)));


if j ≥ 2 && strcmp(cell2mat(table2array(res2(i).approach15(j,12))),...
cell2mat(table2array(res2(i).approach15(j - 1,12))))== 1 ...
&& table2array(res2(i).approach15(j,13)) == ...
    table2array(res2(i).approach15(j-1,13)) + 1

counter = counter + 1;
res2(i).OP(FPSOcounter).instdata(counter,:) = res2(i).approach15(j,:);

else

counter = 1;
FPSOcounter = FPSOcounter + 1;
res2(i).OP(FPSOcounter).instdata(counter,:) = res2(i).approach15(j,:);
res2(i).OP(FPSOcounter).name = table2array(res2(i).approach15(j,12));
end
end
end
```

Near coast - nearcoast.m

```
%%                      Close to shore

%% This script extracts all AIS messages close to shore and determines if
%% the vessel is in port

%% NB! Long computational time

%% Import coastline coordinates
coastpointss = load('coast.mat'); % load long and lat data coast


%% Limit the data to Norwegian waters
SW = [55 0];
NE = [75 40];
counter = 1;

%% Extract coastline coordinates that comply with the limitation
for i = 1:size(coastpointss.lat,1)
waitbar(i/size(coastpointss.lat,1))
if coastpointss.lat(i) ≥ SW(1) && coastpointss.lat(i) ≤ NE(1) && ...
    coastpointss.long(i) ≤ NE(2) && coastpointss.long(i) ≥ SW(2)

coastpointss.NorwayLat(counter,1) = coastpointss.lat(i);
coastpointss.NorwayLong(counter,1) = coastpointss.long(i);
counter = counter + 1;
end
end


%% Plot map projection of the extracted coordinates
geoshow(coastpointss.NorwayLat,coastpointss.NorwayLong,'DisplayType','point')

%% Import referance elipsoid
elip = referenceEllipsoid('earth');


h = waitbar(0,'nearcoast');

%% Extract the AIS messages that are within 30 km of a coastline coordinate

```

```
for i = 1:size(res2,2)
res2(i).coast=table;

tab = 1;

for y = 1:size(res2(i).results,1)
waitbar(y/size(res2(i).results,1))

dist = 10000000; %dummy variable

for k = 1:size(coastpointss.NorwayLat,1)
if distance(coastpointss.NorwayLat(k),coastpointss.NorwayLong(k),...
table2array(res2(i).results(y,16)),table2array(res2(i).results(y,15)),...
elip)/1000 ≤ 30
if distance(coastpointss.NorwayLat(k),coastpointss.NorwayLong(k),...
table2array(res2(i).results(y,16)),table2array(res2(i).results(y,15))...
,earthR) < dist
dist = distance(coastpointss.NorwayLat(k),coastpointss.NorwayLong(k),...
table2array(res2(i).results(y,16)),table2array(res2(i).results(y,15))...
,earthR);

index = k;
end

end
end

if dist < 10000000

res2(i).coast(tab,:) = [res2(i).results(y,4:11) ...
    res2(i).results(y,15:16) {dist} {index} {y}];
tab = tab + 1;
end

end

%% Apply headers
res2(i).coast.Properties.VariableNames{11} = 'Dist_to_shorepoint';
res2(i).coast.Properties.VariableNames{12} = 'shore_lat_long';
res2(i).coast.Properties.VariableNames{13} = 'dataposition';
end
```

Determine Operational mode - mode.m

```
%%            Operational Mode

%% This script finds the operational mode for the shuttle tanker for
%% each AIS message

for i = 1:size(res2,2)



%% Offloadin operation
for j = 1:size(res2(i).approach15,1)
if table2array(res2(i).approach15(j,7)) <0.6/60
res2(i).PosInfo(table2array(res2(i).approach15(j,13))).Operation = ...
    'Offloading Operation';
else
res2(i).PosInfo(table2array(res2(i).approach15(j,13))).Operation = ...
    'Transit';
end
end

%% Port
for j = 1:size(res2(i).coast,1)
if table2array(res2(i).coast(j,7)) < 0.5/60
res2(i).PosInfo(table2array(res2(i).coast(j,13))).Operation = 'Port';
elseif table2array(res2(i).coast(j,7)) > 0.5/60
res2(i).PosInfo(table2array(res2(i).coast(j,13))).Operation = 'Transit';
end
end

%% Waiting
for j = 1:size(res2(i).PosInfo,2)
if isempty(res2(i).PosInfo(j).Operation) == 1
if table2array(res2(i).results(j,10)) < 1/60
res2(i).PosInfo(j).Operation = 'Waiting';
else
res2(i).PosInfo(j).Operation = 'Transit';
end
end
end

```

```

%% If NAN values, the operation is same as last.
for j = 1:size(res2(i).results,1)
if isnan(table2array(res2(i).results(j,10))) == 1
res2(i).PosInfo(j).Operation = res2(i).PosInfo(j-1).Operation;
end
end



end

%% Estimate the loading condition of the shuttle tanker
for i = 1:size(res2,2)



%% Find initial loading condition
for j = 1:size(res2(i).PosInfo,2)

if strcmp([res2(i).PosInfo(j).Operation],'Offloading Operation') == 1
transitMode = 'Ballast';
break
elseif strcmp([res2(i).PosInfo(j).Operation],'Port') == 1
transitMode = 'Laden';
break
end
end

%Determine the loading condition
for j = 1:size(res2(i).PosInfo,2)
if strcmp([res2(i).PosInfo(j).Operation],'Transit') == 1
res2(i).PosInfo(j).Transit = transitMode;
elseif strcmp([res2(i).PosInfo(j).Operation],'Waiting') == 1
res2(i).PosInfo(j).Transit = transitMode;
%Change to ballast condition if it is at port
elseif strcmp([res2(i).PosInfo(j).Operation],'Port') == 1
transitMode = 'Ballast';
%Change to laden condition if it loads oil
elseif strcmp([res2(i).PosInfo(j).Operation],'Offloading Operation') == 1
transitMode = 'Laden';

end
end
```

```
%% If it is in laden condition and leaves for more than 48 hours it is
%% assumed that it unloads at a European port

changeMode = 0;
for j = 2:size(res2(i).results,1)
waitbar(j/size(res2(i).results,1))


if strcmp([res2(i).PosInfo(j).Transit],'Laden') == 1 &&...
days(datetime(table2array(res2(i).results(j,4)))-...
datetime(table2array(res2(i).results(j-1,4)))) > 2

res2(i).PosInfo(j).Transit = 'Ballast';
changeMode = 1;

elseif strcmp([res2(i).PosInfo(j).Operation],'Offloading Operation')
changeMode = 0;


elseif strcmp([res2(i).PosInfo(j).Transit],'Laden') == 1 &&...
changeMode == 1
res2(i).PosInfo(j).Transit = 'Ballast';
end
end
%%

end
```

Results - results.m

```
%%                      Results

%% This script calculates the results from the heuristic analysis

%% Operational profile (total hours)
P = zeros(31,6);

vessel = 31; % Choose vessel i (1-33) that is analysed

for i = vessel

P(i,1) = i;
for j = 1:size(res2(i).PosInfo,2)

if strcmp(res2(i).PosInfo(j).Operation,'Offloading Operation') == 1
P(i,2) = P(i,2) + table2array(res2(i).results(j,11));
elseif strcmp(res2(i).PosInfo(j).Operation,'Transit') == 1
if strcmp(res2(i).PosInfo(j).Transit,'Ballast') == 1
P(i,3) = P(i,3) + table2array(res2(i).results(j,11));
elseif strcmp(res2(i).PosInfo(j).Transit,'Laden') == 1
P(i,4) = P(i,4) + table2array(res2(i).results(j,11));
end

elseif strcmp(res2(i).PosInfo(j).Operation,'Waiting') == 1
P(i,5) = P(i,5) + table2array(res2(i).results(j,11));
elseif strcmp(res2(i).PosInfo(j).Operation,'Port') == 1
P(i,6) = P(i,6) + table2array(res2(i).results(j,11));



end
end



%% Operational profile (%)
PP = zeros(31,5);
for j = 2:6
PP(i,j) = P(i,j)/sum(P(i,2:6));
end
```

```
%% Laden or ballast
Laden = 0;
Ballast = 0;

for j = size(res2(i).PosInfo,2)
if strcmp([res2(i).PosInfo(j).Transit],'Laden') == 1
Laden = Laden + table2array(res2(i).results(j,11));
elseif strcmp([res2(i).PosInfo(j).Transit],'Ballast') == 1
Ballast = Ballast + table2array(res2(i).results(j,11));
end
end





%% Calculate CO2 emissions
E = zeros(31,6);

E(i,1) = i;
for j = 1:size(res2(i).PosInfo,2)

if strcmp(res2(i).PosInfo(j).Operation,'Offloading Operation') == 1
E(i,2) = E(i,2) + nansum(table2array(res2(i).results(j,7)));
elseif strcmp(res2(i).PosInfo(j).Operation,'Transit') == 1
if strcmp(res2(i).PosInfo(j).Transit,'Ballast') == 1
E(i,3) = E(i,3) + nansum(table2array(res2(i).results(j,7)));
elseif strcmp(res2(i).PosInfo(j).Transit,'Laden') == 1
E(i,4) = E(i,4) + nansum(table2array(res2(i).results(j,7)));
end

elseif strcmp(res2(i).PosInfo(j).Operation,'Waiting') == 1
E(i,5) = E(i,5) + nansum(table2array(res2(i).results(j,7)));
elseif strcmp(res2(i).PosInfo(j).Operation,'Port') == 1
E(i,6) = E(i,6) + nansum(table2array(res2(i).results(j,7)));



end
end
```

```
%% Calculate fuel consumption
F = zeros(31,6);

F(i,1) = i;
for j = 1:size(res2(i).PosInfo,2) %8731:63073           %

if strcmp(res2(i).PosInfo(j).Operation,'Offloading Operation') == 1
F(i,2) = F(i,2) + nansum(table2array(res2(i).results(j,5)));
elseif strcmp(res2(i).PosInfo(j).Operation,'Transit') == 1
if strcmp(res2(i).PosInfo(j).Transit,'Ballast') == 1
F(i,3) = F(i,3) + nansum(table2array(res2(i).results(j,5)));
elseif strcmp(res2(i).PosInfo(j).Transit,'Laden') == 1
F(i,4) = F(i,4) + nansum(table2array(res2(i).results(j,5)));
end

elseif strcmp(res2(i).PosInfo(j).Operation,'Waiting') == 1
F(i,5) = F(i,5) + nansum(table2array(res2(i).results(j,5)));
elseif strcmp(res2(i).PosInfo(j).Operation,'Port') == 1
F(i,6) = F(i,6) + nansum(table2array(res2(i).results(j,5)));



end
end


end
```