Master’s degree thesis

LOG950 Logistics

Operational Supply Vessel Planning with Varying Demands from Installations

Bogdan Arabadzhi

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Molde University College
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Preface

The topic of this master thesis is “Operational Supply Vessel Planning with Varying Demands from Installations“. The thesis was written as the final part of Master of Science (MSc) degree with the specialization in Logistics Analytics from Molde University College – Specialized University in Logistics.

This thesis would not have been possible without the infinite patience and support of my supervisor Irina Gribkovskaia and co-supervisor Yauheni Kisialiou, who introduced me to the oil and gas offshore upstream logistics and helped to formulate the research problem.

I would like to express my gratitude to Irina Gribkovskaia for constructive critics and professional experience-based feedback on my writings and the way of thinking. I would also like to thank Yauheni Kisialiou for sharing his implementation experience that helped me avoid a bunch of commonly made mistakes while working on the decision support tool.

I would like to express my appreciation to Halvard Arntzen for being available to give valuable advice on the data treatment and statistical analysis when needed, especially in difficult cases of missing or erroneous data.

The special gratitude should be expressed to the principal consultant in supply chain management working for the company E for collaboration. The principal consultant helped me to gain much better understanding of the problem from the managerial perspective, breaking down the planning process of supply to offshore installations to manageable pieces. He also provided the needed historical data from Norwegian oil and gas company E. This is highly appreciated.

Summary

This thesis is dedicated to the operational supply vessel planning problem with varying demands from installations. We study current principles of fleet and vessels planning on the example of one oil and gas company operating offshore, formulate this principles with the corresponding demand allocation options, develop and implement the algorithm and its extension for the operational supply vessel planning problem. We later compare the performance of the developed operational supply vessel planning algorithms using the evaluation criteria such as the average weekly fleet cost for the ordinal and flexible pools of vessels and the weekly vessel utilization criteria.

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Abbreviations

ALNS	–	Adaptive Large Neighbourhood Search
BP	–	British Petroleum
OSV	–	Offshore Supply Vessel
NCS	–	Norwegian continental shelf
NPD	–	The Norwegian Petroleum Directorate
PSVPP	–	Periodic Supply Vessel Planning Problem
JIT	–	Just-in-time
TW	–	Time Window
LNS	–	Large Neighbourhood Search
VBF	–	Voyage-based formulation

Chapter 1

Introduction

The energetics play a vital role in today's world. Fuel is used in all major aspects of modern life, energizing everything ranging from industrial production facilities to cars and consumer electronics powered by fuel products such as gasoline or electricity. The available energy sources are quite versatile. They are oil, coal, natural gas, hydroelectricity, nuclear and renewable energy. But the world's dominant fuel sources are oil and gas. Oil is making up just over a third of all energy consumed, while natural gas accounted for a record 23.4% of global primary energy consumption according to BP (2018).

Nowadays oil and gas energy companies operate offshore and onshore. The onshore development of oil fields and gas deposits happen on land. In this way the extraction of oil and gas is done by drilling deep holes under the earth's surface whereas offshore drilling is done underneath the seabed while installations placed farther and farther away from the coast into the sea. The offshore oil and gas production takes place in many countries such as Norway (Norwegian Sea, North Sea, Barents Sea), Brazil (Campos Basin, Santos Basin), Saudi Arabia (Persian Gulf), United States of America (California, Gulf of Mexico), Canada (Newfoundland, Nova Scotia), India (Mumbai High), Guinea (Gulf of Guinea) and Russia (Barents Sea, Sakhalin). According to the (The Norwegian Petroleum Directorate, 2019a) a total of 25 companies (Equinor Energy AS, Aker BP ASA, ConocoPhillips Skandinavia AS, Vår Energi AS, etc.) were active operators on the Norwegian continental shelf (NCS) at the end of 2018. While Norway is covering about 2% of the global crude oil demand, it is the third largest exporter of natural gas in the world. In total oil and gas exports equals about 40% of the value of Norwegian exports of goods, see Figure 1.1. This makes oil and gas the most important export commodities in the Norwegian economy (NPD, 2019b).

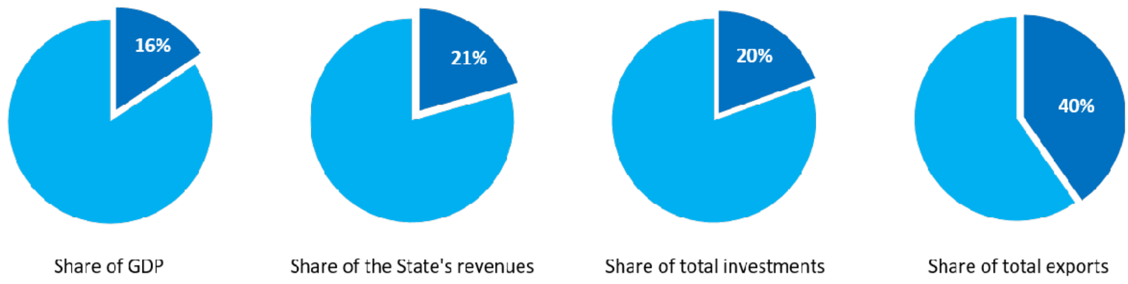

Figure 1.1: Macroeconomic indicators for the petroleum sector (NPD, 2019c)

While we can clearly see the importance of offshore oil and gas production to Norway and the whole world in general, its operations remains complex, highly unpredictable and cost enormous amount of money. The industry stability is tight up to the oil market price (USD/barrel) that is fluctuating over time and already experienced several collapses in its history. The recent oil price collapse of 2014 (Maestro et al., 2018) brought the industry to a decay that took several years to recover from and this process is still ongoing, but as shown in Figure 1.2, confidence is returning to the oil and gas operators while they are improving the financial resilience of their companies by the means of standardization, collaboration, employment of best practices and cost effective operational strategies.

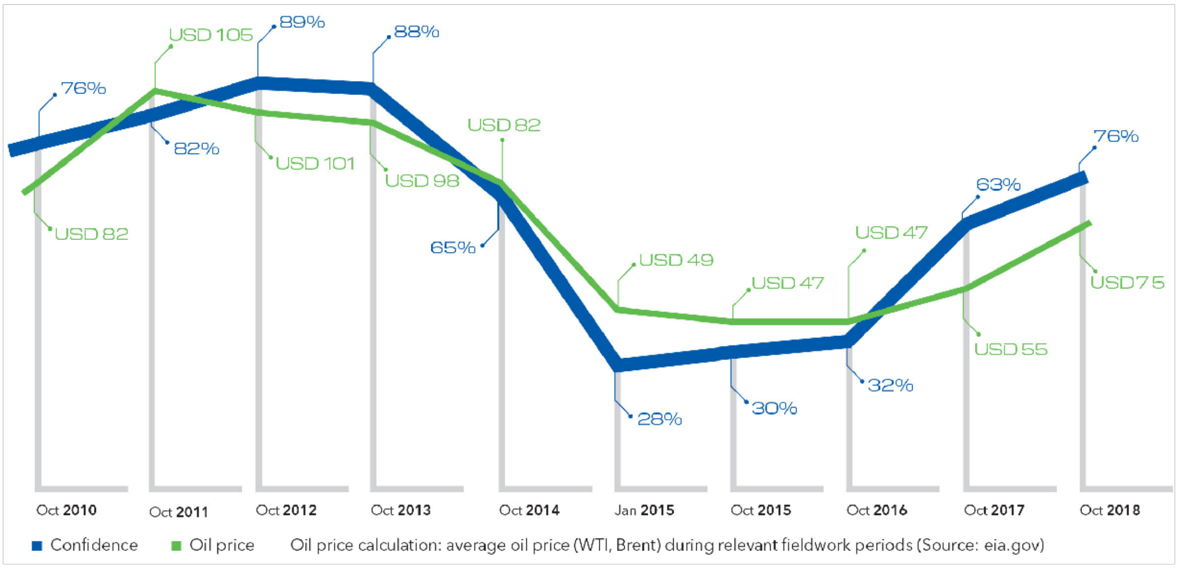

Figure 1.2: Oil price vs. industry confidence (Slater, 2019)

As the result of moving towards cost-effective operation and long term sustainability, oil and gas companies have increased their interest in finding strategies and methods that can improve operational efficiency of their business reducing expenses across the whole supply chain.

In this thesis we study the task of cargo delivery to offshore installations with the particular focus on the operational planning of supply vessels. The offshore installations are represented by production platforms and drilling rigs that come with different and time varying demands. The installations need to be supplied with a great variety of commodities on a frequent basis. The regularity of the supplies is crucial for the offshore installations to the extend that missing or late delivery can lead to postponed or stopped (production or exploration) activity of the installation. This will in turn lead to large monetary losses and great increase of the logistical costs. Shipments to the installations are performed by specialized, so called, offshore supply vessels (OSV). The OSVs are known to be a major cost contributor with the current charting cost trends of NOK 70.000 – NOK 185.000 per day depending on the vessel size (example costs are given for medium to large supply vessels). The aim of the operational supply vessel planning is to decide which cargo demands to assign to each vessel planned for departure on a given day, and to find the sequence of visits to offshore installations on each vessel's voyage. The objective is to minimize the total vessel cost while maximizing capacity utilization of vessel fleet. In practice, the operational supply vessel planning is done on the basis of the expertise and experience of logistic planners, without employment of scientific methods or tailored software. It is also the least studied problem related to supply vessels planning. The main purpose of this thesis is to develop the optimization-based decision support tool for operational supply vessel planning. The research problem is challenging as it relates to combinatorial optimization problems and incorporates demand allocation and routing decisions. Our study is based upon the example data of one of the companies operating on the Norwegian continental shelf, but is not limited to this company case by any means.

The rest of the thesis is organized the following way. Chapter 2 is dedicated to a more detailed problem description and definition. It describes basic concepts and actors of the upstream oil and gas logistics. There is also the description of the planning approaches and challenges on par with the assumptions we made for this research. Chapter 3 is the formulation of the research tasks that we carried out with some details for each of them. The fourth chapter contains literature review divided into sections according to the level of supply vessel planning. Chapter 5 is dedicated to the methodology. In this chapter we explore the relevant approaches presented by other scientists and the potential to apply them in our research, if any. Chapter 6 is the description of the data. It states what data we needed, what data we managed to get and what was the source. Chapters 7 and 8 are dedicated to the decision support tool and the experiments, respectively. Chapter 7 describe the individual demand allocation options, the basic operational planning algorithm developed and the modifications. The experiments chapter is dedicated to the comparative analysis of the application of the developed variants of the basic algorithm for the operational supply vessel planning with the use of the developed discrete event simulation models. The last chapter's focus is on the conclusions and the formulation of possible future research directions.

Chapter 2

Problem Description

This chapter provide a more detailed description of the aspects and challenges of the upstream oil and gas logistics planning process. Section 2.1 describe the concepts and actors of the upstream offshore supply chain as well as present the classification of the accompanying challenges. Section 2.2 is dedicated to the planing process itself. It describes different levels and approaches of supply vessels planning.

2.1 Upstream oil and gas offshore logistics

The offshore oil and gas supply chain can be divided into two parts: upstream and downstream. The downstream logistics deals with transportation of extracted oil and gas onshore for further refining and obtaining various petrochemical products that are transported to the customers alongside the raw oil and gas through the multi-layer distribution network. The upstream logistics is responsible for deliveries of necessary equipment and materials to the offshore installations from the onshore supply base. It is also responsible for brining wastes and equipment (rented, broken, etc.) back onshore. The following sections present main actors of the upstream offshore supply chain. The chain itself can be seen on Figure 2.1.

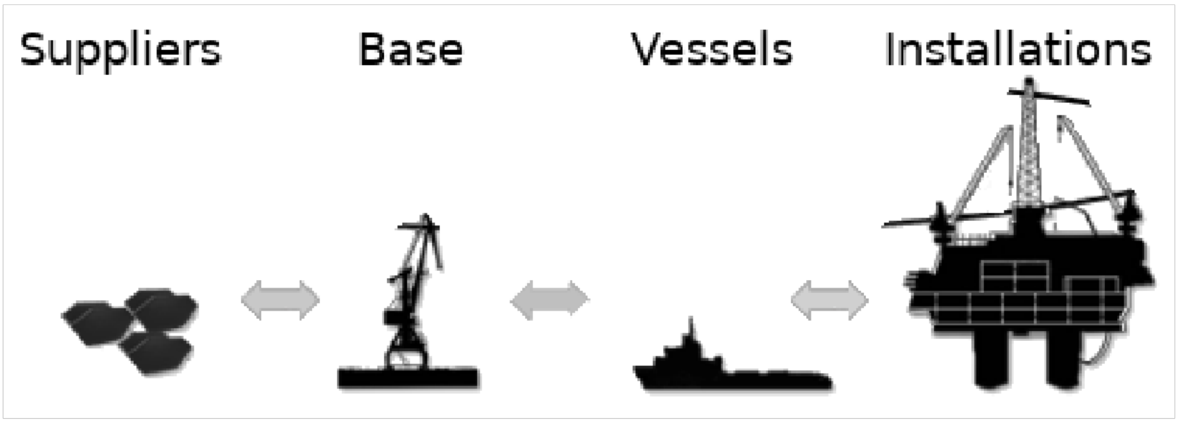

Figure 2.1: Upstream offshore supply chain

2.1.1 Offshore installations

Offshore installations are the end customers in the upstream oil and gas logistics. They are the origin of the need. Offshore installations are usually located on the large distances from the coast and require a long-haul maritime transportation for the demands to be delivered. Each installation is unique. They all have different deck and bulk capacities, number of lift cranes and their characteristics, service times, locations, opening hours, defining the time of possible loading/unloading service. Offshore installations have plans of activities and visit frequency defined to ensure continuous service and a certain amount of delivered cargo. They can be classified according to their construction and type of the operations performed by the installation.

According to the types of activities offshore installations can be divided into three categories: production platforms, exploration rigs and others. Production platforms have a fixed location and usually more stable and predictable demand levels due to the type of operations they perform. Rarely, in case of equipment failures or other unforeseen events, production platform may require an ad-hock (top-priority, emergency) delivery in order not to slow down or even stop production. The case where the installation needs to stop their operation due to the yet undelivered urgent cargo is considered the worst case scenario in the upstream oil and gas offshore logistics. Example of the production platform can be found on Figure 2.2. Exploration rigs are usually mobile. They are moving around the oil and gas offshore field and drilling several wells while they explore the field. If oil or natural gas is found they start development of the well that include lowering the steel casing into the well, cementing it into place to prevent the well from caving in, testing the well and other similar activities.

Figure 2.2: Offshore oil production platform, one of the subtypes of the conventional fixed platform

Due to unpredictability in the nature of this activities exploration rigs are more uncertain in their demand estimates. Deliveries to this installations are usually more variable in demand and happen with higher frequency that is also due to rentals of expensive equipment by the exploration rigs as well as generally higher cost of operating this type of installation. The exploration rigs are usually open for service at night in contrast to production platforms.

Another type of offshore installations classification is by the type of the construction. Figure 2.3 present different types of offshore platforms and drilling rig for oil. Pictures 1 and 2 are the conventional fixed platforms; 3 compliant tower; 4 and 5 vertically moored tension leg and mini-tension leg platforms; 6 spar; 7 and 8 semi-submersibles; 9 floating production, storage and offloading facility; 10 sub-sea completion and tie-back to host facility.

As one might have guessed in contrast to the previous classification by the type of activities performed at installations, this classification is not directly affecting demand fluctuations at the installations, but the other valuable factors. The type of the installation according to this classification is defining the installations parameters and limitations such as possible use cases for the installation, maximum distance from the shore, the deck and bulk capacity, number of lift cranes and their parameters, maximum waves height at which installation can still accept deliveries.

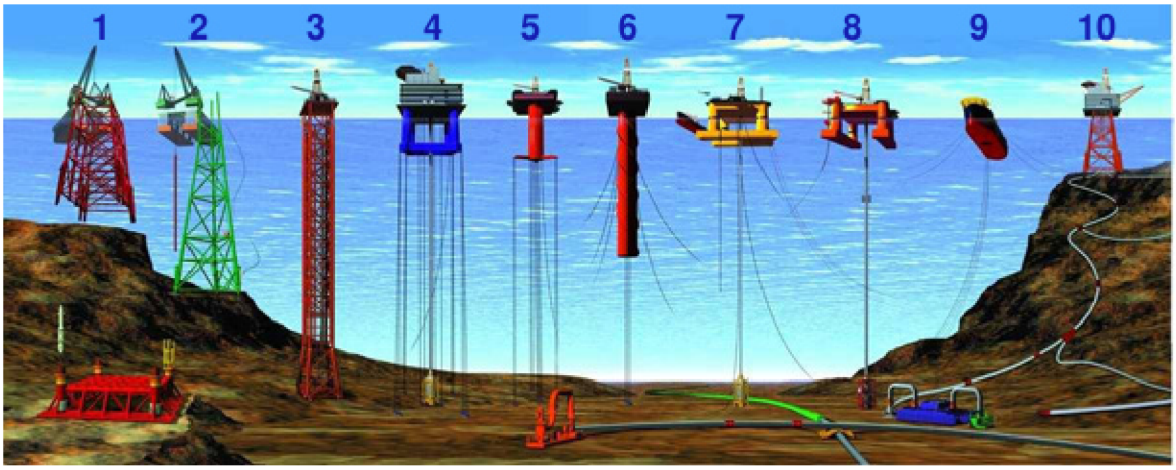

Figure 2.3: Types of offshore oil installations (Ocean Explorer, 2010)

2.1.2 Supply vessels

The supply vessel is the mean of transportation of goods from the onshore supply base to offshore installations. It is also responsible for deliveries of waste and used equipment from installations back onshore. The supply vessel can be either from the contracted fleet of vessels or hired directly from the spot market. The latter is less cost effective than the former. The OSVs are known to be a major operational cost contributor with current charting cost trends of NOK 70.000 – NOK 185.000 per day depending on the vessel size (example costs are given for medium to large supply vessels). The example of the offshore supply vessel can be found on Figure 2.4. This ships are specifically designed for offshore supply to installations. They have a container deck for shipping containers and buckets of different sizes (deck cargo demands) with necessary equipment, pipes, food and other goods as well as tanks located under the deck for bulk cargo transportation. The bulk cargo may include, but is not limited to liquid nitrogen, sand, cement, different other chemicals. The offshore supply vessel is characterized by available deck capacity, charter cost, sailing speed and fuel consumption rate. Extra complexity is added by heterogeneity of the vessel fleet (the fleet consists of vessels with different characteristics) in the real life.

Figure 2.4: The offshore supply vessel

2.1.3 Supply base

The onshore supply base is the operational control centre for the supply of offshore installations. The base is the starting and ending point of each voyage of the supply vessels. It acts as the hub for all the cargo that needs to be delivered to or is returned from installations. Each supply base is managing supplies to the set of offshore installations that is assigned to this base. The location of the supply base is tight to the locations of installations to be served by this base. The allocation and fleet sizing for the particular base is done for the season (usually, several month) according to the set of installations assigned to the base and their plans of activities. Some of the supply bases have regular opening hours when the offshore supply vessels loading and unloading service can be performed. The time required for loading the supply vessel is known as turnaround time at the base. Another limitation to the number of vessels that can be served per day is the number of berths available at the supply base. The supply base can be seen on Figure 2.5.

Figure 2.5: The onshore supply base

2.1.4 Voyages

The voyage of a supply vessel can be defined as the sequence of installations to be visited in order to perform service. Each voyage starts and ends at the supply base. This service is either delivery of cargo or/and pickup of wastes and used equipment. Each voyage is assigned a departure day, a given start time and its duration. The example of the voyage is depicted on Figure 2.6.

Voyage 2		Vessel 4
Mon		**16:00**
	ETA	
Installation 7	Tue	02:45
Installation 3	Tue	06:45
Installation 2	Tue	11:30
Supply base	Wed	02:30

Figure 2.6: The voyage of the supply vessel

The voyage's departure from the supply base is set on Monday at 16:00. The time of voyage departure is usually drawn from the predefined set of departure times given that there should be adequate turnaround time for vessel at the base to be loaded with cargo. The number of this voyage is 2. It means that there is al least one other voyage set for departure on the same day. The voyage can not exist without a vessel to sail to the installations. In our case the vessel that is planned to sail this voyage is vessel number 4. This does not mean that three other vessels have the same day departures. Or that they are available at the base or currently on the voyage. The one thing we can assume is that there are at least three other vessels in the fleet of this supply base (vessels 1, 2 and 3). The installations that are set to be visited on this voyage are Installation 7, Installation 3 and Installation 2. This order is strict and is set during planning. In reality the order can be changed by the Capitan of the vessel or other responsible personnel making this decision on the serious grounds. For example, if Installation 3 will be unable to to handle the delivery due to bad weather condition at the corresponding part of the sea. If this conditions hold for a long time, as reported, the vessel may go to Installation 2 directly. The estimated arrival time (and date) at installation is noted opposite to its name. There is also an expected return time (and date) to the supply base. This time is usually respected, especially with the supply vessel from the fleet as it has to be back on time to go through turnaround cycle and get ready for the next voyage. Each voyage have an associated demand to deliver (not depicted here) to each installation and the duration. The voyage duration consists of sailing time, waiting time and service time at installations.

2.1.5 Offshore logistics challenges

Offshore logistics is a complex problem where with very actor in the offshore supply chain comes a bunch of extra challenges that logistic planners need to deal with. Here we present the most common ones.

- Offshore installations demand uncertainties

  Most of the installation demands become certain only on the day presiding the planned departure day or on the actual day of the planned supply vessel departure.

- Capacity limits

  The most noticeable capacity limitations exist for the installations and for the supply vessels. This two have limited deck space as well as bulk capacity. Similar limitations need to be met for the supply base berths too (limited amount of berths available).

- Multi-period planning

  Usually one supply vessel trip lasts longer than a day. Typically there is at least one departure of the supply vessel from the base each day.

- Service level

  There is a strict requirement for 100% service level for the offshore oil and gas installations. It is not possible to have "lost sales" here. Delivery lead times should be constantly maintained.

- Time windows

  Supply bases have their opening hours as well as some installations. They are not available for loading/unloading or any other service outside their normal working hours.

- Vessel fleet

  There is a vessel fleet that needs to be decided upon and contracted. All of the ships are heterogeneous in the real life, having different storage capacities, sailing speed and other parameters. This fact add extra complexity to the problem.

- Offshore installations ad-hoc and priority calls

  Sometimes the installation may have a really urgent need to be fulfilled as soon as possible. This is usually happen in case of emergency or something that may lead to possible suspension of operation at the installation.

- Weather condition uncertainties

  In the reality of the NCS the weather conditions at the installations and along the voyage should constantly be monitored, especially during the winter season. Bad weather conditions at the base can also affect departures.

- Emissions

  The green logistics is also a part of Norwegian offshore oil and gas logistics. The vessel speed is usually reduced by the operational planners to ensure less CO_2 emissions will come along into the atmosphere. It is known as vessel sailing speed optimization.

2.2 Supply vessel planning

The supply vessel planning is a complex and multi-level process at its core. The following sections feature description of each of this levels.

2.2.1 Strategic

Strategic planning level is a long term (1–3 years) planning related to fleet sizing. One of the major tasks at this level is to determine the required fleet size and mix of the supply vessels. This numbers are affected by the number of installations that are serviced by the operating company. To achieve this logistic planners are solving the packing problem with the objective to minimize number of vessels needed to meet 100% service requirement from installations.

2.2.2 Tactical

Tactical planning level is the scheduling of weekly vessel departures valid for a season (5–8 months). It involves the task of construction of the weekly supply vessel schedule (master vessel schedule). For each onshore supply base the operating company is constructing its own schedule valid for a season with the required fleet. The tactical supply vessel planning is known as the Periodic Supply Vessel Planning Problem (PSVPP). The problem concerns the supply of a set of offshore installations with required materials and equipment on a regular basis from an onshore supply base by a fleet of supply vessels. The solution of PSVPP implies several sub-problems:

- building all possible voyages that could be assigned to the vessels (*vehicle routing problem*)
- assignment of voyages to the vessels' schedules (*assignment problem*)
- "packing" voyages in the minimal fleet of the supply vessels (*packing problem*)

- constructing the final solution – the master vessel schedule (*scheduling problem*).

Example of the master vessel schedule can be found on Figure 2.8.

2.2.3 Operational

Operational planning level is daily demand allocation and routing of supply vessels. It deals with the construction of voyages departing in a given day. Each voyage is defined by the set of visits performed in the particular sequence where each visit is associated with the certain demand. Each voyage is assigned to a certain vessel from the fleet.

At the operational planning level, the planners are working with the following information: the daily set of departures for corresponding vessels taken from the master schedule, the set of installations to be visited by each vessel, and the revealed demand from installations. The aim of the work is to make the operational modifications of the voyages planned in the master schedule and construct additional voyages, if needed, so that all demands of that day are assigned to the minimal possible number of vessels.

One of the major issues in the operational vessel planning is the revealed installations demand. In many cases it may occur that the revealed demand will cause the voyage, it is assigned to, to become infeasible.

The following situations will lead to the need of operational changes:

- Supply vessel capacity violation

  Planning on the tactical level is done with the help of the planned average weekly demand. However, the revealed demand at each departure may differ from the average. In case of higher delivery demand (for example, inclusion of additional cargo that was delayed during transportation from the supplier to the base and did not made it on time for originally planned departure) the vessel capacity constraint may be violated. The other possible reason for capacity violation can arise due to cargo packing. The same tonnage of cargo can be packed in the different number of container by suppliers.

- Voyage duration violation

  Each vessels' voyage in the master vessel schedule has a limited duration as it has to be finished before the next planned voyage of the same vessel should start. Voyage duration violation may happen due to increased service time at installations. The case

Master vessel schedule														
1		Vessel 1	**2**		Vessel 2	**3**		Vessel 3	**4**		Vessel 2	**5**		Vessel 1
Mon		**16:00**	**Mon**		**16:00**	**Tue**		**17:00**	**Wed**		**17:00**	**Wed**		**16:00**
	ETA			ETA			ETA			ETA			ETA	
Installation 1	Tue	04:45	Installation 3	Tue	02:45	Installation 6	Wed	07:00	Installation 9	Thu	07:00	Installation 4	Thu	02:45
Installation 2	Tue	11:00	Installation 4	Tue	06:45	Installation 7	Wed	10:00	Installation 10	Thu	14:30	Installation 3	Thu	06:45
Supply base	Wed	04:30	Installation 5	Tue	11:30	Installation 8	Wed	15:15	Installation 1	Thu	18:30	Installation 11	Thu	09:45
			Supply base	Wed	02:30	Supply base	Thu	03:30	Supply base	Fri	09:45	Supply base	Thu	21:45

Figure 2.7: Master vessel schedule

Master vessel schedule											
6		Vessel 3	**7**		Vessel 2	**8**		Vessel 1	**9**		Vessel 3
Thu		**16:00**	**Fri**		**17:00**	**Fri**		**16:00**	**Sat**		**18:00**
	ETA			ETA			ETA			ETA	
Installation 2	Fri	05:30	Installation 13	Sat	07:00	Installation 3	Sat	02:45	Installation 14	Sun	07:15
Installation 12	Fri	13:15	Installation 7	Sat	13:30	Installation 4	Sat	06:45	Installation 5	Sun	15:00
Installation 5	Fri	18:45	Installation 1	Sat	17:30	Installation 11	Sat	09:45	Installation 2	Mon	00:15
Supply base	Sat	09:30	Supply base	Sun	08:45	Installation 8	Sat	12:15	Supply base	Mon	17:45
						Supply base	Sun	00:30			

Figure 2.8: Master vessel schedule (2)

of this increase may be higher cargo demands or/and longer time per lift due to bad weather conditions.

- Missed time window at installation or the base

  Time windows at installations and the base are adding extra complexity to the problem. Assuming the Installation 7 reveal its demand as 28 containers the vessel performing this voyage will arrive at Installation 3, the next in sequence, only by 19:25 while Installation 3 is closed for service from 19:00. The vessel then should wait till 7:00 the next day to start its service. While in some cases waiting at the installation or the base (even for the extended period of time) may still be feasible in terms of voyage duration it greatly reduce vessel utilization and such a voyage usually will not be approved for the execution by responsible logistics planner.

Voyage 2		Vessel 4						
Mon		**16:00**	Demand	Number of lifts per hour	Sailing time	Calculated arrival time	Closing time	Opening time
	ETA							
Installation 7	Tue	11:45	28	7	03:40	11:45		
Installation 3	Tue	15:45	17	10	02:03	19:25	19:00	07:00
Installation 2	Tue	11:30	14	8	04:00	10:45		
Supply base	Wed	16:20				16:30		

Figure 2.9: Duration-infeasible voyage

- Postponed vessel departure

  The vessel departure time is usually set in stone, but when an urgent cargo is delayed for loading at the supply base the logistic planner may decide to delay the whole voyage. The postponed vessel departure may lead to time windows at installations or voyage duration violations.

- Zero demand visits

  During prior planning installations are reporting their needs to an operating company. Among this needs they request the desired visit frequency (number of visits per week) according to their plan of activities. Some of the installations however may request higher visit frequency than is really needed to reinsure their service level. It may lead to zero demand visits in the planned voyage, Such visit should be cancelled.

- Harsh weather conditions at installations

Weather conditions is the serious factor for consideration at NCS, especially in winter. Weather is a nearly unpredictable factor and can lead to withdrawn of one or several installations from the voyage (bad weather conditions at installations locations) or extra waiting time at the installation to perform service. Bad weather conditions in the area of supply vessel operations may lead to delayed or even cancelled supply vessels departures.

The list above is not pretending to be complete. As example, we do not mention possible causes of voyage infeasibility to pickup services.

As operational planning turns out to be the problem that can significantly increase in complexity in almost no time, usually, in real life, logistic planners that deal with this problem do not search for an optimal solution, opting for "good enough" feasible solution instead. This is a better strategy due to a limited time constraints that they have to make necessary operational changes. Before the voyage is set to be executed, all of its constraints should be checked. This needs to be done every day and for every voyage. In case of voyage constraints violation logistics planners try to apply several different demand allocation options and reroute voyages.

The following demand allocation options can be applied to the excess demand:

- Move the visit with excess demand to the other voyage departing on the same day.
- Move excess demand to the next planned departure to the same installation.
- Move the visit with excess demand to the voyage departing on the next day.
- Move the visit with excess demand to a new voyage departing on the same day.

Rerouting of the voyage implies changing the sequence of its visits in a way to obtain better or feasible solution. Rerouting is done after any modification of the voyage occur whether it is removal or insertion of visits. The objective of rerouting is to obtain the least-cost sequence of visits for the voyage, but it can also be done to find the shortest duration.

The objective of daily operational modifications is to minimize the total vessel cost and the number of vessels used while maximizing vessels utilization.

2.2.4 Planning approaches

There exist several ways offshore operating companies choose concerning supply vessel planning. Some of the companies completely outsource supply vessel planning to the third-party logistics company, another employ the hybrid solution that can not be clearly divided into strategic, tactical and operational levels or invent their own solutions.

Offshore operating companies also differ in the approaches they employ for planning of supply vessels. For example, there are companies that plan supplies of production platforms and drilling rigs separately. And while this approach simplify the planning problem in a way, it may lead to increased fixed and variable vessel costs.

In this section we will describe two approaches used for tactical supply vessel planning by company E. The company is doing service of production platforms and exploration rigs with the same fleet of vessels. The supply demands to installations is subdivided into ordinal, extra and storage. Ordinal supply demand concerns stable demand with minor deviations that is known in advance. Extra supply demand deals with demand that has higher variation and uncertainty factors, such as operational-driven demand or ad-hoc (emergency) demand. Storage is the special type of demand that is related to insufficient storage at installations allowing to use vessel capacity in addition to its own capacity. We do not consider storage demand in this thesis.

Approach A

This approach was used until recently. It implies that master vessel schedule (routing plan) is constructed to cover all the demands despite that demand from installations has different degree of uncertainty with one fleet of vessels (namely, ordinal supply pool). In case of ad-hock or unstable needs from installations that are not covered by the slacks in the plan dedicated vessels will be hired from the spot market.

Approach A was used by the company E for extensive period of time and while it has its advantages, such as higher number of voyage optimization possibilities due to integrated planning for different types of installations (as opposite to separated planning, mentioned above), some disadvantages where discovered as well. This planning approach appeared to require much more frequent operational changes to mitigate effects of significantly more uncertain demands from drilling rigs on service of production platforms. It also led to higher service bills for installations with more stable demand when they where served together with exploration rigs due to shared monetary cost of voyage changes done on operational planning level. The ordinal supply vessel pool (vessel fleet) also need to be huge enough for master vessel schedule to be robust (incorporate enough slack to mitigate uncertainties), reducing the need for costly spot vessels. The model representing this approach is depicted on Figure 2.10.

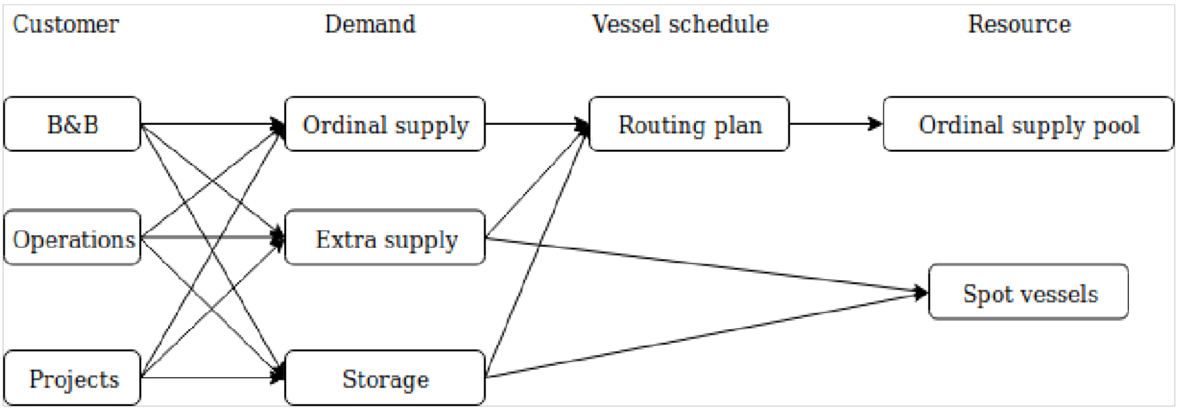

Figure 2.10: Model A

Approach B

Approach B was introduced in order to mitigate problems with varying and uncertain demand.

This approach implies the division to ordinal and flexible type of demand where the type of demand is based upon type and regularity of the need that it is intended to cover. This division criteria helped to separate operation-driven (flexible) demand from the rest of demand with higher uncertainty (extra supply) and known in advance stable (ordinal) demand. Introduction of this changes led to improved master vessel schedule that is no longer responsible for deliveries of demands with higher uncertainty levels. Apart from types of demand from installations supply vessel fleet is now divided to ordinal and flexible pools of vessels. The ordinal pool is covering stable needs by long-term contact vessels while flexible needs are covered by short-term contract vessels from flex pool. The ordinal pool is constructed to ensure 100% service level while keeping its size to a required minimum by maximizing vessel utilization within the pool. Approach B is simplifying tactical planing by introducing new concepts to ordinal planning. One of such concepts is operational plan. This plan is changing weekly and consists of visits to installations with associated demands that are known in advance, but, in contrast to master vessel schedule, they are neither a part of any voyage nor a vessel is assigned to any of them. Visits in the operational plan have known demands, but uncertain day of departure that is tied up to operations at installations. The uncertainty of this visits made them impossible to schedule efficiently prior to the operational level when this uncertainty is eliminated and desired departure date is known. Compared to approach A logistics planners are now responsible not only for modification of planned voyages, but for creation of new flexible voyages, allocation of both types of demand as well as rerouting of the voyages before they can be executed. The model for this approach can be seen on Figure 2.11

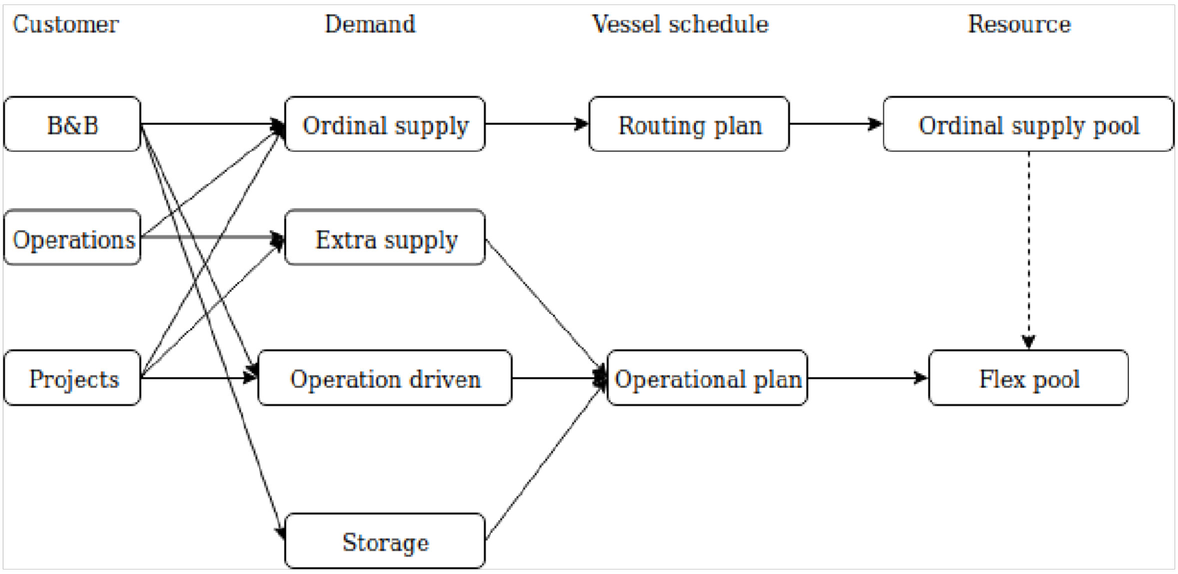

Figure 2.11: Model B

The early results from application of this approach have been highly positive. It led to reduction of production installations service cost, smaller fleet size for the same number of installations and overall higher utilization of supply vessels.

2.3 Problem Definition

This thesis poses the task of operational planning. Approach A involves the use of single pool of vessels for supplies to installations. All voyages are planned according to the master vessel schedule and need to be checked for constraints violation on a daily basis. In case of violation operational modifications are applied to this voyage and additional spot vessel may be hired to cover excess demand. Spot vessel may also be hired in case of unplanned demand (for example, ad hoc demand). Unlike previous approach, approach B deals with simultaneous planning for two pools of vessels and consider different types of demand. Ordinal (planned) demand is allocated to ordinal fleet with respect to master vessel schedule. If possible, flexible demand is also allocated to ordinal fleet. In order to allocate the rest of the flexible demand operational planners construct flexible voyages and then use this voyages for the allocation. In some cases ordinal demand may also appear on flexible voyage. The task of operational planning is considered according to the approach B (two pools of supply vessels; model B).

Operational planning is a complex problem that is solved by professional operational planners with the solutions based on their expertise and experience. It was so, before the new approach was introduced. With the introduction of this approach (and new variables into the problem) the complexity of the operational planning that needs to be performed increased significantly.

For the purpose of problem simplification we have made the following assumptions. We did not consider storage needs from the installations. This is a separate problem in itself and require more data than what is available now. We assume that all of the ad hoc (not planned priority) demands can be served with a flexible pool. The bulk cargo is not considered as the bottleneck for most of the supply vessels is still the deck capacity. We do not include pickups assuming enough space will be left after the deliveries are done. We assume perfect (summer) weather conditions and uniformity of the vessel fleets.

Chapter 3

Research tasks

The supply vessels planning is rather complex and challenging process encountered in offshore oil and gas logistics. The planning is usually done on multiple levels. The operational vessel planning is one of this levels and the one we are focusing on it in this research. At this level logistic planners need to construct daily voyages that where previously planned for this day in the vessel master schedule taking into account revealed demands and weather forecast. The focus of this work is on particular demand allocation in operational supply vessel planning. With the aims to examine the challenges practitioners face during planning process and to develop scientific-based decision support tool for operational supply vessel planning, the following objectives where defined for this thesis:

- Study current principles of fleet and vessels planning on the example of one oil and gas company operating offshore.

  At this stage several visits to the logistics department of offshore operating company E are required to obtain first-hand knowledge on the challenges they face and understand the principles of fleet and vessels planning they currently employ to deal with this challenges.

- Collect and analyse necessary data.

  This stage involves formulation of the data requirements, collection, cleaning and normalizing the data. While most of the data should clearly be requested from the offshore operating company (such as installation demands, vessel master schedule, etc.), some data (such as locations and types of installations, vessel characteristics, etc.) can be gathered from the public sources.

- Formulate the principles for operational vessel planning used by the company and possible options for daily demand allocation.

  With the data and the description of the company operational planning principles in place, the next step should be to come up with the formal definition for each of the possible daily demand allocation options and the development of the basic algorithm for operational planning.

- Implement the basic algorithm for the operational supply vessel planning for a certain subset of available demand allocation options.

  At this stage we need to implement the basic algorithm for the operational supply vessel planning as a computer code according to the selected subset of the demand allocation options.

- Modify the basic algorithm for the operational supply vessel planning for other subsets of available demand allocation options.

  The basic algorithm should be modified to introduce other variants of the algorithm for operational supply vessel planning. The variants of the algorithm correspond to various possibilities of demand allocation.

- Develop a discrete event simulation model to simulate the execution of the vessel master schedule for a certain period under operational modifications.

  To be able to evaluate the application of the algorithm for operational supply vessel planning we need to develop the discrete event simulation model that simulates the activities of vessels over a certain time horizon according to the operational modifications of vessel master schedule for the set of simulated demand scenarios.

- Implement the discrete event simulation models for different variants of the algorithm for operational supply vessel planning.

  This stage involves implementation of the discrete event simulation models as the computer codes. The codes differ in the options for demand allocation used in the algorithm for the operational supply vessel planning.

- Perform comparative analysis of the application of the developed variants of the basic algorithm for the operational supply vessel planning with the use of simulation tools.

The final stage is to compare the performance of the developed operational supply vessel planning algorithms using the evaluation criteria such as the average weekly fleet cost, the average ordinal fleet utilization in time and in capacity; and to discuss the advantages and disadvantages of the developed algorithms with respect to the managerial implications.

Chapter 4

Literature Review

This Chapter is dedicated to the review of available literature related to various phases of the supply vessel planning. It is structured in such a way that each review appears in the section that corresponds to the main focus of the described paper.

The Section 4.1 is dedicated to the strategic phase of the supply vessels planning with the review of Maisiuk and Gribkovskaia (2014). The tactical planning phase is presented in the Section 4.2. The literature in this section is subdivided according to the stochastic and deterministic variants of the Periodic Supply Vessel Planning Problem. This section includes reviews of Fagerholt and Lindstad (2000), Halvorsen-Weare and Fagerholt (2011), Halvorsen-Weare et al. (2012), Shyshou et al. (2012), Norlund and Gribkovskaia (2013, 2017), Norlund et al. (2015), Borthen et al. (2018), Kisialiou et al. (2018a,b, 2019) and Kisialiou (2019). The Section 4.3 is focused on the to the operational supply vessel planning at hand with the reviews of Aas et al. (2007) , Gribkovskaia et al. (2007), Sopot and Gribkovskaia (2014) and Cuesta et al. (2017). We also take a brief look at the role of supply vessels in offshore logistics with Aas et al. (2009).

Aas et al. (2009) is the descriptive academic research that serves as an introduction to various supply vessels planning problems. It outlines the entities involved in the upstream offshore logistics and studies the main characteristics of supply vessels and their features, offshore installations and their operational peculiarities and the general context of operations, namely the NCS. The authors have conducted analyses of the above-mentioned data and were able to identify the main challenges like fleet capacity for different types of cargo, fleet configuration, sailing capacity and cargo operations capability.

4.1 Strategic

The strategic phase of the supply vessel planning is a rather unexplored topic with a few available publications. The research by Maisiuk and Gribkovskaia (2014) is dedicated to the problem of weather uncertainty in strategic supply vessel planning, consequent sailing and operational delays, potential costs of chartering additional vessels or hiring vessels from the spot market based on the predicted rates. This paper propose discrete-event simulation model as the primary tool for evaluating different alternative fleet sizes under stochastic conditions. The simulation was done for the weekly vessel schedules with respect to a certain voyage duration (two or three days). The objective function is minimizing the annual charter vessel costs, annual spot vessel costs and fuel costs of the supply vessels. The results of running the simulation model on the real data have shown that the cost-optimal fleet size depends on the speed of vessels and the total cost is more affected by chartering vessel costs rather than spot vessel costs. The limitations of this work are possibly imprecise intervals for the estimation of model parameter and the possibility to generate solutions only for a relatively small-sized problems.

4.2 Tactical

In comparison to two other phases of the supply vessel planning its tactical phase is the most frequently addressed problem in the literature. Finding the solution for the tactical supply vessel planning problem implies solving the Periodic Supply Vessel Planning Problem (PSVPP) in order to obtain master vessel schedule. The PSVPP may be solved as deterministic or stochastic problem. Both of this options are presented below.

Deterministic PSVPP

Fagerholt and Lindstad (2000) studied operations of the supply vessels and determined inefficiencies in terms of deviations from the vessel schedule while serving the prior needs first with no regard to the optimal schedule. Given the pool of vessels, their capacities and demands for various commodities, the researchers calculated the average number of services at each installation and provided 6 scenarios with different opening hours and number of visits to installations. In order to solve PSVPP the two-step algorithm was proposed. In the first step candidate schedules are generated by including offshore installation visits iteratively. This is done holding a constraint that each offshore installation should be visited at most once on each schedule. Installation demands are fixed at 150% of the average demand levels. Optimal visiting sequences ensured by solving a travelling salesman problem (*TSP*). In the second step, the vessels to be used and their weekly schedules are determined by solving an integer programming model with a fixed minimum number of weekly services (visits) for each installation. A similar two-stage approach is considered by Halvorsen-Weare et al. (2012) with the focus on the minimization of primary costs, i.e. charter vessel costs by finding an optimal fleet size and sailing costs by constructing optimal voyages and vessel schedules. In the first stage they generate all shortest feasible voyages and later solve a set covering model which assigns voyages to vessels and start days ensuring the spread of departures. They are extending the prior work by introducing aspects such as spread of departures, service capacity constraints for the onshore supply depot, and maximum and minimum duration of voyages. Shyshou et al. (2012) is presenting a slightly improved model formulation and a large neighbourhood search (LNS) heuristic for the PSVPP in contrast to prior voyage-based formulation (VBF). This approach is able to solve larger instances involving up to 31 installations (but with increasing loss of the quality of the solution).

The work by Norlund and Gribkovskaia (2013, 2017) is proposing multiple speed optimisation strategies in a deterministic context of PSVPP for building robust solutions that can adapt to stochasticity in weather and demand requirements through speed adjustments. This paper discusses the possibilities of reducing emissions from the supply vessels operating at the NCS through speed optimization. They are made possible by using inter- and intra-voyage waiting time during voyage generation and construction of a weekly schedule. The aim of the research is to achieve better environmental performance of supply vessels without increasing the fleet size and costs incurred. This work has also brought up a three-phased simulation-optimization tool that performs nearly the same in winter season as in perfect conditions. However, it may also result in increasing of fleet size and fixed vessel costs. The benefit of the tool is the selection opportunity i.e. the focus on environmental or efficiency objective.

Kisialiou et al. (2018a) developed an extension of PSVPP — the periodic supply vessel planning problem with flexible departures and coupled vessels (PSVPP-FC). The extensions involve flexible departures (multiple voyage departure options every day) and coupled vessels (possibility of swapping voyages in the second half of the schedule). When the planning horizon for the installation is twice shorter than the one of the supply vessels', then the swapping of schedules in the second half may lead to the cost reduction. It is only possible when the vessels have the same characteristics and their last voyages do not overlap with the potential next ones. Besides that, a voyage-based model for the PSVPP-FC was presented as well as an adaptive large neighbourhood search heuristic (ALNS) which yields optimal or near-optimal solutions on small and mid-sized problem instances considered.

The genetic search-based heuristic for PSVPP was presented by Borthen et al. (2018). In this work authors consider possibilities like voyages spanning over several time periods in the planning horizon. The developed heuristic is capable of providing better solutions to moderate-sized problems (up to 14 installations) using only a fraction of time required by the previous two-stage or LNS methods. They also introduced a new metaheuristic to solve larger problems based on the Hybrid Genetic Search with Adaptive Diversity Control (HGSADC) algorithm of Vidal et al. (2012).The researchers applied the hybrid genetic search first to a fixed fleet os supply vessels in order to determine the near-optimal supply vessel schedules and voyages and then, as a sub-procedure, in order to minimize the fleet size as a primary source of incurred costs.

Stochastic PSVPP

Halvorsen-Weare and Fagerholt (2011) is proposing a two-phase methodology for the set covering PSVPP formulation based construction of robust supply vessel schedules. The first phase is to generate and simulate the set of all shortest feasible voyages to assign a robustness measure (the average amount of non-delivered cargo) to each voyage. The later phase is to increase the cost minimisation objective of the set covering optimisation model by a penalty cost for voyages, depending on their robustness measure. However, the slacks added to each voyage are equal, ignoring voyage characteristics.

Norlund et al. (2015) is addressing the construction of vessel schedules under weather uncertainty in a three-step solution methodology with regard to robustness (robustness measure), environmental performance and cost reduction. The difference between the previous similar researches is that in this case a degree of robustness is introduced. Depending on this degree, both costs and emissions may either increase or decrease. The focus on cost and fuel consumption minimization may lead to insufficient robustness especially in winter season. A simulation-optimization methodology is used to analyse performance under different degrees of robustness (from 0 to 1) for different seasons. An impact of different significant wave heights on the sailing speed and cargo operations is taken into account. First, shortest duration voyages are generated. Second, the voyages are simulated taking robustness requirement into account. Third, a voyage-based set covering model under a cost minimisation objective is solved. This research is trying to solve the problem of emissions reduction in supply vessel planning by proposing a robustness parameter representing a lower bound on the probability that each voyage is feasible within its assigned duration.

Kisialiou et al. (2018b) developed an ALNS-based binary search methodology to generate vessel schedules with different levels of robustness. Robustness was incorporated using the intra- and inter-voyage slacks whose positions and durations depend upon a predefined robustness parameter and voyage characteristics. The evaluation of solutions is based on the simulation model, which allows to define and analyse the trade-off between service level and the total cost of the solution. The following work of Kisialiou et al. (2019) is proposing a methodology for the periodic supply vessel routing problem with uncertain demands. This includes meta-heuristic based on ALNS principles and simulation model used for the assessment of the master vessel schedule performance over a certain time horizon and computation of its expected total cost. The generation of schedules is done with a certain degree of reliability against the uncertainty. The simulation model incorporates several recourse actions alternatives for preventing schedule infeasibility. The latest work by Kisialiou (2019) includes travel and service times uncertainties into the prior formulation. The dynamic inter-and intra-voyage slacks where used in order to control the voyage duration infeasibility under uncertain weather conditions.

4.3 Operational

Operational supply vessel planning is one of the least researched phases of supply vessel planning. This section is the description of several available papers with the main focus on the operational supply vessel planning.

Aas et al. (2007) study the single vessel routing problem with pickups and deliveries (SVRPPD). The researchers examine the role of capacity constraints at installations and the backflow from the installations to the supply base using the single vessel approach in order to find the optimal solution, which minimizes transportation costs, satisfies installations demands and meets the constraints of the supply vessels and the installations. The problem is formulated as the simplified mixed integer linear programming model. The model test results with the real data have shown that the storage and service feasibility requirements have to be introduced and in some cases second visit to the same installation is required to achieve optimality. Another research by Gribkovskaia et al. (2007) considers the single vessel pickup and delivery problem with capacitated customers. The authors develop different construction and improvement heuristics for this problem along with a tabu search heuristic so that they yield load-, storage- and operationally-feasible solutions. For this purpose three basic steps were introduces into each heuristic. Tests on several instances where conducted in order to evaluate results from running developed heuristics and identify the best performing ones. It was spotted that solutions generated by this heuristics are frequently non-Hamiltonian and may contain up to two customers visited twice. The work by Sopot and Gribkovskaia (2014) formulate SVRPPD extended with multiple commodities (deck and bulk; SVRPDMC). There is a possibility for each customer to be visited once or twice. The methodology starts by considering the creation of neighbourhoods to ease the delivery and pickup process. For the separation of the pickup and delivery services this paper introduces a new parameter called the split factor which represents the probability of the "split". The authors compare performance and quality of the solutions obtained with described metaheuristic algorithm yielding non-Hamiltonian routes to Unified Tabu Search algorithm and optimization solver. The former may be ahead of the others in speed while offering comparable quality solutions in accordance with the tests. The extension in form of the multiple selective orders is introduced to the single-vessel pickup and delivery routing problem (VRPSPD) by Cuesta et al. (2017). The authors also present the extended version of the problem in form of the multi-vessel model (mVRPPD) for joint vessel planning and improved utilization. The formulated model has been described as providing considerable economic benefits and improved fleet utilization without complicating current planning procedure. The ALNS heuristic was also presented as the possibility to reduce mVRPPD computational time.

As the conclusion to this Chapter we would like to admit that none of the approaches presented above where identified to be suitable for the operational supply vessel planning problem in our setting. Presented approaches are either different in number of considered commodities or limited to the single-vessel method or both. Similarly, none of the above considers multiple types of demands from installations or their simultaneous allocation.

Chapter 5

Methodology

The purpose of this research is to develop a methodology for operational supply vessel planning with varying demands from installations. The literature on operational supply vessel planing considers deterministic problem formulations without stochastic factors. Moreover, most of the studied operational supply vessel planning problems are single-vessel routing problems with pickups and deliveries. Thus, the optimization models and algorithms developed for these problems can not be used as the methodology for this work. The problem of simultaneous demand allocation and routing of several voyages departing from the supply base on the same day has been studied only recently in Kisialiou et al. (2019) in the context of tactical periodic supply vessel planning. In this paper, the operational modification of voyages called "recourse actions" was applied during the simulation of constructed master vessel schedules to evaluate the expected cost of schedule recourse. However, the demand allocation is done for the single pool of supply vessels and does not consider different types of demands from installations.

The mentioned paper analysed installation demands on the real life data and develop a method to solve PSVPP with demand uncertainty. Literature review showed that PSVPP with demand uncertainty is poor studied yet. However, uncertainty in the sailing and service times was studied by several researches with various approaches. Thus, we can emphasize three main solution approaches for PSVPP with uncertainty.

The methodology we consider the most relevant to our work is formulated as the simulation model with recourse. Its description is as follows. The assumption that the demands are always revealed one day in advance before the planned departure is made. In order to reflect resource actions according to the available alternatives the copy of the master vessel schedule is created for each planning period $n = 1, \ldots, N$. The feasibility of the voyages is ensured by applying recourse actions to each voyage on the daily basis ($d = 1, \ldots, D$) throughout the planning period. Following demands simulation, the service times at installations to be visited on the voyages starting on days d and $(d + 1)\ mod\ D$ are recalculated. The voyages are then rerouted to obtain lower cost visit sequences. The service times at installations are adjusted up or down according to the relation of simulated demand to the planned demand. After rerouting takes place, the set of all vessel capacity and voyage duration infeasible voyages (V^d) is defined. The least-cost recourse actions are executed by feasibly relocating visits from V^d to other voyages departing on the same or the following day (d or $(d + 1)\ mod\ D$). The resulting vessel schedule after the rerouting and recourse actions applied in the planning period n is saved with the corresponding cost. This operation is done for every replication of the simulation. The average expected schedule cost is returned after all of the replications has been executed. The pseudocode of this algorithm can be found in Algorithm 1.

Algorithm 1 Schedule simulation for Model A

```
Modelled demand;
for all replications do
    for n = 1 to N do
        copy of the schedule ← master vessel schedule
        for d = 1 to D do
            if d = 1 and n = 1 then
                Simulate demand for each visit on voyages started on days d and (d+1) mod D;
                Recalculate service times and reroute planned voyages;
            end if
            Simulate demand for each visit on voyages started on day (d + 1) mod D;
            Recalculate service times and reroute planned voyages;
            V^d ← Find infeasible voyages;
            if V^d ≠ ∅ then
                copy of the schedule ← Perform the least cost recourse actions for voyages
                in V^d;
            end if
        end for
        Calculate cost of copy of the schedule;
    end for
    Calculate the average expected schedule cost;
end for
return the average expected schedule cost;
```

As can be seen from the description above the algorithm is working according to the Approach A (Model A) that does not imply multiple vessel pools and several types of demands from installations. The algorithm also assume that demands are always revealed one day in advance.

We will now describe the recourse action alternatives as formulated in Kisialiou et al. (2019). All of the alternatives imply relocation of the excess amount of cargo from the infeasible voyages in V^d to other feasible voyages in a way that they remain feasible in terms of vessel capacity and voyage duration constraints. Feasible voyages used for the insertion of visits are referred to as target voyages.

- Relocation of visits into the planned voyages.

  For all the infeasible voyages from V^d d some visits are relocated into feasible planned voyages departing on days d or $(d + 1)\ mod\ D$.

- The use of available charter vessels.

  An alternative recourse action will be to relocate visits from V^d to the newly created empty voyages starting on day d and performed by available charter vessels. Available charter vessels are vessels available for departure on day d that do not already have planned voyage on the same day.

- Hiring of a spot vessel.

  Hiring of a spot vessel is done in case of impossibility to achieve schedule feasibility with the insertion of visits into the planned and unplanned empty voyages performed by charter vessels. In this case the relocation of visits from V^d is performed onto new empty voyage departing on day d.

  When the recourse action is performed constraints of the target voyage are checked.

  The described methodology is applied to the similar problem, but simplified in a way that it does not consider multiple pools of the supply vessels and types of demands from installations. However, we found it good enough to use as the reference while working on the design support tool. More detailed description of the tool you can find in the Chapter 7.

Chapter 6

Data

The therm *data* represents “facts and statistics collected together for reference or analysis“ according to Oxford Online Dictionary (2019). Thus working with data should be mandatory part of any research focused on data analysis, where the basis for reasoning or calculation is formed by this data.

6.1 Required data

Demands from installations is the major factor in supply vessels planning, especially in the operational planning. Installations demand is fluctuating in time while affected by many factors with different degree of uncertainty. This fact make it necessary to collect as much installations demand data as possible in order to formulate a set of grounded demand allocation options and to choose realistic demand simulation approach. Demands data can be retrieved from the database in the form of daily historical records.

In order to make operational changes one of the things we need to have is the master vessel schedule. The data defined in the schedule is represented by number of planned voyages (departures) on a given day, start and end time of each voyage, voyage to vessel assignment and the set of installations to be visited on the voyage and the sequence of visits. This data will serve as the basis for subsequent modifications.

The records of executed voyages will be helpful to assess the quality of operational changes performed by the decision support tool we are working on.

We also need to have basic data about the offshore installations (name, location, working hours, etc.), supply vessels (name, capacity, sailing speed, etc.) and the onshore base (name, location, working hours, turnaround time, etc.). Some of the required data is shown on Figure 6.1.

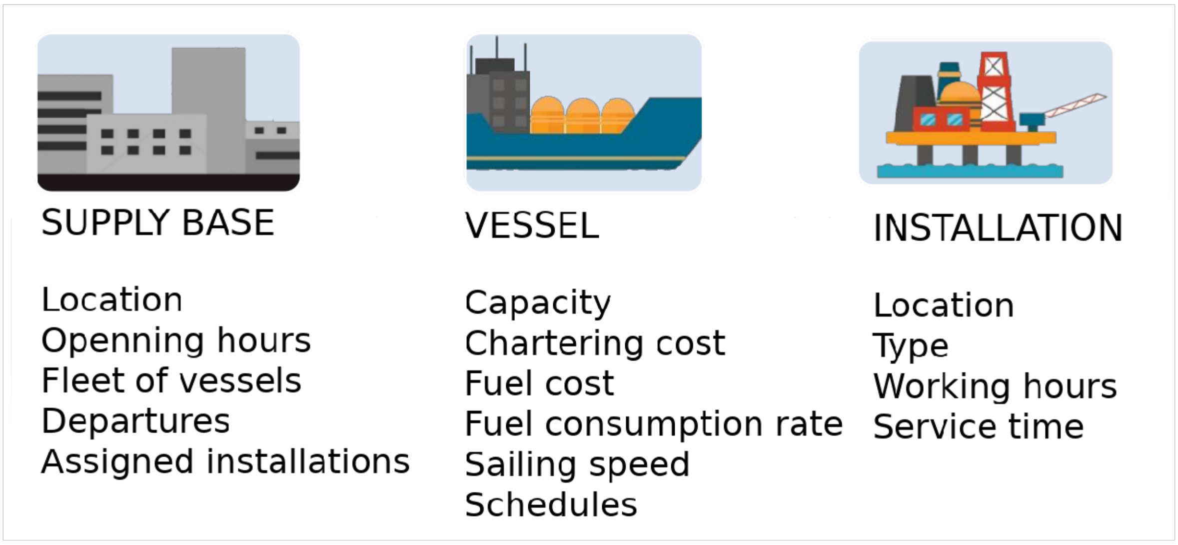

Figure 6.1: Some of the required data

6.2 Data collection

To obtain required data we first turned to offshore operating company E. At our request, the company provided us with the following data:

- Master supply vessel schedule

  The weekly supply vessel schedule is the required basis for our work. Example of the provided data is shown on the Figure 2.8.

- Executed voyages records

  This records are valuable for us, because they represent executed voyages that already undergone manual operational changes by professional logistic planners. They can be used for further comparison with the output of the decision support tool assuming the same input data is given. Example of the executed voyage record can be found on Figure 6.2. The data on pickups and deliveries (in tons) and the total number of lifts for the executed voyage is shown on Figure 6.3.

- Basic data about the supply base and offshore installations

  The basic data about the supply base, such as working hours and turnaround time was provided to us. The company E also provided installations data, such as service time estimates and if the installation is closed at night. The last, but not least was some data about the supply vessels.

Voyage Type	Voyage number	Leg no.	Installation ID	ATD - Date	ATD - Time	ATA - Date	ATA: Time	# of Voyages	Total number of actual calls	Stay time at installation in hours	WOW in hours	Deviation time in hours
Ordinal	115	1	Supply base	04.01.2019	18:00:00	#	00:00:00	1	1	0.0	0.0	0.0
Ordinal	115	2	Installation 7	05.01.2019	13:00:00	05.04.2018	07:05:00	1	1	5.9	0.0	0.0
Ordinal	115	3	Installation 3	06.01.2019	13:10:00	05.04.2018	13:05:00	1	1	0.1	0.0	0.0
Ordinal	115	4	Installation 4	05.01.2019	15:10:00	05.04.2018	14:05:00	1	1	1.1	0.0	0.0
Ordinal	115	5	Supply base	06.01.2019	00:00:00	06.04.2018	08:10:00	1				

Figure 6.2: Executed voyage record

Voyage number	Route	Installation ID	Transport Direction	NR. VOYAGES	TOTAL WEIGHT TRANSPORTED (TON)	DECK OUT (TON)	DECK IN (TON)	# LIFTS
107320	1070	INST1	OB	1	33.33		33.33	13
107320	1070	INST4	OB	1	120.05		120.05	28
107320	1070	INST7	OB	1	33.1		33.1	9
107320	1218	INST1	BO	1	67.81	67.81		16
107320	1302	INST7	BO	1	18.7	18.7		4
107320	1755	INST4	BO	1	211.5	66.3		29
107320	Result			1	484.49	152.81	186.48	99

Figure 6.3: Executed voyage demand data

Unfortunately, we could not get historical data on the demands from installations that would be the most valuable to have. In connection with this we decided to recreate this data based on the secondary processed data for the executed voyages we have.

Some of the basic data about the installations, such as type and location of the installation was retrieved from public sources, namely *The Norwegian Petroleum Directorate Fact Pages* (`http://factpages.npd.no/factpages`). We also got some information about the supply vessels from the websites of several offshore vessel renting companies.

6.3 Data analysis

The huge amount of data is usually required to perform the high quality data analysis. This happens to be a major limitation to us as the current approach for the operational planning at company E is relatively new thus the only data we where able to get is limited by one month. Another complexity is added by the time data is gathered. The only data we are able to use is corresponding to the winter month that is usually greatly affected by the weather conditions. We also encountered numerous voyages with missing data, like start or end data (the vessel departed from the supply base and never finished the voyage, etc.). As expected from secondary data, there where a lot of deviations from the original schedule (the master supply vessel schedule) and the defined set of customers. Reasons behind some of this changes were not clear to us and resulted in multiple struggles along the way. After we cleared out everything that we managed to, the evaluation of different statistical techniques to get the independent representative demand distribution for every installation and each type of its demand come into play. Most of the distribution bootstrapping methods happen to be not applicable, due to small sample sizes we have. At the end we decided to assume that demands from the installations will follow PERT probability distribution as advised in Kisialiou et al. (2018a).

The PERT distribution is a special case of the four parameter beta distribution and can be thought of as a smooth version of the triangular distribution. It is defined by minimum (a), mode (b), maximum (c) and a shape parameter, λ. In contrast to triangular distribution its most likely value is calculated as follows $\mu = \frac{a+\gamma b+c}{\gamma+2}$ and is not simply the average of the three parameters. The resulting distributions for each installation and type of demand (sand colour for ordinal, blue colour for flexible) are shown on the Figure 6.4. The demand distributions happen to be rather versatile. The noticeable difference of the curve for different types of demands emphasises the importance of this separation.

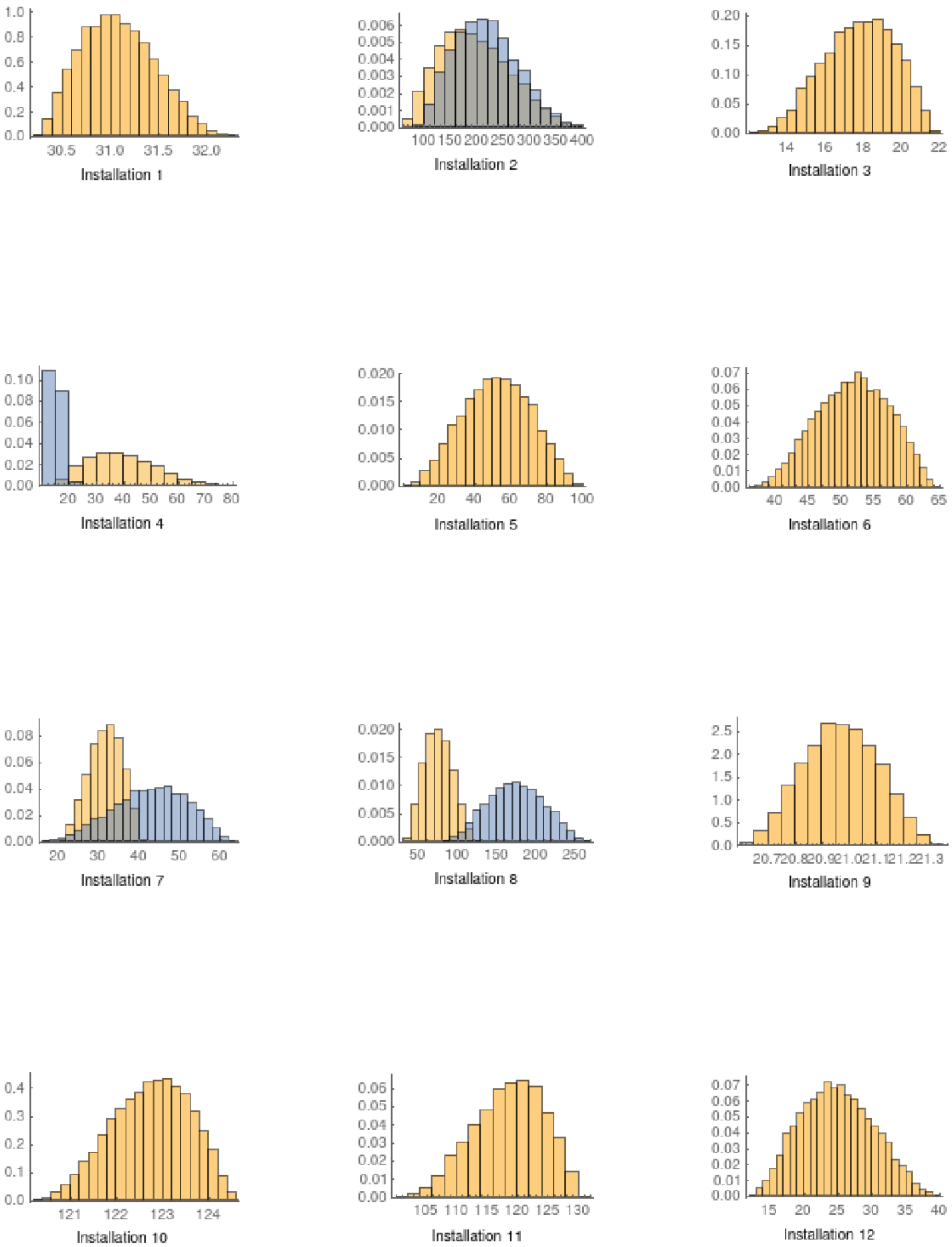

Figure 6.4: Demands from installations (ton)

Chapter 7

Algorithms for operational supply vessel planning

In this chapter we present a new methodology for the operational supply vessel planning. The methodology involves the optimization algorithms for construction of feasible voyages departing at any given day according to master vessel schedule.

The objective of the optimization algorithms is to find the least cost allocation of demands revealed for a given day. Each algorithm considers a set of possible demand allocation options applied simultaneously. The main idea of the algorithms is to remove visits with demands that cause voyage invisibility and feasibly reinsert them into other voyages minimizing the added cost of insertion.

In this thesis we have developed two algorithms for operational supply vessel planning: the basic algorithm using limited set of demand allocation options and the extended version of the basic algorithm with the larger set of demand allocation options.

The reminder of this chapter is organized as follows. In Section 7.1 we introduce the description of demand allocation options. We present the basic optimization algorithm developed for the operational supply vessel planning in Section 7.2 and its extended version in Section 7.3.

7.1 Demand allocation options

In what follows we formulate the demand allocation options identified during interviews with the logistics planners of company E.

According to the ordinal vessel schedule, for each day it is defined a set of vessel departures (voyages) with a set of installations assigned to each voyage. After the actual demand of installations is revealed, for each voyage the capacity feasibility check is performed. In case of vessel load violation the installations whose demand should be allocated are identified. This installations identification is based upon the “fair capacity share“ principle. The principle implies that if the total revealed demand of all installations on the voyage exceeds the total vessel capacity, the installations whose demand exceeds the value equal to (the total vessel capacity) / (number of visits on the voyage) are identified as those whose demand should be allocated. In what follows we refer to the installation whose demand should be allocated as the visit with excess demand.

The following demand allocation options can be applied to the excess demand:

- Move the visit with excess demand to the other voyage departing on the same day.

  This is usually the preferred option. It can be used if there is other vessel set for departure on the same day that has enough spare capacity and time to do the service. This will generally lead to a longer route, but no extra monetary costs for the installation.

- Move excess demand to the next planned departure to the same installation.

  This option is to split the excess demand, moving part of it to the next planned visit (for example, move part of the demand from voyage on Monday to voyage on Thursday, where visit to the same installation is planned). This changes will introduce the reduction on service level of this particular installation forcing it to wait several days for remaining cargo to be dispatched. Such option will require negotiations with the installation.

- Move the visit with excess demand to the voyage departing on the next day.

  If installation is eager to get all of its demand as soon as possible due to reasons, it will not accept previous option. In this case, if installation agreed, excess demand can be moved to the next day (for example, the visit from Monday voyage can be moved to the voyage departing on Tuesday). The effect of this changes will be reduced flexibility and increased complexity of operational planning the next day.

- Move the visit with excess demand to a new voyage departing on the same day.

This is the least-cost effective option. As the last resort logistics planner may decide to setup a new previously unplanned voyage for the vessel available at the base or hire a spot vessel for this voyage. Creating a new voyage may result in significant costs increase (in case of the spot vessel), but sometimes it is necessary to react to ad-hock (emergency) situation at the installation. Assigning unplanned voyage to charter vessel available at the base require confirmation that this vessel will be able to return to the base to be loaded for its own planned voyage.

7.2 The basic algorithm for the operational supply vessel planning

The following section contains a brief description of the basic algorithm for the operational supply vessel planning that was developed and implemented as the part of this thesis.

The definitions needed for feather description are as follows. In-construction voyages set – set of voyages which are manipulated before they can be executed. This set can include both feasible and infeasible voyages. Initially populated with planned voyages from master schedule. Ready-to-operate voyages set – set of voyages that undergone necessary changes and ready to be executed. Pulled-out visits set – set of visits that violated constraints of their original voyage and need to be inserted into a different voyage.

The possible alternatives for demand allocation options include the following. Couple (C/NC) – alternative to couple installations' ordinal and flexible demands to be delivered on the same voyage. Delay (D/ND) – alternative allowing to postpone delivery to the next day. Split (S/NS) – alternative to split installations' demand to be delivered via different voyages.

Algorithm alternatives can be defined as a set of possible demand allocation options:

- NC, ND, NS
- C, ND, NS
- NC, ND, S
- C, ND, S

In this work we opt out of splitting the demands or delaying cargo departures due to required negotiations. In real life logistics planners facing this problem can contact the installation and negotiate in order to apply some of the options mentioned above. We do not have this possibility, thus intentionally skipping this options.

In what follows we formulate the basic (NC, ND, NS) algorithm and its extended version with coupled demands (C, ND, NS).

The basic algorithm for operational supply vessel planning (NC, ND, NS) implies the following steps.

Algorithm 2 The basic algorithm for operational supply vessel planning (NC, ND, NS)

1: Define empty set of ready-to-operate voyages.
2: Define empty set of pulled-out visits.
3: Define the set of in-construction voyages that originally includes planned (ordinal) voyages for a given day.
4: Removal loop
For each voyage in the set of in-construction voyages check if the voyage is capacity-feasible for revealed daily demands. If not, gradually remove visit(s) violating fair capacity share until the voyage become capacity-feasible. Put removed visit(s) into pulled-out visits set. If the capacity utilization of an in-construction voyage exceeds a certain value (ex. 90%), move this voyage into the set of ready-to-operate voyages.
5: If the total demand of pulled-out visits exceeds the total spare capacity of in-construction voyages, add additional voyage(s) to the in-construction voyages set. Assign each voyage to ordinary vessel available at the base otherwise assign it to the flexible vessel.
6: Insertion loop.
Generate all possible insertion options of all visits from the pulled-out visits set into voyages from the in-construction voyages set, considering all sequences of visits in in-construction voyages.
Check all insertion options on capacity- and time-windows- feasibility.
If there aren't any feasible insertion options of all visits from the pulled-out visits set, add additional voyage to the in-construction voyages set. Assign this voyage to the ordinary vessel available the base otherwise assign it to the flexible vessel.
Repeat until all visits are inserted.
From all insertion options select the option with the lowest insertion cost (NB! The cost of insertion to a voyage assigned to the flexible vessel includes vessel charter cost).
Implement the insertion option with the lowest insertion cost.
7: Check capacity utilization of all in-construction voyages. If the capacity utilization of an in-construction voyage exceeds a certain value (ex. 90%), move this voyage into the set of ready-to-operate voyages.
8: Fill pulled-out visits set with flexible demand visits.
9: If the total demand of pulled-out visits exceeds the total spare capacity of in-construction voyages, add additional voyage(s) to the in-construction voyages set. Assign each voyage to ordinary vessel available the base otherwise assign it to the flexible vessel.
10: Repeat the insertion loop.

7.3 The extended version of the algorithm

In this section we present the version of the algorithm extended with coupled demands (C, ND, NS). The benefit of the extended version of the operational supply vessel planning algorithm is the potential savings on multiple visits to the same offshore installation in case of the delivery of both types of demand (ordinal and flexible).

Algorithm 3 The version of the algorithm extended with coupled demands (C, ND, NS)

1: Define empty set of ready-to-operate voyages.
2: Define empty set of pulled-out visits.
3: *Couple ordinal and flexible demands to the same installation on the given day if any. Consider coupled demands as ordinal.*
4: Define the set of in-construction voyages that originally includes planned (ordinal) voyages for a given day.
5: Removal loop.
For each voyage in the set of in-construction voyages check if the voyage is capacity-feasible for revealed daily demands. If not, gradually remove visit(s) violating fair capacity share until the voyage become capacity-feasible. Put removed visit(s) into pulled-out visits set. If the capacity utilization of an in-construction voyage exceeds a certain value (ex. 90%), move this voyage into the set of ready-to-operate voyages.
If the total demand of pulled-out visits exceeds the total spare capacity of in-construction voyages, add additional voyage(s) to the in-construction voyages set. Assign each voyage to ordinary vessel available the base otherwise assign it to the flexible vessel.
6: Insertion loop
Generate all possible insertion options of all visits from the pulled-out visits set into voyages from the in-construction voyages set, considering all sequences of visits in in-construction voyages.
Check all insertion options on capacity- and time-windows- feasibility.
If there aren't any feasible insertion options of all visits from the pulled-out visits set, *try to decouple previously coupled demands, if any and retry the insertion loop*. In case there is no coupled demands to decouple, add additional voyage to the in-construction voyages set. Assign this voyage to the ordinary vessel available the base otherwise assign it to the flexible vessel.
Repeat until all visits are inserted.
From all insertion options select the option with the lowest insertion cost (NB! The cost of insertion to a voyage assigned to the flexible vessel includes vessel charter cost).
Implement the insertion option with the lowest insertion cost.
Check capacity utilization of all in-construction voyages. If the capacity utilization of an in-construction voyage exceeds a certain value (ex. 90%), move this voyage into the set of ready-to-operate voyages.
7: Fill pulled-out visits set with flexible demand visits.
8: If the total demand of pulled-out visits exceeds the total spare capacity of in-construction voyages, add additional voyage(s) to the in-construction voyages set. Assign each voyage to ordinary vessel available the base otherwise assign it to the flexible vessel.
9: Repeat the insertion loop.

Chapter 8

Evaluation of algorithms with discrete event simulation models

In order to evaluate the performance of operational supply vessel planning algorithms and to do comparative analysis we have developed a discrete event simulation models for the computation of vessels utilization and costs. The models simulate over a certain horizon the execution of voyages performed by vessels from the ordinal and flexible fleet after their operational modifications.

The model for the simulation tools is similar to the one in Algorithm 1. The difference is in application of the basic algorithm developed and its extension instead of line 14 in the above mentioned algorithm. The more major difference lies in management of several pools of the supply vessels in the developed simulation models, compared to the one described in Algorithm 1.

In order to compare the developed basic algorithm for supply vessel planning and its extension with coupled demands an instance of the problem with 14 installations was considered. The fleet size of the supply base was set at 4 ordinal supply vessels and 3 flexible vessels. The corresponding discrete event simulation models where launched then. The results of their execution are presented below.

The results given by the extended algorithm are mostly of the better quality, but in several cases of high utilization of ordinal supply vessels pool it may yield a more expensive solution (week 2).

Week	Ordinal cost, NOK	Flexible cost, NOK	Ordinal utilization	Flexible utilization
1	301238.52	221616.18	3.2	1.5
2	347162.79	536382.85	3.3	2.2
3	500060.64	192112.11	3.8	1.4
4	356361.70	493985.48	3.5	1.9

Table 8.1: Results from the basic version of the algorithm

Week	Ordinal cost, NOK	Flexible cost, NOK	Ordinal utilization	Flexible utilization
1	309735.17	179744.56	3.6	1.3
2	493321.10	468451.58	3.8	1.9
3	418831.82	200050.13	3.5	1.4
4	430870.46	393678.77	3.7	1.7

Table 8.2: Results from the extended version of the algorithm

Chapter 9

Conclusion and future research

In this thesis we studied current principles of fleet and vessels planning of the offshore operator company, collected and analysed necessary data, formulated the set of possible demand allocation options, developed and implemented as a computer code the basic algorithm for the supply vessels planning and the modification of this algorithm for each option from the subset of possible demand allocation options. To evaluate the application of the developed algorithms the discrete event simulation model was implemented for every modification of the algorithm. At last we made the performance comparison of the developed operational supply vessel planning algorithms with the help of the simulation models.

The possibilities for future research considered to be fairly wide. The one may find an inspiration in the assumptions of this thesis. There exist several possibilities of varying difficulty for extending the problem. The precented formulation may be extended with pickup service at installations, bulk cargo, heterogeneous fleet of supply vessels, storage needs from installations or weather uncertainties.

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