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Strategic Fleet Renewal for Offshore Support Vessels

A maritime fleet size and mix problem

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PREFACE

This master's thesis is the final result for a Master of Science at the Norwegian University of Science and Technology. The degree specialization is in Marine Systems Design at the Department of Marine Technology.

This thesis examines optimal fleet renewal plans for a fleet of offshore support vessels operating in the offshore market. The master's thesis is a continuation of my work for the project thesis delivered in December 2014.

I would like to express my gratitude to my supervisor Professor Bjørn Egil Asbjørnslett at the Department of Marine Technology, who has been an invaluable resource and provided me with great guidance and counselling. I would also like to thank DeepOcean for providing me with both information and opinions about their offshore operations and offshore support vessels. Last, I would also like to give special thanks to the Ph.D. candidates Rikard Bakkehaug and Øyvind Patricksson at the Department of Marine Technology, who gave me guidance in working with Mosel Xpress.

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ABSTRACT

In this thesis, a model is proposed for the maritime fleet renewal problem (MFRP) with applications for offshore support vessels (OSVs). This topic of strategic fleet renewal is important in order to ensure a cost efficient deployment of the future fleet. The central problem to be addressed within this work is to study if it is possible to develop a suitable and relevant model to determine the different aspects of renewing a fleet of OSVs.

The MFRP consists of deciding how many ships of each type to use in order to meet future demand. The MFRP is suitable for planning a fleet for a long time horizon, and it finds the best modification of the current fleet of ships in order to adapt to changes in the future market.

The proposed model is developed for the MFRP, and contains decision variables that state how many and of what type of ship that should be sold or bought. In addition, tactical decisions are included, such as chartering in or chartering out and fleet operations, while at the same time maximizing profit. The model is a mixed integer programming (MIP) model, developed as a two-stage scenario based model with a stochastic approach. The demand, costs, and revenues are dependent on the uncertainty for this problem, and a scenario is a possible development of the market status for the offshore industry. This scenario-based technique provides advantages in handling the uncertainty of the future market, when modeling this problem. By using stochastic programming, the problem gets a realistic approach on the uncertainty aspects of programming.

The model is implemented in commercial software with input data for three test instances, with three scenarios. The test instances are chosen to reflect shipping companies of different sizes. The computational study shows that the model is able to solve all test instances. The main results of the computational study show that the model gives results which indicate that the model works well with a fleet of OSVs. In addition, the results show that the deterministic solution can be sufficient in many of the test cases. The deterministic solution captures the right fleet mix in order to meet future demand, and this can be useful information to reduce the complexity of the problem.

When performing a sensitivity analysis, the model structure did not show much sensitivity about changes. This gives an indication that the model is developed in a robust manner, and can withstand impacts from parameter changes in a large degree. However, the input data can contain some sources of error, connected to how the costs and revenues are developing through the planning horizon.

The results from the expected value of perfect information indicate that the testing is done with too few scenarios. The scenarios could be improved by introducing a better method for scenario generating, in addition to a probability distribution. The scenarios developed in this thesis can be seen as a representative example, which give the possibility of doing tests and evaluations of the model.

Strategic fleet renewal of ships is a crucial and difficult problem in maritime transportation, and the proposed model may serve as a decision support tool for fleet renewal for offshore shipping. The key findings from the computational study have not been the results themselves, but on the different ways in which the model can be handled as a strategic decision support tool for a fleet of OSVs. For the presented problem, there are limitations connected to the lack of earlier studies about this topic. In addition, the computational study is performed based on input data provided by second-hand distributors.

The model performs sufficient regarding fleet renewal decisions, and the underlying operational decisions are also satisfactorily performed. The presented model identifies the strategic decisions regarding fleet renewal, in order to maximize profit for future deployment of the fleet.

SAMMENDRAG

Denne masteroppgaven presenterer en modell som fungerer for det maritime flåtefornyelsesproblemet (MFRP) av offshore support skip (OSVer). Strategisk flåtefornyelse er et viktig bidrag for å sikre en kostnadseffektiv utnyttelse av den fremtidige skipsflåten. Hensikten med denne oppgaven er å undersøke om det er mulig å utvikle en passende flåtedisponeringsmodell, som inkluderer viktig aspekter ved en OSV-flåte.

MFRP er et problem hvor man ønsker å bestemme hvor mange skip innen hver skipskategori som skal benyttes, for å være godt forberedt til å møte den framtidige etterspørselen. Modeller for MFRP er passende i tilfeller hvor man vil planlegge flåtedisponeringen for en lang planleggingshorisont, og den vil finne den beste måten å modifisere dagens flåte, slik at den kan møte fremtidens etterspørsel og endringer i markedsutviklingen på best mulig måte.

Den matematiske modellen inneholder beslutningsvariabler, som tar avgjørelser rundt hvilke skip som skal selges, kjøpes, chartres ut, chartres in og legges på opplag. Disse beslutningene tas med et ønske om å maksimere den totale profitten. I tillegg har modellen operasjonelle beslutningsvariabler, som bestemmer hvilke skip som skal operere på hvilke kontakter. Den utviklede modellen er en blandet heltallsmodell (MIP), som er utviklet som en to-stegs scenariobasert modell med stokastisk tilnærming. Dette gjør det mulig å inkludere usikre elementer slik som den fremtidige markedsetterspørselen. Et scenario er en mulig utvikling av offshoremarkedet, hvor oljeprisen er den avgjørende faktoren. Etterspørselen, kostnadene og inntektene er avhengig av markedet, og er derfor usikre parametere. Ved å benytte scenarier er det mulig å betrakte usikkerheten rundt den fremtidige utviklingen. Gjennom stokastisk programmering får problemet en virkelighetsnær tilnærming, da den stokastiske programmeringen tar hensyn til de usikre aspektene av modelleringen.

Modellen er testet i en beregningsstudie. Den er implementert med inputdata for tre testtilfeller, hvert med tre scenarier. De tre testtilfellene er valgt for å reflektere rederier i ulike størrelser. Beregningstiden viser at modellen er pålitelig nok til å løse alle tre testtilfeller. Hovedresultatene viser at modellen fungerer godt for en OSV-flåte. I tillegg viser resultatene at den deterministiske løsningen kan være tilstrekkelig i mange av testtilfellene, da den fanger opp den rette flåtesammensetningen for å møte den fremtidige etterspørselen. Dette kan være nyttig informasjon, for å kunne redusere kompleksiteten av det stokastiske problemet.

Modellen har gått igjennom en sensitivitetsanalyse, hvor forskjellige parametere har blitt endret for å teste hvordan modellen reagerer. Resultatene av disse testene viser at modellen fungerer tilfredsstillende for alle testkjøringene. I tillegg viser resultatene at modellstrukturen har lite følsomhet mot endringer i parametere. Dette gir en indikasjon på at modellen er utviklet på en robust måte, og den tåler parameterendringer i en stor grad.

Verdien av perfekt informasjon (EVPI) er også regnet ut. Resultatene ved EVPI indikerer at testingen er utført med for få scenarier. Scenariene kan forbedres ved å innføre en bedre metode for generering av scenarier, i tillegg til at hvert scenario kan gis en sannsynlighetsfordeling. Scenariene som er utviklet i denne oppgaven kan anses som et representativt eksempel, som gir muligheten for å gjøre tester og evalueringer av modellen.

Strategisk flåtefornyelse er et viktig og vanskelig problem i maritim shipping. Den utviklede modellen kan tjene som et beslutningsverktøy ved strategisk flåtefornyelse i offshore shipping. Det er visse begrensninger ved den utviklede modellen. Litteraturstudien viser at det er begrenset med tidligere studier rundt flåtefornyelse for OSVer. Modellen er derfor utviklet helt fra bunn, kun inspirert fra tidligere flåtefornyelsesmodeller innen linjeshipping. I tillegg er inputdataen til beregningsstudien basert på data fra andrehånds distributører. Dette kan føre til unøyaktige svar med tanke på kostnader og inntekter. Hovedfunnene fra studien har ikke vært selve resultatene, men hvordan modellen fungerer for en flåte av OSVer. Modellen gjennomfører tilfredsstillende beslutninger, både når det gjelder operasjonelle og strategiske beslutninger.

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1 INTRODUCTION

Oil and gas production and exportation make up one of the biggest industries in Norway, where the production takes place offshore. It is necessary to regularly supply these installations to ensure efficient and continuous production. The only way to supply all of these installations is through offshore support vessels (OSVs). These vessels can perform supply and maintenance operations, in addition to supporting various subsea installations and operations through tasks such as installing, demolishing, maintaining, and repairing subsea installations. All of these operations are necessary to keep the down-time on installations to a minimum.

Offshore support vessels are a costly resource for both operators and ship owners. In fact, these vessels represent the largest cost elements in the upstream supply chain of oil and gas installations (Aas et al., 2009). In order to reduce costs, it is beneficial to have good logistical planning for the fleet of vessels for the future. This can be accomplished by ensuring good utilization of the fleet, by maximizing the number of days in operation at sea and the ship's capacity on each trip.

When performing logistical planning for future years, it is important to predict the market demand. The ship owner has a big challenge when predicting the future demands of ships. The shipping industry has market development with cyclic behaviour with varying peaks and troughs (Stopford, 2009). The market conditions of OSVs are mainly dependent on the offshore market and the oil price. Stopford (2009) indicates an average cycle length of about 7 years in shipping industries, where a cycle contains a peak and a trough. This is only an estimate and the variance is large. The world's economic and political status affect these cycles significantly, as do changes in the industry. Changes in market conditions can happen rapidly from year to year, such as the financial crisis in 2008. In addition, the current offshore market in Norway is being affected by the decrease in the oil price, as well as by rising costs in the industry, which have an impact on the demand of OSVs. The price of oil is dependent on supply and demand, and the sentiment of the market. When the supply is much bigger than the demand, costly offshore oil exploration is no longer in demand. This affects the demand for OSVs. In situations like this, it can be essential to have an appropriate fleet at hand.

A trough in the market condition can cause many challenges for a ship owner. Today's decrease in oil prices gives an increased market uncertainty in oil services because of financial challenges. The demand growth of OSVs is expected to come down, where the demand is driven by production support, rig support and subsea construction support

(Platou, 2015). The decrease in demand affects shipbuilding, where speculative orders are made and orders are placed at inexperienced yards (Platou, 2015). Cancellations are made more often and deliveries are further postponed. This also affects the ship owners as the utilization of ships and charter rates decreases. There are many theories as to how the oil price will continue to behave. However, an important aspect when predicting market behaviour is to remain prepared for both good and bad scenarios.

High costs and low oil prices present a difficult market situation for the OSV industry. Strategic planning can contribute by helping companies survive in a tough market. By adapting fleet capacity and vessel characteristics to new market requirements, the ship owner will be better equipped to meet future market changes (Pantuso, Fagerholt, & Wallace, 2014).

When it comes to the acquisition and disposal of ships, the shipping industry generally has long planning horizons. Lead times from an order until new ships are delivered are normally from one year to four years. The lifetime of a ship is around 25 years. These factors make it difficult to plan for investments that will last several decades, especially when the market changes in the same period. Good strategic planning can therefore be difficult to perform.

When performing strategic planning, the planner wants to foresee the requirements for the different types of vessels. Bigger OSVs are more complex and often well-equipped. These vessels can do almost all kinds of operations. Smaller OSVs have less space for equipment and their flexibility is therefore smaller than for bigger vessels. The main question for planners is basically if they should financially decide to have a few big vessels or many small vessels.

Good decision tools have proven to be valuable for planners in earlier research (Halvorsen-Weare et al., 2012). They can result in reducing the unnecessary number of OSVs in the fleet, while maintaining an efficient and reliable supply service. Such efforts can result in great cost saving.

Maritime transportation problems are classified into three different shipping modes: Industrial, tramp, and liner shipping (Lawrence, 1972). Liner shipping includes ships that follow a fixed route, trying to maximize profit. One can compare liner shipping to public bus routes. Tramp shipping is shipping where the vessels follow the available cargos, trying to maximize profit, similar to a taxi. Industrial shipping is shipping where the operator owns the cargo and has control over the fleet. The operator wants to minimize the costs of delivering cargos.

The planning horizons in maritime transportation problems are commonly divided into three types, depending on the length of the planning horizon. The three types are strategic, tactical, and operational planning. Strategic planning has the longest planning horizon, which may be a planning horizon from several months up to years into the future. Tactical problems have a planning horizon of weeks to months, while operational problems have a shorter planning horizon from hours up to days. Operational planning problems involve day-to-day operations, and are based on here and now decisions. Uncertainty tends to increase for longer planning horizons. Tactical and operational problems usually have less uncertainty than strategic problems.

One type of decision tool that can be applied in these cases is the maritime fleet size and mix problem (MFSMP). The MFSMP is based on an optimization model, where the purpose is to find the ideal fleet composition and size to meet future market requirements. The MFSMP consists of deciding the best fleet to service a given demand, while at the same time optimizing the utilization of the fleet capacity. The problem can be defined as deciding how many ships of each type to use in order to perform some transportation task (Pantuso, 2014). The reason for using the MFSMP is to focus on how to manage the fleet over time. Decisions such as how many ships to buy, sell, charter-in and -out can also be included in the model (Christiansen et al., 2013). The timing of these activities might also be beneficial to include in the model. These aspects can make the model more flexible, and it increases the possibility of meeting changes in supply and demand at every stage in the market.

The MFSMP can give decision makers a good decision tool when making strategic decisions, especially when incorporating the above mentioned factors. Shipping companies can have an extensive heterogeneous fleet which might be difficult to manage when planning. To make good strategic decisions, a great amount of fleet information needs to be collected. The workload for this can be large, and the uncertainty of the market makes it even harder to make good decisions. In cases like this, the MFSMP can liberate much of the workload, and at the same time give better results.

The strategic version of the MFSMP is in operations research called the fleet renewal problem (MFRP), which is suitable for planning a fleet for a long time horizon. The MFRP consists of deciding how many ships of each type to use in order to meet future demand, as well as when and how to do so (Pantuso, Fagerholt, & Wallace, 2014). This is important because of the long life expectancy of ships, large investment costs, uncertainty in demand, freight rates, and operational costs (Patricksson et al., 2015). The MFRP finds the best modification of the current fleet of ships in order to adapt to changes in the market. The fleet renewal problem also has an underlying tactical problem. Tactical decisions are decisions such as chartering in or out and fleet operations, while at the same time minimizing costs or maximizing profit.

The MFRP is traditionally a combination of strategic fleet size and mix decisions, and vehicle routing decisions in order to minimize lifecycle costs (Patricksson et al., 2015). The combination of these decisions gives us the possibility to link important aspects into the problem of fleet renewal. This can include important aspects such as physical dimensions, ship compatibility, and operating costs. Acquisition, selling, scrapping, chartering out, and chartering in vessels are typical decisions in a MFRP. Acquisition includes ordering new-builds, buying second hand, and engaging in long-term charter contracts (Patricksson et al., 2015). The underlying deployment problem also includes routing decisions (Patricksson et al., 2015).

Traditionally fleet renewal decisions can include decisions such as the sale of ships, which can be preferable for tactical reasons. Old and outdated vessels can be scrapped. If the market or demand is poor, it might be relevant to have some ships laid-up or chartered out for a shorter period. Reconfigurations and updates to the existing vessels can also be relevant in feet renewal decisions. This can for example involve increasing cargo capacities by increasing the dimensions of a ship or replacing machinery.

There is a high degree of uncertainty in strategic planning with a long planning horizon, related to the uncertainty in future market demands. There are two main approaches to handle uncertainty in operations research; robust optimization and stochastic programming. This thesis will handle stochastic programming with a scenario-based optimization model.

This thesis presents a decision tool that can be applied for strategic decision problems in the offshore industry. The model is designed to support the decision process and it is not designed to replace expert opinions. The model is based on the fleet renewal problem, which will find the optimal size and composition of a fleet of offshore support vessels.

This thesis is structured as follows: Chapter 2 will describe the problem and presents different aspects of the problem. Chapter 3 presents a short literature study done for this thesis. Chapter 4 will give an introduction to uncertainty and how this is implemented into the model. In Chapter 5, a description of the optimization model is presented. Chapter 6 presents the results of the computational study. The main results are discussed in Chapter 7. The conclusion is presented in Chapter 8. Chapter 9 presents recommendations for further work.

2 PROBLEM DESCRIPTION

This chapter presents the problem addressed for this thesis. First the maritime fleet renewal problem (MFRP) is described, followed by a presentation of ship types and contracts specific for the problem assessed in this thesis. Last, the uncertainty aspects and objective of the thesis is presented.

2.1 The maritime fleet renewal problem

The problem considered in this thesis is a fleet renewal problem for the offshore industry, where the renewal decisions consider when to buy and sell ships, in addition to recourse actions such as chartering in and chartering out. The problem is established from the offshore service company point of view, where the company acts as both the operator and the ship owner. The problem for offshore service companies is to determine how to manage their fleet in the long term, when it comes to selling, buying, and chartering of vessels, given an uncertain future market. The goal is to maximize profit for the offshore service company. The objective of the problem is to determine how many ships to sell and buy, in order to meet the future market requirements.

The aim of this thesis is to study if it is possible to develop a new model for a fleet of OSVs, inspired by already developed models in liner shipping. The offshore oil and gas segment has a diversity of installations that requires different services from OSVs. The OSVs are a type of vessel can be designed in nearly any size and design, with different equipment onboard.

When solving a MFRP, operational decisions are considered in order to find how much capacity is needed to meet the demand. Operational decisions are decisions on which contract to operate. The MFRP is on decisions to be taken here and now, i.e. which ships to buy and sell in the upcoming period. The decisions proposed for the following periods are meant as decision support, meaning that they explain how the solution will affect the development of the fleet in the following periods. The final decisions for these following periods are taken at a later point in time.

There are several ways of managing the composition of a fleet of vessels. It is possible to buy ships in the second-hand market, where the ships are ready to be delivered to the buyer as soon as the arrangements have been made. It is also possible to charter in ships. By chartering in ships, it can provide flexibility in operating decisions. Ships can also be disposed by selling the ships on the second-hand market. Lay-ups can be necessary if the ship owner still wants to own the ship, but does not plan to sail with it. This will save the company operational costs due to less crew and minimum engine activity. Insurance costs can also be reduced if a ship is on lay-up for a longer time period. Chartering out ships is also possible, in order to make a profit without operating contracts, but still owning the ships.

When working with the MFRP, the income and costs are important factors when optimizing the system. The ship owner has a set of fixed costs and variable costs. Capital costs are a fixed cost related to the amount paid when buying a ship. Operating costs have both fixed and variable costs. The fixed costs are connected to manning, insurance, maintenance and repair, in addition to administrative costs (Pantuso, Fagerholt, & Wallace, 2014). The variable costs consist of fuel costs, port fees and cargo handling costs at ports. Revenues are generated by operating contracts, selling, or chartering out ships.

2.2 Ships and contracts

The fleet of OSVs and their operations offers a high level of complexity, when it comes to necessary equipment on board and the size of the ship. In order to model this problem, it is important to make some assumptions and divide the possible operational contracts and ships into types. The following sections present the possible contracts and ship types in the offshore industry.

2.2.1 Contract types

In this problem, it is assumed that the negotiation of contracts and the design of the shipping network take place in a separate strategic problem. The contract types and their demand are input parameters in the problem. The contract types are described in the following sections.

The offshore support vessels supply offshore drilling and production units with necessary supplies, and this can include support to either offshore production rigs or subsea constructions (Aas et al., 2009). The need for supplies can vary from food and clothing to drill pipes and casings. The supplies are necessary to maintain daily operations when producing oil and gas. Offshore installations do not only need to receive or return supplies or waste, there is also a need for offshore services, such as diving or ROV operations, and a need to maintain good operability of these installations. Different operations performed by OSVs are illustrated in Figure 2.1.

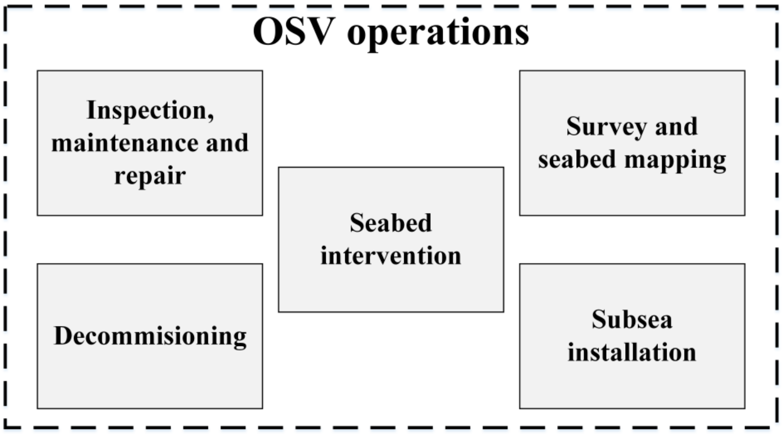


Figure 2.1: Operations performed by OSVs

All operations are performed according to the contract specification between the ship owner and the oil company. The contracts vary in price and time. Both the oil company and the ship owner want to carry out the marine operations at the best price (V. R. Gibson, 1999). For OSVs, the ship owner is often an offshore service company, acting as both the owner and the operator. The offshore service company is specialized in doing marine operations. The crew on board the vessel is therefore a crew experienced in doing a variety of marine operations.

The contract types are based on what the subsea operations require on board a ship in terms of deck capacity, bunkering capacity, cranes, ROVs, divers, crew and general equipment. The contracts include specifications, such as operational work tasks. Table 2.1 presents the different contract types for an OSV.

Table 2.1: Detailed overview of all contract types

Contract type	Specified work tasks
Survey and seabed mapping	Seabed mapping Route survey Pipeline inspection Lay support Cable survey
Subsea installation	Cable lay Flexible product and umbilical Subsea structures Diverless subsea installation Spool installation
Seabed intervention	Trenching Ploughing Excavation and dredging
Decommissioning	Pre and post survey Cutting and recovery Removal of subsea structures Towing and transport Disposal
Inspection, maintenance and repair	Structure and cable inspection Remotely operated tool operations Scale squeeze operations Maintenance and repair of subsea systems Pipeline and cable repair Commissioning Module replacement

Survey and seabed mapping

Survey and seabed mapping includes operations such as pipeline inspections, lay support, and surveys (DeepOcean, 2015). Seabed mapping is necessary for the planning of pipeline installations and looks at the composition of the seabed. The topography of the seabed is examined for wrecks, debris, manmade artifacts or other abnormalities (DeepOcean, 2015). The purpose of seabed mapping is to avoid laying pipes and cables in hazardous areas.

Route and cable surveys are also sometimes necessary to perform on the seabed. This kind of survey is similar to seabed mapping, where it is important to ensure that the route is safe and clear of obstructions (DeepOcean, 2015). A route can typically be utilized for future cables, pipeline and flexible installations, subsea modules, and trenching projects.

Survey and seabed mapping also includes operations such as pipeline inspections. Pipeline inspections and surveys are performed to detect free spans, damages, defects, leaks, cathodic erosion, and pipeline movement. These operations require typical ROV or dive support. There is no need for much deck space or big scale special equipment.

Subsea installations

Subsea installations are operations such as laying cable, flexibles, and umbilical lay, as well as installation subsea structures and spools. These operations typically require good deck space, crane capacity, and ROVs.

The laying of cables, flexibles, and umbilical requires certain equipment on board, such as a tension system, storage capability, and a suitable crane (DeepOcean, 2015). This equipment is much smaller for umbilical lay than what it is for laying flexibles. Ships that perform flexible lay are normally equipped with this equipment when these ships are built. In this thesis, it is therefore assumed that ships performing pipe lay are only pipe lay vessels.

Seabed intervention

Seabed intervention covers operations where the aim is to prepare for the laying or removal of pipelines, flowlines, power cables, and umbilical. Trenching, ploughing, excavation, and dredging are typically operations covered by seabed interventions (DeepOcean, 2015). These operations require special equipment that is placed on deck. The deck space is therefore important, as well as the crane capacity.

Decommissioning

The decommissioning of offshore constructions is basically the destruction of production systems that are no longer in use. Structural decommissioning is necessary when oil and gas fields diminish. These operations covers areas of work where offshore structures are dismantled (DeepOcean, 2015).

Decommissioning includes operations such as the removal of subsea structures and the transportation and disposal of recovered steel, risers and flexibles, umbilical, and concrete to onshore facilities. Other operations within decommissioning are the cutting and recovery of subsea objects and towing.

When preparing for a decommissioning operation, mobilization takes a shorter amount of time than demobilization. The demobilization of the ship can be difficult, since the crew must be careful when working with and lifting the removed structures and waste. These structures have been on the seabed for a long time, and can have lost much of their previous properties in terms of material strength.

Inspection, maintenance, and repair

Inspection, maintenance, and repair (IMR) operations are a collective term for a diversity of operations within inspection, maintenance, and repair. IMR operations require experienced offshore crews that are familiar with IMR operations. Vessels on IMR contracts are typically on long term contracts with oil and gas operators, continuously working on different IMR jobs.

An IMR contract requires a vessel that can manage to operate on a diversity of operations. Typically IMR services include all types of subsea inspections, scale squeeze operations, maintenance and repair of subsea systems, pipeline and cable repair, construction, and commissioning operations (DeepOcean, 2015). All types of IMR services require an extensive use of ROVs.

Earlier, divers were employed for most IMR operations. Nowadays the technology has improved and the use of ROVs has increased. ROVs can now do nearly all IMR work (V. Gibson, 2009).

IMR contracts are assigned for a long time period. The time for mobilization, operations, and demobilization is therefore longer than for other contract types.

In this thesis, general supply of mud, chemicals, fuel, drill water, and portable water are also included in IMR operations. This requires good bunkering capacities on board the ship. Scale squeeze operations also require good bunkering capacities. It is assumed that the bunkering requirements are relative to the complexity of the contract. Good bunkering capacities are therefore only necessary on the largest vessels operating in IMR.

2.2.2 Ship types

The term offshore support vessel covers a diversity of ships and it is always a multi-task vessel. It is a fairly new category of ships, and demand for them started in the mid-1950s (Aas et al., 2009). The exploration of new oil fields and an increase in offshore activity has contributed to the increase in the demand for the OSVs (Platou, 2015).

The ship owner wants to make a profit on operating the crewed vessels, and it is important that the vessels are always in contracts to ensure a steady cash flow (Aas et al., 2009). The ship owner needs to be certain that there are possibilities for contracts, in order to order a tailor-made vessel. The owner may also charter the vessels for long term contracts, often for five years straight from the builders (V. R. Gibson, 1999). There is often a tendency for vessels to be chartered for long periods on a rising market. Ships are also chartered for short periods on a falling market.

The OSVs are managed to transport supplies back and forth between land and installations, and to participate in installation and maintenance operations offshore (Aas et al., 2009). The vessels are designed for many different purposes. There are good storage possibilities on board, both on deck and in deck tanks. Some OSVs also have special safety equipment on board to help in safety situations offshore, such as fire-extinguishing or oil-spill preparedness (Aas et al., 2009).

The geographical location of where the OSV will operate is an important factor when designing the vessel (Aas et al., 2009). Weather conditions and icing are important for the deck and hull design. The geographical location also indicates the amount of equipment needed on board. The distance to shore is also important when choosing a supply vessel.

Offshore installations are often located in clusters due to the natural locations of the discovered oil and gas. It is also economically beneficial for oil companies to cluster offshore (Aas et al., 2009). There are therefore many different heterogeneous installations within a cluster, and the demands and capacities of the installations might be different from each other. For the ship owner, it is therefore important to retain high flexibility when operating a cluster of installations.

On the Norwegian continental shelf, it is normal to have the clusters supplied from one or two dedicated supply bases. Most installations are visited by supply vessels one to three times a week (Aas et al., 2009).

OSVs are reliable vessels with good operational capabilities. When an oil company is chartering an OSV, it is available at all hours year round. The only limitations are during crew changes every second week and for maintenance for a few days each year (Aas et al., 2009).

OSVs can carry a diversity of cargo. The stowage of deck cargo is on board the OSV. Deck cargo must be packed in suitable packages on board these ships. Robust and small offshore containers, skips, and baskets are normally handled for this purpose (Aas et al., 2009). Heavier and bigger constructions are placed directly on deck (Aas et al., 2009). There are safety regulations on how to stack and place all deck cargo. It is not allowed to stack containers and baskets, and not all types of cargo can be mixed (Aas et al., 2009).

Bulk cargo is defined as fluids and dry bulk cargo, and is transported in tanks underneath the deck. These fluids can be methanol, pre-blended drill fluids, brine, water, and oil (Aas et al., 2009). Dry bulk cargo can be for example cement, barite, and bentonite. Most of all bulk cargo is loaded within the tanks on board and discharged by hoses (V. R. Gibson, 1999).

Other equipment on board an OSV is a dynamic positioning system, bigger and smaller cranes, moon pool, and good ROV or diver capabilities. The following sections introduce the different types of OSVs: Dive support vessel, ROV support vessel, Construction vessel, and Pipe lay vessel.

Dive support vessel

Dive support vessels can be converted vessels fitted with air diving spreads or purpose built vessels with extensive and complex saturation diving systems (Ritchie, 2008). These vessels are operated in cases where, for example, the ROV is physically too large to be deployed into the space or where there is a need for equipment manipulation. Divers may also be employed in cases where decision making skills are required in real time on-site (Ritchie, 2008). Most dive support vessels are also fitted with ROV systems, and many operations can be performed by using a combination of divers and ROVs (Ritchie, 2008).

Dive support vessels have equipment on board to participate in diving operations, in addition to general equipment as a generic offshore support vessel. Specific equipment that is characteristic for a dive support vessel are life support, chamber system, diving bell, diving bell handling systems, and emergency evacuation systems (Ritchie, 2008).

For offshore support vessels, it is important to have a high level of position accuracy and excellent station keeping capabilities. This is especially true for a dive support vessel from which diving operations will be performed. It is expected that a dive support vessel has a minimum of DP class 2 or DP class 3 for certain operations. In addition, good manoeuvring capabilities and propulsion systems are also of great importance for a dive support vessel.

ROV support vessel

ROV support vessels have no human intervention involved in the operations. As opposed to using divers, ROVs can be operated for longer periods and in harsher conditions. ROVs can be operated in many different situations. Some typical operations are mentioned in Table 2.2.

Table 2.2: Operations performed by a ROV support vessel

ROV operations
Diver observation
Installation inspection, cleaning and debris removal.
Pipeline inspection
Seabed surveys
Drilling support
Subsea installation construction support
Telecommunications support
Location and recovery
Pipe lay support

The systems and equipment onboard ROV support vessels can vary from vessel to vessel. Excellent station keeping capabilities and a high level of position accuracy are necessary for ROV operations. Dynamic positioning systems with good maneuvering and propulsion systems are also of great importance (Ritchie, 2008).

Launching ROVs through the moon pool is beneficial when it comes to protecting the ROV from harsh weather conditions. ROVs can also be deployed over the ship side. The deployment is done together with a tether management system (TMS) (Ritchie, 2008). The TMS works as a kind of housing for the ROV and protection for the main umbilical. The umbilical supplies the ROV with electricity and allows for data transmission. The ROV is launched and controlled by ROV pilots. These pilots operate from their own control station on board the ship.

Most types of offshore support vessels have ROV capabilities, since ROV intervention can be applied during diving, pipe laying, surveying and construction operations (Ritchie, 2008).

Construction vessel

A construction vessel has the capability to lift and deploy subsea hardware to and from the seabed (Ritchie, 2008). It is essential during operations to have a high level of position accuracy and good station keeping capabilities. Operations are typically to transfer any subsea or surface loads to or from the deck of the construction vessel.

The most important equipment for construction vessels are the crane and a suitable anti-heeling system. The type, capacity and positioning of the crane is one of the most important features of the construction vessel. It is beneficial to position the crane to provide optimum outreach with good capacity on the preferred side of the vessel (Ritchie, 2008). It might also be necessary to have a counter weight or ballast systems available in heavy lift operations in order to maintain the stability of the vessel. In addition, dedicated tugger winches may be necessary during the loading and discharging of lifts.

ROVs or divers are normally required during operations. To transfer any subsea or surface load, a large and suitable deck is also beneficial for a construction vessel.

Pipe lay vessel

A pipe lay vessel has the main function of laying pipe along the seabed with good accuracy along a designated route (Ritchie, 2008). The vessel's manoeuvring and propulsion systems are of major importance due to the accuracy requirements when laying the pipe. In addition, there must be enough deck space on board for the storage of the product.

Pipe laying operations require specific systems and equipment. Storage capacity for the pipe, a deployment system, and suitable crane capacity are essential requirements for a pipe lay vessel. It is also necessary to have a system that maintains the predetermined tensions during the deployment of the pipe.

2.2.3 Compatibility between ships and contracts

To determine the compatibility between the ship types and contracts, different ship types and contract types are developed. Each type has a set of properties specific to that type, and these types are presented in this section presents.

The fleet of ships is divided into four categories: Dive support, ROV support, Construction and Pipe lay. The types differ from each other in terms of available functions on board and size. Each ship type is therefore also divided into sizes, depending on the diversity of ships within each ship type, as presented in Table 2.3. The characteristics and capacities are found by comparing ships from Ulstein (2015).

Because of the complexity of OSVs, certain areas are taken into account when finding the capacity for each ship type. Number of divers and ROVs, deck and bulk space, crane capacity, and pipe installing equipment are the areas of most interest when finding capacity constraints. Available deck space is deck space that can be managed for placing cargo, such as containers and pallets.

Each contract type covers a diversity of operations and is therefore divided into sizes of operation; small, medium and large. The abbreviated name for each contact type is presented in Table 2.4. The requirements for each contract are within divers or ROV, necessary deck space, bulk space, crane and pipe installation, as presented in Table 2.5. There are not needed for both divers and ROVs on contracts, and it are assumed that a smaller observation ROV is always on board when there are divers on board.

Table 2.3: Ship types and the capacities of each ship type

		Capacities							
Ship Type		Divers [men]	ROV	Available deck space [m^2]		Bulk space	Crane [Te]		Pipe lay equipment
				Min	Max		Min	Max	
Dive Support Small	DSS	<18	1	0	750	No	0	150	No
Dive Support Medium	DSM	>18	1,5	750	900	No	0	150	No
ROV Support Small	RSS	None	2	0	750	No	0	100	No
ROV Support Medium	RSM	None	2	750	900	Yes	100	150	No
Construction Small	COS	None	2	0	750	No	0	150	No
Construction Medium	COM	None	2	750	900	Yes	150	400	No
Construction Large	COL	None	2	900	-	Yes	400	-	No
Pipe lay Medium	PLM	None	2	0	900	Yes	0	150	Yes
Pipe lay Large	PLL	None	2	900	-	Yes	150	-	Yes

Table 2.4: The abbreviations to each of the contract type

Contract type	Size	Abbreviation
Survey and seabed mapping	S	C1
	M	C2
	L	C3
Subsea installations	S	C4
	M	C5
	L	C6
Seabed intervention	S	C7
	M	C8
	L	C9
Decommissioning	S	C10
	M	C11
	L	C12
IMR	S	C13
	M	C14
	L	C15

Table 2.5: Contract types and the requirements for each contract

	Requirements							
Contract type	Divers [men]	ROV	Deck space $[m^2]$		Bulk space	Crane [Te]		Pipe lay equipment
			Min	Max		Min	Max	
C1	12	1	0	0	No	0	0	No
C2	18	2	0	0	No	0	0	No
C3	24	2	0	0	No	0	0	No
C4	No	1	0	500	No	0	100	No
C5	No	2	500	900	No	100	150	Yes
C6	No	2	900	-	No	150	-	Yes
C7	No	1	0	750	No	0	120	No
C8	No	2	750	900	No	120	150	No
C9	No	2	900	-	No	150	-	No
C10	12	1	0	750	No	0	150	No
C11	18	2	750	900	No	150	400	No
C12	24	2	900	-	No	400	-	No
C13	12	1	0	750	No	0	100	No
C14	18	2	750	900	No	100	150	No
C15	24	2	900	-	Yes	150	-	No

2.3 Uncertainty

When optimizing the optimal fleet size and mix for OSVs, there are several uncertain factors affecting the optimal solution. In the OSV segment, the uncertainty is mainly connected to the future market development. There are many factors that are dependent on the market status. The oil price is in our case an important factor, which is dependent on market development. The current oil price also adds a dimension to the demand for offshore oil and gas exploration. A low oil price is equivalent to low demand in oil and gas. This corresponds to low demand in offshore services and operations performed by OSVs.

When the demand is low, the profit of performing offshore operations will also be lower, than for a case where the market status is high. Offshore service companies are decreasing their tender prices, in order to win contracts. The difference between costs and revenues is therefore lowered in periods with low demand, in order to stay competitive.

This problem will have scenarios to treat the uncertain factors. Revenues, costs, demand, and limits for available ships are parameters that are dependent on the market scenario.

2.4 Objective

The MFRP is a strategic decision problem, in which a strategic decision support tool is needed in order to make long-term fleet renewal decisions for a fleet of OSVs. The objective of this thesis is to develop this strategic decision support tool for OSVs. The planning horizon is set to five years. The decisions made today will have a great impact on the economics and fleet disposition for the ship owner in the future, and the MFRP will include this in order to find the optimal fleet renewal plan. The solution to the MFRP should determine the optimal decisions for fleet renewal and fleet composition for the planning horizon, in order to meet the future market requirements in the best possible way.

3 LITERATURE REVIEW

In the field of maritime fleet size and mix problem (MFSMP), there exists a great amount of research. This thesis is related to the strategic version of the MFSMP, which is commonly referred to as the maritime fleet renewal problem (MFRP). This literature review is divided into two parts. First, research on the MFSMP are given, with a focus on studies within the offshore industry. Second, publications on the MFRP are given, where also research on uncertainty in modeling these problems is mentioned.

Three survey articles have been used to get an overview over relevant literature. Pantuso, Fagerholt, and Hvattum (2014) give an overview of relevant literature within the MFSMP and the MFRP. Christiansen et al. (2013) focus on research done about maritime transportation in the new millennium. Hoff et al. (2010) give a wide-ranging picture of research done on fleet composition and routing.

3.1 The maritime fleet size and mix problem

The first known research within MFSMP is by Dantzig and Fulkerson (1954). Since then there have been some more specific studies within the topic. Still, the literature on the MFSMP is limited. The survey performed by Pantuso, Fagerholt, and Hvattum (2014) shows that there are only a few studies on the MFSMP that treat uncertainty. In addition, most of the studies consider the design of a new fleet, and do not include the possibility of renewing an initial fleet. Pantuso, Fagerholt, and Hvattum (2014) have listed articles within different topics of MFSMP, and among these research papers, only four articles have been written about MSFMP and MFSP for the offshore industry. These articles mainly focus on short-term planning.

Christiansen et al. (2013) present a survey on a different set of articles on maritime transportation. They review research on ship routing and scheduling as well as related problems during the new millennium. They find that the research on ship routing and scheduling has grown a lot over the last decade and that there has been more interest in increasing research for offshore logistics. Articles within this topic cover the routing and scheduling of OSVs as well as analyze OSV design in order to better support operations.

Hoff et al. (2010) present a review of literature within the field of fleet composition and routing for land-based and maritime transportation problems. They find that there is a general lack of literature concerning tactical and strategic decisions. The reasons for this lack of research might be because of the level of uncertainty and complexity that grows with longer and longer planning horizons. Hoff et al. (2010) also mention that the land-based context of FSMP is not directly transferable to MFSMP. Investments and capital costs are higher for maritime problems. The lifetime of a ship is much longer than for trucks, and this is important to keep in mind when modeling a FSMP for maritime transportation problems.

There is a considerable level of difficulty when it comes to analyzing supply vessels, as vessels come in all shapes and sizes and have different equipment onboard. One of the first articles written about supplying offshore installations is the article by Fagerholt and Lindstad (2000). They studied the problem of maintaining an efficient supply service for a number of offshore installations in the Norwegian Sea. The focus of their paper is mainly on the routing aspects of supply vessels and not on how the design of the supply vessels affects the logistics.

As mentioned in Pantuso, Fagerholt, and Hvattum (2014), Christiansen et al. (2013) and Hoff et al. (2010), it is hard to meet all aspects of uncertainty when optimizing complex systems. By ensuring robustness, it is possible to meet uncertainties such as the changeable and stochastic behavior of the seaborne economy, amongst others. Fagerholt and Lindstad (2000) included some robustness by generating different scenarios to include possible changes in the opening hours of the offshore installations and the minimum number of weekly services at the installations.

Pantuso (2014) studied how to meet uncertain real-life aspects when having a MFSMP. He developed knowledge and methods based on mathematical programming for the MFSMP. He points out the uncertainties in the market where shipping companies are operating. By not following market changes, the risk is that the ship owners end up with ships laid up in ports rather than generating revenues and paying back debts and expenses (Pantuso, 2014). The fleet size and mix of ships is therefore one of the crucial decisions that ship owners must make as efficient as possible in order to survive in commercial markets.

Simulation can also be applied to ensure robust routes and fleet solutions with respect to different real-life aspects, such as weather. This is done in the article by Halvorsen-Weare et al. (2012). They present a solution on how to determine the optimal fleet composition of offshore supply vessels and their corresponding weekly voyages and schedules. This is also called the supply vessel planning problem and has similarities to the vehicle routing problem. The solution method is a two-phased voyage-based method, where the first phase consists of generating all candidate voyages the vessels may sail and phase two involves solving the voyage-based model.

Aas et al. (2009) discuss the role of supply vessels in offshore logistics. They state the importance of giving more attention to the supply vessels. Generally speaking, there is a low level of competence and knowledge in how to optimize an offshore service fleet. In most of the articles written about offshore fleet optimization, the articles are written about the supply of offshore installations and not on the vessels themselves. They argue that it would be beneficial for the offshore industry to pay more attention to offshore support vessels, as these vessels are the most costly part of the offshore supply chain.

There are also other written articles within MFSMP which are highly adaptive to offshore transportation problems. Fagerholt et al. (2010) present a decision support methodology that is applicable to a wide range of strategic planning problems in industrial and tramp shipping. The authors state that it is also important to consider underlying short-term routing decisions in a strategic planning problem. The paper focuses on two classes of strategic decisions; contract analysis and the fleet size and mix. To minimize the complexity of the problem, it is considered wise to treat the two classes independently.

The decision support methodology presented in Fagerholt et al. (2010) is mainly to combine the strengths of simulation and optimization to eliminate or reduce the drawbacks of these methods when considered separately. This proposed methodology is basically a Monte Carlo simulation framework built around an optimization-based decision support system for short-term planning. The simulation treats the uncertainty in the parameters. By doing this, it is possible to deal with the stochastic aspects and at the same time have the flexibility to work with a wide range of strategic planning problems. This method is not efficient in cases where there are a large number of alternative fleet configurations.

3.2 The maritime fleet renewal problem

In most practical situations there already exists a fleet. This is in contrast to the majority of literature on MFSMPs. The maritime fleet renewal problem (MFRP) is a multi-period MFSMP, where there already exists an initial fleet. The MFRP decides how and when to make long-term modifications to the fleet given a starting position and has a strategic perspective by nature. In the survey from Pantuso, Fagerholt, and Hvattum (2014), only seven papers were found on the MFRP, mainly discussing general, bulk, and container shipping. These papers explicitly handle operating decisions, by using a higher level deployment model.

Most of the papers that consider MFRP also consider uncertainty. Uncertainty increases with longer planning horizons, which explain why uncertainty is an important aspect in MFRPs. MFRPs often have a long planning horizon, often around five years into the future.

There are different approaches applied to handle uncertainty. Stochastic programming and robust optimization are two of the common methods to use when handling uncertainty in the MFRP. Pantuso, Fagerholt, and Wallace (2014) address the uncertainty in the maritime fleet renewal problem, by presenting a stochastic programming model for the MFRP. The model is developed for a case in liner shipping, where the purpose is to see if the stochastic model proposes better decisions than a deterministic model using average data. The stochastic model is based on scenarios and the probability for each scenario is implemented in the objective function. The model has no optional demand or contracts, and the operating decision is deployment of trades. The results of the computational study show that the stochastic solutions are better than the solutions from the deterministic model.

Alvarez et al. (2011) present a robust optimization model to handle uncertainty. They proposed a mixed programming model for a multi-period fleet sizing and deployment problem. By considering the model with a robust approach, it is possible to find a near-optimal solution, even if it is based on uncertain predictions. This model does not consider uncertainty in demand.

Bakkehaug et al. (2014) study a stochastic programming formulation for MFRPs. They propose a multi-stage stochastic programming formulation, where uncertain parameters such as future demand, freight rates, and vessel prices are explicitly handled. The model is node formulated, including decisions on when and how to scrap, sell, buy, or charter vessels. Bakkehaug et al. (2014) also present a way to generate a simple scenario tree, and how to calculate the probability for each scenario.

It is also applicable to extend the traditional MFRP in terms of including the impacts of environmental changes, the natural ageing of vessels, new regulations, and development of new and more efficient technologies. Patricksson et al. (2015) present the maritime fleet renewal problem in terms of looking at the possibility of extending the model to include regional limitations in the form of emission control areas. The reason is to minimize increased operational costs caused by stricter emissions regulations. The proposed optimization model is a node formulated, stochastic programming model, where future fuel price uncertainty is discretized into scenarios. The model is tested on a liner shipping case, where it is also possible to modify ships that were already in the fleet.

Erikstad et al. (2011) propose an optimization model for the ship design and deployment problem (SDDP), which has the same objective as the MFRP. The purpose of the SDDP for non-cargo vessels is to provide decision support to the ship owner by determining the optimal ship design for deployment in the future. This is done while concurrently taking the lifetime deployment of the vessel into consideration, such as which future contracts the ships should be deployed in. The model is a binary integer programming (BIP) model.

The model presented by Erikstad et al. (2011) is developed in terms of finding the optimal fleet composition, where the fleet will meet the future market requirements when it comes to available contracts. The model is developed for contracts where the vessels are non-cargo, service type of ships, similar to the OSVs. A set of several scenarios is created to help determine what design to select. The scenarios can be developed on the basis of actual contracts or on expected contracts based on future market opportunities. Each contract has a set of requirements regarding vessel capabilities. The optimization model identifies the design that maximizes revenue by selecting the most profitable sequence of contracts (Erikstad et al., 2011).

4 MODELING UNCERTAINTY

An important issue of the maritime fleet renewal problem (MFRP) and the maritime fleet size and mix problem (MFSMP) is the uncertainty of the problem, especially when the strategic MFRP and MFSMP are considered. Decisions are often made on elements that are unknown beforehand, with high volatility in the market and long planning horizons. Cyclic fluctuations in the market are the main contributor when looking at uncertainties in strategic planning. The main reason for the fluctuations in the offshore market is the impact of oil price. The offshore industry has uncertainty connected to the high unpredictability of the market, which has its impact on demand, fuel prices, and political situations. Other real-life problems that affect decisions, such as weather conditions, are also unknown beforehand.

Uncertain aspects in the industry introduce different risks. There is a high financial risk when ordering a new vessel. The cost of a new ship is typically high and the time horizon long, typical 25-30 years (Erikstad et al., 2011). Cost efficient solutions are therefore important in order to survive in a competitive market. This is also important for offshore contractors, which have long-term leasing contracts of five to ten years for a vessel. The contractors will require vessels with capabilities for existing contracts and at the same time are open for new and uncertain opportunities (Erikstad et al., 2011).

This chapter will give an introduction to how to treat uncertainty in MFRPs. Stochastic programming is introduced in section 4.1, and section 4.2 contains a short introduction on how to evaluate stochastic solutions.

4.1 Stochastic programming

There are different ways of approaching uncertainty. In operations research, stochastic programming and robust optimization are the most commonly applied approaches. Robust optimization considers uncertainty in deterministic means. Sensitivity analysis is applied to study the robustness of the solution when data is changed. This can give an indication of how much data can change before the optimal solution changes. However, deterministic solutions are still solved with deterministic data, and an uncertain future is not taken into account in these models.

Stochastic programming takes the uncertain future into account when modeling. The core of stochastic programming is about modeling what might happen and how to handle each situation (King & Wallace, 2012). It consists of representing uncertain parameters by random variables and solves the mathematical program based on this. Stochastic programming uses scenarios to describe the potential outcomes in the best possible way.

The solution will then be a result that is well positioned against all scenarios. Stochastic programming is chosen for this thesis because of the dynamics of the problem.

Stochastic programming makes it possible to model the interplay between decisions and new information (Pantuso, 2014), and it can postpone decisions until new information is obtained. A stochastic approach provides flexibility and makes it possible to base the model on uncertain predictions, and it provides a near real life option theory.

In stochastic programming, a stage is a point in time where new information about the future is obtained and new decisions can be made. A two-stage stochastic program first contains a decision that must be done in the first stage, before knowing the realization of the uncertain parameters. The second-stage decision is made once the uncertain parameters are known.

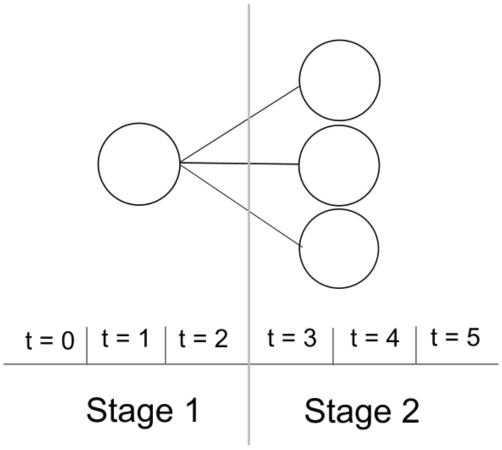


Figure 4.1: Example of a scenario tree for a two-stage model with three scenarios

It is easy to get confused with time periods and stages. Time periods are a way of monitoring the time, while stages are where new decisions are made based on new information. One stage can have a duration of many periods.

It you include more stages in the modeling, it is called a multi-stage stochastic program. The pro of two-stage stochastic programming is that it gives a simple structure, where you can include more details into the model. Multi-stage programming gives a precise representation of information, where two-stage programming has a rough representation. The con of multi-stage programming is that the algorithm and solution time grows exponentially with the complexity of the structure.

The first stage is the most important stage. This is the stage where here-and-now decisions are made, in order to get an optimal fleet configuration in the end (Patricksson et al., 2015). It is these decisions that are of interest for the planner. The later stages are only included to make it possible for better decisions in the first stage.

Scenarios are included since realizations of the uncertain parameters often follow a continuous probability distribution. It can therefore be difficult to implement the possible outcomes of the future. This will most likely include solving an integral in the objective function. By using a discrete representation of the uncertainty, it is possible to avoid this. The discrete representation of uncertainty can be modelled in the form of scenarios. Each scenario corresponds to a given realization of the random variables throughout the planning horizon (Mørch, 2014).

A scenario tree contains the set of possible outcomes of the discretized stochastic variables. It contains different possible scenarios, where each scenario has its own path through the nodes, from root node to leaf node (Bakkehaug et al., 2014). In a scenario tree, the number of stages is included where new information is obtained. If a tree has a high number of scenarios and stages, it will most likely give a realistic approach to the problem, in addition to increasing the complexity and the solution time. A node representation of a two-stage scenario tree is presented in Figure 4.1. Decisions are made in each node, and each scenario is represented by a set of nodes (Patricksson et al., 2015).

The scenarios are dependent on the development of the market. A probability distribution can be applied to represent this development. Figure 4.2 illustrates how the market status can develop in three scenarios in a two-stage model. In the offshore shipping industry, the market is dependent on the oil price. The oil price affects the market development, and it can therefore be included when developing scenarios for our case.

There are several methods of how to generate a scenario tree. As mentioned by Kaut and Wallace (2007), there are two commonly used methods to generate scenarios. The first one is sampling method, such as the sample average approximation method presented by Verweij et al. (2003). The second alternative for scenario generation is the moment matching heuristic, as presented by Høyland et al. (2003).

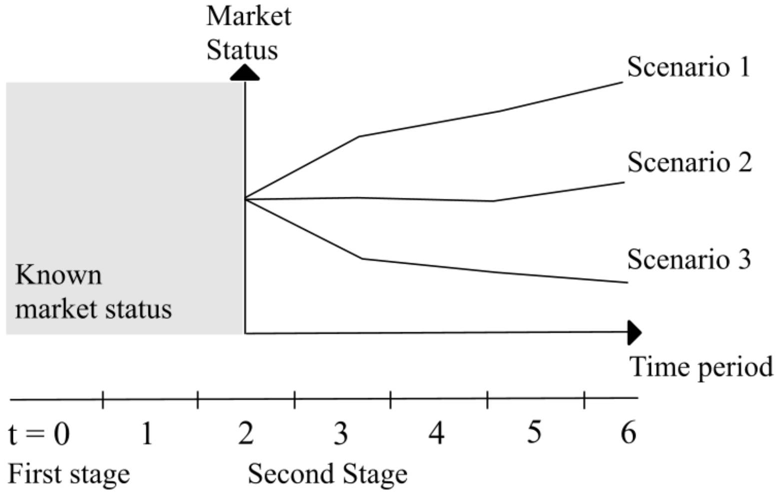


Figure 4.2: Example of how the market status changes in a two-stage model with three scenarios.

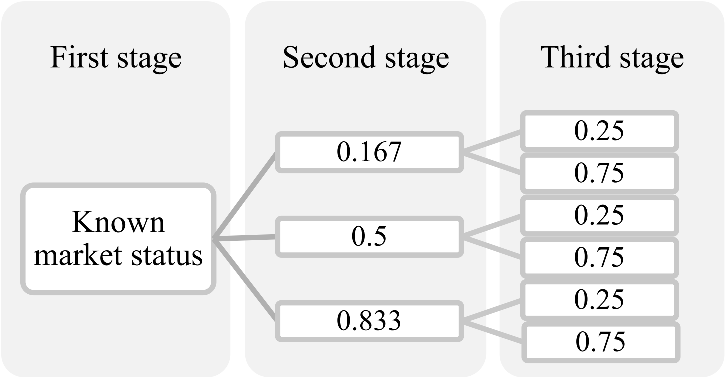


Figure 4.3: A three-stage scenario tree (Bakkehaug et al., 2014).

Bakkehaug et al. (2014) present an alternative to these methods. This method is better suited when generating small scenario trees. The possible market status values have values between 0 and 1, where 1 represents a good market and 0 a bad market. Within this interval, the market status values are divided into *n* equally sized subintervals, where the midpoint in each interval is the representative value for each possible market status.

Figure 4.3 illustrates a three-stage scenario tree, where the first discretization is with three intervals, followed by the second discretization with two intervals. The first stage is based on the current market status, and is a known uncertainty. Based on this scenario tree, the probabilities of visiting each node can be calculated (Bakkehaug et al., 2014). A probability distribution can then be made to represent each scenario development.

Recourse actions are sometimes also applicable in stochastic programming, which gives the opportunity to adapt a solution to a specific outcome (Mørch, 2014). This can be applicable in the MFRP where investments and scrapping decisions must be made in the first stage, before demand and price rates are known (Mørch, 2014). This will give the possibility to meet capacity problems in the fleet, where the chartering in and chartering out of ships are typical recourse decisions.

Scenario trees can also be evaluated, in order to see if the generated scenarios are of good enough quality. It is important to make sure that the generated scenario tree does not influence the final solution of the stochastic program. A wanted situation is one where the original continuous distribution is sufficiently close to the discretization. Kaut and Wallace (2007) study different ways of testing a scenario generation method. They state that the quality of the scenario tree is dependent on the quality of the final solution. It is therefore necessary to look at the error of approximation, instead of the scenario tree itself, to evaluate the precision of the scenario tree. For more information on the development and evaluation of scenario trees, see Kaut and Wallace (2007)

4.2 Evaluating the model

Stochastic models can be computationally demanding. Evaluating tools can therefore be useful, in order to evaluate if it is necessary to use a stochastic model. In some cases it might be sufficient to use a deterministic approach. The effort can then be aimed at determining the uncertain parameters, instead of using unnecessary work in difficult stochastic computations. The value of stochastic programming and the expected value of perfect information are two methods for evaluating stochastic solutions.

4.2.1 The value of stochastic programming

The value of stochastic programming can be measured by using the method introduced by J.R. Birge (1982). The method is called the value of stochastic solution (VSS), and is a method that measures the value of using a stochastic approach instead of a deterministic approach. The VSS is possible to find even if the decision maker do not have much information about the future uncertainty.

Equation (4.1) presents how the VSS can be calculated, where SS is the solution of the stochastic programming (J. R. Birge, 1995). Expected value (EEV) is the expected value of using an expected value approach, i.e. the expected value of the objective function when the parameters are fixed to average values. EEV is calculated by solving the expected value problem (EV) and use this solution to solve the SS with a fixed stage solution from the EV. In Figure 4.4, the VSS is illustrated, where the green nodes illustrates the fixed first stage decisions.

The VSS reaches zero if the deterministic solution is as good as the stochastic solution. In this thesis, the VSS is applied in percent (VSS%), which indicates the percentage of VSS from the SS. For a maximization problem, the general property between the EEV and the SS is as presented in equation (4.2). If this property is not obtained, the SS is not the optimal solution to the stochastic problem (J.R. Birge & Louveaux, 2011).

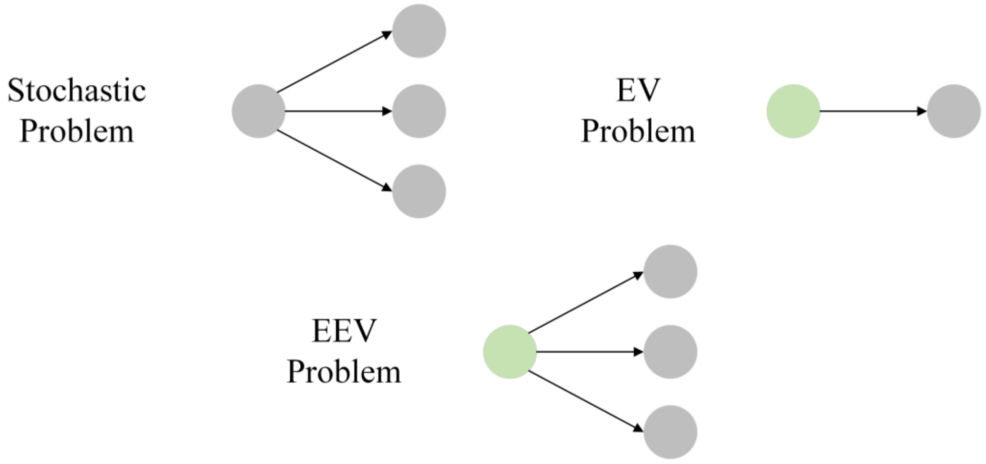


Figure 4.4: Illustration of a stochastic problem, EV problem and EEV problem

$$VSS = EEV - SS \tag{4.1}$$

$$SS \geq EEV \tag{4.2}$$

4.2.2 Expected value of perfect information

The value of perfect information (EVPI) is a measure of the maximum amount a decision maker would be willing to pay to get complete information about the future market, in other words removing all uncertainty. The EVPI represent the loss of profit because of the degree of uncertainty in the modeling (J.R. Birge & Louveaux, 2011).

The EVPI is a measurement which compares the wait-and-see approach to the here-and-now approach. By doing this, it is possible to get an indication on whether it is economically worth reducing the uncertainty that is present in the problem. With a low EVPI, there will be little savings in reaching perfect information.

The EVPI is the calculated difference between the wait-and-see solution (WS) and the SS, as presented in equation (4.3) (J. R. Birge, 1995). The WS is calculated by adding the independent solutions for each scenario from the stochastic problem. In Figure 4.5, the EVPI is illustrated by showing the difference by the SS and WS.

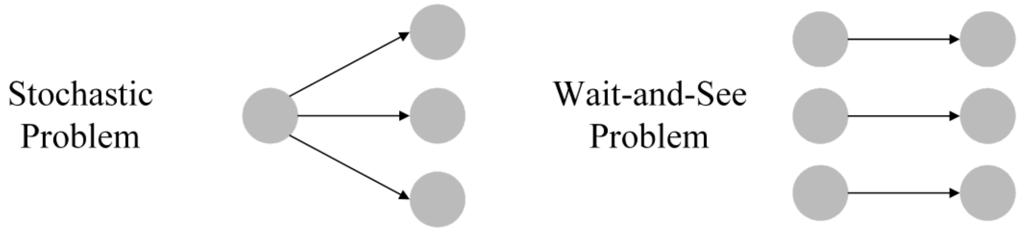


Figure 4.5: Illustration of the stochastic problem and WS problem

The probability for each scenario is also included into the WS. In this thesis, the EVPI is applied in percent (EVPI%), which indicates the percentage of EVPI from the SS. For a maximization problem, the general property between the WS and the SS is as presented in equation (4.4).

$$EVPI = WS - SS \tag{4.3}$$

$$SS \leq WS \tag{4.4}$$

5 MATHEMATICAL MODEL

In this chapter, a mathematical model for the maritime fleet renewal problem (MFRP) is presented for a fleet of offshore support vessels (OSVs). The model is developed with a stochastic scenario formulation and it is applicable for a big market segment. It is also possible to adapt the model to other market segments by changing the possible scenarios for the model.

The fleet renewal problem is applied in order to find the best strategy for developing a fleet over time. In our case it means generating a mathematical optimization model in order to find the best size and composition of a fleet of OSVs, where the fleet is operating mainly outside the coast of Norway.

The model is formulated as a mixed integer program (MIP). It is inspired by the liner shipping models developed by Pantuso, Fagerholt, and Wallace (2014), Patricksson et al. (2015), and Mørch (2014).

The model can be applied for any realistic fleet size. Requirements due to capacities, duration, chartering options, and compatibility restrictions are all included in the model with constrains. In addition, compatibility between different contracts and vessels are analyzed. The fleet decisions are made based on the scenario-based future demand for the chosen period of time.

5.1 Modeling assumptions

The optimization model has an objective function that handles all the costs and revenues that are important for the fleet of OSVs. When owning a fleet of OSVs, the economy is dependent on having all the vessels on continuous contracts. If a ship is without a contract or a contract is terminated, it is important that the focus is on maximizing the utilization of the ship. This can be done by lay-up, chartering out, or selling. The aim for the ship owner is to always maximize profit and continue to win contracts. The objective function in the presented optimization model is therefore to maximize the profit.

It is assumed that all ships are paid for with cash and not by financiered loans from banks. The negotiation of the contracts is assumed made in another strategic problem. The input to our problem is the contracts to fulfil, the expected demands, and required frequencies.

Charter possibilities

Bareboat charter possibilities are included in the model, which means chartering in and out for a whole time period. For simplicity reasons, voyage charter is neglected in the model. Time charter possibilities are also neglected, which means chartering in and chartering out for a fraction of a time period. However, a time charter can be included by changing the constraint of the bareboat variable from an integer to a real number.

Deployment of contracts

It is assumed that the ship owner has an initial fleet of OSVs, with information about capacity, charter rates, and speed. The requirements for each contract must be matched with the capabilities of the vessels. The MFRP make deployment decisions in order to solve the optimization model. The deployment decisions are only made in order to give good advice regarding fleet renewal. This model is therefore not developed to give advice on the deployment itself.

Ballast sailing

Each contract it is required to have a plan for mobilization and demobilization, in addition to plans for the sailing and operation itself. The time utilized for an operation is included in the sailing time. It is assumed that the ships can perform mobilization for a new contract in the same port as the demobilization of the previous contract. In other words, it is assumed that there will be no ballast sailing between ports. This is an optimistic assumption, where the total sailing time is underestimated. Figure 5.1 illustrates the contributors to the total contract duration.

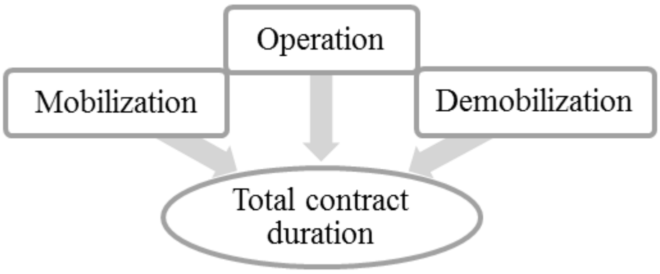


Figure 5.1: Illustration of the contributors to the total contract duration

Time periods

Time is the most important parameter in this model. A time period is defined as the interval of time in which decisions can be made. The length of each time period may vary through the whole planning period, but in our case each time period will be one year.

The fleet renewal decisions are assumed to be made at the end of a time period. For example, if a ship is sold in one period, it is delivered in the next time period. This also applies for ships that are bought and sold in the second-hand market.

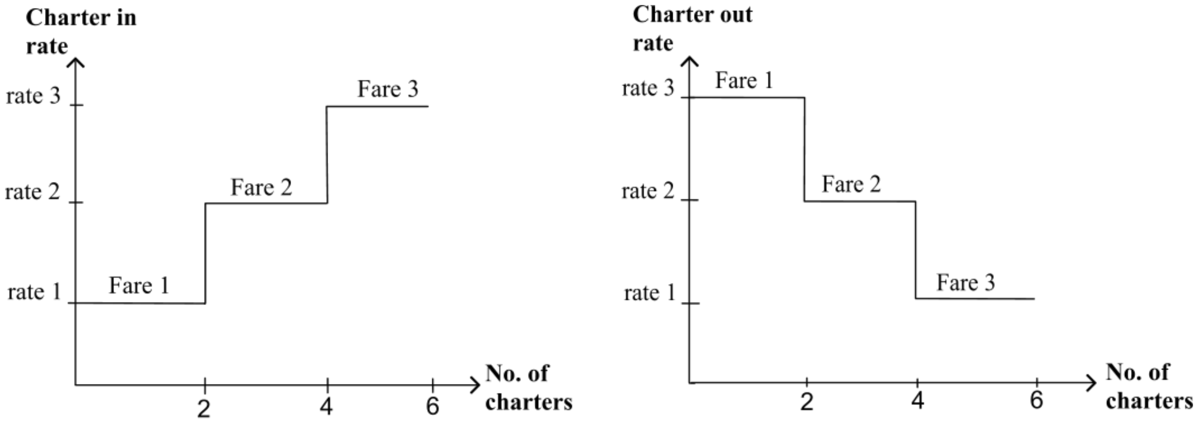
Fares

Since the charter and second-hand market consist of a finite number of ships, it is assumed that the marginal ship purchase prices and charter in rates are increasing.

Similarly, it is assumed that the marginal ship selling prices and charter out rates are decreasing. This means that ships become more expensive when the competition increases, and vice versa. To keep the model linear, piecewise constant functions are therefore created by means of fares (Pantuso, Fagerholt, & Wallace, 2014). The constant functions describe the rates of second-hand costs, selling prices, and charter rates.

A fare is characterized by a charter rate or price. For each fare, there are a number of ships available at that fare. When all the vessels within one fare are purchased, sold, or chartered, the next ship must be purchased, sold, or chartered at a new fare. This is included to keep the model linear.

A qualitative description of how the fares work is presented in Figure 5.2. In Figure 5.2a, it is illustrated that if two ships are chartered in, the third ship must be chartered in at the next fare. This is also similar to chartering out, as illustrated in Figure 5.2b.



(a) Charter in fares (b) Charter out fares

Figure 5.2: Fares description (Pantuso, Fagerholt, & Wallace, 2014)

Number of stages

The model is developed as a scenario-based stochastic model. The model is formulated with the future market as an uncertain parameter. This affects the market demand, prices and available ships in the market. The uncertainty is assumed to be discrete, where each scenario represents a different market development.

A two-stage stochastic optimization approach is chosen as the modeling concept, as described in chapter 4. The first stage is today, and at this stage the ship owner must decide the number of ships that should be sold or bought at the second-hand market, and delivered in the next time period. In the second stage, new information about the market status is obtained. In this stage, recourse decisions and operational decisions are made, in addition to the fleet renewal decisions.

5.2 Model formulation

Let $T = \{0, \dots, \bar{T}\}$ be the set of periods, indexed by *t*. $\bar{T}$ is then the final period in the planning horizon. Deployment or operating considerations are not taken into account in period 0. Ships can be operated, chartered, sold, bought, or set on lay-up in time $t \in T \backslash \{0\}$. Let S be the set of scenarios, indexed by *s*. S_{ts}^{NA} is a set that consists of all scenarios that are connected to scenario *s* in time *t*. This means that all decisions made in scenario *s* in time *t* must be the same in all scenarios in S_{ts}^{NA}. The probability P_s is the probability for scenario *s* to occur, where $\sum_{s \in S} P_s = 1$.

The ship types are defined in sets. Let V_t be the set of ship types existing in the market in period *t*, indexed by *v*. The possible vessel designs in V_t are based on a pool of vessels. The pool can be random or systematic generated or based on actual available vessel designs (Erikstad et al., 2011). Some of the vessels can be complex and specialized, when it comes to ship size and equipment on board. Let V_t^S be the set of special ships in period $t, V_t^S \subseteq V_t$. Let F^{SH}, F^{SE}, F^{CI}, and F^{CO}, indexed by *f*, be the set of fares for buying, selling, and chartering in and out, respectively. Then, let N_t be the set of contracts operated in period *t*, indexed by *i*.

With respect to the decisions variables, let x_{ivtrs} be the variable stating the number of ship type *v* working on contract *i* in period *t* in region *r* under scenario *s*. Let y_{vts}^{P} be the pool variable stating the number of ships in pool in period *t* under scenario *s*. An initial fleet is initially set by parameter Y_v^P before the planning starts in period $t = 0$. In later periods, changes can be done in the fleet regarding ships sold and bought in the second-hand market. The variables y_{fvts}^{SE} and y_{fvts}^{SH} are stating ships sold and bought respectively, of ship type *v* and fare *f* in period *t* under scenario *s*. Let l_{vts} be the lay-up variable stating the number of ships on lay-up of ship type *v* in period *t* under scenario *s*. Ships can be placed on lay up for a portion of a period, where fractions of l_{vts} indicates the portion of the period that a ship has been on lay-up. Let w_{fvts}^{CI} and w_{fvts}^{CO} be the chartering variables, stating the number of ships of type *v* to be chartered in or out respectively in period *t*, under scenario *s*. Let β_{its} be a binary variable set to 1 if contract *i* is operated in period *t*, under scenario *s*. Then, let δ_{iv} be a binary variable set to 1 if vessel type *v* has the capability to take contract *i* in period *t*.

Objective function

$$\max z = \sum_{s\in S} P_s \left\{ \sum_{t\in T} \sum_{v\in V_t} \sum_{i\in N_t} (R^{OP}_{ivts} x_{ivts} \ - C^{OP}_{ivts} x_{ivts}) \right. \tag{5.1a}$$

$$+ \sum_{t\in T\setminus\{0\}} \sum_{v\in V_t} \left(\sum_{f\in F^{CO}} R^{CO}_{fvts} w^{CO}_{fvts} - \sum_{f\in F^{CI}} C^{CI}_{fvts} w^{CI}_{fvts} \ + R^{LU}_{vts} l_{vts} \right) \tag{5.1b}$$

$$+ \sum_{v\in V_{\bar{T}}} R^{V}_{vs} y^{P}_{v\bar{T}s} \tag{5.1c}$$

$$\left. + \sum_{t\in T\setminus\{\bar{T}\}} \sum_{v\in V_t} \left(\sum_{f\in F^{SE}} R^{SE}_{fvts} y^{SE}_{fvts} - \sum_{f\in F^{SH}} C^{SH}_{fvts} y^{SH}_{fvts} \right) \right\} \tag{5.1d}$$

The objective function (5.1) maximizes the profit. The expressions (5.1a) – (5.1d) represent the expected revenues and costs of providing and operating ships within the planning horizon. The probability of a scenario taking place is included in expression (5.1a), followed by the revenue R^{OP}_{ivts} and cost C^{OP}_{ivts} of operating vessel type *v* on contract *i* in period *t* under scenario *s*. Expression (5.1b) includes the revenue and cost of chartering out and chartering in ships, respectively, and also includes the lay-up savings. In this expression, R^{CO}_{fvts} is the revenue from chartering out, C^{CI}_{fvts} is the cost of chartering in and R^{LU}_{vts} is the savings when placing a ship on lay-up of type *v* in period *t* under scenario *s*. Expression (5.1c) represents the value of ships in the pool, where R^{V}_{vs} is the value of ship type *v* in period $\bar{T}$. Expression (5.1d) represents the revenues of selling ships and the cost of buying ships on the second-hand market, where R^{SE}_{fvts} is the revenue of selling ships and C^{SH}_{fvts} is the cost of buying ships on second-hand market.

Compatibility constraints

$$\delta_{iv} = Q^{CV}_{iv} \qquad t \in T \setminus \{0\}, i \in N_t, v \in V_t \tag{5.2}$$

Constraint (5.2) states the value to the binary variable δ_{ivt}, which states that if vessel *v* can operate on contract *i*. Q^{CV}_{iv} is a parameter that states if vessel *v* has the capacity to operate on contract *i*, and can be represented by a compatibility matrix.

$$x_{ivts} - \ M\delta_{iv} \ \leq 0 \qquad t \in T \setminus \{0\}, i \in N_t, v \in V_t, s \in S \tag{5.3}$$

Constraint (5.3) makes sure that the ships only take the contracts compatible for the respective vessel type in one period, for a scenario. This constraint uses the compatibility variable δ_{iv} to only assign suitable contracts to each ship. M is a big value and is equal to the maximum number of contracts that a ship can take in a time period.

Frequency and demand constraints

In the recent year, oil and gas operators have placed less priority on IMR operations. This is because of the high oil price and high costs. In waiting for a lower oil price and more income, the operators have postponed or terminated important IMR contracts. Inspired by these events, the possibility of excluding contract types in certain periods is included into the mathematical model. When determining the input for excluding contracts, the type of scenario is important. For a scenario with a bad market status, there are fewer contracts that are operated on in each period, than for a scenario with a good market status. For a good market scenario, all contracts will be possible to operate. In a bad market scenario, only a few contracts are available for operation.

$$\beta_{its} = A_{its} \qquad t \in T \setminus \{0\}, i \in N_t, s \in S \qquad (5.4)$$

Constraint (5.4) makes sure that a contract type can be terminated for a whole time period, where A_{its} is a parameter that states if contract *i* is operated on in period *t*, in scenario *s*.

$$\sum_{v \in V} x_{ivts} \leq \bar{F}_{its}\, \beta_{its} \qquad t \in T \setminus \{0\}, i \in N_t, s \in S \qquad (5.5)$$

$$\sum_{v \in V} x_{ivts} \geq D_{its}\, \beta_{its} \qquad t \in T \setminus \{0\}, i \in N_t, s \in S \qquad (5.6)$$

The operation of each contract must be evenly visited and not too often. Constraint (5.5) makes sure that each contract is evenly serviced according to the needs in each period. $\bar{F}_{its}$ is the maximum need of an operation on contract *i* in period *t*, scenario *s*. Constraint (5.6) states the minimum demand of an operation on contract *i* in period *t*, where D_{its} is the minimum need of an operation on contract *i* in period *t*, scenario *s*. These two constraints concern the number of times each contract should and can be operated.

Time constraints

$$\sum_{i \in N} (Z_i^{mob} + Z_i^{op} + Z_i^{demob}) x_{ivts} \leq Z_{vt}(y_{vts}^{P} + \sum_{f \in F^{CI}} w_{fvts}^{IN} - \sum_{f \in F^{CO}} w_{fvts}^{OUT} - l_{vts})$$

$$t \in T \setminus \{0\}, v \in V_t, s \in S \qquad (5.7)$$

The time lapse for all operations in a time period cannot exceed the total available time for a ship in that same time period. The duration of an operation contains time for mobilization, operation and demobilization. It is assumed that the sailing and transfer time is included into the duration of the operation. Constraint (5.7) states that the operating time for the contracts cannot exceed the available time for a ship, where Z_i^{mob}, Z_i^{op} and Z_i^{demob} are the times a ship needs to mobilize, operate and demobilize contract *i*. Z_{vt} is the total available time for one vessel of type *v* in period *t*. This constraint also keeps the consistency between the number of ships in a fleet and the number of ships operating contracts.

Pool constraints

$$y^P_{vts} = y^P_{v,t-1,s} + \sum_{f \in F^{SH}} y^{SH}_{fv,t-1,s} - \sum_{f \in F^{SE}} y^{SE}_{fv,t-1,s} \qquad t \in T \setminus \{0\}, v \in V_t, s \in S \qquad (5.8)$$

Constraint (5.8) refers to the relationship between the ships in pool and those bought and sold in the second-hand market in each period. This constraint define the current ships in the pool equal to the sum of ships in pool, ships sold, and ships bought in the previous period.

$$y_{v0s} = Y^P_v \qquad v \in V_0, s \in S \qquad (5.9)$$

Constraint (5.9) defines the initial pool of ships in the fleet for the beginning of the planning horizon.

$$\sum_{f \in F^{CO}} w^{OUT}_{fvts} - \sum_{f \in F^{CI}} w^{IN}_{fvts} + l_{vts} \leq y^P_{vts} \qquad t \in T \setminus \{0\}, v \in V_t, s \in S \qquad (5.10)$$

Constraint (5.10) ensures that the number of ships on lay-up and the balance of ships chartered in and chartered out does not exceed the total number of available ships in the fleet. This constraint contains the recourse action variables, such as the possibilities for chartering in, chartering out, and laying-up. By including these recourse actions, the model will be more flexible.

Charter and second-hand market constraints

$$w^{IN}_{fvts} \leq L^{CI}_{fvt} \qquad f \in F^{CI}, t \in T \setminus \{0\}, v \in V_t, s \in S \qquad (5.11)$$

$$w^{OUT}_{fvts} \leq L^{CO}_{fvt} \qquad f \in F^{CO}, t \in T \setminus \{0\}, v \in V_t, s \in S \qquad (5.12)$$

$$y^{SH}_{fvts} \leq L^{SH}_{fvt} \qquad f \in F^{SH}, t \in T \setminus \{\bar{T}\}, v \in V_t, s \in S \qquad (5.13)$$

$$y^{SE}_{fvts} \leq L^{SE}_{fvt} \qquad f \in F^{SE}, t \in T \setminus \{\bar{T}\}, v \in V_t, s \in S \qquad (5.14)$$

$$\sum_{f \in F^{CI}} \sum_{v \in V_t} w^{IN}_{fvts} \leq L^{CI}_t \qquad t \in T \setminus \{0\}, s \in S \qquad (5.15)$$

$$\sum_{f \in F^{CO}} \sum_{v \in V_t} w^{OUT}_{fvts} \leq L^{CO}_t \qquad t \in T \setminus \{0\}, s \in S \qquad (5.16)$$

$$\sum_{f \in F^{SH}} \sum_{v \in V_t} y^{SH}_{fvts} \leq L^{SH}_t \qquad t \in T \setminus \{\bar{T}\}, s \in S \qquad (5.17)$$

$$\sum_{f \in F^{SE}} \sum_{v \in V_t} y^{SE}_{fvts} \leq L^{SE}_t \qquad t \in T \setminus \{\bar{T}\}, s \in S \qquad (5.18)$$

There are a limited number of OSVs in the market. Constraints (5.11) to (5.14) make sure ships chartered and ships bought and sold in the second-hand market do not exceed the maximum number of available ships in the market, at each fare. The parameters $L_{fvt}^{CI}, L_{fvt}^{CO}, L_{fvt}^{SH}$, and L_{fvt}^{SE} are the maximum number of ships of type v available at a fare f in period t to charter in, charter out, be bought, and sold on the second-hand market. Constraints (5.15) to (5.18) limit the total number of ships to be chartered in or chartered out, as well as bought and sold in each time period, where $L_t^{CI}, L_t^{CO}, L_t^{SH}$ and L_t^{SE} refers to the limits.

Specialized ships constraints

$$\sum_{f \in F^{SH}} y_{fvts}^{SH} \leq 1 \qquad t \in T \setminus \{\bar{T}\}, v \in V_t^S, s \in S \qquad (5.19)$$

$$\sum_{f \in F^{CI}} w_{fvts}^{IN} \leq 1 \qquad t \in T \setminus \{O\}, v \in V_t^S, s \in S \qquad (5.20)$$

The OSVs are specialized ships in many shapes and sizes. Some OSVs might be specialized in terms of size and equipment on board, and the number of these ships in the market is limited. Specialized vessels can only be built and there is little possibility to charter in these ships or buy the ships in the second-hand market, as stated in constraints (5.19) and (5.20). The limits on chartering in and buying these ships are set at a maximum of one ship, each time period.

Non-anticipativity constraints

$$\sum_{f \in F^{SH}} y_{fvts}^{SH} = \sum_{f \in F^{SH}} y_{ftv\bar{s}}^{SH} \qquad t \in T, v \in V_t, s \in S, \bar{s} \in S_{ts}^{NA} \qquad (5.21)$$

$$\sum_{f \in F^{SE}} y_{fvts}^{SE} = \sum_{f \in F^{SE}} y_{ftv\bar{s}}^{SE} \qquad t \in T, v \in V_t, s \in S, \bar{s} \in S_{ts}^{NA} \qquad (5.22)$$

Constraints (5.21) and (5.22) are the non-anticipativity constraints for selling and buying on the second-hand market. The non-anticipativity constraints restrict the variables from anticipating in a future state.

These constraints are needed since the variables for selling and buying have scenarios as an index in the first stage. In addition, these variables are not necessarily equal for all scenarios in the second stage. Constraints (5.21) and (5.22) are therefore added to keep the scenarios with a common history having the same set of decisions.

Convexity and integer constraints

$$y^{SH}_{fvts} \in \mathbb{Z}^{+} \qquad f \in F^{SH}, t \in T \setminus \{\bar{T}\}, v \in V_t, s \in S \tag{5.23}$$

$$y^{SE}_{fvts} \in \mathbb{Z}^{+} \qquad f \in F^{SE}, t \in T \setminus \{\bar{T}\}, v \in V_t , s \in S \tag{5.24}$$

$$x_{ivts} \in \mathbb{Z}^{+} \qquad t \in T \setminus \{O\}, v \in V_t, i \in N_t, s \in S \tag{5.25}$$

$$w^{CI}_{fvts} \in \mathbb{Z}^{+} \qquad f \in F^{CI}, t \in T \setminus \{0\}, v \in, s \in S \tag{5.26}$$

$$w^{CO}_{fvts} \in \mathbb{Z}^{+} \qquad f \in F^{CO}, t \in T \setminus \{0\}, v \in V_t, s \in S \tag{5.27}$$

$$y^{P}_{vts} \in \mathbb{R}^{+} \qquad t \in T, v \in V_t, s \in S \tag{5.28}$$

$$l_{vts} \in \mathbb{R}^{+} \qquad t \in T \setminus \{O\}, v \in V_t, s \in S \tag{5.29}$$

$$\delta_{iv} \in \{0,1\} \qquad t \in T \setminus \{O\}, v \in V_t, i \in N_t, s \in S \tag{5.30}$$

$$\beta_{its} \in \{0,1\} \qquad t \in T \setminus \{O\}, i \in N_t, s \in S \tag{5.31}$$

Constraints (5.23) to (5.27) impose non-negativity and integer values on the respective variables. Constraints (5.28) to (5.29) restrict the related variables to real and non-negative values. Constraints (5.30) to (5.31) restrict the variables to binary values.

6 COMPUTATIONAL STUDY

The mathematical model derived in Chapter 5 is implemented in commercial software for operation analysis. This chapter presents the results from a computational study on the mathematical model. The results are analyzed in order to discuss the performance of the model. The aim of the computational study is to test how the model works for a case in OSV shipping.

The model is tested with an appropriate set of input data, with three different scenarios. These scenarios are developed in order to investigate if the model is suitable as a stochastic formulation, and these scenarios are not to be taken literally. The model is also tested with a deterministic approach, with only one scenario as input. This scenario is developed as an average scenario. In order to evaluate the quality of the developed model, the limitations of the model must be determined. The limitations can be due to solution time, selection of input data or modeling assumptions. The optimal solution is of no economic benefit, if the solution does not give any reasonable decisions in the planning horizon. The computational study will address possible limitations, in addition to the model solution itself.

The cost data used in the scenario generation is based on second-hand sources, and might be inaccurate in some degree. This is important to keep in mind when generating solutions from the model. The intention with the computational study is to determine how the model can be applied as a decision support tool in decision making for OSVs, and not to give an extensive economic analysis.

The progression of work is done in steps, where the first step is to calculate all input data in Excel, before it is converted into a text file. The text file serves as input into the model in the commercial software. Xpress-IVE Version 1.22.04 64 bit is used to solve the implementations with Xpress Optimizer Version 22.01.09. Mosel Xpress is the modeling language. All runs are performed on a computer running Windows Server 2008 R2 Enterprise operating system, having an Intel® Xenon® CPU @ 3.33 GHz and 32 GB RAM.

6.1 Input parameters and test instances

A case is created to test the MFRP model for a fleet of OSVs. The test case must be as realistic as possible. This section presents assumptions and the data gathered for the computational study of the mathematical model. Assumptions are sometimes made in order to minimize the computational time.

Test instances

The solutions from the model will be highly dependent on the given input parameters and the generated scenarios. In order to compensate for this, different test instances are made for the computational study. Each test instance varies with the size of the fleet at the start of the planning horizon. Three sets of test instances are made in the sizes small, medium and large, and are meant to describe shipping companies of different sizes. The small set has a fleet of 12 ships, and the medium set has 20 ships, while the large set has 28 ships. Table 6.1 presents the details for each test instance.

These instances are tested with one and three scenarios, for deterministic and stochastic solutions, respectively. For each of the test instances, the ship types and contract types are the same. All test instances use the same input parameters, except for parameters that state the initial fleet.

Capacity and demand

The capacity of each ship type is presented in Table 6.1, which also presents the initial fleets for each test instance. The capacity for each ship type is chosen by gathering information from different ship designs from Ulstein (2015), in addition to inspiration by the reports from Platou (2015) and Fearnley Offshore Supply (2014).

The demand for each contract is determined by using DeepOcean (2015) as an example. Table 6.2 presents the demand for each contract type. Table 6.1 and Table 6.2 are then compared in order to develop a relation matrix to illustrate the compatibility between ship types and contracts, as presented in Table 6.3.

Table 6.1: Set of ship types, where the initial fleet is included.

	Capacities						Ships in Initial Fleet		
Ship Type	Divers [men]	ROV	Available deck space [m^2]	Bulk space	Crane [Te]	Pipe lay equipment	S	M	L
DSS	<18	1	<750	No	<150	No	1	2	2
DSM	18 – 24	1,5	750 – 900	No	<150	No	1	1	3
RSS	None	2	<750	No	<100	No	2	3	4
RSM	None	2	750 – 900	Yes	100 – 150	No	2	4	4
COS	None	2	<750	No	<150	No	1	2	3
COM	None	2	750 – 900	Yes	150 – 400	No	2	3	4
COL	None	2	>900	Yes	>400	No	2	3	3
PLM	None	2	<900	Yes	<150	Yes	1	2	3
PLL	None	2	>900	Yes	>150	Yes	0	1	2

Table 6.2: Set of contracts and the requirements for each contract type

	Requirements					
Contract Type	Divers [men]	ROV	Necessary deck space [m^2]	Bulk space	Crane [Te]	Pipe lay equipment
C1	12	1	0	No	0	No
C2	18	2	0	No	0	No
C3	24	2	0	No	0	No
C4	No	1	<500	No	<100	No
C5	No	2	500 – 900	No	100 – 150	Yes
C6	No	2	>900	No	>150	Yes
C7	No	1	<750	No	<120	No
C8	No	2	750 – 900	No	120 – 150	No
C9	No	2	>900	No	>150	No
C10	12	1	<750	No	<150	No
C11	18	2	750 – 900	No	150 – 400	No
C12	24	2	>900	No	>400	No
C13	12	1	<750	No	<100	No
C14	18	2	750-900	No	100 – 150	No
C15	24	2	>900	Yes	>150	No

Table 6.3: Compatibility between ship types and contracts

	Ship Type								
Contract Type	DSS	DSM	RSS	RSM	COS	COM	COL	PLM	PLL
C1	1	1	1	1	1	1	1	1	1
C2	1	1	1	1	1	1	1	1	1
C3	0	1	1	1	1	1	1	1	1
C4	0	1	1	1	1	1	1	1	1
C5	0	0	0	0	0	0	0	1	1
C6	0	0	0	0	0	0	0	0	1
C7	0	1	0	1	1	1	1	1	1
C8	0	1	0	1	0	1	1	1	1
C9	0	0	0	0	0	0	1	0	1
C10	1	1	0	1	1	1	1	1	1
C11	0	0	0	0	0	1	1	0	1
C12	0	0	0	0	0	0	1	0	1
C13	1	1	1	1	1	1	1	1	1
C14	1	1	1	1	0	1	1	1	1
C15	0	0	0	1	0	1	1	0	1

The maximum number times a contract is operated on in each period is determined by assuming the realistic maximum frequency of these contracts according to each scenario. Clarkson Research (2014) has an overview of all contracts operated on by OSVs in the North Sea for the past years. By studying these numbers for different market situations in modern history, the parameters for maximum frequencies are set. The minimum demand of visiting for each contract is assumed to be according to the realistic minimum frequency and market status of each scenario. This also applies to the limits on how many ships to sell, buy, charter in, and charter out. The ship type PLL is set as a specialized ship type, where there are limited possibilities to charter in or buy this kind of ship type.

Contract duration and planning horizon

Time is an important part when trying to optimize this system, where the income is dependent on the timeline. A contract is often specified with a mobilization, operation, and demobilization time. Transfer time is assumed to be included in the operational time. Each contract is given an average time within mobilization, operation, and demobilization (Thuestad, 2015).

When assuming an average mobilization and demobilization time for each contract type, it is assumed that equipment such as ROV tools and additional trenching and ploughing equipment is already on board. It is therefore assumed that the same vessels have the same contracts over time and the equipment stays on board.

The time lapse of mobilization, operation, and demobilization are presented in Table 6.4. The available time for each ship time in each period is assumed to be 365 days. Maintenance work on the ships including eventual down time, classification surveys, and other inspections, is not included into our case.

The strategic planning horizon should have a length that is not too uncertain to predict. Viewed against short time fluctuations in the offshore market, the strategic planning horizon should not exceed five years into the future.

Table 6.4: The time required for mobilization, operation and demobilization on each contract type

		Time [days]	
Contract Type	Mobilization	Operation	Demobilization
C1	0.33	1	0.33
C2	0.5	2	0.5
C3	1	4	1
C4	0.67	2	0.67
C5	3	7	3
C6	5	14	5
C7	0.33	1	0.33
C8	0.5	4	0.5
C9	2	7	2
C10	0.33	1	0.5
C11	0.5	4	0.75
C12	1	7	1.5
C13	6	91	6
C14	12	182	12
C15	18	273	18

Collection of critical input data

Different costs and revenues are found by using raw data from Clarkson Research (2014). Platou (2015) and Drewry Maritime Research (2015) also give information about cost developments within the OSV market. By using these sources, the costs and revenues are estimated for our computational study.

Operational costs include costs related to management, administration, dry docking, spares, insurance, and manning. Fuel costs are estimated by assuming that 40% of the operating costs must be fuel costs (Stopford, 2009). Operational revenues are set by expressing a daily rate for each ship type. This daily rate can have a large degree of variation, as expressed in Erikstad et al. (2011). Savings for lay-ups are calculated by estimating the savings related to reducing costs with manning, fuel costs, and insurance. It is assumed that the prices for selling and buying, in addition to charter-rates at any fare, are perfectly correlated. Furthermore, it is assumed that ships are sold at a cheaper price than their buying price, when estimating the revenue of selling a ship on the second-hand market.

The revenue of the ships in the pool at the end of the planning horizon is derived as the sunset value (Alvarez et al., 2011). The sunset value is in our case calculated by using a depreciation rate of 5% per year and an inflation rate of 3% per year on the original value of the ship, in addition to a margin of 70% in a market peak and 30% in a market trough, as recommended in Stopford (2009).

$$F = P(1+p)^n \tag{6.1}$$

The future value is calculated by the equation of present value, as presented in equation (6.1). In this equation, F is the future value, P is the present value and n is the year. The discount factor p is set as 12% per year, and is included when calculating all costs and revenues. The discount factor is chosen as suggested by Stopford (2009). The fares are calculated by increasing costs with 2% for each fare, and decreasing revenues with 2% for each fare.

Scenario generation

The stochastic approach to the model includes handling the uncertainty as discussed in Chapter 4. A two-stage stochastic programming model has been implemented. Three scenarios have been developed in terms of low, normal, or high market status in each period of the second stage. The probabilities are set to one third for each scenario, as presented in Table 6.5.

Table 6.5: Probability for each scenario

Scenario	Probability
High market scenario	33%
Normal market scenario	33%
Low market scenario	33%
Deterministic scenario	100%

The different stages, scenarios and time periods are illustrated in Figure 6.2. Information about the market status is revealed after one time period. The first stage consists of buying and selling decisions made in the first time period (t = 0). The deliveries of ships bought or sold on the second-hand market are fulfilled in the following time period (t > 0). No fleet deployments are made in the first period, and all scenarios have the same information about the market status in this stage. In the second stage, new information about the market status is revealed. The second stage consists of all decisions until the end of the planning horizon. Figure 6.3 illustrates the different market scenarios in the second stage.

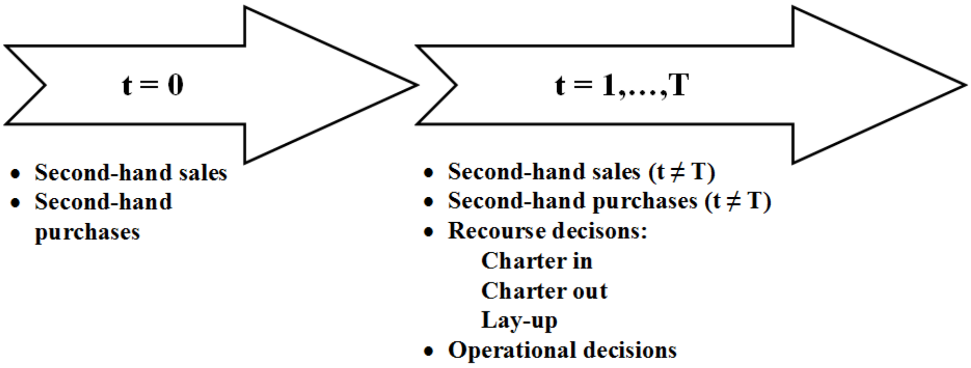


Figure 6.1: Decisions done in the first and second stage for the computational study

The number of scenarios is of a great importance when running the calculations. Too many scenarios might make the model unnecessarily hard to solve. Few scenarios might impact the solutions in such a manner that the results might be useless for comparison with other formulations of the problem (Mørch, 2014). Evaluation of the scenario generation can therefore be applicable, as discussed in Chapter 4. More scenarios will give a solution closer to the optimal solution. Since our scope is to study if the MFRP can be applied for a fleet of OSVs, scenario generation evaluation is not further studied in this thesis.

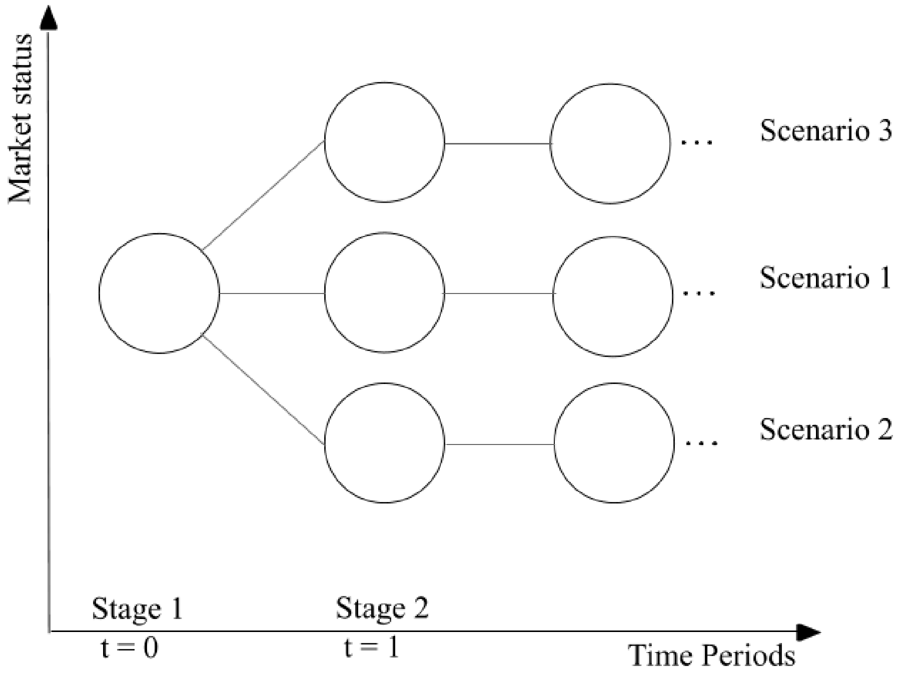


Figure 6.2: Scenario tree with three scenarios, in a two-stage stochastic model

The market status is assumed to have great impact on the demand, prices for chartering and second-hand prices. The revenue for operating contracts is also dependent on the market status. The market status is assumed to have high correlation with the oil price. The market development for determining the scenarios is not explicitly included in the scope of this thesis. However, the low market scenario is chosen by decreasing the normal scenario by 20% each period from the first period, while the high market scenario is developed by increasing the normal scenario by 10% each period from the first period.

In order to calculate the EV and the following EEV, a mean value scenario must be developed. The mean value scenario is determined by calculating the average prices and costs based on all the scenarios for the SS. This scenario is illustrated as the weighted average in Figure 6.3.

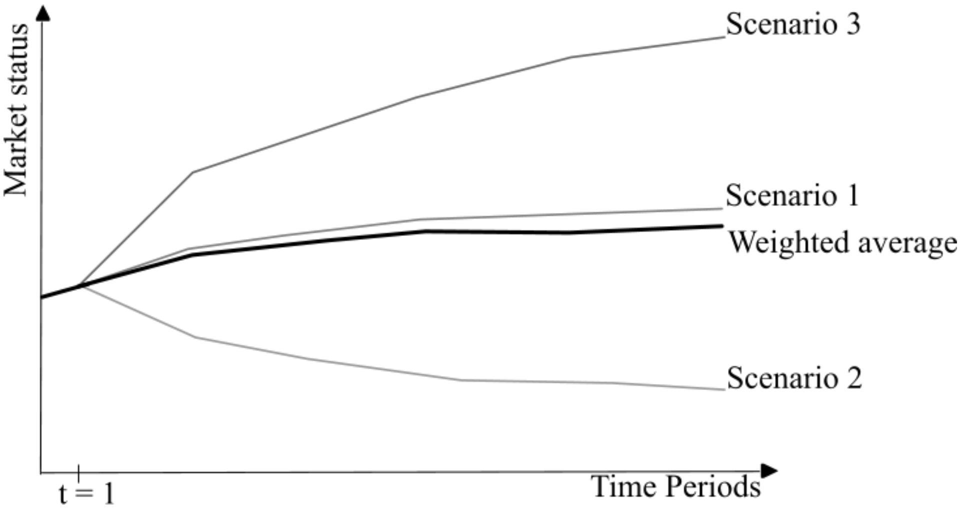


Figure 6.3: Market scenarios in second stage

6.2 Model solution

In Table 6.6, the results of running the model with input data for three test instances are presented. The deterministic solution time for each of the test instances has a duration of around ten seconds. For the stochastic solution, the solution times are 2 minutes for the small fleet, 41 seconds for the medium fleet, and 2 minutes and 30 seconds for the large fleet. These solution times indicates that the model is not too complicated to solve.

The stochastic solutions for the small and medium test instances, want to buy ships in the first stage. The large instance does not buy any ships, but rather sells the limit of possible ships in each time period. The medium test instance does also sell the maximum limit of ships during the planning horizon. However, the stochastic solution for the small instance does not sell any ships in the first stage. This might be because the stochastic solution prefers to wait and see how the market will develop in the next stage, for this instance.

For all instances, the deployment actions regarding the number of contracts operated increases with larger fleets. This indicates that the vessels are actually managed in operational decisions.

Recourse actions, such as chartering options, are also included in all instances. There are fewer ships chartered in, than there are chartered out. In addition, the solutions show that there are many ships that are sold. The model sells the maximum possible amount of ships on the second-hand market, in addition to chartering out ships. This indicates that the scenarios contribute in decreasing the number of ships in a fleet. It is more economically beneficial to charter out some ship types, than having them on contracts.

Table 6.7 presents the difference in initial fleet and the fleet in the last time period. The results show that the optimal solution suggests selling larger ships, focusing on having a fleet with smaller ships. The total amount of ships at the end of the planning horizon is 6 for the small fleet, 12 for the medium fleet, and 18 for the large fleet. This is equal to a decrease in the fleet of 6, 8, and 10 ships in the small, medium and large instances respectively.

The stochastic solution gives the results in real values, even though many of the decision variables have integer values. The reason for this is simply that the stochastic solution has a probability included for each scenario, which can result in giving answers as fractions.

Table 6.6: Comparison of the results from the small, medium and large test instances

	Test Instances		
	Small	Medium	Large
Ships bought on second-hand market			
t = 0	2	1	0
t = 1,…,T	0.66	0	0
Ships sold on the second-hand market			
t = 0	0	2	2
t = 1,…,T	8	8	8
Chartered in			
t = 1,…,T	1.65	1	1
Chartered out			
t = 1,…,T	10	10	10
Contracts operated			
t = 1	244.53	272.91	276.87
t = 2	237.27	268.95	267.30
t = 3	237.93	274.23	285.78
t = 4	231.33	279.18	308.88
t = 5	197.67	285.12	304.59
Profit (MUSD)			
SS	777	1146	1398
EEV	769	1146	1395
DS	909	1231	1480
VSS%	1.0%	0%	0.2%

Table 6.7: Comparison on how the pool changes from the first period to the last period

Ship Type	Small		Medium		Large	
	t = 0	t = 5	t = 0	t = 5	t = 0	t = 5
DSS	1	1.65	2	2	2	2
DSM	1	1	1	1	3	3
RSS	3	2	3	3	4	4
RSM	2	2	4	4	4	4
COS	1	0	2	2	3	3
COM	2	0	3	0	4	2
COL	2	0	3	0	3	0
PLM	1	0	2	0	3	0
PLL	0	0	1	0	2	0

6.2.1 Value of stochastic solution

For each instance, the value of the stochastic solution (VSS) is calculated. The VSS gives an indication of how well or how poorly the deterministic solution performs compared to the stochastic solution (SS). As presented in Chapter 4, the VSS is calculated by comparing the SS with the expected value problem (EEV), where the first stage decisions are considered. In the first stage, there are no deployment decisions, only whether to buy or sell ships on the second-hand market.

The solutions of VSS% for each test instance are presented in Table 6.6. All VSS% values are positive, which coheres with the property from equation (4.2). The VSS% values are not of significant size, and this indicates that there is not a significant need for a stochastic model in this case.

Table 6.8 presents the first stage decisions for the medium instance, with details on what ship types were bought and sold. The SS decides to buy a PLL and sell two COM. The DS do also sell a COM, but it also decides to both sell and buy a COL in the first stage, which is a large construction vessel. This could be a weakness with the deterministic model, since there is no need to both sell and buy the same kind of vessel type in a time period. This could have been a possibility if the ship was too old or should be replaced for other reasons, but these possibilities are not included in the model.

The first stage decisions of buying and selling ships are presented in Table 6.9. Since the maximum limit of buying and selling in each time period is set to the maximum of two ships total for all ship types, there is a big chance that the DS and SS get a quite similar solution. This is also the case in Table 6.9, where it is shown that the DS an SS sometimes make similar decisions. Based on the results from the test, it is possible to conclude that the value of using a stochastic model is not significant compared to a deterministic model.

Table 6.8: First period solutions from the medium instance

	Ship Type	DS	SS
Sales	COM	1	2
	COL	1	0
Purchase	COL	1	0
	PLL	0	1

Table 6.9: Ships bought and sold in the first stage

	Ships Bought		Ships Sold	
	DS	SS	DS	SS
Small	1	2	2	0
Medium	1	1	2	2
Large	1	0	2	2

6.2.2 Expected value of perfect information

The expected value of perfect information (EVPI) is the amount of money one is willing to pay for perfect information about the uncertain parameters. The EVPI is difficult to calculate when the future is so uncertain, as it is with the offshore industry. When the market is so uncertain, the EVPI can be of little value. However, the EVPI will give information about what one would be willing to pay for better market predictions.

In Chapter 4, the method of how to calculate the EVPI is presented. The wait-and-see solutions are calculated for each scenario. This is done by using the three different scenarios as a single scenario, each with a probability of one, which will give three deterministic solutions. In Table 6.10, the results of calculating the EVPI for each of the test instances are presented.

All the EVPI values are positive, which coheres with the property from equation (4.4). The EVPI is decreasing for larger fleets, and the EVPI for the medium and large instances is not particularly high, compared to the SS.

Table 6.10: Calculation of EVPI for each test instance

		Profit (MUSD)	
Scenarios	Small	Medium	Large
Scenario 1	909	1231	1480
Scenario 2	818	1008	1153
Scenario 3	954	1379	1696
WS	885	1194	1429
SS	777	1146	1398
EVPI	108	48	31
EVPI%	13.9%	4.2%	2.2%

6.3 Sensitivity in parameter values

The solutions from the model might be sensitive to changes in the input parameters. For instance, revenues and costs might initially be set too low or too high, which may not capture the future profit potential. As mentioned before, the objective of our computational study is to mainly see how the model works for cases within OSV shipping. The economic input data is not to be taken too literally. Nevertheless, it can be interesting to see how the model reacts to changes in the input parameters.

In this section, different parameters are changed, in order to test the sensitivity of the model. Only one parameter will be changed at a time. All tests have been done with a maximum running time of 3 000 seconds and an optimality gap of 0.01%.

6.3.1 The impacts of increasing the operational revenue

The operational revenue parameter reflects the income the company must have in order to make a profit on operating contracts. The parameter is found by calculating operational costs related to the contract duration and fuel costs, multiplied with a profit margin. These costs were found by using data provided by a second-hand company (Drewry Maritime Research, 2015). The level of operational revenue for each contract is important, since this determines the possible profit and investments that are profitable.

The model is tested for sensitivity on increasing the operational revenue, where the revenue for operating contracts is increased by 50%. It would seem reasonable that by increasing the operational revenue by 50%, more ships would be bought. When solving this, the solution time increases rapidly, with a solution time of over 3 000 seconds. The solution time for each test is therefore shortened by ending the run when having an optimal solution with a 0.1% gap.

The results from increasing operational revenues are presented in Table 6.11. The number of operated contracts increases with the size of fleet, which indicates that the operational decisions are performed as normal. The results show that the decisions regarding selling and buying are exactly the same in all test instances. It is profitable to have vessels on contracts, and the model buys and charters in ships to earn more profit from completing contracts. As predicted, the model chooses to buy more vessels, compared to the results in Table 6.6.

The SS do not sell any ships in the first stage, which show that the SS will wait and see until more information about the market is known in the second stage. The VSS% is equal to zero for all test instances. In this test case, the DS is therefore as good as the SS.

Table 6.11: Solutions when increasing operational revenue

	Test Instances		
	Small	Medium	Large
Ships bought on the second-hand market			
t = 0	2	2	2
t = 1,…T	2.64	2.64	2.64
Ships sold on the second-hand market			
t = 0	0	0	0
t = 1,…T	8	8	8
Chartered in			
t = 1,…,T	6.6	6.6	6.6
Chartered out			
t = 1,…,T	3.3	3.3	3.3
Contracts operated			
t = 1	292.71	313.83	304.26
t = 2	261.03	286.44	266.64
t = 3	276.21	297.33	299.97
t = 4	302.94	318.45	330.00
t = 5	268.62	304.26	308.88
Profit (MUSD)			
SS	814	1258	1593
EEV	814	1258	1593
DS	1078	1560	1927
VSS%	0%	0%	0%

6.3.2 The impacts of decreasing the maximum demand

Constraint (5.5) is included in the model to limit the maximum visits on each contract, i.e. the maximum demand for each contract type. The model is now tested in order to see how the model reacts to a decrease in the maximum demand for each contract type. The parameter for maximum demand for each contract type is now decreased by 40% in each time period, and the results are presented in Table 6.12.

For the medium and large instances, the maximum limit is reached for selling and chartering out ships in the planning horizon. In other words, the model wants to send out as many ships as possible, in order to avoid having ships in fleet without contracts. For all test instances, ships are placed on lay-up in periods, because of the low demand for operations. This is also logical, since there are fewer available contracts when the contract demand is decreased. The number of operated contracts increases with the size of fleet, which indicates that the decreasing in maximum demand do not prevent ships on performing contracts.

The VSS% is still low and positive. This indicates that by decreasing the limit of maximum demand, the solution is still not dependent on having a stochastic approach in order to meet the future uncertainty.

Table 6.12: The solutions when decreasing the demand of maximum demand

	Test Instances		
	Small	Medium	Large
Ships bought on second-hand market			
t = 0	2	1	0
t = 1,…T	0	0	0
Ships sold on the second-hand market			
t = 0	0	2	2
t = 1,…T	8	8	8
Chartered in			
t = 1,…,T	1.32	0.33	0.33
Chartered out			
t = 1,…,T	9.24	10	10
Contracts operated			
t = 1	167.97	175.89	176.53
t = 2	165.00	168.30	175.23
t = 3	162.36	173.58	182.82
t = 4	158.73	183.81	197.34
t = 5	146.85	164.67	189.42
Profit (MUSD)			
SS	654	1019	1271
EEV	651	1019	1268
DS	906	1228	1477
VSS%	0.5%	0%	0.2%

6.3.3 The impacts of increasing the planning horizon

The planning horizon is initially set to five years. It can be interesting to see how the model reacts to increasing the planning horizon from five to ten years. By increasing the planning horizon, the sunset value will become a bigger part of the potential future profit. The sunset value is as previously mentioned, the value of the fleet at the end of the planning horizon.

When increasing the planning horizon, all parameters are modeled the same way as with the five-year planning horizon. In other words, nothing is changes about the problem except for the planning horizon. The results from increasing the planning horizon are presented in Table 6.13.

The values for costs and revenues are all discounted, which will make the impact from these values less influential in the later periods of the planning horizon. In addition, the demand has a higher value for the high and normal scenario in the later periods, than what it is in the earlier periods. The demand is increasing, since the high and normal scenarios both have an overall increase in the market status.

The results show that the model does not charter in any ships. The limit of maximum number of ships to charter out is reached in each time period. The model does not sell any ships in the first time period, as it prefers to wait for more information about the market development.

The VSS% is now equal to zero for all test instances. A longer planning horizon gives the possibility of correcting bad decisions done earlier in the planning horizon and in the first stage. The impact of the decisions done in the first stage will therefore have less impact on the solution, when having an extended planning horizon.

Table 6.14 presents the changes in the pool from the beginning until the end of the ten year long planning horizon. Compared to Table 6.7, the model has also invested in some of the largest ship types. The scenarios for high and normal market development are both developed with a steady increase in the market status for each time period. This also contributes to making the average scenario increase throughout the planning horizon. This will make it profitable to have larger vessels at the end of the planning horizon, in contrast to the beginning of the planning horizon.

Table 6.13: The results of increasing the planning horizon for the test instances

	Test Instances		
	Small	Medium	Large
Ships bought on second-hand market			
t = 0	1.98	1.98	1.98
t = 1,…T	6.27	5.94	5.94
Ships sold on the second-hand market			
t = 0	0	0	0
t = 1,…T	12.54	13.86	13.86
Chartered in			
t = 1,…,T	0	0	0
Chartered out			
t = 1,…,T	19.8	19.8	19.8
Profit (MUSD)			
SS	1665	2276	2738
EEV	1665	2276	2738
DS	1733	2368	2844
VSS%	0.0%	0.0%	0.0%

Table 6.14: Comparison on the pool changes from the first period to the 10^{th} period

Ship Type	Small		Medium		Large	
	t = 0	t = 10	t = 0	t = 10	t = 0	t = 10
DSS	1	2.31	2	4.62	2	5.61
DSM	1	1	1	0.99	3	2.97
RSS	3	2	3	2.97	4	3.96
RSM	2	1.65	4	3.96	4	3.96
COS	1	0.66	2	1.32	3	2.97
COM	2	0	3	0.66	4	1.65
COL	2	1.98	3	1.98	3	1.65
PLM	1	3.96	2	3.96	3	3.63
PLL	0	3.96	1	4.29	2	5.28

6.3.4 The impacts of increasing the limits on sales and purchases

The model has a parameter that states the maximum limit of the total number of ships that can be chartered in, chartered out, sold, and bought. This limit was previously set at a maximum of 2 ships total for each of these categories. This is a strict limit, since it does not allow much for an increased charter, purchase, or sale when this is needed. In this section, the calculations are done with an increased limit for chartering in, chartering out, selling and buying. The limit is now set to a maximum of 5 ships in each period.

Table 6.15 shows the results of increasing the limits on buying and selling. The solution show that the model wants to charter out as many ships as possible. It gives more revenue for chartering out ships, than having ships on contracts. However, contracts are still operated, and the number of contracts operated increases with the size of the fleet.

In Table 6.16, the changes in the pool during the planning horizon are presented, when the limits on buying and selling of ship types are increased. Here, the results show that the number of vessels in the pool is decreasing over the planning horizon, even though the limits on buying and selling are increased. This is due to how the market is developing in each of the scenarios.

In the previous tests, the DS gives a higher profit than the SS. The DS is the average of all scenarios in the SS, and it makes sense that the DS should give a higher profit. When increasing the maximum number of visits on contracts, the medium and large test instances have a DS lower than the SS. When increasing the limits on ships that can be bought, sold, chartered in and chartered out, the scenario for high market development has potential of making more profit, than the two other scenarios. In the high market scenario, there is a higher demand for ships to perform operations. With increased availability of ships, there is now a possibility to deploy more ships on contracts. This results in an overall high SS for the medium and large scenario.

On the contrary, the DS gives an average scenario, with a lower demand for ships. The profit of the DS is therefore lower than the SS. However, the SS still has the properties of equation (4.2), which states that the optimal solution is found.

Table 6.15: Solutions when increasing the limits on buying and selling

	Test Instances		
	Small	Medium	Large
Ships bought on second-hand market			
t = 0	5	5	4
t = 1,…T	3	1.32	0
Ships sold on the second-hand market			
t = 0	0	0	4
t = 1,…T	5.18	19.8	19.8
Chartered in			
t = 1,…,T	5.28	2.97	2.97
Chartered out			
t = 1,…,T	24.75	24.75	24.75
Contracts operated			
t = 1	252.45	277.86	271.26
t = 2	244.53	271.92	264.33
t = 3	252.78	266.97	271.92
t = 4	206.91	236.94	241.56
t = 5	183.15	183.15	182.82
Profit (MUSD)			
SS	1189	1621	1923
EEV	1189	1610	1913
DS	1195	1604	1895
VSS%	0.0%	0.7%	0.5%

Table 6.16: Comparison of the number of ships in pool in the planning horizon, when increasing the limit on buying and selling

Ship Type	Small		Medium		Large	
	t = 0	t = 5	t = 0	t = 5	t = 0	t = 5
DSS	1	1.65	2	2.31	2	2
DSM	1	0.33	1	1	3	2
RSS	3	2.31	3	3	4	4
RSM	2	0.33	4	1	4	0
COS	1	0	2	0	3	0
COM	2	0	3	0	4	0
COL	2	0	3	0	3	0
PLM	1	0	2	0	3	0
PLL	0	0	1	0	2	0

6.3.5 The impacts of removing charter options

The possibilities of chartering in and chartering out ships are recourse decisions, which can contribute to making the model more flexible. Flexibility is good when solving the model with a deterministic approach. Chartering options reduce the need for making new investments for the fleet, since the model can chose to charter in ships when needed. In addition, ships can be chartered out when there are too many ships in the fleet compared to the available contracts.

Table 6.17 shows the results from the model when the possibility for charter options is removed. The VSS% increases for the small test instance, which is connected to the decrease in flexibility. When the VSS% is above 1%, the uncertainty is of such degree that it is beneficial to use a stochastic model.

The decisions regarding buying and selling are exactly the same as in Table 6.6. However, the profit decreases when removing the charter options. This is a side effect of removing the options of charter out ships, as this is a good source for additional profit.

Table 6.17: Solutions when removing charter options

	Test Instances		
	Small	Medium	Large
Ships bought on second-hand market			
t = 0	2	1	0
t = 1,…T	0.66	0	0
Ships sold on the second-hand market			
t = 0	0	2	2
t = 1,…T	8	8	8
Chartered in			
t = 1,…,T	0	0	0
Chartered out			
t = 1,…,T	0	0	0
Profit (MUSD)			
SS	625	993	1244
EEV	617	993	1241
DS	876	1197	1446
VSS%	1.1%	0.0%	0.2%

6.4 From bareboat charter to time charter

In the original model solution, the chartering variables are given integer values, i.e. bareboat charter. Bareboat charter means that the ship owner is hiring a ship for a long time period, typically a year, while a time charter means that a ship is chartered for a specified period of time. The charter variables can be changed from a bareboat charter to a time charter by giving the variables real values. Then, a fraction will mean that a ship is chartered in or chartered out for portions of the year.

When changing a variable from an integer to a real value, the model will become more flexible. It gives flexibility similar to the lay-up of ships, where ships can be made profitable without operating contracts. The difference from having a ship on lay-up to being chartered out for portions of the year, is that the lay-up is only contributing with savings in fuel costs and general operation costs. On the contrary, chartering out will generate revenues for the ship owner, and will be more profitable than lay-ups.

Table 6.18 show the results of including time charters instead of bareboat charter. The results are similar to the model solution in Table 6.6. In other words, the model did not act any differently when going from bareboat charters to time charters. The reason for the small difference from Table 6.6 to the results in Table 6.18 is that the charter out limit is already reached in Table 6.6. It is reasonable to assume that by introducing the time charter into the model it will be more favorable to charter out ships, instead of laying them up. However, since the chartering limits are already met in Table 6.6, the results are nearly exactly the same. The VSS% for the small test instance has a small decrease, which can be due to the increase in the model flexibility by introducing time charter.

Table 6.18: Solutions from introducing time charter, instead of bareboat charter

	Test Instances		
	Small	Medium	Large
Ships bought on second-hand market			
t = 0	2	1	0
t = 1,…T	0.66	0	0
Ships sold on the second-hand market			
t = 0	0	2	2
t = 1,…T	8	8	8
Chartered in			
t = 1,…,T	1.7	1.0	1.1
Chartered out			
t = 1,…,T	10	10	10
Profit (MUSD)			
SS	777	1145	1398
EEV	771	1145	1394
DS	909	1230	1479
VSS%	0.8%	0.0%	0.3%

7 DISCUSSION

In the computational study, the model is run as a two-stage scenario-based model, which is a stochastic approach to treat the uncertainty in the future market. The results of the computational study are given for three different initial fleets of various sizes, which represent three test instances.

The model is developed in a manner where it can work for both a deterministic and a stochastic approach. In both cases, the model presents flexible characteristics, where the fleet can both increase and decrease when the market status is good or bad. With a stochastic approach, the model has the ability to withstand random parameters. However, the computational study show that both approaches take the same decisions at the same time considering different scenarios, which make both the SS and DS appear quite robust.

An observation of the results shows that there is a trend that the model prefers to sell ships in order to have a smaller fleet, where the smallest ship types are desirable. For a longer planning horizon, the model decides to invest in larger ships. These results indicate that the model accepts both increasing and decreasing of the fleet, for different market developments.

7.1 Evaluation of the sensitivity analysis

When studying the impacts of changing the input parameters, the model structure did not show much sensitivity against changes. The model act as expected in nearly all cases, where the impacts of changes gave consequences as predicted. This gives an indication that the model is developed in a robust manner, and can withstand impacts from parameter changes to a large degree.

The model has a low solution time for all cases, except when increasing the operational revenue. When the operational revenue is increased, the model uses longer time in order find a strategic plan the underlying operational decision problem.

7.2 Evaluation of the value of stochastic solution

In the computational study, the VSS% is calculated for both the model solution and the sensitivity tests. To calculate the VSS%, the first stage DS solutions are applied in order to calculate the EEV. There are two decisions for each ship type in the first stage. These decisions are to choose to buy or sell any of the ship types. If any ship types are bought or sold, the ships are delivered in the next time period.

The main finding in the computational study for the model solution and sensitivity analysis is that the VSS% does not change in a significant manner in any of the tests. In other words, a deterministic approach can be applied in our case, to describe and optimize the fleet renewal problem for OSVs.

The VSS% may change drastically by changing one parameter in the problem. In the computational study, the VSS% is quite low in all cases. A positive VSS% means that it is profitable to use a stochastic formulation (Maggioni & Wallace, 2012). When the value of VSS% is under 1%, it is reasonable to consider this as equal to zero, since the VSS value can be affected by all the uncertainties in the choice of input parameters. In cases where VSS% are equal to zero, the DS can in practice be as good as the SS.

Pantuso, Fagerholt, and Wallace (2014) point out that the VSS% increases with the size of the instance, because of the charter limit. The charter limit represents a tighter restriction in the larger test instances (Pantuso, Fagerholt, & Wallace, 2014). In our case, the smallest instance gives the highest VSS% in almost all test cases, except for the case where the limits on charter options, sales, and purchases are increased. The VSS% increases with the size of the instance, when these limits are increased from three to five ships. When the limits are below five ships, it represents a tight restriction for the smallest instance. This applies with the theory proposed by Pantuso, Fagerholt, and Wallace (2014).

The high degree of flexibility can be one of the contributors of the low VSS%, which keeps the difference between the DS and the SS to the minimum. The options of chartering in and chartering out ships, in addition to lay-up, are the main contributors in making the model flexible. When removing chartering options, the VSS shows a slight increase for the small instance. Yet, the VSS did not show any difference for the medium and large instances. These results give indications that the DS is as good as the SS in nearly all cases.

By increasing the number of ships available for charter options, the VSS% can decrease (Pantuso, Fagerholt, & Wallace, 2014). The reason for this is the increase in flexibility, when it comes to a better possibility for recourse actions. If there are too many or too few ships in the fleet, recourse actions can be applied in order keep the fleet balance. In the computational study, the model is tested for cases where charter options are removed. The removal of charter options only gives a slight increase in VSS% for the small instance. This gives an indication that the DS is robust also against decreased flexibility in the model.

Even though the results from the VSS% show that the DS give good results, the DS does show some weakness. The DS wants to both sell and buy the same kind of ship in the first stage. This is unnecessary, both in a practical and an economical manner. For the economical part, there is a profit loss of several millions dollars by selling and buying the same ship type in a period. It is also practically wrong to do this, since the ships in the models are not given any age or any other property to make it beneficial to replace a ship with an identical ship.

For the DS, all future developments are given. The first stage decisions in the DS are performed based on known future uncertain parameters. The DS will not consider different future developments than expected. Hence, it does not include the possibility of keeping ships in case they might be useful in any future scenarios. The decisions done in the first stage will not be flexible, since the DS already know the future developments. The DS does not capture the dynamics of the problem, and the first stage decisions leads to imbalances in the second stage (Pantuso, Fagerholt, & Wallace, 2014).

Although the DS performs worse in terms of including future expectations, it still gives good decisions in the first stage when it comes to capturing the right mix of ships. The overall solutions from the DS and SS appear similar. The DS can therefore give useful information, and can be applied in order to simplify the stochastic problem.

A stochastic model is always harder to solve than a deterministic model. The SS will wait until more information is revealed, and it will consider the possibility for higher or lower market status in the next scenarios. A deterministic model is easier to solve, and can therefore be preferable to use.

7.3 Evaluation of the expected value of perfect information

The EVPI is decreasing for larger fleets, and the EVPI for the medium and large instances is not particularly high, compared to the SS. The reason for this might be that the decision on buying and selling ships does not change much with different market status in these two fleet sizes. The EVPI is high for the small test instance. This gives an indication that the testing is done with too few scenarios, and the number of scenarios should be increased (Uryasev, 2000).

The model solution has an overall low VSS%, even when the parameter values are changed. Therefore, the stochastic solution is adequately safe against any future market scenario. However, the EVPI is higher than the VSS, which indicates that there is a will to pay for more information about the future.

7.4 Evaluation of the scenario generation

The scenarios developed in our model are developed in means of a good, average and bad market development. The good and the bad development are given as percentage increase or decrease for each period. The probabilities for each scenario are assumed to have even probability. As stated in Erikstad et al. (2011), the model solution is dependent on the scenarios, and it is therefore important that the future scenarios have a good quality and realism, in order to get solutions with good quality.

The scenarios should have a probability distribution that reflects possible market developments for the future. A probability distribution will contribute in making the scenarios more realistic, and this can reflect the future market development in a better way.

When developing scenarios, there is a degree of uncertainty related to the development. In the long term planning horizon, the scenarios are based on predictions and assumptions about the future. However, when determining the development for the short time planning horizon, the scenarios can be based on actual available data about the market.

The scenarios developed in this thesis are not to be taken too literally. If the number of scenarios developed is increased, the solutions would be improved. This can also result in producing precise economic answers. One way of improving the scenario generation, is by the generation method proposed by Bakkehaug et al. (2014). This method is also briefly described in Chapter 4, and it applies well when developing small scenario trees. By introducing this scenario generation method, it can contribute to giving better solutions, without making the model too complicated.

Nevertheless, our scenario-based model with the developed scenarios can be seen as a representative example. By having three scenarios, it is possible to test and evaluate the model. The details in the economical answers do not need to be correct when developing a new model. The most important part is to validate the model and check if it works for the segments it is supposed to work for. However, for further development of the model, a extensive scenario generation should be performed.

7.5 Input parameters

The input file can contain sources of error, connected to how the costs and revenues are developing through the planning horizon. One of them is the way the operational costs and revenues are implemented in a low market scenario. The operational costs and revenues are decreasing in the low market scenario. This is implemented into the input file by decreasing the earning factor for operational revenues, but the operational costs are still decreasing. In reality, the costs will stay the same, as the revenues will decrease when the market status is low. This could be performed in a greater extend when developing scenarios, in order to make the scenarios differ from each other. Hence, the difference between costs and revenues will then be smaller.

7.5.1 Compatibility matrix

There are many possible difficulties with modeling a system for OSVs. One of the challenges is how to model the diversity of ship types, and what contracts the ships can operate on. In order to simplify the MFRP model for OSVs, a compatibility matrix is introduced. The matrix provides the compatibility between ship types and contracts, and it gives a good indication on which ships can operate on what contacts.

As mentioned before, OSVs are a type of ship category with a diversity of ship types, which may vary in size, type and equipment on board. In other segments of shipping, it is possible to use containers or volume in order to define the capacity of the ships. In OSV shipping, the capacity has many dimensions. The different capacities on board an OSV are dependent on many different elements, such as cranes, moon pool, deck space, and bulk space, and much more.

A compatibility matrix presents the compatibility between different types of OSVs and the applicable OSV operations, and it systemizes all the different elements of the capacity. The compatibility matrix is a simplified way of presenting the compatibility in our case. Cranes, bulk space, deck space, pipe lay equipment, ROVs, and divers are included in the compatibility matrix, but there are many other important elements with the OSV that should be included when determining the capacity of the ship. Some examples of other important elements are moon pools, A-frame crane, winches, DP system, and indoor hangar.

If more details regarding the capacity of ships are included in the model, the number of ship types and contract types will increase. This can contribute in making the stochastic problem more complicated. If the model gets too complicated to solve in commercial software, the integer boundaries can be changed to continuous decision variables in second stage, in order to solve bigger problems easily. Another way of simplifying the stochastic problem is to eliminate variables that are determined from the deterministic model.

The presented mathematical model is developed as a decision support tool. The compatibility matrix is developed in order to meet the complexity of the OSV fleet in a simplified manner. This can have a negative effect on the accuracy of the results from the model. The solutions of the decision variables are based on roughly estimates, which can give inaccurate results. However, the model is developed in order to provide decision support, and not to act as a single decision tool. The compatibility matrix can therefore be seen as a sufficient way of modeling the system, at least at this stage.

8 CONCLUSION

An optimization model is presented for the maritime fleet renewal problem (MFRP), tailored for offshore support vessels (OSVs). The model is a scenario-based mathematical model, with a two-stage stochastic approach. The presented model identifies the strategic decisions regarding fleet renewal, in order to maximize profit for future deployment of the fleet. Fleet renewal of ships is a crucial and difficult problem in maritime transportation, and the proposed model may serve as a decision support tool for fleet renewal for offshore shipping.

To validate the model, the model is solved for a test case with three test instances. The test instances are chosen to reflect shipping companies of different sizes. By using stochastic programming, the problem gets a realistic approach on the uncertainty aspects of programming. However, the results show that the deterministic model can be sufficient in many of the test cases.

The key findings from the computational study have not been the results themselves, but on the different ways in which the model can be handled as a strategic decision support tool for a fleet of OSVs. The model performs sufficient regarding deployment decisions, and the underlying operational decisions are also satisfactory done. The deterministic solution captures the right fleet mix, in order to meet the future demand, and this can be useful information in order to reduce the complexity of the stochastic problem.

For the presented problem, there are limitations connected to the lack of earlier studies about this topic. In addition, the computational study is performed based on input data provided by second-hand distributors.

Strategic fleet renewal can be beneficial to use in offshore shipping, as the OSVs are a costly resource in the supply chain. It is expected that the need for OSVs will remain high in the future, and there is a large potential in saving costs for OSVs by doing strategic planning. The proposed mathematical model can therefore be a contribution in introducing the fleet renewal for this segment of shipping.

9 FURTHER WORK

There have only been a few attempts of introducing fleet renewal for offshore shipping, based on our literature study. This chapter presents an important topic of further work for the presented model.

9.1 Including new vessels and the possibility to scrap vessels

Ships must differ from each other in speed, capacity, fuel, consumption and age. At some point in time, a ship can be outdated in terms of any of these properties. The presented model does not include these properties, and this should be extended in terms of deciding how many vessels to buy as new builds or scrap, and when to do so.

Pantuso, Fagerholt, and Wallace (2014) propose a way of including new vessels and scrapping of ships. Their case is from liner shipping, but it is possible transform this to offshore shipping. In their proposed model, ships are scrapped if they reach the maximum lifetime of a ship. In reality, ships are scrapped not only because of age, but also because the ship's properties do not satisfy today's requirements.

9.2 Spot market and voyage charter options

Placing the ship on the spot market is a way of maximizing the utilization of the fleet. When a ship is on the spot market, it is usually on one hour notice (V. R. Gibson, 1999). There is little time to prepare for the operation, and it is not unusual for the vessel to operate on an installation that the crew has never seen before. The spot market is not included into the presented model. This could be included by having a set of optional contracts which the ships can operate on.

The ship owner can charter out their ships for one voyage only to other OSV ship owners, who need a specific ship type in order to perform an operation. This type of charter option is called voyage charter, and could also be included into the model. A voyage charter is chartering a ship to do only one voyage with operation for a contract. It is then normal that the ship owner pays the fuel and port fees (Pantuso, Fagerholt, & Wallace, 2014), but it is the charterer who operates the ship.

9.3 Contract requirements for more than one vessel

Some contracts may have many requirements that are only possible to fulfil with more than one vessel. An example is when laying pipes or umbilical on the sea bed. The ship that lays the pipe or cable will be dependent on having a ship to support it with an extra crane and ROV. This can be included into the model in terms of adding constraints, as proposed by Erikstad et al. (2011).

9.4 Delay due to weather

In this thesis, the fleet of ships is thought to be operating on the oil and gas installations outside the coast of Norway. The weather conditions can have an impact on the sailing capability, which is weather sensitive (Aas et al., 2009). Some delays due to weather are always included in the contract specifications, but a large delay can contribute to delaying the next contract in line for the ship.

By including a meteorological parameter, this can give a more realistic approach to the model. The meteorological parameter can be included as a parameter that influences the operational duration. The parameter is dependent on a set of weather regions. Outside the coast of Norway, the regions can for example be divided in terms of using proper meteorological tools. This makes it possible to include possible weather delays in the modeling, which is important for the duration of each contract. This metrological parameter could also be dependent on the season of the year.

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APPENDIX I - THE MATHEMATICAL MODEL IN COMPACT FORM

Sets

T– Set of periods, indexed by t.
V_t – Set of ship types existing in the market in period t, indexed by v.
V_t^S – Set of special ships in period *t*, $V_t^S \subseteq V_t$.
F^{SH} – Set of second- hand fares, indexed by *f*.
F^{SE} – Set of selling fares, indexed by *f*.
F^{CI} – Set of charter in fares, indexed by *f*.
F^{CO} – Set of charter out fares, indexed by *f*.
N_t – Set of contracts operated in period *t*, indexed by *i*.
S – Set of scenarios, indexed by *s*.

Parameters

P_s – The probability of scenario *s* taking place.
R_{ivts}^{OP} – Revenue for completing contract *i*.
C_{ivts}^{OP} – Cost of operating on contract *i*.
R_{fvts}^{CO} – Revenue from charter out ship.
C_{fvts}^{CI} –Cost of charter in ship.
R_{vts}^{LU} – Revenue of lay-up of ship.
R_{fvts}^{SE} – Revenue of selling ship on second-hand market.
C_{fvts}^{SH} –Cost of buying ship on second-hand market.
R_{vs}^{V} – The value of ship of type *v* in period $\bar{T}$.
Q_{iv}^{CV} – A parameter that states if vessel *v* has the capacity to operate on contract *i*.
M – Big M, equal to maximum number of contracts operated.
A_{its} – A parameter that states if contract *i* is operated in period *t*, scenario *s*.
$\bar{F}_{its}$ – The maximum needs of operation on contract *i* in period *t*, scenario s.
D_{its} – The minimum demand of operation on contract *i* in period *t*, scenario *s*.
Z_i^{mob} – The time a ship needs to mobilize contract *i*.
Z_i^{demob}– The time a ship needs to demobilize contract *i*.
Z_i^{op} – The time a ship needs to operate on contract *i*.
Z_{vt} – The total available time for one vessel of type *v* in period *t*.
Y_v^P – A parameter that set the initial pool variable in period 0, which gives the initial fleet.
L_{fvt}^{CI} – The maximum number of ships of type *v* available at a fare *f* in period *t* to charter in.
L_{fvt}^{CO} – The maximum number of ships of type *v* available at a fare *f* in period *t* to charter out.

L^{SH}_{fvt} – The maximum number of ships of type *v* available at a fare *f* in period *t* to be bought at the second-hand market.

L^{SE}_{fvt} – The maximum number of ships of type *v* available at a fare *f* in period *t* to be sold at the second-hand market.

L^{CI}_{t} – The maximum limit of total ships chartered in, in period *t*.

L^{CO}_{t} – The maximum limit of total ships chartered out, in period *t*.

L^{SH}_{t} – The maximum limit of total ships bought, in period *t*.

L^{SE}_{t} – The maximum limit of total ships sold, in period *t*.

Decision variables

y^{SH}_{fvts} – The number of ships bought at fare f in the second-hand market, scenario *s*.

y^{SE}_{fvts} – The number of ships sold at fare f in the second-hand market, scenario *s*.

y^{P}_{vts} – The number of ships in pool, scenario *s*.

w^{CI}_{fvts} – The number of ships chartered in for period *t*, scenario *s*.

w^{CO}_{fvts}– The number of ships chartered out for period *t*, scenario *s*.

l_{vts} – The number of ships on lay-up for period *t*, scenario *s*.

x_{ivts} – The number of ship type *v* working on contract *i* in period *t* in scenario *s*.

β_{its} – A binary variable set to 1 if contract *i* is serviced in period t scenario *s*, 0 otherwise.

δ_{iv} – A binary variable set to 1 if vessel type *v* has the capability to take contract *i* in period *t*, 0 otherwise.

Objective function

$$\max z = \sum_{s \in S} P_s \left\{ \sum_{t \in T} \sum_{v \in V_t} \sum_{i \in N_t} (R^{OP}_{ivts} x_{ivts} \; - C^{OP}_{ivts} x_{ivts}) \right. \tag{0.1a}$$

$$+ \sum_{t \in T \setminus \{0\}} \sum_{v \in V_t} \left(\sum_{f \in F^{CO}} R^{CO}_{fvts} w^{CO}_{fvts} - \sum_{f \in F^{CI}} C^{CI}_{fvts} w^{CI}_{fvts} \; + R^{LU}_{vts} l_{vts} \right) \tag{0.1b}$$

$$+ \sum_{v \in V_{\bar{T}}} R^{V}_{vs} y^{P}_{v\bar{T}s} \tag{0.1c}$$

$$\left. + \sum_{t \in T \setminus \{\bar{T}\}} \sum_{v \in V_t} \left(\sum_{f \in F^{SE}} R^{SE}_{fvts} y^{SE}_{fvts} - \sum_{f \in F^{SH}} C^{SH}_{fvts} y^{SH}_{fvts} \right) \right\} \tag{0.1d}$$

Constraints

$$\delta_{iv} = Q_{iv}^{CV} \qquad t \in T \setminus \{0\}, i \in N_t, v \in V_t \tag{0.2}$$

$$x_{ivts} - M\delta_{iv} \leq 0 \qquad t \in T \setminus \{0\}, i \in N_t, v \in V_t, s \in S \tag{0.3}$$

$$\beta_{its} = A_{its} \qquad t \in T \setminus \{0\}, i \in N_t, s \in S \tag{0.4}$$

$$\sum_{v \in V} x_{ivts} \leq \bar{F}_{its}\, \beta_{its} \qquad t \in T \setminus \{0\}, i \in N_t, s \in S \tag{0.5}$$

$$\sum_{v \in V} x_{ivts} \geq D_{its}\, \beta_{its} \qquad t \in T \setminus \{0\}, i \in N_t, s \in S \tag{0.6}$$

$$\sum_{i \in N} (Z_i^{mob} + Z_i^{op} + Z_i^{demob}) x_{ivts} \leq Z_{vt}(y_{vts}^P + \sum_{f \in F^{CI}} w_{fvts}^{IN} - \sum_{f \in F^{CO}} w_{fvts}^{OUT} - l_{vts})$$

$$t \in T \setminus \{0\}, v \in V_t, s \in S \tag{0.7}$$

$$y_{vts}^P = y_{v,t-1,s}^P + \sum_{f \in F^{SH}} y_{fv,t-1,s}^{SH} - \sum_{f \in F^{SE}} y_{fv,t-1,s}^{SE} \qquad t \in T \setminus \{0\}, v \in V_t, s \in S \tag{0.8}$$

$$y_{v0s} = Y_v^P \qquad v \in V_0, s \in S \tag{0.9}$$

$$\sum_{f \in F^{CO}} w_{fvts}^{OUT} - \sum_{f \in F^{CI}} w_{fvts}^{IN} + l_{vts} \leq y_{vts}^P \qquad t \in T \setminus \{0\}, v \in V_t, s \in S \tag{0.10}$$

$$w_{fvts}^{IN} \leq L_{fvt}^{CI} \qquad f \in F^{CI}, t \in T \setminus \{0\}, v \in V_t, s \in S \tag{0.11}$$

$$w_{fvts}^{OUT} \leq L_{fvt}^{CO} \qquad f \in F^{CO}, t \in T \setminus \{0\}, v \in V_t, s \in S \tag{0.12}$$

$$y_{fvts}^{SH} \leq L_{fvt}^{SH} \qquad f \in F^{SH}, t \in T \setminus \{\bar{T}\}, v \in V_t, s \in S \tag{0.13}$$

$$y_{fvts}^{SE} \leq L_{fvt}^{SE} \qquad f \in F^{SE}, t \in T \setminus \{\bar{T}\}, v \in V_t, s \in S \tag{0.14}$$

$$\sum_{f \in F^{CI}} \sum_{v \in V_t} w_{fvts}^{IN} \leq L_t^{CI} \qquad t \in T \setminus \{0\}, s \in S \tag{0.15}$$

$$\sum_{f \in F^{CO}} \sum_{v \in V_t} w_{fvts}^{OUT} \leq L_t^{CO} \qquad t \in T \setminus \{0\}, s \in S \tag{0.16}$$

$$\sum_{f \in F^{SH}} \sum_{v \in V_t} y_{fvts}^{SH} \leq L_t^{SH} \qquad t \in T \setminus \{\bar{T}\}, s \in S \tag{0.17}$$

$$\sum_{f \in F^{SE}} \sum_{v \in V_t} y_{fvts}^{SE} \leq L_t^{SE} \qquad t \in T \setminus \{\bar{T}\}, s \in S \tag{0.18}$$

$$\sum_{f \in F^{SH}} y_{fvts}^{SH} \leq 1 \qquad t \in T \setminus \{\bar{T}\}, v \in V_t^S, s \in S \tag{0.19}$$

$$\sum_{f \in F^{CI}} w_{fvts}^{IN} \leq 1 \qquad t \in T \setminus \{O\}, v \in V_t^S, s \in S \tag{0.20}$$

$$\sum_{f \in F^{SH}} y_{fvts}^{SH} = \sum_{f \in F^{SH}} y_{ftv\bar{s}}^{SH} \qquad t \in T, v \in V_t, s \in S, \bar{s} \in S_{ts}^{NA} \tag{0.21}$$

$$\sum_{f \in F^{SE}} y_{fvts}^{SE} = \sum_{f \in F^{SE}} y_{ftv\bar{s}}^{SE} \qquad t \in T, v \in V_t, s \in S, \bar{s} \in S_{ts}^{NA} \tag{0.22}$$

$$y_{fvts}^{SH} \in \mathbb{Z}^+ \qquad f \in F^{SH}, t \in T \setminus \{\bar{T}\}, v \in V_t, s \in S \tag{0.23}$$

$$y_{fvts}^{SE} \in \mathbb{Z}^+ \qquad f \in F^{SE}, t \in T \setminus \{\bar{T}\}, v \in V_t, s \in S \tag{0.24}$$

$$x_{ivts} \in \mathbb{Z}^+ \qquad t \in T \setminus \{O\}, v \in V_t, i \in N_t, s \in S \tag{0.25}$$

$$w_{fvts}^{CI} \in \mathbb{Z}^+ \qquad f \in F^{CI}, t \in T \setminus \{0\}, v \in, s \in S \tag{0.26}$$

$$w_{fvts}^{CO} \in \mathbb{Z}^+ \qquad f \in F^{CO}, t \in T \setminus \{0\}, v \in V_t, s \in S \tag{0.27}$$

$$y_{vts}^{P} \in \mathbb{R}^+ \qquad t \in T, v \in V_t, s \in S \tag{0.28}$$

$$l_{vts} \in \mathbb{R}^+ \qquad t \in T \setminus \{O\}, v \in V_t, s \in S \tag{0.29}$$

$$\delta_{iv} \in \{0,1\} \qquad t \in T \setminus \{O\}, v \in V_t, i \in N_t, s \in S \tag{0.30}$$

$$\beta_{its} \in \{0,1\} \qquad t \in T \setminus \{O\}, i \in N_t, s \in S \tag{0.31}$$

APPENDIX II - ATTACHMENTS

Included into the attached ZIP-file:

- Mosel code for the MFRP used for OSVs.
- Input file for three scenarios.
- Description of notations used in Xpress and Excel.
- Academic poster.