Marine Fleet Optimization for Offshore Substation Maintenance

An application for the German and Dutch Offshore Transmission Grid

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by

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to obtain the degree of

Master of Science
in Transport Infrastructure & Logistics

at the Delft University of Technology,
to be defended publicly on August 27 2018, 4:00 PM.

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This thesis is confidential and cannot be made public until August 27 2018

Preface

The research presented in this thesis is conducted in the context of the Master program in Transport Infrastructure & Logistics at the Faculty of Civil Engineering & Geosciences of the Delft University of Technology. The thesis is the result of a graduation project, which was carried out in cooperation between the TU Delft and TenneT TSO B.V. The research addresses the development and application of an optimization model for the Maritime Fleet Size and Mix for TenneT, the Transmission System Operator in Germany and the Netherlands. The choice for this research stems from my passion and drive to contribute in the energy transition to mitigate the impact of human induced climate change and keep our World a lovely place to live for us and the future generations. In this sense, optimized maritime fleets should reduce costs for the offshore transmission of sustainable wind energy and subsequently this should promote the further growth of offshore wind power generation which can count on a reliable and cost-effective transmission grid.

In full honesty, I could not have achieved any of my success without a strong support group. First of all, I express great gratitude to my committee members, each of whom has provided patient advice, guidance, flexibility and understanding throughout the research process. A special thank you goes out to Ir. Mark Duinkerken, whom put a lot of effort in supporting me with my model, especially during the periods of struggle with the model. I also thank Dr. ir. Ioanna Kourounioti for the support to guide the thesis towards the end result and consulted me with the decisions, especially in the early stages of shaping the research. A very special thanks goes to Ir. Jan Heinrich, my external supervisor from TenneT Offshore GmbH, for always ensuring that I possessed over all means to get the work done. Jan Heinrich showed great interest in the project and was always available for validation questions and a nice talk in Dutch. A special thanks also goes out to the chair of the committee, Prof. dr. ir. Lóránt Tavasszy, whom always provided me with critical comments to sharpen my work. Also, I would like to thank my colleagues at TenneT Offshore GmbH for being a sparring partner, providing data, validating assumptions and supporting me in the relatively unfamiliar field of offshore logistics.

I want to express great gratitude to my parents and sister, who supported me with love and understanding. Moreover, they always set the right example to show that results can only be achieved with hard work, perseverance, tolerance and dedication. Finally, special thanks go out to my friends for their unconditional support and positive distraction during stressful times.

Thank you all for your unconditional support, Grantangi.

Devin D.D. Diran
Delft, August 2018

Executive Summary

Our World's electricity demand is increasing rapidly and in the main scenario of the International Energy Agency, the Global energy demand is expected to increase with 30% in 2040, relative to 2016. In order to meet this growing demand, while complying with the Paris Climate Agreement to mitigate the emission of Greenhouse gases, the World Energy Outlook estimates that in 2040 nearly 60% of all new electricity generating capacity will need to be based on renewable energy such as wind and solar (International Energy Agency, 2016).

The offshore wind energy industry is one of the most mature contributors to renewable energy production Globally and continues to grow at an astonishing pace. This is necessary to meet Climate goals in terms of reducing Greenhouse gas emission by means of replacing fossil based energy with renewable energy. To transport the energy coming from offshore wind-farms (OWF) to the end-users, a network of offshore transmission platforms with sub-sea cables is in place, functioning as the supply chain of electricity. This infrastructural chain offshore, called the Offshore Transmission Grid (OTG), poses great challenges for Transmission System Operators (TSO), in terms of transportation and logistics. Especially the costs are a, if not the biggest, challenge facing the industry (Dalgic, Lazakis, Dinwoodie, McMillan, and Revie, 2015a, Nederlandse WindEnergie Associatie, 2016). High costs are induced by, among others, extreme wind and wave conditions, limiting the deployment of transportation means needed to access OWF and supporting infrastructure such as the transmission platforms. These access related aspects can constitute to about 84% of OWF operating cost (Dalgic et al., 2015a). A well-coordinated and possibly integrated organization with optimized maintenance and logistics strategies is required for OWF to reduce the cost of offshore wind and maximize its deployment (Dalgic et al., 2015a, Ho and Mbistrova, 2017).

The reliability of the OTG is critical, as an unavailable OTG implies production losses for all connected OWF (Bresesti, Kling, Hendriks, and Vailati, 2007). And with an increasing share of offshore wind power in our energy mix, pressure from society and governments, the TSOs are driven to increase the efficiency of logistics planning and transport operations offshore, in order to reduce costs while maintaining high reliability performance as mandated by law. The main research question is formulated as:

> *To what extent can an optimal Marine Fleet Size and Mix established via integrated planning of the transport and accommodation strategy, minimize costs for the maintenance of the offshore substations in Germany and the Netherlands?*

With the TSOs puzzling to establish an offshore strategy which enables the operation of a reliable and cost efficient OTG, this study aims to propose a model for optimized fleet management taking into account strategic decisions in the field of maintenance, accommodation and manning. This problem will be referred to as the Fleet Size and Mix Problem in OTG, and will be addressed using methods from the field of Operations Research (OR) and according to the System Engineering methodology. To exhibit the functionality of the model, OptiFleet will be applied on the case of TenneT TSO B.V. This case entails the offshore transmission platforms in both the Dutch and German North Sea.

For the execution of activities related to the O&M of offshore substations, the determination of the fleet size and mix with which the O&M activities can be executed in a cost-efficient, safe and reliable way, is an important aspect. Within TenneT as TSO, fleet management is of particular importance, as the organization is moving away from the transportation of crew to and from the platforms using helicopters. Helicopters have been common practice in the Oil&Gas industry and this has been taken over by the OTGs (Wolfsturm, 2017a). The alternative is to utilize marine vessels instead of the helicopters and this leads to questions from the TSO on how to best implement these marine vessels (Heinrich, 2017b, Wolfsturm, 2017a).

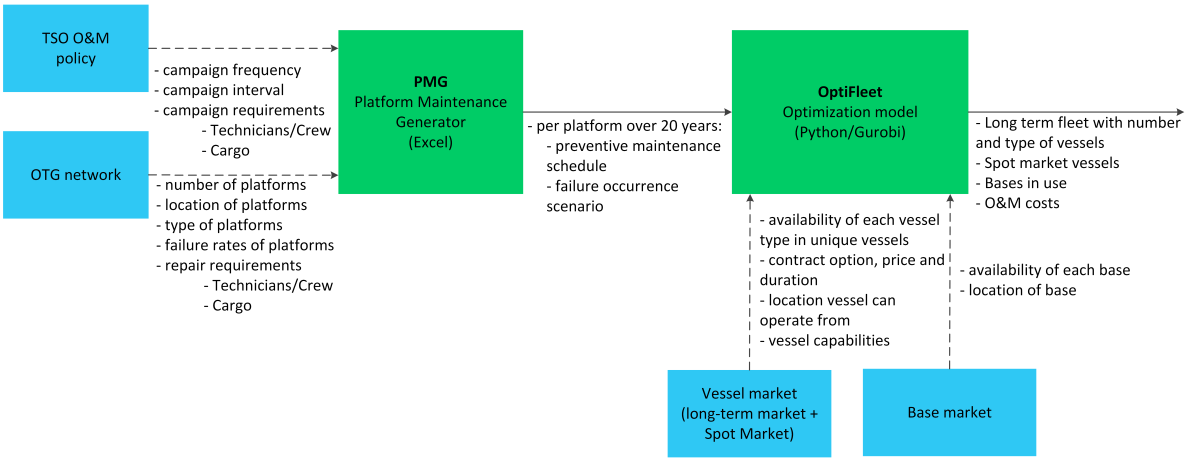
Helicopters, which are commonly used for crew change activities in offshore Oil&Gas, Wind and OTGs, can cost up to 3,400 $/hour in variable costs only (Conklin and de Decker, 2017). This while the cost of vessels range from 3,000 $/day, to 35,000$/day, depending on the type of vessel and contract type (Rupert et al., 2016). In addition, the prices can deviate with up to 60% from year to year, which brings a lot of uncertainty in when to lease vessels and on which contracts (Gundegjerde and Halvorsen, 2012). In addition to the financial challenge, vessel management is subject to a) time pressure in case of OTG failures due to lacking redundancy and big financial consequences in the case of production losses for the wind farm operators and b) the extreme offshore conditions related to the weather, in particular wind and waves, which strongly impact the accessibility of platforms with vessels. These factors increase the uncertainty in determining the optimal vessel fleet management.

Moreover, vessel fleet management is significantly influenced by strategic decisions regarding the maintenance strategy, the use of harbours and the accommodation strategy. These decisions may provide opportunities for fleet management to be optimized, but may also narrow down possibilities for optimal fleet management if not well thought through.

Finally, the societal relevance of the research thus lies in the aim to contribute in the realization of reliable and cost efficient OTG O&M, by means of integrated fleet mix and size decision making. This should subsequently enable further growth in renewable offshore wind capacity at low costs and high availability. The scientific contribution of this research lies in the development of an integrated model and literature on the logistic optimization of OTG. The decision support provided by this model is necessary for TSOs around the world, to realize the cost effective operations or the best possible return on investments. An integrated approach resulting in a holistic model, has the potential to improve the existing knowledge on offshore vessel fleet optimization. The holistic approach entails the integration of the vessel fleet composition and size, the maintenance strategy and the accommodation strategy for offshore transmission platforms.

Research Approach

At the center-piece of this study, stands an optimization model addressing the fleet mix and type problem for an offshore substation network. However, this optimization model, called OptiFleet, is not the sole subject of this study, this optimization model is namely surrounded and supported by various modules which provide the optimization model of input with respect to the decision variables, but also the constraints. The modules provide structure to the modelling framework and provide a means to keep track of the information flow. The distinction in modules provides the flexibility to develop the model in components whereby simplifications and adjustments can be applied per component in a controlled manner. The division in modules is based on the findings regarding current logistics planning and the associated information flows at TSO TenneT. In addition inspiration is drawn from the studies by Gundegjerde and Halvorsen (2012), Joshi and Bolstad (2016).



Presentation of the model process flow with the corresponding components. A distinction can be noticed between the modules, namely a distinction in data modules, blue boxes, and computational modules, the green boxes. In total the model consists of two computational modules and four data modules.

The data modules are providing the computational modules of input, see the dashed arrows. This input establishes the environment for the computational modules to execute calculations and yield results which contribute towards an efficient and effective fleet. The data modules are:

- **TSO O&M policy**: this module sets the value for the model parameters related to the characteristics of maintenance planning according to the policy of the TSO or the organization under study. TSO O&M policy targets parameters such as: 1) the frequency of maintenance on platforms which can be derived from the organization's risk assessments, and 2) the requirements for the transport and accommodation of technicians and cargo required for the maintenance activities, based on for instance the organization's safety culture.
- **OTG network**: the OTG network module provides data on the network of offshore platforms which are included in the case. The data addresses: 1) the number of platforms and their location, 2) the type of platforms and what failure rate is associated to the platforms and 3) requirements for technicians and cargo.
- **the vessel market**: the vessel market module contains data regarding the vessels (helicopters and ships) which are available on the market and can be acquired to execute the O&M activities on the given OTG network. The data is addressing various aspects of the vessels such as: 1) the contract under which they can be acquired, containing information on e.g. remuneration and the length of the lease agreement, 2) which type of vessels are available in terms of their operational characteristics, such as pax capacity, operable weather conditions, speed and fuel consumption, and 3) the location or ports these vessels may operate from.
- **the base market**: this data module is comparable to the vessel market module, but instead of vessels it provides data on the availability of bases.

The computational modules are characterized by computational functionality which make the model fit for use. The incorporated computational modules are:

- **PMG**: The Platform Maintenance Generator (PMG) creates the base demand for transportation services which have to be provided by the fleet. This is done by generating maintenance schedules. These maintenance schedules are generated from data coming in from the "OTG network" and "TSO O&M policy" data modules.
- **OptiFleet**: the OptiFleet optimization model is the component which, based on the base maintenance demand from the PMG, will determine which vessel fleet fits best with which maintenance scheme, leading to the lowest costs. The mathematical model behind OptiFleet and other aspects related to model development and implementation are discussed in section 5.6.

Results and Recommendations

In short it can be stated that operations research provides the necessary means to study the economic benefits of integrated fleet planning and support decision making for long term strategic fleet planning. These strategic decisions cover not only the geographic and organizational integration of the German and Dutch Grid, but also the integration of different logistic aspects, namely: vessel type selection, vessel contracting, accommodation strategy and maintenance strategy. However, for the model to be put to use effectively, it is necessary to acquire accurate and detailed data on, in particular, the vessel charter rates and the crew accommodation rate as these cost categories contributes for over 70% in the total logistic costs addressed by this study. This research did not sufficiently manage to gather all this data, hence the model could not be applied for detailed cost analysis. However, analysis was conducted with approximated data from literature, stakeholders and TenneT, and with this output conclusions could be drawn for the direction in which strategic logistic decisions could be made in the years to come.

After OptiFleet was conducted over the six sub-cases, the following can be concluded and recommended to TenneT:

- *Fleet composition.* For the situation in 2023, the combination of a medium PSVs with a medium CTV is recommended to transport the cargo and crew respectively. On the other hand, the situation in 2030 is recommended to be operated with the large PSVs, a solution which integrates both cargo and crew transportation in an integrated vessel solution. In short, the motivation can be given by the insufficient scale of the platform network associated to the 2023 cases, subsequently the 2023 situation cannot gain sufficiently from the integrated solution. On the other hand, the 2030 situation provides sufficient scale and clustering opportunities to make the shift to the integrated vessel solution.
- *Fleet size* the fleet size required to sufficiently meet the logistic demand by the different sub-cases is as follows:
  - DE-2023: three vessels of each PSV-M and CTV-M

  - NL-2023: two vessels of each PSV-M and CTV-M
  - DE-NL-2023: four vessels of each PSV-M and CTV-M
  - DE-2030: three vessels of type PSV-L
  - NL-2030: three vessels of type PSV-L
  - DE-NL-2030: six vessels of type PSV-L
- *PSV over OSV*, due to its lower cost, as compared to the newer OSV with comparable characteristics, the large PSV is selected over the OSV by OptiFleet. Due to the novelty of the OSVs these vessels are currently very high priced in the market and little operational experience exists. On the contrary, there is an oversupply in PSV vessels leading to low prices and a relatively easy inclusion of the vessel in the organization due to the ample operational experience with these vessels in the offshore industries (Daleel, 2018, Døsen and Langeland, Rosetti Marino, 2015).
  For the OSV vessels to be economically attractive compared to the PSV, significant rate drops are necessary, ranging from 30% for DE-2023 to 14% for DE-NL-2030. For OSVs to drop in costs that significantly, a bigger market and more adopters are necessary and this will take time. Hence, the recommendation is to take advantage of the oversupply in PSVs and opt for these vessels instead, up to the point that OSVs drop is price sufficiently.
  However, it is necessary to dive into the operational aspects of the two vessel types in a detailed manner to make the final decision. Especially benefits of the OSV which are difficult to express in costs, e.g. travelling and accommodation comfort and reduced emissions, should be included in the comparison between the vessel concepts.
- *Vessel contracting*, all vessels are recommended to be contracted on the less flexible, but least expensive long term contracts. A recommended measure to add flexibility while maintaining the low cost of long-term contracts is to take advantage of the strong position clients have in the PSV market with oversupply and include early-termination clauses in the contracts (Daleel, 2018, Valbrek). These early-termination contracts allow, in this case TenneT, to terminate existing contracts and flexibly opt for new vessels and contracts which are more attractive at that point in time.
- *Maritime vessels over helicopters*, the vessel selection clearly conveys that the helicopter is not part of the long-term fleet. This supports the decision of TenneT to make the shift away from helicopters, to vessels out of safety and economic reasons. Note that this is the case for the long-term fleet composition. On the short term, given uncertainty and irregularities, helicopters might still be necessary to be temporarily chartered. For instance if skilled labour needs to be transported to the platforms or for emergencies and when the vessels in the fleet are already en-route. In this scenario, heading back to the coast for the pick-up of the specially skilled technicians is not considered economic and a helicopter might be necessary. In addition to the helicopters, vessels other than the large low-speed vessels can be utilized. The alternative to the helicopter for these irregular, high speed operations is the CTV. Opting for the CTV, makes the helipads on the platform not needed and allows for the decommissioning of the helipads on the platforms leading to more cost reductions.
- *Accommodation strategy 2023.* For the 2023 case the recommendation is to maintain accommodation of the crew on the platforms and transport cargo with the PSV-M and crew with the CTV-M. In the meantime, the organization can gain experience and acclimatize to executing maintenance campaigns with maritime vessels instead of helicopters. Additionally, the organization is left with more time to prepare for the implementation of integrated vessel solutions with vessels such as the large PSV and OSVs.
- *Accommodation strategy 2030.* For the 2030 situation, given the specific characteristics of the recommended large PSV as a multi-purpose vessel which can transport both crew and cargo, accommodate crew on-board and boast other facilities to support offshore operations, the recommendation is to make the shift from platform accommodation to floating vessel accommodation of crew.
- *Importance of vessel charter rates.* Vessel charter costs contribute for an average of 52% in the logistic cost. This implies that for detailed cost analysis it is absolutely critical to derive detailed and accurate vessel charter cost from the market, before making decisions. This data could be derived via the tenders, launched once the desired requirements for the desired transport mode are determined in the field of crew capacity, deck-space, lifting capacity, accommodation facilities, vessel operability or availability (days per year that the vessel can be operated) and crew transfer capability (days per year that the crew can be transferred from vessel to platform and vice-versa). The latter two are dependant on the weather conditions.
- *Benefits from geographic integration.* Regarding the geographic integration of the German and Dutch

grid with a single fleet approach, this entails that both grids are considered as a single grid for the fleet planning, the results are not as expected. Where major benefits where expected if grids are geographically and organizationally integrated, OptiFleet shows small (3%) benefits for the case in 2023. However, the model generates higher costs for the integrated cases in 2030. On the contrary to the economic benefits which are not as expected for the integrated approach, OptiFleet does provide output which indicates that a leaner fleet, that is a fleet with less vessels, is possible in the integrated approach. This, compared to the sum of the individual Dutch and German fleets.

In short, it can thus be stated that the model provides means to study the benefits of OTG integration to a certain extent, but the results are not as expected. The following can be proposed to improve the results and bring them closer to the expected and desired behavior: include a maintenance planning mechanism with combined vessel routes. This could improve the ability of the model to reduce operational costs and be more fit for analysis of the integrated DE-NL cases. The maintenance planning mechanism should align and coordinate the periods, day-to-day and hourly, when maintenance should be carried out on the platforms in combined campaigns, taking into account the available vessels and possible routes along the platforms. The maintenance planning should thus go further, than the per year aggregate maintenance planning currently implemented in OptiFleet.

The OptiFleet model can be considered to be a relevant tool to support the strategic decisions regarding the future logistic operations, where different platform networks and maintenance strategies can be tested to determine the appropriate fleet composition, base utilization and accommodation strategy. However, the model is limited to predominantly the strategic level and partially the tactical level. Hence, the main recommendation for future work, after acquiring accurate vessel rate and accommodation rate data, is to expend the model to the operational level. Hereby, the recommendation is to execute this in an stochastic style to account for weather-, failure- and vessel uncertainty in a more detailed and sophisticated way than OptiFleet.

Finally, it is recommended to TenneT, that if knowledge from the model wants to be optimally utilized in the strategic fleet planning, there is a need to integrate the model in the asset management and risk analysis activities of TenneT Offshore. Input and output from the models for asset management and risk analysis are recommended to be interactively utilized with the input and output for OptiFleet. In this way risk analysis on for instance platform failure rates can be adjusted based on the vessel fleet characteristics proposed by OptiFleet and on its turn OptiFleet can adjust the fleet based on the updated platform failure rates. Integration of the model in the greater organization is expected to be the best way to gain support for the application of the model and subsequently realize cost effective and reliable fleets for an equally reliable and cost-effective Offshore Transmission Grid.

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Introduction and Research Definition

1.1. Introduction

1.1.1. The offshore wind energy domain

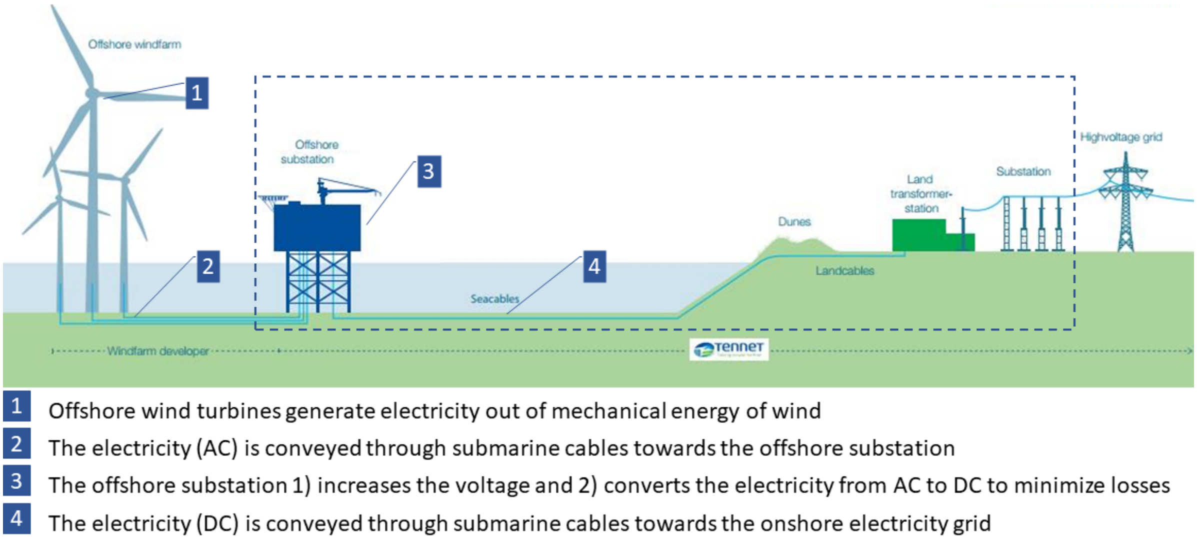
The World's energy demand is increasing rapidly as a consequence of a variety of reasons related to Globalization, Economic Development and welfare dynamics. In the main scenario of the International Energy Agency, the Global electricity demand is expected to increase with 30% in 2040, relative to 2016. In order to meet this growing demand, while complying with the Paris Climate Agreement to mitigate the emission of Greenhouse gases, the World Energy Outlook estimates that in 2040 nearly 60% of all new electricity generation capacity will need to be based on renewable energy such as wind and solar (International Energy Agency, 2016).

Within this required growth in renewable energy capacity the offshore wind energy sector is one of the most fast growing and maturing industries. Throughout the world, but particularly in Europe, North-America and Asia, major projects are developed to further increase this generation capacity of offshore wind power. The availability of large areas for the development of large offshore wind farms (OWF), the absence of limitations associated to noise and visual impact, higher wind speeds and the lower turbulence levels in the offshore environment are driving these investments in offshore wind projects. In the process of growth, offshore wind energy is still facing a variety of challenges. Especially the costs are a, if not the biggest, challenge facing the industry (Dalgic, Lazakis, Dinwoodie, McMillan, and Revie, 2015a, Nederlandse WindEnergie Associatie, 2016). High costs are induced by, among others, extreme wind and wave conditions, limiting the deployment of transportation means needed to access OWF. These access related aspects can constitute to about 84% of OWF operating cost (Dalgic et al., 2015a). A well-coordinated and integrated organization with optimized maintenance and logistics strategies is required for OWF to reduce the cost of offshore wind and maximize its deployment (Dalgic et al., 2015a, Ho and Mbistrova, 2017).

In this unprecedented growth of the offshore wind industry, OWF consisting of wind turbines are not the only infrastructure critical for a successful and reliable offshore wind energy industry. The wind parks need to be connected to shore by means of high voltage cables, via offshore transformation substations, in order to deliver the generated power to the onshore grid towards the end-users of electricity. This needs to be executed in a reliable way, as an unavailable transmission net implies production losses for all connected OWF (Bresesti, Kling, Hendriks, and Vailati, 2007). With an increasing share of offshore wind power in the energy mix, the importance of reliable and economically efficient infrastructure to convey wind power generated offshore to the end-users onshore also increases. The collective of offshore infrastructure with the function to convey electricity to shore is called an Offshore Transmission Grid.

1.1.2. The Offshore Transmission Grid

The aforementioned Offshore Transmission Grids (further abbreviated as OTG) consist of two main elements: submarine transmission cables and offshore converter substations. In figure 1.1, such an OTG is schematically presented including its components and the associated functionality. Within the blue framework, lies the scope of OTG. Transmission System Operators or TSOs are the organizations which operate these OTGs. The TSO is responsible for grid balancing services, grid congestion services and transmission services on land and offshore. The research presented in this thesis is conducted with TenneT TSO B.V and TenneT TSO GmbH, and together these two TSOs are responsible for the grid balancing services in parts of Germany and the Netherlands. Hence, this study will specifically address the OTG in the German and Dutch part of the North Sea. Moreover, within TenneT TSO GmbH, TenneT offshore GmbH is responsible for the design, planning, construction management and operation of the OTG. This, according to the grand vision of TenneT to realize a large European electricity system in the North Sea, a vision which aims to realize the CO_2 reduction targets in a feasible and affordable way (TenneT Group, n.d.).



1 Offshore wind turbines generate electricity out of mechanical energy of wind

2 The electricity (AC) is conveyed through submarine cables towards the offshore substation

3 The offshore substation 1) increases the voltage and 2) converts the electricity from AC to DC to minimize losses

4 The electricity (DC) is conveyed through submarine cables towards the onshore electricity grid

Figure 1.1: Schematic overview of an OTG, adapted from TenneT (n.d.)

The reliability of these OTGs is of paramount importance, as the availability and generation efficiency of OWF can be undermined by unreliable offshore transmission systems. Hence, cost efficient and reliable design, construction and operation of these OTGs contribute towards reducing the cost of offshore wind energy and increasing its availability (Bell, Cirio, Denis, He, Liu, Migliavacca, Moreira, and Panciatici, 2010, Bresesti, Kling, Hendriks, and Vailati, 2007).

Often neglected in the current state of academic research in offshore logistic optimization, these OTGs, in particular the transmission platforms, share comparable challenges with the wind farms. These challenges form a bottleneck for cost-effective operations. In addition to the contribution of extreme offshore conditions towards high costs for the operation and maintenance (O&M) of OTG, the following problem can be defined for the OTG in Germany and the Netherlands:

Novel technology, sub-optimal planning and insufficient integration on the strategic, tactical and operational echelon, between sub-systems of the TSO are leading to high costs for the Operations and Maintenance (O&M) of offshore substations.

Within these echelons of decision-making there is thus a need for a holistic approach which integrates, in an optimal way, the decision making over not only various levels of decision making, but also different functionality. This need could, among others, be derived from the interview with Jan Heinrich, Manager Logistics at TenneT Offshore (Heinrich, 2017a,b). For the execution of activities related to the O&M of offshore substations, the determination of the fleet size and mix with which the O&M activities can be executed in a cost-efficient, safe and reliable way, is an important aspect. Within TenneT as TSO, fleet management is of particular importance, as the organization is moving away from the transportation of crew to and from the platforms using helicopters. Helicopters have been common practice in the Oil&Gas industry and this has been taken over by the OTGs (Wolfsturm, 2017a). The alternative is to utilize marine vessels instead of the helicopters and this leads to many questions from the TSO on how to best implement these marine vessels (Heinrich, 2017b, Wolfsturm, 2017a).

Helicopters are commonly used for crew change activities in offshore industries and can cost up to 3,400 /hour in variable costs only (Conklin and de Decker, 2017). This while the cost of vessels range from 3,000 /day, to 35,000/day, depending on the type of vessel and contract type (Rupert, Wester, van der Heijden, vor dem Brocke, van der Horst, Kuijpers, and Breuer, 2016). In addition the prices can deviate with up to 60% from year to year, which brings a lot of uncertainty in when to lease vessels and on which contracts (Gundegjerde and Halvorsen, 2012). In addition to the financial challenge, vessel management is subject to a) time pressure in case of failures of the OTG due to lacking redundancy and considerable financial consequences in the case of production losses for the wind farm operators and b) the extreme offshore conditions related to, but not limited to, the weather and in particular wind and waves, which greatly impact the accessibility of platforms for crew and cargo transfer. These factors increase the uncertainty in determining the optimal vessel fleet management.

Furthermore, vessel fleet management is significantly influenced by strategic decisions regarding for instance the maintenance strategy, the use of ports and the accommodation strategy Heinrich (2017a). These decisions may provide opportunities for fleet management to be optimized, but may also narrow down possibilities for optimal fleet management if not well thought through.

With the TSOs puzzling to establish an offshore strategy which enables the operation of a reliable OTG, in a way which is best for the return on investment, this study will aim to propose a model which optimizes fleet management. This model, takes into account higher strategic decisions in the field of maintenance, accommodation and manning. In short, the problem can be referred to, as the Fleet Size and Mix Problem in OTG, which will be addressed using Operations Research (OR).

The approach will propose a primarily deterministic model, in which the focus is on establishing and testing the modeling of decisions in equations by means of the decision variables and constraints. Furthermore, the step will be set towards a proposal for a stochastic model. For a higher validity of the model the stochastic extension is inevitable. The offshore industry and its logistics can namely be characterized by inherent uncertainties in its planning and execution. The source of the uncertainty lies in for instance the weather and its impact on the accessibility of platforms and the failure of equipment in an offshore environment compared to an onshore situation (Algra, 2017, Gundegjerde and Halvorsen, 2012).

1.1.3. Societal and Scientific relevance

From the previous sub-sections, the societal relevance of this research can be derived. This is namely to contribute in the realization of reliable and cost efficient O&M of OTG, by means of integrated fleet mix and size decision making, to enable further increase in renewable offshore wind capacity at low costs and high availability.

Although the offshore wind energy industry is a relatively novel industry, over the years a significant body of literature is composed in the optimization of logistics for OWF O&M, where Operations Research (OR) has played an important role. In a literature review conducted in 2014 by Shafiee (2015), 102 publications on maintenance logistics for offshore wind energy could be identified. The methods applied for the fleet optimization models in the Offshore Wind and Oil&Gas industry are applications of the Operations Research field, and thus in that sense also applicable for the OTG. However, there are significant differences between offshore transmission substation platforms on the one hand, and Offshore Oil&Gas platforms, Wind Farm Platforms and Wind Turbine platforms on the other hand. This calls for adjustment of the methods for the specific characteristics of OTG. Compared to the offshore Oil&Gas platforms, the processes on the substation platforms are significantly different. This leads to different needs in terms of the transportation and logistics of material and supplies for different maintenance patterns. Compared to the Wind farm platforms and wind turbines, the OTG transmission platforms are different in terms of the structure shape and size. Furthermore, the seemingly straightforward integration of logistics for OWF and TSOs, for instance the operation of a joint fleet for both OTG and OWF O&M, is complicated due to competition regulation as a consequence of the fact that many TSOs are State owned, or regulated organizations, while the operators of OWF are predominantly private parties (Algra, 2017).

The lack of this literature, and the significant differences with fields for which literature exists, may be the reason why TSOs such as TenneT are not applying methods in the field of OR sufficiently in the current operations. Hence, the aim of this study is to learn from the rapid and unprecedented growth of offshore wind power in Germany, and subsequently the rapid and unprecedented growth of OTG, and propose a model which can help the TSO in Germany, the Netherlands and around the world to plan and operate the fleet for their OTG cost effectively. More specifically, this model should provide decision support to decision makers within TSOs when planning the fleet management in terms of the size of the vessels and the mix of vessel types in the fleet.

The scientific relevance of this research lies in the belief that developing a model and literature on the logistic optimization of OTG, is necessary for TSOs around the world to be provided with the currently lacking decision support on cost effective logistics. As previously stated, models do exist for wind farms and this will be elaborated on in section 4.3, however the existing models apply targeted approaches on parts of the problem. The scientific motivation for this thesis, is that an integrated approach resulting in a holistic model, can potentially improve the existing knowledge on offshore vessel fleet optimization. The holistic approach entails the integration of vessel fleet decisions, maintenance strategy decisions and manning strategy decisions for offshore transmission platforms, whereby geographic integration is also addressed. After stating the societal and scientific relevance, the knowledge gap which will targeted by this research can be summarized as:

There is a limited scientific body of research in the field of integrated logistics, regarding maintenance strategies, accommodation strategies and vessel fleet management for the OTG, aiming to increase cost-effectiveness of operations and the reliability of the OTG.

In the remainder of this chapter, the research definition based on the aforementioned knowledge gap will be further elaborated on.

1.2. Research Definition

This section will elaborate on which problem this research will specifically target in order to bridge the aforementioned knowledge gap. The problem definition will be followed by the research objectives and finally the research questions.

1.2.1. Problem Definition

In the previous chapter it was mentioned that there is a need for an integrated approach of logistics optimization. The source of this need can be traced back to, first of all, the limited budget made available for O&M. Furthermore, there generally is societal pressure to reduce the costs for the transmission of power in order to keep electricity at socially acceptable prices (Heinrich, 2017a). This desire to reduce costs is present for TSOs worldwide and it can be derived from, among others annual reports of TSOs in Norway, China and the United States of America (California ISO, 2013, State Grid Corporation of China, 2016, Statnett, 2017). In the quest to reduce these costs structurally, TSOs are looking to optimize logistics. However, analysis at the German TSO TenneT showed that although optimization efforts are made, these efforts are occurring independently. With independently it is meant that the sub-systems do not sufficiently align their planning with each other in terms of the strategic, tactical and operational transportation planning.

This independent planning implies that sub-systems are able to realize local optimal performances. Local in the sense that with the performance indicators of the sub-system they realize optimal performance, but the setback of this sub-system optimization is that at the end of the day when sub-systems come together for the operational planning of the transportation and logistics, the optimal solutions of the various sub-systems do not necessarily align, hence leading to short-term sub-optimal planning with necessary compromises of the optimal solution for the separate sub-systems.

With the necessity to operate more cost effective while guaranteeing reliability there is a need for integrated and proactive logistic planning. According to Heinrich (2017a) and Pattison, Xie, and Quail (2013) there is ample potential for integrated planning optimization to deliver these cost reductions. However, the field and application of integrated logistics is very broad. In order to propose specific solutions for TSOs to operate cost effectively it is proposed to decompose the field of decision making. First of all, decisions can be made in the strategic, tactical and operational echelon. Secondly a distinction can be made between the functionality – e.g., decision making in O&M, decision making in fleet management and decision making in transportation routing.

To start off, TSOs are making decisions on strategic, tactical and operational level. Since TSOs are service providers, they provide transmission and net balancing services for electricity, it is critical to have a firm strategy which anticipates in the needs of society, energy generators and the government. Particularly, because electricity is considered a basic good, the transmission grid, like e.g. the highway network, is subsequently considered as a backbone of the economy (TenneT Holding B.V., 2017).

In the last decade, the energy transition, that is the transition away from fossil based energy towards sustainable energy, has placed itself in a very significant position in the strategy of TenneT (Heinrich, 2017a, TenneT Holding B.V., 2017). In line with the strategy of facilitating renewable energy and the obligation to do so, TenneT needs to anticipate on the developments of offshore wind parks with the construction of transmission capacity, instead of chasing the developers of wind farms and risking the occurrence of unfinished transmission grids when the wind farms are ready to generate energy. Due to the rules in the German North Sea and Baltic Sea, the TSO has the liability to not only connect the offshore wind parks to shore, but also to have the connection ready when the wind farm is commissioned for the generation of wind power. If this is not the case, the consequence are lost production for the wind farms and high fines for the TSO for noncompliance with the liability regime (Federwisch and Schmitz, 2013, von La Chevallerie, 2013). TenneT's strategy of timely anticipating, planning and constructing offshore transmission infrastructure is save-guarding the philosophy to reduce costs, to comply with the desires of society and shareholders, while guaranteeing reliability.

In line with this philosophy, TenneT is now drafting various strategies for the operation and maintenance of their Offshore substations. This entails, among others, how the manning of offshore platforms will be dealt with from 2020 onward and what this means for O&M logistics and transportation. Regarding this manning strategy there are some premises as a consequence of decisions which take action before 2020, however many questions are still awaiting answers. In the following, these questions will be briefly introduced, in terms of the strategic field they are related to.

1. **Platform manning strategy:** will the platforms be manned or unmanned and how should that occur? This largely determines the needs for crew transfer in terms of the time, frequency and quantity. Additionally, it determines which facilities are necessary on the platforms (Edwards et al., 2015, Rysst, 2016).
2. **Accommodation strategy:** Related to the manning strategy is the accommodation strategy, for instance manned platforms require the permanent installation and maintenance of accommodation on the platforms itself. However in the case of unmanned platforms, one can choose to either maintain accommodation on the platforms, but the alternative is to arrange accommodation on separate structures than the platform during periods the platforms are temporarily manned e.g., for maintenance activities. For this alternative the strategy could utilize floatels (vessels with accommodation for crew) or for instance dedicated accommodation platforms which are stationary and functioning as a hub for the O&M operations of the offshore substations. From this offshore hub shorter trips relative to trips from shore, can be made towards the sub-stations, see e.g. figure 1.2.

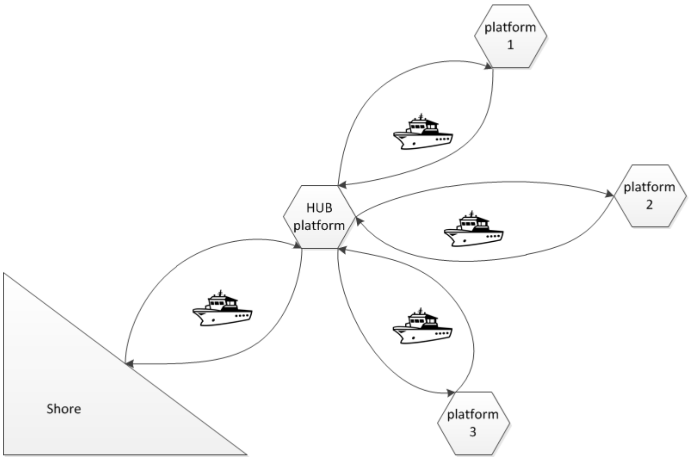


Figure 1.2: the hub-platform concept

3. **Maintenance strategy:** What is the strategy behind the O&M activities? Is the strategy around scheduled maintenance, risk based maintenance or condition based maintenance? The maintenance strat-

egy strongly influence the requirements for fleet management and operations within the offshore logistics (Stålhane, Vefsnmo, Halvorsen-Weare, Hvattum, and Nonås, 2016).

4. **Transport Strategy:** This strategy is related to choices that have to be made regarding the transport mode to be utilized for the transportation of crew, material and supplies to and from the substations. For offshore transportation the TSOs utilize either helicopters or maritime vessels. Regarding the vessels different options are possible and this is dependent on a) the requirements for the transportation of crew in terms of for instance comfort and acceptable travel times, b) the weather conditions and c) the platform structure, height and facilities such as the presence of helipads or vessel landing structures. Consequently, the methods and tools in the field of fleet management, or in literature also called Marine Fleet Size and Mix Problems (MFSMP), offer the means to optimally plan fleet management for a 2020 strategy which still carries significant uncertainty.

TSOs such as TenneT acknowledge the challenges when it comes to making the optimal decisions regarding the manning strategy and the associated accommodation and transportation strategy, given the characteristics of the OTG. Since this knowledge is relevant for all parties providing transmission services offshore, this research will focus on an optimization model which will determine the optimal accommodation strategy and fleet size and mix for a TSO to operate and maintain its OTG in a cost-effective manner. Within the broad horizon of planning for OTG O&M, the choice to specifically focus on the aspect of fleet size and mix management, is in line with the study for which this thesis is written, namely the Master of Science program in Transport Infrastructure & Logistics at the Delft University of Technology. Fleet size and mix refers to the number of vessels in use and the type of the vessels. In the area of study both waterborne and airborne vehicles, respectively ships and helicopters, are of interest. The main overarching problem statement can be defined as:

There is a need to integrate decisions in the field of manning, accommodation, O&M and logistics for Offshore TSOs, surpassing geographic borders, in order to perform cost-effectively and guarantee reliability in an energy system with unprecedented growth of offshore wind energy capacity.

1.2.2. Research Objectives

Based on the defined problem above, research objectives can be presented. These research objectives break down the defined problem and propose a strategy on how to solve the problem statement successfully. The research objectives are as follows:

1. Identification and analysis of the elements, processes and interactions between the aspects relevant for the fleet management with respect to the OTG.
2. Develop a holistic vessel fleet size and mix optimization model, taking into consideration the needs and characteristics identified by objective 1. This optimization should provide strategic and tactical decision support to decision makers within TSOs and in particular TenneT.

1.2.3. Research questions

The aforementioned research objectives are aimed to be realized with this study and that is done by providing an answer to the main research question. The research question is defines as follows:

> *To what extent can an optimal Marine Fleet Size and Mix established via integrated planning of the transport and accommodation strategy, minimize costs for the maintenance of the offshore substations in Germany and the Netherlands?*

The main research question can be specified in 7 sub-research questions. Together these questions should ultimately contribute towards answering the main research question and close the research gap. The sub-questions are:

1. *What aspects of the OTG are the drivers behind the demand and challenges for offshore logistics?*
2. *How might these drivers develop in the future with the eye on an expected strong increase in offshore wind energy capacity and innovation in offshore transmission technology?*

3. *What are relevant performance measures and how can these be implemented in the model objective function?*
4. *What are possible alternatives for the manning strategy, accommodation strategy and transport strategy of OTG?*
5. *What are the external factors which place constraints on the fleet management for the OTG?*
6. *What are the internal, TSO specific, factors which place constraints on the fleet management for the OTG?*
7. *How can the robustness of the fleet be guaranteed for different scenarios of platform quantity, platform location and maintenance philosophy?*

After presenting the main, and sub-research questions in this section, the next section, on the research methodology, will proceed with the approach according to which these research questions will aimed to be answered.

1.2.4. Research Methodology

Subsection 1.2.3 was concluded with research questions through which the knowledge gap will aimed to be bridged. This subsection presents the methodological framework applied to address the thesis's research questions.

From the research questions and research objectives it can be concluded that there is a void in the functioning of the offshore logistic system leading to operations which are not performing optimally in terms of cost-effectiveness. Hence, there is a need for the design of an artifact which can realize cost-effective and reliable functioning of the OTG. For this purpose the study proposes a design approach in which an optimization model will be designed to enable the desired cost-effective and reliable fleet management for OTG.

Furthermore, this project proposes the inclusion of several sub-systems which are ultimately responsible for the O&M of the OTG, therefore the Systems Engineering approach is considered suitable for the study and complementary to the design approach. The Systems Engineering approach provides a structured way of studying and designing systems whereby the methodology takes into account the breakdown of the overall system in sub-systems, all with their specific characteristics which can be translated to specific requirements and constraints and with several complex interfaces entailing various interactions (Armstrong and Sage, 2000). The system under study addresses the logistics organization for O&M of the OTG in Germany and the Netherlands, whereby the specific focus lies on the strategic and tactical decisions on the fleet size and mix.

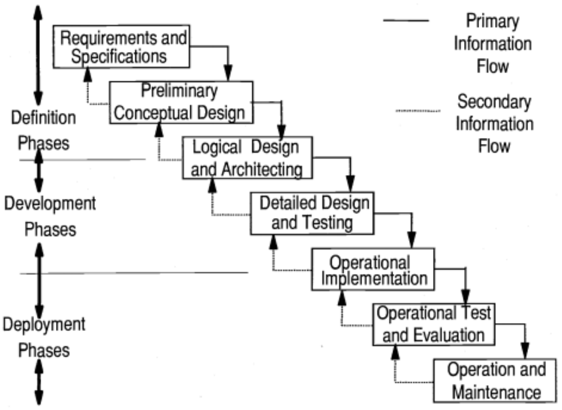


Figure 1.3: Systems Engineering framework for production or acquisition, adapted from (Armstrong and Sage, 2000)

Armstrong and Sage (2000) have developed various frameworks for Systems Engineering, applicable over a variety of industries or project types from an systems perspective. The frameworks discuss the life-cycle of projects consisting of various phases and steps. The framework in figure 1.3 is one out of Sage & Armstrong's book on the introduction to Systems Engineering, and is an application of System Engineering for production or acquisition (Armstrong and Sage, 2000). In this example, three aggregated phases can be distinguished, each with several life-cycle steps.

The first aggregated phase is the Definition phase, where the main problem is defined, requirements and specifications are formulated and a conceptual design is developed, out of several possible concepts.

The second aggregated phase, the development phase, leads to a logical design with specifications to be able to execute the system development. Furthermore, in this phase, a detailed design is generated, which is chosen among different alternatives through design testing and preliminary operational implementation.

The third aggregated phase is the deployment phase, where the design is made operational, tested, evaluated, and finally maintained. Each aggregated phase consists of three comparable and iterative steps, namely formulation, analysis and interpretation.

Such a framework according to the Systems Engineering methodology can also be generated for this specific research. An attempt to do such, is presented in figure 1.4. In this research framework it can be seen that the *definition phase* starts with the *problem definition*. During the *problem definition* the core of the problem is searched for. The second step in the *definition phase* is the *value system analysis* where it is determined what the needs and objectives are of the offshore transmission grid and how that should be translated into requirements and constraints for fleet management. See chapter 3 for these steps.

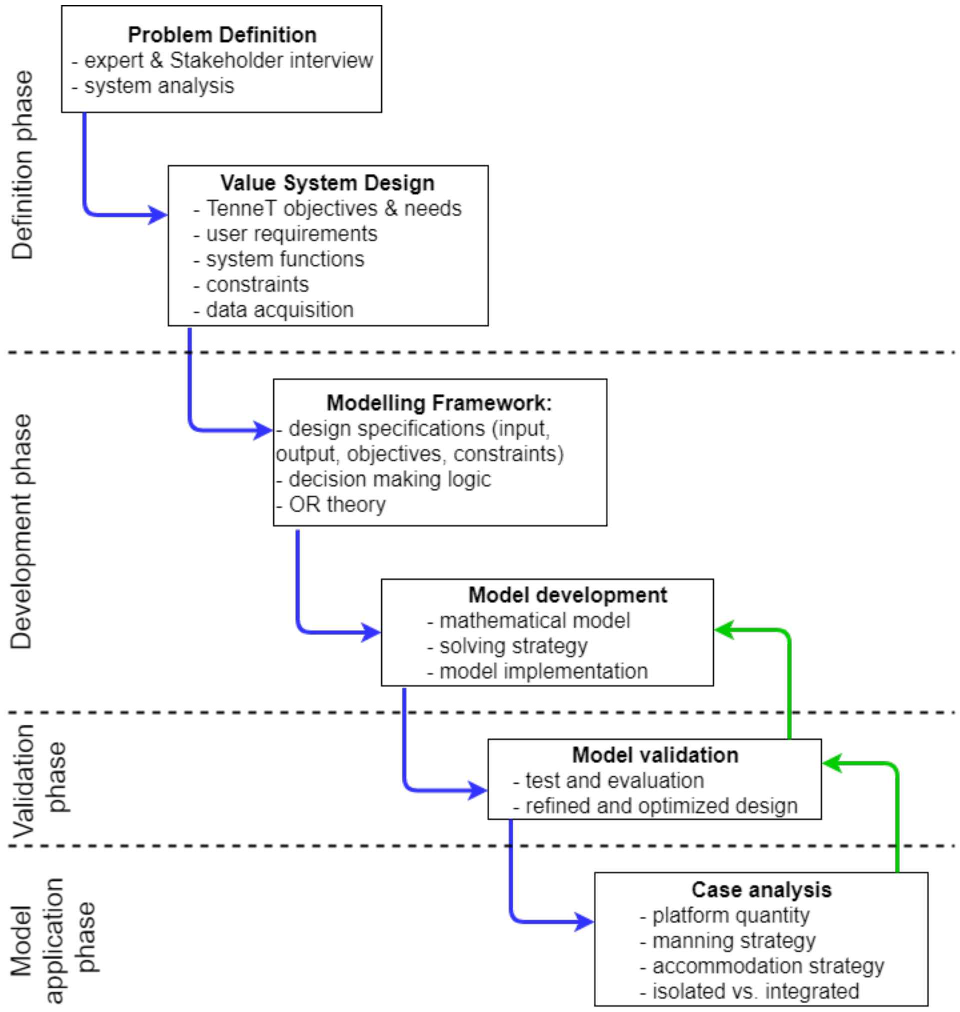


Figure 1.4: Research framework according to the Systems Engineering Approach

The *Development phase* starts off with the *Modeling Framework* where the aim is to conceptualize the optimal interactions and decision processes regarding Marine Fleet Management. Accordingly, it will be determined which theories and methods in the field of Operations Research are relevant for this *Modeling Framework*. This *Modeling Framework*, in the form of a decision process model, will subsequently be transformed into a mathematical model as the first step of the *Model Development* phase, see chapter 5. Moreover, the mathematical model will be operationalized with a solving strategy to run and solve the model of integrated Marine Fleet Management optimization for specific cases.

After the *Model Development*, where a working model is the product, follows the phase of *Model Verification*. Here the optimization model is assessed for errors and consistency with the modeling framework and the optimization model will undergo various experimental tests, such as input checks, continuity tests, extreme value tests and verification with analytical results. Finally the model is also assessed on its computational limitation in handling case of different sizes. More on this is discussed in section 6.2.

Finally, and as addressed in chapter 7, the phase of *Case Analysis* follows, or more general Model application. Here various sub-cases regarding the German and Dutch case will be run, with scenarios for e.g. the maintenance strategy and the amount and location of platforms. It will be assessed how these scenarios influence the OTG performance via the predefined KPIs. This will produce information on how to organize the Logistics and Transportation for the OTG in order to cope with future developments optimally.

During the process, the optimization model and all gathered knowledge coming from this model and helping to bridge the knowledge gap are documented and communicated to stakeholders through the Thesis.

After addressing the methodological framework within which this study will maneuver, the following subsection goes in on the problem description. This problem description provides an introduction of the case under study, namely the offshore transmission grid for Germany and the Netherlands, operated by TenneT.

1.2.5. Problem Description: The TenneT case for Germany and the Netherlands

In sub-section 1.2.1 the problem definition was presented in a more generic way. However, it is the aim of this study to apply OR and concretely propose an optimal fleet mix and size, hence it is desired to base the model on a case which represents reality in a way which validates the applicability of the model for real-world situations. To this end, the case which will be subject to the study is the OTG in the German and Dutch part of the North Sea. This OTG is operated and managed by TenneT TSO GmbH and TenneT TSO B.V., part of the TenneT group.

First of all, in the problem definition it is mentioned that there is a need to align planning between subsystems in order to reach an overall system optimal. In the case of TenneT the relevant sub-systems are exhibited in figure 1.5. Grid Service Offshore is the overarching system within the offshore organization and is responsible for the cost effective and reliable operation of the offshore substations. A further decomposition leads to three sub-systems.

Figure 1.5: Current sub-systems in the German TSO TenneT

First, the sub-system for offshore Maintenance Planning & Coordination plans and executes the maintenance for various elements of the OTG such as: HVDC & electrical equipment, Mechanical equipment and Cables and Civil works.

Second, the sub-system of Operations planning and coordination plans and executes operations for the platforms per offshore cluster area: BorWin, DolWin and North. These area partitions or clusters, each consist of three substation platforms. Note that these clusters represent the 2018 situation, hence are all in the German part of the North Sea. The platforms in the Dutch part of the North Sea will be operational from 2019 onward.

Finally, the Offshore Logistics Planning and Coordination department plans and executes the logistics and transportation of all people and material towards the platforms and back, to enable the successful and on-time execution of the maintenance and operations.

For these sub-systems, it was stated that the independent planning implies that sub-systems are able to realize local optimal performances. Local in the sense that with the performance indicators of the sub-system they realize optimal performance, but the setback of this sub-system optimization is that at the end of the day when sub-systems come together for the operational planning of the transportation and logistics, the optimal solution of the various sub-systems do not align, hence leading to short-term sub-optimal planning with many compromises of the optimal solution from the separate sub-systems.

The following aims to describe a story-line of how sub-system planning may lead to sub-optimal performance. This starts with the O&M planning and coordination generating a one year O&M plan for the 9 offshore platforms in the German North Sea, see figure 1.6. Part of this plan is: which O&M activities will occur, what is required for these activities in terms of technicians, tools and material and when the activities need to be conducted. These aspects are determined based on the maximization of reliability and the minimization of O&M costs, whereby the maintenance philosophy is leading. At the moment TenneT is applying a scheduled maintenance philosophy whereby maintenance activities are carefully planned and conducted by the crew on the platforms. For these maintenance activities, the platforms are permanently manned with the necessary technicians and engineers. And subsequently these crews, require crew change activities based on bi-weekly shifts (Diekmann, 2018, Heinrich, 2017b).

Figure 1.6: Geographic layout of the 9 platforms in the German North Sea

However, for the platform strategy from 2020 onward, TenneT has decided to shift to platforms which are usually unmanned in Germany. In the Netherlands, the platforms are, by definition, designed and operated as unmanned platforms. This revised platform manning strategy entails that the planning of the maintenance activities, based on a specific maintenance strategy, will be leading for logistics and transportation of supplies and crew to and from the platforms. In addition, the possibilities for condition based maintenance want to be studied as this may further decrease the costs. These new maintenance and manning strategies yield questions and challenges in terms of the offshore logistics. For instance it still needs to be determined which accommodation and transportation strategy fits the new maintenance and manning strategy best, given that it is uncertain what the division will be between scheduled, preventive maintenance and corrective maintenance.

Within the maintenance strategy, especially the corrective maintenance poses a big challenge, and the reason for this is the following: uncertainty. There is ample uncertainty in the time and type of defects occurring, resulting in uncertainty for which corrective maintenance will be necessary. If corrective maintenance is required for a certain defect, which leads, or may lead, to a substation shutting down, technicians and the necessary material need to be at the platform as soon as possible to fix the defect. If this is not the case and the platform shuts down, for instance due to uncertainty where as a result the defect could not be anticipated and no transportation mean is available on the short term to support the repair activities, a consequence of the platform shutting down, is that all connected wind farms cannot convey the generated power to shore, resulting in the necessary shut-down of wind turbines. On its turn this leads to production losses for the wind power operators and this has to be compensated by the TSO Heinrich (2017b).

From these uncertainties and inefficiencies, it becomes clear why there is a need for a holistic and integrated approach which aligns the maintenance operations with the accommodation and transportation, over the spectrum of strategic to operational decisions.

Regarding the transportation strategy, as mentioned before, TenneT is moving away from the primary use of helicopters for the transportation of crew, towards the use of marine vessels. Because of this strategic choice, fleet management turns into a relevant subject within TenneT, which is in its core a energy service provider. Helicopters have been common practice in the Oil&Gas industry and this has been copied by OWF, but also TSOs for their offshore operations (Wolfsturm, 2017a). Because TenneT has little prior experience with the use of Marine Vessels, it is necessary for TenneT to determine which fleet size and mix fits their future strategy best (Heinrich, 2017b, Wolfsturm, 2017a).

For marine fleet composition, there is a wide variety of options available on the market, or being developed, which could be considered for the marine fleet utilized by TenneT. Possibilities range from using Operations Support Vessels (OSVs), Platform Supply Vessels (PSV), Crew Transfer Vessels (CTV) of different types and capacities equipped with specific crew transfer systems. These methods can be used for trips towards the platforms from onshore locations, such as ports, and back. The different methods of vessel access to and from platforms are discussed elaborately in 2.2.4.

The previous approach on fleet decisions assumes that the offshore platforms are equipped with accommodation facilities and crews can stay on the platforms for longer periods. On the other hand it may be interesting in terms of costs, to rethink accommodation and decommission the accommodation facilities from the platforms (Edwards et al., 2015, Heinrich, 2017b). Alternatively the TSO could operate, either floating accommodation vessels such as floatels or SOVs, or fixed offshore accommodation stations for the manned periods of the platforms. The fixed accommodation stations can be for instance the current platforms, where instead of accommodation on all platforms, one or more platforms are chosen to consolidate accommodation facilities for the entire network.

For these new accommodation concepts, new questions arise such as: how to route floating accommodation vessels to enable on time maintenance at each platform in a cost-effective manner? Furthermore, the capacity and facilities the vessels should have to satisfy the demand, and how these vessels should be leased or acquired are relevant questions.

For the concept of utilizing fixed offshore accommodation stations as hub there are also some voids to close, such as: where should this accommodation platform be located?, what should its capacity be?, what vessels are required to operate cost effectively on this shore-to-hub-to-platform strategy?, and which routes should be utilized for this concept?

These questions need to be answered first, in order to plan, implement and operate offshore O&M and logistics according to a strategy which is cost-effective, while the reliability of the platforms is guaranteed. It can be observed that the questions are quite wide ranging and diverse, hence this study is scoped around the Marine Fleet Mix and Size. Similar as for OWF, for the fleet to enable cost reductions, it is critical that an integrated approach is applied (Fagerholt and Lindstad, 2000).

Based on the statement by Gundegjerde and Halvorsen (2012) vessel prices can vary up to 60% on a year to year basis. In order to minimize costs of acquiring vessels it is thus necessary to align strategic and tactical decisions and anticipate operational decisions. This should subsequently enable the minimization of costs for vessel acquisition by acquiring or leasing vessels in advance and on longer term arrangements. Furthermore aligned and integrated decisions contribute in the maximization of vessel utilization. To illustrate this, by aligning platform visits and consolidating on transport volumes of crew and material, the vessel utilization can be optimized.

Finally, an important question is whether the integration of the decisions on a cross-border level can also contribute in optimized logistics at the lowest costs and guaranteed reliability. The opposite to treating the Dutch and German offshore grids separately and subsequently planning and operating fleets exclusively for these two offshore grids, is to overlook the borders and integrate fleet management for the Netherlands and Germany. The hypothesis is that combined fleet decisions, and thus a combined fleet, also lead to lower cost due to economies of scale whereby in the integrated situation less vessels are necessary, among other as a result of higher vessel utilization.

1.3. Outline of the thesis

After the subject is introduced and the research definition along with the applied methodology are presented in chapter 1, the thesis proceeds with background information on the subject of Offshore Transmission Platforms and Offshore Logistics in chapter 2. A more in-depth problem description, continuing with what was provided in chapter 1, is presented in chapter 3. This is followed by literature on the current state of maritime fleet management in chapter 4. With the problem well defined and literature presented on how such problems can be approached, chapter 5 sheds light on the development of the OptiFleet model. The OptiFleet model is implemented in a computer model, and the verification of the model implementation together with the limitations are discussed in chapter 6. Subsequently, OptiFleet is applied for the TenneT case study and the results are presented in chapter 7. Finally, the thesis is concluded and recommendations for the stakeholder and future research are presented in chapter 8.

2

Background

The Offshore Transmission Grid is not among the most thoroughly studied systems in offshore logistics, hence this chapter provides the reader with an understanding of the Offshore Transmission Grid via background information on the Offshore Transmission Grid and the technology utilized in these grids. Moreover, background information is provided on all the aspects which are identified as being relevant for offshore fleet management, namely: vessel concepts, crew transfer options and offshore bases.

2.1. The Offshore Transmission Grid

For the improved understanding of OTG, this sub-section addresses the characteristics and components of OTG, trends in OTG and the challenges posed to the O&M of these OTG.

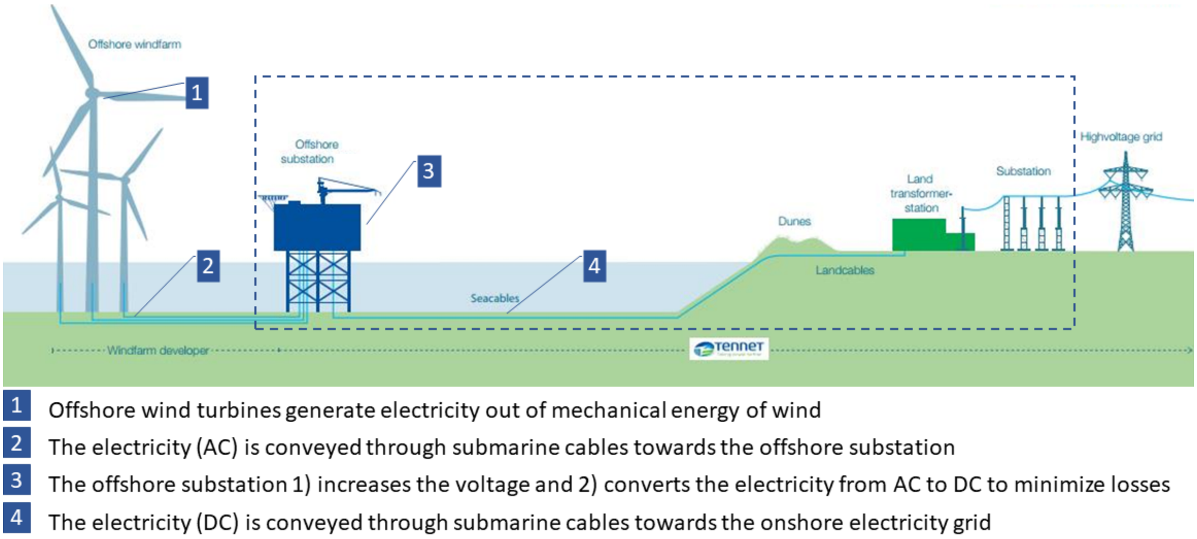
2.1.1. Characteristics of the Offshore Transmission Grid

After the transmission of electricity was first demonstrated by George Westinghouse and William Stanley on March 20, 1886 in Great Barrington in the State of Massachusetts, USA, electric power grids have been developed into one of the most complex man-made structures (Saffiudin, 2013). These electric power transmission grids, developed from the small local grids, transmitting power within neighbourhoods, to national and even transnational grids to transmit power over long distances (Overbye and Weber, 2001).

Offshore Transmission Grids (OTG) can be considered as the offshore extension of the extensive electric grid on land. The onshore transmission grid is connecting onshore power generation plants, traditionally based on fossil fuels such as coal and natural gas, with consumers of electricity in the residential sector and the industry. However, over the years these grids have been changing in order to accommodate new sources of energy coming from for instance the wind and sun. In addition to the traditional use of electricity in households and buildings, electricity is getting an increasing role in society and industry. The rise of electric mobility and the electrification of industrial processes such as in the chemical industry are examples of the increasing role of electricity. These are both sectors which are still dominated by fossil fuels, but will make the shift to electricity as the energy carrier of choice (Overbye and Weber, 2001). Hence, the trend is that the electric transmission grids will consequently have to grow along with the role of electricity in society (Statnett, 2017).

The offshore transmission grid is established to accommodate the generation of offshore wind energy, one of the most mature and widely-used sources of renewable energy. In this context, the OTG connects the offshore wind parks, consisting of the wind turbines, with the onshore transmission grid. In this way the generation of offshore wind energy is accommodated, and the generated wind power can be transported from the offshore wind parks to the consumers of electricity in the residential sector, industry and transportation.

This study will focus on the offshore transmission grid, leaving the onshore transmission grid out of scope. The scope is demarcated in figure 2.1 by the blue dashed frame. The transmission system within this demarcation is commonly presented in literature as the offshore transmission grid or OTG, see for instance (Bell et al., 2010, Bresesti et al., 2007).



1 Offshore wind turbines generate electricity out of mechanical energy of wind

2 The electricity (AC) is conveyed through submarine cables towards the offshore substation

3 The offshore substation 1) increases the voltage and 2) converts the electricity from AC to DC to minimize losses

4 The electricity (DC) is conveyed through submarine cables towards the onshore electricity grid

Figure 2.1: Schematic overview of an OTG, adapted from TenneT (n.d.)

The offshore wind farms, these are the clusters of wind turbines offshore with the function to generate electricity from the energy of the wind, are outside of the dashed framework and thus not included in the scope of this study. Note that the study is conducted according to a systems approach. This entails that although the offshore wind farms and onshore grid are out of the model scope, they will be taken into account during the study in terms of their interaction with the OTG and how these interactions influence the operation and performance of the OTG.

In general a distinction can be made in two main elements constituting the OTG, these are:

1. **Transmission substations**: these transmission substations are the center-point of OTG, see figure 2.2 for such a platform in the German OTG. These substations are also called converter substations and function as a power-socket for offshore wind turbines in the sense that these substations collect the electricity generated by the wind turbines, ramp up the voltage of the electricity generated by wind turbines from 25-40 kilovolts (kV) to 130-150 kV, and finally transmit the power to shore. The higher voltage reduces the losses during transmission to shore and enables the use of submarine cables with a smaller diameter, ultimately resulting in lower costs for offshore electricity transmission (Bell et al., 2010). Depending on the location of the wind farms and the resulting distance to shore, the platforms can either utilize High Voltage Alternate Current (HVAC) technology or High Voltage Direct Current (HVDC) technology. The differences will be elaborated in more detail in sub-section 2.1.3.

2. **Submarine transmission cables**: in order to convey the electricity from the substations to the onshore grid, high voltage AC or DC submarine cables connect the substations with the onshore grid. See figure 2.3, which illustrates the components of such a submarine DC cable. Whether HVAC or HVDC cables are utilized depends predominantly on the distance to shore and the available substation being either HVAC or HVDC (Bell et al., 2010).

2.1.2. Trends in OTG

OTG are relatively new in the offshore landscape and are undergoing continuous technological development in terms of transmission technology, cable technology, structure topology and access methods. Before proceeding with the actual trends of OTG, the trends in the offshore wind energy generation sector will be addressed. The OTG can be considered enabling infrastructure for the offshore wind energy generation sector, hence the trends in OTG are intertwined with those in the offshore wind energy generation sector. Rodrigues, Restrepo, Kontos, Teixeira Pinto, and Bauer (2015) state the following trends in offshore wind, which imply inevitable challenges for the TSO:

- Immense growth in offshore wind generation capacity. From 2001 to 2017 the Global installed wind

Figure 2.2: The BorWin alpha and beta substation platforms in the North Sea, adapted from (TenneT, n.d.)

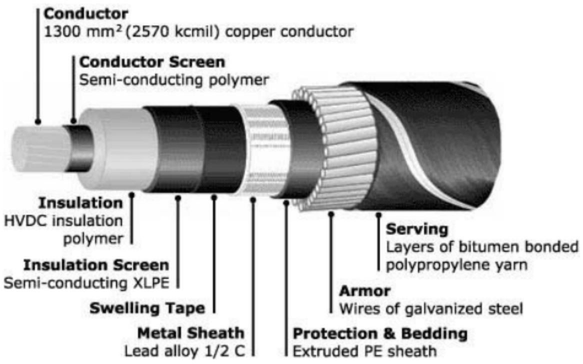


Figure 2.3: DC submarine cable, adapted from (Wright et al., 2002)

power capacity has grown with 36.1% annually. This trend is expected to continue, and in addition, wind projects will increase in size, enforcing this trend.

- The distance to shore of wind projects is increasing, see for instance the German Global Tech 1 project which is located 127 km from shore, compared to the Vindeby project at only 2.25 km from shore. This means that the TSO has to construct and operate transmission infrastructure which is also further away from shore, with the associated challenges related to severe offshore conditions due to e.g. waves and wind.
- The Ocean depth of area's where offshore wind power capacity is and will be developed, is increasing. Comparable to the bigger distances from shore, these deep waters imply increasingly challenging conditions for the TSO. See figure 2.4 for a visualization of these trends.
- In the offshore environment, location specific characteristics complicate the construction and operation of OTG. In some areas of the North Sea and the Wadden Sea for instance, there are limitations to the laying of transmission cables and the construction of substations. Nature reserves, fishing areas, defense areas, shipping lanes and other areas of economic value should be taken into account (Koch, 2013).

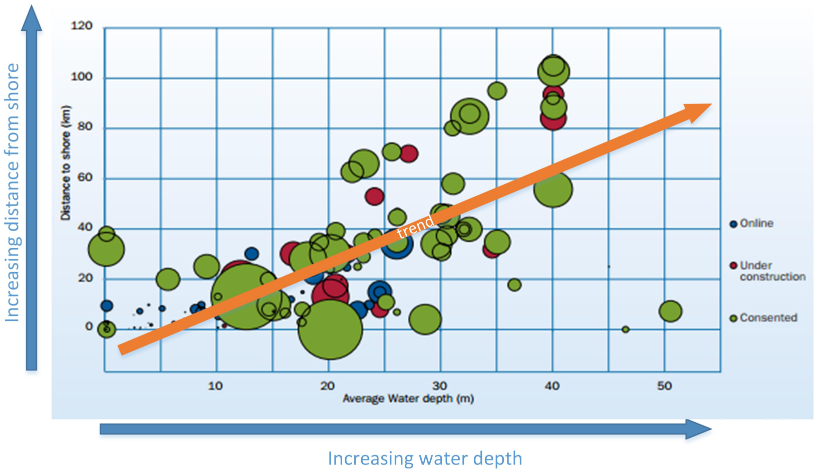


Figure 2.4: The trend of increasing distance to shore and water depth of OWF, adapted from (European Wind Energy Association, 2013)

For the offshore wind power industry these challenges result in limitations on the availability of maintenance vessels and ports (Massachusetts Clean Energy Center, 2017), and organizational issues in the field of skills, labor and training (Dickinson, Cook, Welstead, Thompson, Yuille, and Chapman, 2011, Shafiee, 2015). Shafiee (2015) elaborates further on these different fields where the logistic and transport challenges manifest themselves in the operational echelon. In the following, the main categories which can be found in Shafiee's (2015) work on OWF will be discussed, and in which way they are present for OTG:

- **Scheduling of maintenance tasks**: generating a detailed schedule of maintenance tasks that must be executed within a specific time horizon. In the OTG context, typically for each O&M task a worksheet is produced stating the start date, due date, processing time and a list of the parts on which maintenance services must be carried out. But this is very challenging as the scheduler has to take into account not only the maintenance activities, but also the availability of resources such as spare parts, qualified personnel, helicopters or service vessels, and this while minimizing disruption in the process. In addition this scheduling process has to be based on a rolling horizon, in which the maintenance plan reacts quickly to changes in the maintenance needs, resource availability and weather- and marine conditions.

- **Routing of maintenance vessels and helicopters**: routing and scheduling of vessels and helicopters to align with the scheduling of crew and O&M tasks, while coping with the dynamic weather and marine conditions. In the OTG context: Once sub-stations are in the operational phase the required O&M activities require materials, spare parts and qualified technicians to conduct the various O&M activities. For these supplies and crews, the vessels and helicopters are necessary and the routing and scheduling of helicopters and vessels is an elementary part of the logistics operations of OTG. Regarding this subject earlier studies have been conducted within TenneT, focused on the German OTG. Hereby the routing for offshore transport and crew transfer were studied, applying concepts such as the Traveling Salesman Problem and the Vehicle Routing Problem, complemented with the Single vehicle pickup and delivery problem with capacitated customers (Wolfsturm, 2017a).

- **Measuring the maintenance performance**: frequent reports on the performance of O&M activities, the logistic and transportation operations and organization, and interactions with e.g. the TSO and other OWF, are required to assess the quality and effectiveness of O&M. In the OTG context: Performance measurement of the OTG can vary per country in terms of specific KPI's and their importance. However, Reliability, Safety, costs-efficiency and emissions are present in the goals of TSO's all over the world, such as in Norway, China and the USA (California ISO, 2013, State Grid Corporation of China, 2016, **?**). From Heinrich (2017a), Team manager Offshore Logistics at TenneT Offshore GmbH, it could be derived that at the moment, cost reductions (both operational and fixed) enjoy most attention. However, according to the legislation reliability of energy supply must be the number one focus. In its current state TenneT is performing above legislative constraints in terms of reliability, hence the focus has shifted to costs. In 2018 TenneT has a reliability of 96.5% for its offshore grid in Germany, while the minimum reliability according to regulation is 92% for OTG (Heinrich, 2017a). This thus creates an interesting trade-off in order to reduce logistics cost, at the expense of grid reliability. In the Netherlands however, the grid reliability is required to be above 98% according to legislation. Due to different legislation the landscape to optimize logistics is different between the Netherlands and Germany. This poses challenges to the aim of TenneT to centralize the logistics for both the Netherlands and Germany in an integrated, yet optimal way.

In addition to the above-mentioned challenges, which can be considered the more conventional operational offshore O&M challenges, Shafiee (2015) mentions some more modern issues:

- **(RAM) Data availability**: recent developments in computerized maintenance systems have resulted in an increased role of data gathering, processing and analysis methods and tools for O&M activities. However, data availability issues in the form of incomplete, inaccurate and inconsistent data, are still a stumbling block. In the OTG context: Within TenneT in both the Netherlands and Germany, data-supported operations are becoming the standard (Algra, 2017, Diekmann, 2018). However, the previous challenges mentioned are also present for the O&M systems of TenneT. In addition, incompatibility between databases is a barrier for the seamless integration of both Dutch and German OTG

- **O&M costing and budgeting**: from the perspective of management/shareholders, resources for O&M are finite, resulting in some constraints when planning O&M and the incentive to minimize O&M costs.

- **Weather forecasting tools**: Accessibility, or the fraction of time in which save access to offshore structures is possible, is a very important prerequisite to proceed with transport activities offshore.

- **Information and environmental legislation**: the offshore wind energy industry is under pressure from legislation to reduce the polluting emissions such as Greenhouse Gases (GHG), over the overall lifecycle of OWF and thus also OTG.

2.1.3. Offshore transmission substation platforms

In section 2.1.1 the offshore transmission substation platforms, or substation platforms, were mentioned as the center-point of the OTG. The transmission substations, serve the function of ramping-up and stabilizing the voltage of power generated offshore by wind turbines. This is required to reduce the electrical losses during transmission of the energy to shore and allow for submarine cables with a smaller diameter and thus lower cost (Bell et al., 2010, Bresesti et al., 2007, Koch, 2013, Wright et al., 2002).

Structure and components of substation platforms

There are two main components in the structure of a substation platform, namely the topside and the foundation support structure. The topsides houses the technology and equipment necessary for either HVDC or HVAC transmission, and they are constructed as immense blocks onshore and then transported offshore in order to be erected on the foundation support structure. It is possible for the support foundation to be either mobile, e.g. jack-up structure, or fixed to the seabed, examples here are mono-pile or jacket structures which are also common for the offshore Oil&Gas platforms (Adeuyi and Wu, 2015). In figure 2.2 a substation platform can be seen next to a Oil&Gas exploration platform in figure 2.6, where the similarity in terms of structure is significant.

Figure 2.5: The BorWin alpha and beta substation platforms in the North Sea, adapted from (TenneT, n.d.)

Figure 2.6: The Mars B/Olympus Oil&Gas Platform from Shell, adapted from (Open Ocean, 2017)

Although the structural similarities between the substation platforms and the Oil&Gas Production platform are significant, this is not the case for the processes and activities which are taking place on each of these platforms. The differences in processes and activities lead to different needs in terms of the transportation and logistics of material and supplies. In essence Oil&Gas production platforms are extraction platforms with the goal to extract natural resources from the Ocean bottom. This entails that the platforms include equipment related to e.g. 1) the extraction of natural resources such as pumps and valves, 2) the processing of these resources and 3) temporary storage.

On the other hand, the substation platforms involve predominantly electrical equipment, in general a platform is equipped with (Ackermann, 2005, Madariaga et al., 2013):

- voltage transformers
- switch gear
- control and instrumentation system
- communication unit

- emergency diesel generators and fuel
- staff accommodation, sanitary, working and catering facilities
- a helipad
- a crawler crane
- emergency evacuation boats

These parts require different O&M activities and subsequently different technicians and logistics compared to the equipment on Oil&Gas platforms. In terms of transportation vessels, however, there is again significant commonality especially regarding the vessels which can be used for the transfer of crew (Wolfsturm, 2017a).

HVDC and HVAC considerations

A major consideration in the offshore OTG sector is whether the systems are based on Direct Current (DC), or Alternating Current (AC). According to Ackermann (2005), the distance between the OWF and shore is the main determining factor on whether the system will be based in DC or AC, while the size of the connected OWF is also influencing the choice to a certain extent. This statement is also supported by the work of e.g. Bell et al. (2010), Bresesti et al. (2007), Green et al. (2007), Koch (2013), Madariaga et al. (2013).

AC technology is the more mature technology and the preferred choice if the wind farms are close to shore, due to their simplicity and relatively low cost. However, if the distance increases, and to a certain extent the size of OWF, the main disadvantage of AC systems prevails, namely: significantly increasing losses of electricity load. These losses in load can offset the relatively lower cost of HVAC systems. The distance to shore, considered the turning point when HVDC systems becomes more economically efficient than the HVAC system, depends on the particular situation with factors such as OWF size playing a role. Ackermann (2005) provides an example that for a medium sized OWF of 200 MW, the turning point is at around 100 km distance to shore. HVAC platforms are significantly less complex and smaller in size compared to HVDC platforms. In terms of size HVAC platform will generally be a third of the HCDC alternative (Ackermann, 2005, Green, Bowen, Fingersh, Wan, et al., 2007). HVAC platforms consist of, at least, an offshore transformer station with offshore reactive power compensation, three-core polyethylene insulation, HVAC cable(s) to shore, and a static VAR compensator on shore (Ackermann, 2005).

HVDC platforms on the other hand, consist of, at least: three-phase two-winding converter transformers with filters and either a Statcom or a diesel generator that supply the necessary short-circuit capacity, DC cable(s) to shore, and an onshore converter station with a single-phase three-winding converter transformer with the relevant filters (Ackermann, 2005). Logistically the HVDC platform thus form a bigger challenge as they are bigger and more complex. The bigger size and complexity is also reflected in the O&M needs, whereby O&M of HVDC platforms may turn out significantly more expensive.

2.1.4. O&M cost of substation platforms

Regarding the cost measurement, the challenge can be related to the finite resources for O&M and the incentive to minimize these costs. For current O&M operations, cost stand at 20 € million per year, per platform. Of this figure around 20% is the contribution of logistics and transportation. Social pressure is one of the main drivers to reduce these costs, while also improving the reliability of transmission services. The aim of management is to decrease this figure downwards of 12 € million in 2019, while on the longer term the number must go downwards of 10 € million (Heinrich, 2017a).

2.2. Review of offshore access systems

For the transportation of people and material to and from offshore structures, the offshore access system is in place. What this system consist of will be elaborated in this section. Moreover, background information will be provided on what the current state is of this offshore access system.

For the execution of transportation activities required for offshore operations such as in the Oil&Gas industry and now also in the Offshore Wind Energy industry, a wide variety of vessels is available today at different capacities, fuel consumption, deck space, operating speeds, prices, contracts and equipped facilities. Moreover the vessels differ in the weather condition they can operate in. This makes the challenge of optimal fleet size and mix even greater, while the solution space to find a optimal fleet gets bigger. The choice for the operating vessel can influence O&M cost significantly. Three factors that significantly influence the vessel choice are: distance to the platform from the harbour, water depth and weather conditions (Joshi and Bolstad, 2016). Notably, Joshi and Bolstad (2016) does not mention the size and weight of material and equipment required for O&M as an important factor. More on these factors will be discussed in section 3.2 and section 3.3.

From the O&M related transportation for the offshore wind industry, Joshi and Bolstad (2016) present an overview on vessels which are commonly used. Hereby they state that these vessels satisfy the following functions: transfer crew to the wind generators, accommodate technicians offshore and perform heavier maintenance tasks which require lifting capabilities and the transportation of larger parts. These function requirements are similar for OTG.

There are three factors to be taken into account regarding the utilization of O&M vessels:

- The weather conditions, more precisely wave height, wind speed and water currents may limit the operability of a boat by taking into account the personnel safety and accessibility of offshore structures.
- The distance between the working area (platform) and the port determines in conjunction with the vessel's transit speed the required journey time and therefore the working time on site ("technician time on platform").
- The water depth in the working area limits the choice of vessels that can be utilized in case jack-up vessels are required.

2.2.1. Crew Transfer Vessels

The first vessel type to start of with are the Crew Transfer Vessels or CTVs. CTVs are relatively small in size and are used to transport predominantly people, whereas there is little capacity for supplies or parts. Commonly there is a cargo capacity of between 1 and 2.5 Metric Ton (MT). Due to their high operational speed, 25 to 30 kn, these CTVs can be used for the rapid transportation of people and materials from ports towards platforms and vice versa for O&M activities which do not require heavy parts (Bard and Thalemann, n.d.).

Traditionally these CTVs are mono-hull vessels as can be seen in figure 2.7, vessels which can still be found in offshore wind operations. These vessels have a high operating speed, but on the other hand they have many operational disadvantages. Among others these vessels are uncomfortable for crew, because the single hull design does not provide a lot of stability under conditions with significant wave heights. Commonly these single-hull vessels only guarantee save access when the wave height is < 1m. In terms of size, the single-hull vessels are small providing a limited passenger capacity of between 6 to 8 passengers. This limited space is also the case for cargo and the limited facilities on-board which reduces the comfort for passengers even more.

Figure 2.7: The Wind Transporter as example of a Monohull CTV (HVIDE SANDE, n.d.)

Figure 2.8: The Tia Elizabeth as example of a Catamaran CTV (OffshoreWind.biz, 2015a)

Figure 2.9: The Sea Storm as example of a SWATH CTV (ODFJELL WIND AS, n.d.)

Figure 2.10: An example of a RIB as Quick Response Vessel (World Maritime News, 2012)

In figure 2.8 an example is exhibited of a twin-hull vessel functioning as CTV. These catamaran vessels have increasingly taken a share in the CTV market over the years and are subsequently widely available in the market with the possibility to be leased on long term contracts. Catamaran CTV possess superior qualities compared to the mono-hull vessels. To start, the double-hull structure provides more agility and stability when operating under rough sea conditions. This provides pax with a more comfortable journey from shore to platform and vice versa. The benefits of utilizing catamaran CTVs include the higher pax capacity (12 and up), the higher cargo capacity (2 to 3 MT), the potential to include lifting equipment if the vessel is large enough, more space for the inclusion of facilities which improve comfort for pax, operating at significant wave-heights < 1.8 m and finally they can provide save access to offshore structures for significant wave-heights > 1.2 m, with the potential to install access systems if the vessel is large enough. See subsection 2.2.4 for more information on the access systems. On the other hand, these catamaran vessels generally have a lower speed compared to the mono-hull vessels. Secondly, Echavarria et al. (2015) state that due to lacking facilities, especially on vessels which are on the market a long time, these vessels are unsuitable for journeys longer than ± 2 hours.

Small Waterplane Area Twin Hull (SWATH) vessels are increasingly entering the market of CTVs nowadays (Bard and Thalemann, n.d.). Due to their twin-hull structure, these vessels look similar to the catamaran twin-hull vessels above the water line, see figure 2.9. The difference lies in the torpedo shaped structures under each hulls, which is not the case for the catamaran vessels. These torpedo structures minimize the contact area of the vessel with water, which leads to operating abilities at even rougher sea conditions compared to the catamarans. Bard and Thalemann (n.d.) mention operable wave heights < 2.5 m, while save access to the offshore structures is possible at wave heights > 1.5 m. In terms of size, these SWATH CTVs are commonly bigger than both the monohull and double-hull CTVs, with capacities of 12 pax and up. The bigger size also means there is sufficient space to install facilities which increases the comfort of the journey for pax, such as beds, drying store for survival suits etc. Also there is potential for the installation of access systems and lifting equipment if the vessel is large enough.

On the contrary to the aforementioned benefits, a setback of these SWATH vessels is that they sail at moderate speeds, slower than the single-hull and catamaran CTVs. Furthermore the floating characteristics of the SWATH design limits the ability of the vessel to carry cargo in terms of the maximum weight which can be carried. Finally, these vessels are expensive (Echavarria et al., 2015).

The final category of CTVs which will be mentioned are the Quick Response Vessels. It is common that for this category, widely available Rapid Inflatable Boats (RIB), with a good fuel efficiency compared to the other CTVs, are utilized as can be seen in figure 2.10. These RIBs are only deployed for short distances and good weather for operations from e.g. a mother-ship (see sub-section 2.2.3 on the concept of mother-ships) (Gardner et al., 2009). According to Echavarria et al. (2015) these RIBS are operable at wave heights < 1.25 m. Due to the small size the RIBs can facilitate a limited number of pax and they are not capable of parts which are large and heavier than ± 50 kg.

2.2.2. Helicopters

In the offshore environment, helicopters have been used as the dominant mode of transporting crew to and from offshore platforms for decades. The main reason for the use of helicopters is because it offers a fast and flexible transport service, and for many years a good alternative was lacking. The use of helicopters is however considered a very costly resource in the upstream logistics chain, in which the transportation itself does not add any extra value to the offshore business. The level of comfort provided by helicopter transportation is debatable. According to a study by Morrison (2001), helicopter transport is perceived as more comfortable in terms of reduced travel sickness and easier personnel transfer onto an installation compared with travel by vessel. However, according to a study by Vinnem, Aven, Husebø, Seljelid, and Tveit (2006) helicopter transport is considered by crew members as uncomfortable and risky, because of heaviness and weightlessness experiences during take-off and landing, noise, vibration, and sometimes accidents. In addition crew members need to undergo several days of training, depending on the country, before they are allowed to board a helicopter to go offshore. Another disadvantage is that helicopter flights are restricted to daytime operations, while vessels can operate day and night.

Benefits of helicopter transport are in the fact that helicopter operations are not limited by the wave condition, e.g. significant wave height. On the other hand helicopter operations require good visibility and wind speeds which are within operating boundaries (Gundegjerde and Halvorsen, 2012).

2.2.3. Vessels and structures for Offshore Accommodation concepts

With the growth in the offshore wind energy industry, also the need for offshore accommodation grows. The aim of this offshore accommodation is to have skilled labor such as engineers and mechanics close to the wind farms for rapid and convenient O&M of the wind farms. Especially in the current phase of the offshore wind sector, a relatively new industry with strong growth, there are still many uncertainties and lessons to be learned in terms of possible failures (Gundegjerde and Halvorsen, 2012). Transportation of skilled labor from shore to OWF, which are reaching further and further from shore, each time a failure occurs in a wind generator is considered to be unfeasible with high risks of production losses meaning losses in revenues for the OWF operators. The challenge is further complicated by the fact that the CTV vessels for these maintenance activities can only stay offshore for a limited time (Gundegjerde and Halvorsen, 2012, Joshi and Bolstad, 2016).

Figure 2.11: The Wind Solution, an example of a floatel (Windpower Offshore, 2013)

Figure 2.12: the Atlantic Enterprise, example of a Mothership (OffshoreWind.biz, 2015b)

The developed accommodation concepts are expensive to acquire and maintain, but they are considered to boast benefits which outweigh these high costs. Offshore accommodation provides the ability to make use of the smaller weather windows, which would be impossible to operate in when including the transit from shore. Moreover, the elimination of long transit times contributes in preventing crew to be seasick or tired due to the rough journey and this increases their productivity. Also in the future OWF which will be further away from shore, at around 55-75km and more, will be relying on offshore accommodation facilities to avoid loss of production due to O&M occurring too late and tired and seasick crew due to the long and rough journeys (Echavarria et al., 2015).

The OTG sector is relatively novel and undergoing strong growth. For this reason TenneT Offshore included

Figure 2.13: The Highland Knight, an example of an OSV (World Maritime News, 2013)

Figure 2.14: On the right is the accommodation platform next to the substation at the Horns Rev2 Wind farm (Energia, 2015)

Figure 2.15: Hub island concept (TenneT, 2017)

accommodation for crew including various service facilities such as catering, computer facilities and facilities for showering on its current substation platforms in the North Sea. On all platforms in the North Sea, TenneT currently has permanent manning working in 2-weekly shifts for the execution of O&M activities in the platform.

As alternative to these accommodation facilities on each platform itself it is possible to facilitate the accommodation of crew in separate structures, than the platforms. For this alternative the option exist to either use multi-purpose vessels such as Operation Support Vessels (OSV) or Platform Supply Vessels (PSV) with accommodation facilities or Fixed Offshore Accommodation Stations (FOAS).

Multi-purpose accommodation Vessels exist in various types whereby the differences can be found in the crew capacity of the vessels, the capability to jack-up, the floating capabilities, the deck-pace for cargo, the lifting capacity, the presence of daughter-vessels and the facilities on-board such as working facilities and access systems.

Floatels are accommodation vessels which have been upcoming in the last few years in the offshore vessel market. As the name proposes these floatels can be seen as floating hotels, meaning that the vessels are equipped with hotel-like facilities for the accommodation of crew to execute extensive activities such as maintenance campaigns or commissioning of Oil&Gas platforms, wind generators and substation platforms (Salzmann, Prezzi, ten Haaf, Groenteman, et al., 2015). Due to the hydrodynamic properties of these large vessels, often a conventional gangway, this is a gangway without active motion compensation, is utilized for the transfer of crew from the floatel to the platform and vice versa. If such gangways are not present, there is a dependency on smaller CTV to transfer crew via boat-landing. These floatels can accommodate a large number of personnel, reportedly ranging from 50 to 500. Additional features are in the deck space to transport supplies and spare parts, and the possibility for CTVs to dock and refuel. In figure 2.11 the Wind Solution is exhibited as an example of a floatel. This converted Roll-On-Roll-Off ferry vessel is converted in a floatel for offshore operations and boosts facilities such as accommodation cabins, a gym, a cinema, laundry services and catering. On the downside these floatels have high capital and operating costs, a large vessel draft and not always direct access to offshore structures which makes them dependant on smaller vessels and hence they do not improve the capabilities to operate under higher waves heights (Echavarria et al., 2015).

Offshore Operations Support Vessels (OSVs) can funtion as mothership and are another type of multi-purpose accommodation vessels which may be specifically designed and constructed for the offshore wind industry. Hence, these vessels are equipped with all equipment and facilities necessary for the commissioning and maintenance of offshore wind turbines. Alternatively these vessels could be utilized for the substation platforms. From the dedicated design for offshore wind, these vessels are made to operate in rough weather conditions and they commonly include helipads and daughter vessels, smaller CTVs or quick response vessels, for the in-field transportation of crew from the OSV to wind turbines or substation platforms and vice versa (Joshi and Bolstad, 2016). These vessels can also be equipped with access technology, such as Heave-Compensated Gangways, for direct access to the offshore structures. An example of such a OSV is exhibited in figure 2.12, this vessel is the Atlantic Enterprise by Atlantic Marine and Aviation. The report by Echavarria et al. (2015) state that also these OSV have high operating and capital costs and a large vessel draft, while the limited experience with launching and recovery systems of daughter vessels is also a potential drawback.

The last category which will be mentioned in the field of multi-purpose accommodation vessels are the Platform Supply Vessels (PSV). PSV are widely available in the Oil&Gas sector as they are originally designed to supply offshore Oil&Gas platforms as large work boats with the possibility for crew accommodation in addition to facilities such as spare parts transportation, lifting equipment and access systems. Compared to CTVs, PSVs are bigger and hence able to transport crew under rougher offshore conditions with the presence of access systems such as Heave-Compensated Gangways (Echavarria et al., 2015). In figure 2.13 an example of a PSV is exhibited, it can be seen that the PSV has more deck space than an OSV for the transportation of parts and supplies.

The alternative to multi-purpose accommodation vessels are the FOAS. FOAS include offshore structures which are comparable to the substations or Oil&Gas platforms, but have as sole purpose the accommodation of crew and optionally the storage of supplies and spare parts. The accommodation platforms are becoming more common at OWF. Dong Energy was the first to add an accommodation platform near their Horns Rev wind farm in 2007, see figure 2.14 (A2 Sea, n.d.). A downside to these accommodation platform, is that while they do shorten travelling distances, they do not improve the capabilities to operate under higher waves as CTV with a limited wave height are still necessary to transport crew from these platforms to the wind generators or substation platforms (Joshi and Bolstad, 2016).

An alternative to the current accommodation on each substation platform is to remove the accommodation facilities on the platforms and consolidate the accommodation of crew and storage of spare parts in a dedicated accommodation platform. If this accommodation platform is placed strategically within the network of substation platforms, it can act as hub. To this hub, transport from shore can be accommodated in bigger vessels, saving cost compared to needing more individual trips from shore to each platform, while short trips from the hub-platform can be conducted to the platforms for the maintenance campaigns. The short trips to the platforms from the hub-platforms can be done with CTVs docked at the accommodation platform and maximize productivity of crew.

In addition to these fixed accommodation platforms, new concepts such as artificial islands are proposed by a consortium of companies among which TenneT as TSO is also participating. This artificial island, as is depicted in figure 2.15, should make it possible to house crew, while it includes facilities for helicopters and airplanes to land and take-off, facilities for vessels to dock and facilities to store supplies and spare parts for the OWF and OTG. It is proposed by the consortium that this concepts contributes in minimizing logistics costs, while at the same time increasing the performance of O&M.

2.2.4. Crew transfer technology

There are several ways to get crew from a vessel onto a offshore platform and vice verse. Collectively these means are called Offshore Crew Transfer Technology or Offshore Access Systems. These access systems make it possible to move from a moving vessel to the offshore platform at sea. In the offshore crew change industry, offshore access is possible via mainly four different access methods.

1. The "step-over" approach allows for the crew to step across the bow of the vessel to the platform boat-landing facilities. This approach is one of the most conventional and most used ways of crew transfer,

Figure 2.16: Step-over approach with the boat Landing (Bourbon Offshore, 2015)

Figure 2.17: Basket transfer (Pugh, 2015)

Figure 2.18: Motion Compensated Gangway transfer (Ampelmann, n.d.)

Figure 2.19: Swing Rope (The Ships and Oil, 2017)

due to its simplicity and low cost, allowing for vessel to platform transfer and vice versa. For this approach the vessel used for crew transportation lands at the designated an specifically built boat-landing facilities at the platform, see figure 2.16. After landing, the vessel utilized its propulsion and dynamic motion control to stay connected to the landing point and allow for the crew to make the transfer from vessel to platform access ladder and vice versa.

2. Crew can be lifted from a vessel onto a platform in a personnel basket or capsule, using a crane, this is called basket transfer or frogging (Echavarria et al., 2015). Figure 2.17 illustrates such a basket transfer. To allow this transport either the platform or the vessel must have a crane with a crane operator, which makes it an unsuitable method to access unmanned platforms if the vessel does not include such a deck crane. Access via basket transfer is allowed at a maximum significant wave height of 1.5 meters. Beyond this wave-height and under stormy conditions it is considered too dangerous to use this method of crew transfer. Globally, this method is commonly used due to its low cost.

3. The third method is crew transfer by means of swing rope. Here, crew swings from a vessel to a landing platform on the offshore platform or vice versa, see figure 2.19. This method requires a rope and landing platform arrangement and is for safety reasons restricted to very calm weather and wave conditions.

4. The Walk-to-Work method, utilizes a motion or heave-compensated platform that compensates for the motion of the vessel with a gangway system which connects the vessel with the platform at for instance its boat landing facilities. An example of such a system is the Ampelmann Motion Compensated Gangway, developed by Ampelmann Operations B.V. Ampelmann Operations B.V. state that their system makes the transfer from vessel to platform, and vice versa, convenient, comfortable and more reliable in terms of weather resilience (Ampelmann, n.d.). The Ampelmann system can handle up to 4.5 meters

significant wave height depending on the type of Ampelmann system. Moreover, the system does not require changes to the infrastructure on the platform in terms of the need of a crane or boat-landing facilities. Figure 2.18 shows an example of an Ampelmann system. In addition to the motion or heave-compensated gangways, this method of transfer can also be applied using a deployable gangway from a big vessel with dynamic positioning capabilities (Echavarria et al., 2015).

5. Finally the transfer of crew by helicopters can be fulfilled with either a full helicopter landing after which the crew can board or disembark the helicopter. This is possible in the case the platform is equipped with a helideck. If this is not the case, transfer via helicopter is possible by means of hoisting, where crew is lifted from the helicopter to the platform and vice versa using hoisting equipment (Echavarria et al., 2015). This method has the benefit that it can be conducted under the more extreme weather conditions in comparison with the conventional vessel based methods.

2.3. Maintenance strategies

The maintenance of transmission substations has been around since mankind started using electricity as and energy-carrier. However, the substation platforms offshore are relatively new technology. For instance, the substation platforms built in the German grid in the North Sea, were all the first real-life units of its kind. This brought the necessary challenges regarding the operation and maintenance of these substations, due to the absence of experience with this new technology in a very challenging environment. Classically, two type of maintenance exist, namely preventive maintenance and corrective maintenance (Gundegjerde and Halvorsen, 2012, King, 2011). In the next two sub-sections it will be discussed what these two methods of maintenance entail for OTG.

2.3.1. Preventive Maintenance

Preventive maintenance is conducted to extend the lifetime of a substation platforms and minimize the downtime by preventing failures. At the offshore platforms of TenneT, between 12,000 and 16,000 hours are spent annually on the preventive maintenance per platform (Vianden, 2018). These resources are primarily spent on the mechanical and electrical maintenance of primary systems and auxiliary systems, but in the offshore environment a significant 21% of the cost is spent on the prevention of corrosion (vor dem Brocke, 2013).

For preventive maintenance a maintenance strategy addresses how the effectiveness of maintenance can be measured and what should be done to reach satisfying performance. The strategy can address:

- the different types of preventive maintenance activities including the type of monitoring and control of the system state
- the classification of components and sub-systems on for instance criticality and the associated maintenance priority
- the frequency of preventive maintenance activities to be conducted on various platform components
- the duration of maintenance campaigns and the maintenance activities such a campaign consists of. A maintenance campaign can be defined as a sequence of maintenance activities to be conducted on a platform within a predefined time-period

An optimal maintenance strategy for reliable operation of the platforms, is not only dependant on the type of platforms used and the experience with that specific technology, but also on the conditions of the offshore environment the platform is located in. Moreover, since the maintenance activities still require skilled human technicians to conduct processes such as inspections, part replacement, part lubrication and gas refill, and resources such as parts, tools and transportation means, the strategy depends on the availability of these resources. At TenneT, the preventive maintenance strategy primarily targets the reliability performance of the platforms. In legislation it is stated for the availability to be above 92% per year and it is desired for downtime due to maintenance to not exceed 10 days per campaign (vor dem Brocke, 2013).

2.3.2. Corrective Maintenance

Where preventive maintenance aims to prevent failures, corrective maintenance is required in the case such failures or breakdowns do occur, potentially leading to downtime. In 2017, between 2,000 and 4,000 hours is spent on corrective maintenance per platform annually (Vianden, 2018). The failure of platforms, or components of platforms, can happen due to a variety of reasons and is dependant on the experience with the technology, the environmental conditions leading to e.g. corrosion, but also for instance the quality of the platforms provided by the manufacturer. In figure 2.20 platform components are presented and to what extent the failure of those components contribute in the total downtime of a platform. As previously mentioned, offshore substation platforms are novel technology, hence little research is done on the failure rates of these platforms and their components. However, the manufacturers do provide calculations on the failure rate of their products, which form the basis of the maintenance planning by the users of the technology. With the experience in operating and maintaining these platforms by companies such as TenneT gained over the years of operating the platforms, more data becomes available on the failure rate of the platforms. This experience based data is considered an enabler of the next level in maintenance, namely condition based maintenance. Condition based maintenance should reduce the resources put into the maintenance. This by planning maintenance proactively based on the actual condition of the platform and the knowledge regarding the relation between failures and the condition of a platform, instead of reacting only when a failure occurs and conducting unnecessary maintenance preventively (vor dem Brocke, 2013).

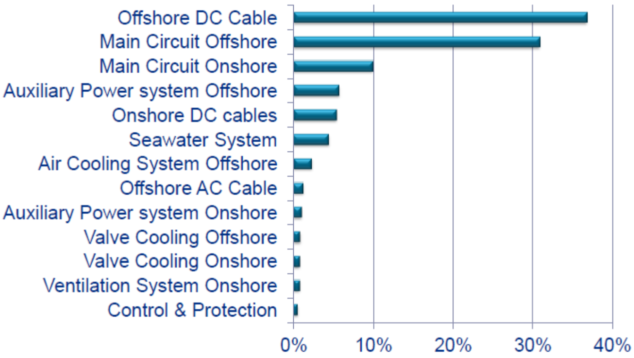


Figure 2.20: components and their contribution to the unavailability of platforms due to a failure, adapted from vor dem Brocke (2013)

In figure 2.21 a breakdown is presented of the downtime of a platform after a failure occurs. Once a failure occurs, technically the downtime of a platform depends on the criticalilty of the failed component and its redundancy in the design. However, the downtime, starting from the occurrence of the failure and lasting until the repair is completed, is also dependant on the time it takes for the technicians and spare parts to reach the platform. This entails that the choice of vessels to provide the transportation to the platform under the given weather conditions and transportation demand for spare-parts and technicians, is critical to minimize downtime if the technicians and spare-parts are not present on the platform permanently. This is the case for unmanned platforms and platforms with limited storage of spare-components.

2.4. The influence of weather

The influence of weather is significant for all offshore operations, however, the extent of this influence is different for different offshore operations. For personnel transfer, the weather limitations depend on the type of transfer technology used. To illustrate this, for vessels with basket transfers the workable weather conditions are significantly more limited than the workable conditions for helicopters or vessels with gangway systems (Norwegian Shipowners' Association et al., 2013).

Furthermore, different gangway types allow different weather conditions, as depicted in sub-section 2.2.4. For sailing from shore to platforms and vice versa, but also between platforms, the operational characteristics of the vessel are decisive. Due to bad weather conditions, vessels may have to reduce speed, or in a more extreme case the vessel journey needs to be aborted completely. Helicopters can operate in more extreme weather conditions. They are not restricted by sea conditions, such as waves and current, when transferring crew onto platforms, but are restricted in terms of both wind speed and visibility (Echavarria et al., 2015).

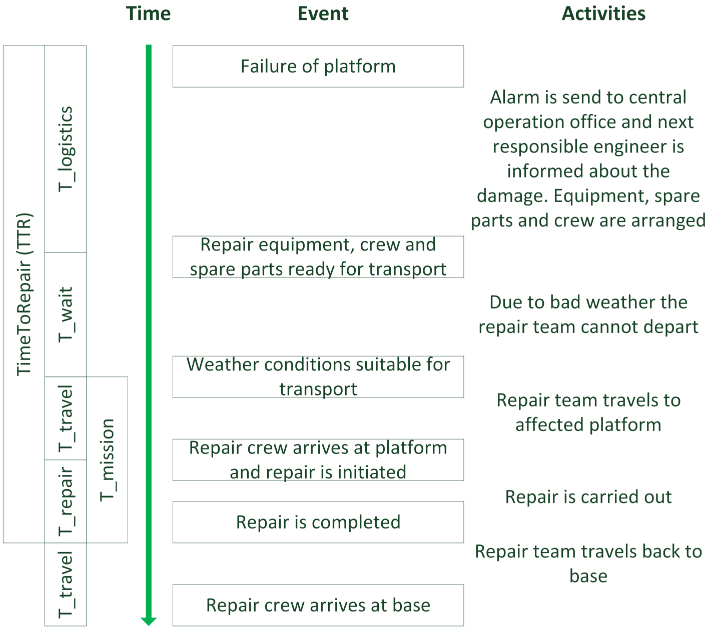


Figure 2.21: breakdown of the downtime in the case of failures, adapted from Gundegjerde and Halvorsen (2012)

For vessel transport and transfer there are mainly two important weather influences: wave conditions and wind speed (Halvorsen-Weare and Fagerholt, 2017). Wave conditions are generally described by two parameters, the significant wave height (Hs) and the mean zero-crossing wave period (Tz). Together the Hs and Tz form the wave conditions of a certain sea state, during which the climate is considered constant for a period of three hours (Cerda-Salzmann, 2004). The most important variable to take into account is the significant wave height which can be defined as "the mean of the highest one third of the waves per observation period", measured in meters (Maisiuk and Gribkovskaia, 2014a). Some individual waves within the time period will be larger than the significant wave height (Cerda-Salzmann, 2004). The mean zero-crossing wave period (Tz), defined as the average value of all upward (or downward) zero crossing wave periods within the observation period, has less influence on the limitations of offshore crew transport (Echavarria et al., 2015). The wind speed (Wsp) is commonly measured in knots and while being less influential as the significant wave height, it is mainly affecting the operational speed of the vessel (Maisiuk and Gribkovskaia, 2014a). The influence of wave conditions and the wind speed are used to determine the weather window, which is "the time interval during which both (Hs) and (Wsp) do not exceed safety limits". This window has to be equal or larger than the time needed for the operation (Maisiuk and Gribkovskaia, 2014a).

2.5. Chapter conclusion

In this chapter, the challenges for the operation and maintenance of the novel offshore transmission technology are addressed in a fairly superficial way to provide the reader of a basic understating of OTG. To tackle these challenges, many logistic alternatives exist which potentially offer reliable and fast transportation of crew and goods with each of these solutions having specific pros and cons. It in now necessary to further specify these challenges for the TenneT case in order to develop a model which represents the TenneT case as much as possible. The further specification of this problem is discussed in the next chapter.

3

Problem Description

In this chapter, light is shed on all relevant aspects to be taken into account by TSOs when aiming to establish and operate a marine fleet cost effectively for the execution of O&M activities on offshore substation platforms.

3.1. O&M planning

In section 2.3 it was presented that two type of maintenance activities can be distinguished: preventive maintenance and corrective maintenance. Preventive maintenance is usually planned according to a "lowest total cost" philosophy as can be seen in 3.1. According to this total cost relation, a preventive maintenance schedule can be generated which will be executed over the operational time-frame to minimize total costs. The scheduled, preventive maintenance tasks can be executed before or after the scheduled moments, however this brings along extra costs. If the preventive maintenance is conducted before the optimal point in scheduling, this results in extra costs for the higher frequency of inspecting and/or replacing components, but also extra costs for extra unscheduled vessels which have to be rented from the spot market. On the other hand, if preventive maintenance is delayed beyond the scheduled point, extra costs can be incurred as a consequence of downtime due to the higher risk of component failure.

Various concepts exist for the planning of preventive maintenance, but as this study will address the case of Tennet, it makes sense to study the concepts under consideration by TenneT. In this TenneT maintenance strategy, TenneT will be working with maintenance campaigns of the converter platforms on a quarterly basis. Maintenance campaigns consist of a sequence of maintenance activities to be conducted on a platform in a predefined period. The TenneT plan assumes campaigns lasting for two weeks.

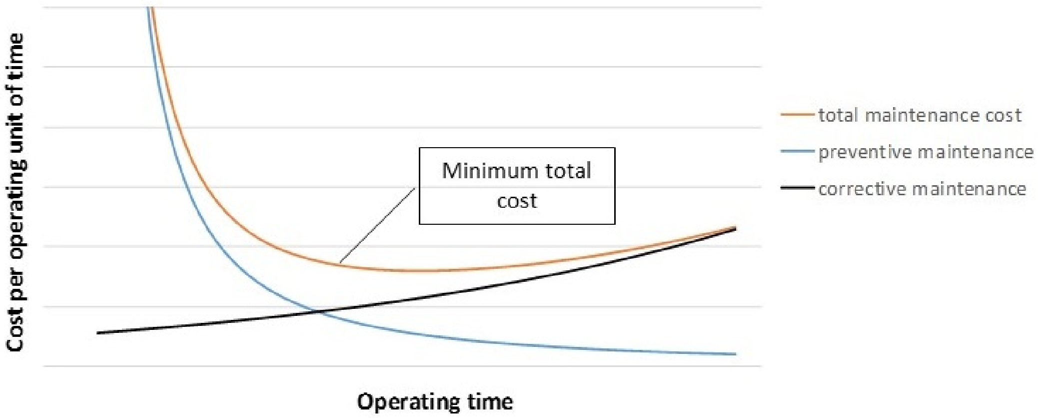


Figure 3.1: Maintenance cost profiles, adjusted from (Reliability Hot Wire, 2014)

The corrective maintenance is required to repair failure of components on the substation platforms in such a way that the downtime can be minimized. In order to model this aspect of maintenance it is necessary to gain knowledge on the failure rate of the components on the substation platforms and subsequently the probability of substation downtime. These failures can occur over the entire operational period and depending on e.g. the redundancy characteristics, this leads to downtime of the substation or not. When these failures occur, and there is a lack of redundancy, the TSO has to head out and fix the failure as soon as possible in order to minimize downtime and prevent further damage and financial penalties. Each maintenance task has a specific predefined period in which the crew will be occupied with the specific task on the specific platform. In reality this predefined number of hours can change, either up or down. For instance if more technicians are put on the task, the total amount of hours for that specific task decreases, on the other hand weather conditions may be so severe that tasks involving activities on the exterior of the platform cannot be conducted in the current weather window, in this case the total amount of time a crew is occupied with a specific task increases. However, it should be noted that this study is scoped around the fleet planning on a strategic level, and not on the planning and execution of maintenance. Hence, the study will not extensively include maintenance planning as subject of the study, but rather include maintenance needs as the source of demand for the vessel fleet operated by the TSO. For the OTG of the Netherlands and Germany in the North Sea, this data is partially available on an aggregated level per platform. The failure data is based on the historical data of platform component failures.

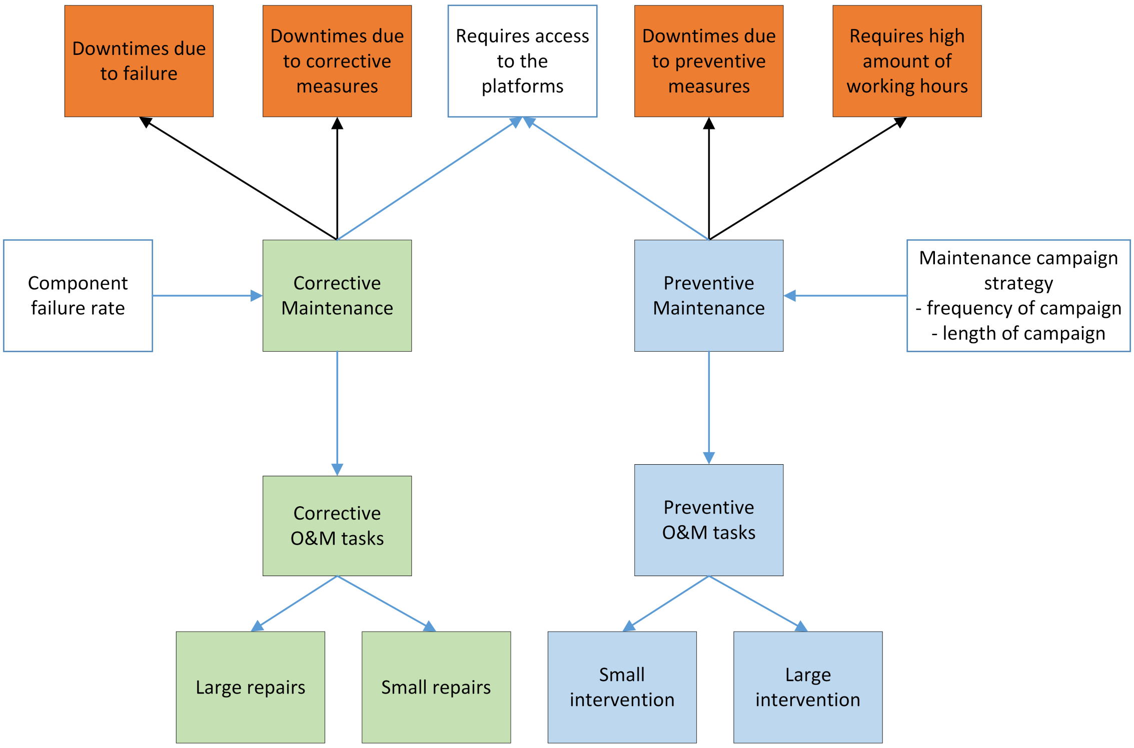


Figure 3.2: An overview of the maintenance aspects

In figure 3.2 an overview is presented on the two streams of maintenance activities. The commonality here is that both types of maintenance require access to the platforms, this implies that logistic solutions should not only consider the transportation from port to platform and vice-versa, but also the manner through which crew and cargo can gain access to the platform.

Another highly relevant aspect, as mentioned before, is the temporal planning or scheduling of maintenance activities. In addition to being highly relevant to guarantee platform availability and reliability, the scheduling of maintenance tasks, or in other words: determining when maintenance should be executed, is also relevant for fleet decisions. Vessel availability depends on the type of vessel, location of the vessels and the required time and cost for mobilization and the type of contract. In order to also have the transport means available when maintenance needs to be executed, it is necessary to align the decisions on maintenance scheduling and fleet composition. How this alignment can be modelled is discussed in section 5.5.

3.2. The relation between vessels and O&M activities

Preventive and Corrective Maintenance consist of various activities which are required to be executed timely and correctly for successful maintenance operations. In figure 3.3 it is presented what activities these maintenance operations consist of. And for each of these activities different vessels are suitable.

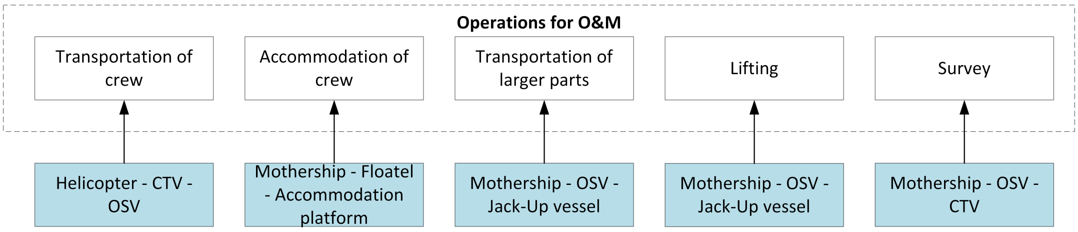


Figure 3.3: Maintenance cost profiles, adapted from

For the transportation of people (crew) either helicopters, CTVs, PSVs or OSVs can be utilized, with a specific pax capacity. Section 2.2 presented more details on the characteristics of these vessels. These CTVs, PSVs, OSVs or helicopters drop the crew at the platforms to conduct the maintenance operations and pick them up when the tasks are finished.

If it turns out that the maintenance operations involve the replacement of bigger parts, such as transformators, dedicated vessels are required with larger cargo transportation capacities such as larger deck space, measured in m^2, and larger carrying capabilities, measured in metric tons (MT).

The accommodation of crew, can be argued an auxiliary service, however for the TSO it is an integral part of Maintenance Operations. Where the substation platforms are commonly designed as unmanned stations, they are not meant to accommodate crew for extended periods of time. However, due to the fact that these substation platforms are new and a lot still needs to be learned, often these platforms include facilities for accommodation. However, this is a costly option and alternatives are being sought after which can reduce costs. With the eye on the total logistics costs reduction, concepts such as OSVs, accommodation PSVs, floatels or dedicated accommodation platforms have the potential to reduce costs (Dewan, 2014, Gundegjerde and Halvorsen, 2012, Stålhane et al., 2016).

The big multi-purpose accommodation vessels and floatels often have the capacity to carry larger parts when replacement of these larger parts on platforms are necessary. In the case of maintenance operations requiring large parts, it is often also required that the vessel has lifting capabilities (in MT of lifting capacity) if cranes on the platform are absent for the lifting of big parts. Typically the jack-up vessels and larger scale OSVs and PSVs are equipped with some type of lifting ability.

Finally, when not occupied with crew or parts transportation activities, OSVs, PSVs and CTVs, could be deployed on marine survey activities Dalgic et al. (2013). However, this means that if the vessel is occupied with survey activities, unscheduled crew transportation has to wait until the survey is finished. In the case of emergency transports, e.g. with a platform failure occurring, the survey activities have to be interrupted, which implies extra costs if the survey has to be done all over again.

3.3. Fleet composition

This section will further elaborate on the mechanisms regarding the composition of a vessel fleet, given the vessel characteristics and the demand profile coming from the maintenance activities. First, aspects impacting the fleet composition will be summarized in one figure. Second, the subject of vessel contracting will be introduced to intelligently guarantee vessel capacity at low prices.

3.3.1. Factors which impact fleet composition

The diversity in types of vessels available on the market, means that there also is diversity in the characteristics and capabilities of vessels. It is relevant to take into account the duration vessels can stay offshore as this influences how the vessel can be deployed for various maintenance tasks. A distinction can be made between vessels which can stay offshore for short periods of times, e.g. the smaller CTVs and quick response vessels. Typically these vessels can stay offshore up to a day. On the other hand there are vessels with the capability to stay offshore for periods longer than one day. These are typically, the PSVs, floatels, larger CTVs, OSVs and the jack-up vessels.

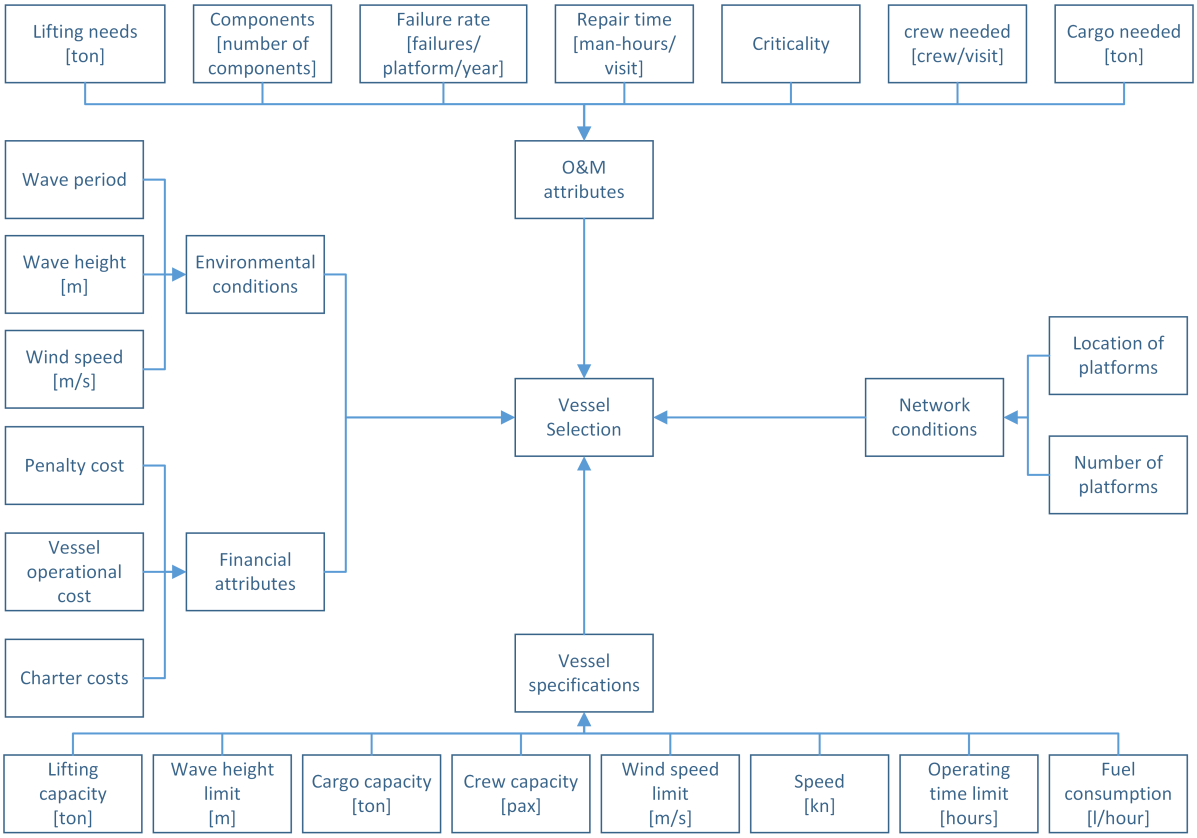


Figure 3.4: aspects surrounding vessel selection

The results of the search for aspects influencing the selection of vessel types for fleet composition, among others introduced in the previous chapters, are summarized and presented in figure 3.4. These aspects and their impact on fleet composition will be taken into account in the model development in chapter 5.

3.3.2. Vessel Contractual arrangements and alternative chartering periods

In the world of maritime vessel markets, voyage chartering (spot market or short term leasing), time charter and bare-boat charter are the commonly used types of contractual agreements between parties owning the vessels and parties in need of vessel services (Dalgic et al., 2013).

Under a voyage charter agreement, the ship owner is contracted to carry a specific amount of weight or passengers with a specific vessel at a negotiated price per ton or passenger which covers the capital charges of the vessel, daily running costs and voyage costs.

The time charter agreements involve a contract between the vessel owner and client to hire a ship for for a certain period, commonly complete with crew, whereby the remuneration occurs on the basis of a day-rate. Here the ship owner pays the capital costs and operating expenses, while the charterer pays the voyage variable costs.

Finally, bare-boat chartering entails that the ship owner leases out the ship to the client without crew or any operational responsibility. In this case the charterer is responsible for the daily operational costs, the voyage variable cost and the cost related to cargo handling and claiming, while the ship owner is paying the capital costs.

In table 3.1 an overview is provided to the reader on the differences between these contract types regarding: duration, advantages and disadvantages. When taking a closer look to the advantages and disadvantages it can be determined when the various contract types suit a specific situation.

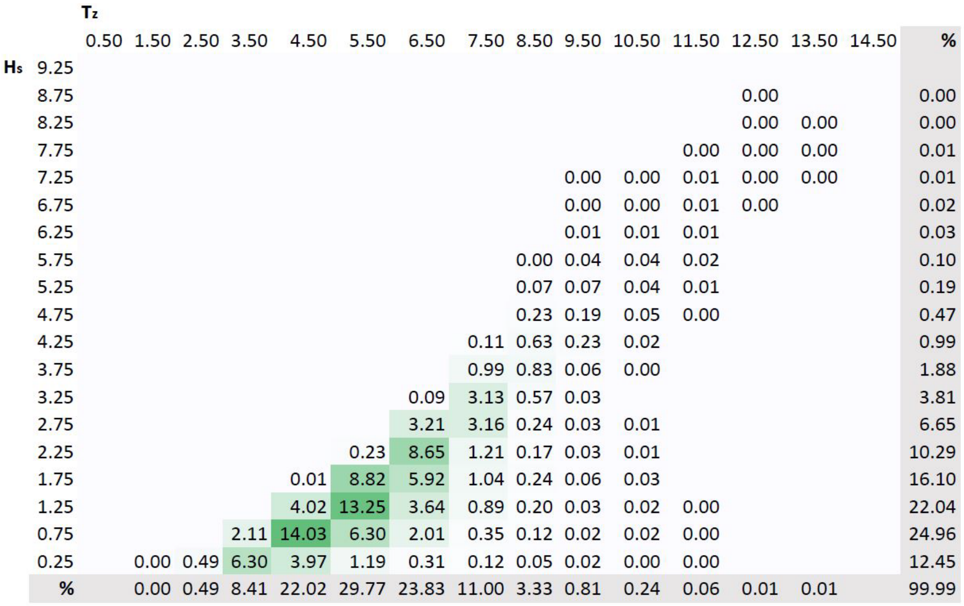
Table 3.1: Vessel lease or charter type and the associated advantages and disadvantages (Dalgic et al., 2013)

Strategy	**Advantages**	**Disadvantages**
Long-term lease 1 year to 20 years	- Reduced mobilization time and costs - No risk of vessel unavailability - Increased operational control - less varying cost over time - Vessels can be used across multiple sites	- Paying for vessel even when not in use - Need more internal staff and resources to maintain/operate vessel - Vessel not optimized for individual sites - Repair and maintenance expenses may be internalized - A port is needed for vessel docking
Medium-term lease 1 month to 1 year	- Reduced risk of weather effect on prices (if performed during summer) - Lower number of vessels being chartered - Vessels can be used across multiple sites	- Risk of low utilization in e.g. winter months - In case of maintenance/supply delays there is a risk of uncompleted/faulty repairs
Short-term lease spot-market 1 day to 1 month	- Use vessel only after a failure occurs or maintenance needs to be conducted - Select optimal vessel for each activity - Only use vessel when needed - Maximum utilization of vessel	- Uncertainty in vessel availability, mobilization time and costs - High day-rates and mobilization costs

3.4. Weather in the North Sea

In the North Sea weather conditions can be harsh. Therefore, a fitting weather window is necessary that enables both the crew transport and the crew transfer. The weather window is dependent on the percentage of the time that a suitable sea state is present for the type of transport and transfer used. The occurrence of certain sea states can be related to the Beaufort numbers (BN), which is a measure to describe wind speeds and the related sea conditions. For the North Sea case the occurrence of each Beaufort Number is deducted from the wind and wave scatter diagrams based on annual data from waveclimate (2017).

Figure 3.5: 2017 wave data for the North Sea, derived from (waveclimate, 2017)



		Tz															
		0.50	1.50	2.50	3.50	4.50	5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50	13.50	14.50	%
Hs	9.25																
	8.75													0.00			0.00
	8.25													0.00	0.00		0.00
	7.75												0.00	0.00	0.00		0.01
	7.25										0.00	0.00	0.01	0.00	0.00		0.01
	6.75										0.00	0.00	0.01	0.00			0.02
	6.25										0.01	0.01	0.01				0.03
	5.75									0.00	0.04	0.04	0.02				0.10
	5.25									0.07	0.07	0.04	0.01				0.19
	4.75									0.23	0.19	0.05	0.00				0.47
	4.25								0.11	0.63	0.23	0.02					0.99
	3.75								0.99	0.83	0.06	0.00					1.88
	3.25							0.09	3.13	0.57	0.03						3.81
	2.75							3.21	3.16	0.24	0.03	0.01					6.65
	2.25						0.23	8.65	1.21	0.17	0.03	0.01					10.29
	1.75					0.01	8.82	5.92	1.04	0.24	0.06	0.03					16.10
	1.25					4.02	13.25	3.64	0.89	0.20	0.03	0.02	0.00				22.04
	0.75				2.11	14.03	6.30	2.01	0.35	0.12	0.02	0.02	0.00				24.96
	0.25		0.00	0.49	6.30	3.97	1.19	0.31	0.12	0.05	0.02	0.00	0.00				12.45
	%		0.00	0.49	8.41	22.02	29.77	23.83	11.00	3.33	0.81	0.24	0.06	0.01	0.01		99.99

As mentioned before the significant wave height (Hs) related to the zero crossing wave period (Tz), is the most

Table 3.2: BN occurrence percentage with the corresponding wind speed and wave height, derived from (waveclimate, 2017)

BN	Wsp	Hs	%
12	64	14	0
11	56-63	11.5-14	0
10	48-55	9-11.5	0.002
9	41-47	7.5-9	0.038
8	34-40	5.5-7.5	0.439
7	28-33	4-5.5	2.593
6	22-28	3-4	**7.819**
5	16-22	2-3	**19.34**
4	11-16	1-2	**35.28**
3	7-11	0.5-1	**21.87**
2	3.5-7	0.2-0.5	**11.51**
1	1-3.5	0-0.2	0.914
0	0-1	0	0.188

significant factor for vessel operations and for the North Sea this data is presented in figure 3.5. Together with the wind speed, the probability (yearly average) of each Beaufort Number (BN) to occur in the SNS case can be derived. See table 3.2 for the BN probability distributions.

For waves, Hs instead of Tz is decisive for the weather window. When taking the common limit of 3m Hs as an example, this leads to operating capabilities or vessel availability of 92.50% of the time. However, it has to be noted that a large difference exists between the summer and winter period in the North Sea. In the months from May to August, the weather is much calmer than in the months from November to February. For the Hs of 3m, the month of June gives a 98.60 % operating time and the month of January only 82.87% as can be seen in figure 3.5.

3.5. Chapter Conclusion

In this chapter the challenges for the operation and maintenance of offshore transmission technology are further specified for the TenneT case. Moreover it is described what the role of vessels can be in the operation and maintenance of OTG and what the relation is between the maintenance strategy and the fleet. With these findings, the next step is set towards the development of a model to tackle the strategic fleet planning for the maintenance strategy. In the next chapter a literature overview is provided, which discusses how the modelling of strategic fleet planning has been conducted in general and in the maritime industry. This overview should provide the means to translate the aspects mentioned in this chapter in a fleet planning model for OTG.

4

Literature Review

In this study the objective is to develop a model which provides strategic decision making support on the subject of vessel fleet mix and size. The proposed model can be embedded in a vast field of literature on the methods and theories applied in the field of fleet composition models. In this chapter this field of literature will be discussed, in order to make the step towards the model developed for this study.

First, in section 4.1 literature on classical applications of strategic fleet planning will be addressed. Classical fleet planning is performed predominantly for land-based fleets of vehicles.

The classical fleet planning will be followed by literature which elaborates further on the specific application of strategic fleet planning in the offshore industries. By doing so the similarities and differences between these two domains can be captured. Regarding the strategic fleet planning for the offshore industries, typically the term of Maritime Fleet Size and Mix Problems (MFSMP) is encountered in literature.

In the following section 4.3, specific applications of MFSMP in the offshore wind power industry will be discussed. Since the OTG is inherently related to the offshore wind power industry this literature will directly bring the subject of MFSMP closer to the subject of this study, namely MFSMP for OTG. Since it could be derived from literature such as Dalgic et al. (2014), Joshi and Bolstad (2016), Stålhane et al. (2016) and the interviews with Algra (2017), Heinrich (2017a) that uncertainty in the offshore environment is inevitable, section 4.3.1 addresses literature on how models coped with uncertainty. This is followed by literature on multi-level modelling to address the modelling of decisions on different levels, e.g. the strategic and tactical level.

Finally, section 4.4 will presents literature on what solving methods coming from the field of OR can be applied for the developed MFSMP model in this study.

4.1. Strategic, Tactical and Operational fleet management

According to Bielli et al. (2011), fleet management represents activities on a tactical and operational level in organizations providing passenger and/or freight services.

Here fleet planning is considered as a combination of fleet composition and routing. In a literature overview dating back to 1983, Etezadi and Beasley (1983) already tackled the Fleet Composition Problem (FCP) which are still considered a complex problem. In the literature overview, Etezadi and Beasley (1983) distinguish two types of FCP namely:

- **Vehicle fleet size problems**: FCP dealing with a given set of vehicles, and the problem relates to the number of each vehicle type to operate.
- **Vehicle fleet composition problems**: these FCPs deal with both the type of vehicles and the number of each type to operate.

Between these types of FCP, at that time vehicle fleet composition problems were insufficiently studied, since most of the attention went to the vehicle fleet size problems. It was the beginning of a new field, and in the literature review Etezadi and Beasley (1983) mention the work by Golden et al. (1984) and Gould (1969) as trendsetters, respectively developing a linear programming model and an integer programming model for the vehicle fleet composition problem.

The literature overview by Hoff et al. (2010) addresses literature published on combined fleet composition and routing for both maritime and road-based transportation. The rapid increase in volumes of load to be transported over the road, lead to fleet dimensioning challenges for the industry on all levels. It should be noted, that although not included by Hoff et al. (2010), air and rail transportation is also a relevant industry in which fleet planning plays a significant role (Bielli et al., 2011).

The definition for the terms *route, tour and trips* can be derived from Hoff et al. (2010) and are used interchangeably throughout the thesis. A route, journey or tour can be defined as a round trip performed by a vehicle starting and ending at a depot, visiting a predefined sequence of points or clients. Here the depot can be a warehouse, port etc. depending on the application area, and the clients can be supermarkets, other warehouses or port. On the contrary, after a trip the end-location is not the same as the star-location.

An interesting finding by Hoff et al. (2010) is that there is a lack of literature on a tactical and strategic level possibly due to the increasing uncertainty over longer time windows which these strategic and tactical decision generally comprehend.

Hoff et al. (2010), state that for strategic fleet management decisions it usually does not make sense to include routing on a very detailed level, unless for cases where the transportation demand is highly predictable. But on the other hand, all the relevant revenue related aspects related to the acquisitions and operation of the fleet have to be included in detail. Relevant aspects are e.g the contract types to which the fleet can be acquired.

For tactical fleet management, uncertainty will tend to be less than on a strategic level as more information becomes available on the shorter time windows. The tactical decisions will be more on capacity adjustment, given an existing fleet which is determined on the strategic level. The decisions are for instance: which new vehicles to acquire on a more shorter term, e.g. lease or chartered in or out and how to deal with demand fluctuations. An important aspect on the tactical level is the decision which vehicles to deploy on which route according to a schedule and specific demand. Moreover there is a "dual" problem in the tactical level related to contract optimization whereby, given a set of contracts and the fleet, the question is on which contract to potentially bid on for future operations. Hence, Christiansen et al. (2007), Hoff et al. (2010) state that the combination of tactical fleet composition and contract optimization may prove beneficial and necessary.

The difference between strategic and tactical decisions is commonly based on the time over which these decisions have to be effective. In the comparison between land based and maritime fleet management by Hoff et al. (2010), it is stated that the time constants are generally longer for maritime transportation relative to land based transportation. Typically the planning horizon for tactical decisions in the maritime industry are somewhere between weeks and months.

On the operational level the transportation planning generally consists of selecting the specific set of vehicles to accommodate the daily transportation demand and to determine the specific daily or even minute-to-minute routes and schedules to accommodate the transportation demand (Hoff et al., 2010).

4.2. Maritime fleet planning

Maritime fleet planning is the exact application of combinatorial fleet sizing and composition for the maritime industry. Both Pantuso et al. (2014) and Christiansen et al. (2007) conducted surveys on the existing maritime fleet planning literature, whereby the latter focused on publications in the current millennium and the first broadens the scope to all publications on the subject. Dantzig and Fulkerson (1954) are commonly considered the pioneers in marine fleet size problems. Their iconic publication from 1954, addresses an OR approach to minimize the number of marine fuel oil tankers needed to guarantee a fixed set of schedules.

4.2.1. Differences between the maritime industry and other industries

The specific focus on the Maritime Fleet Size and Mix Problems (MFSMP) can be motivated by the significant differences between maritime vessels and the other modes of transportation. Pantuso et al. (2014) state that not only are there operational differences but the maritime industry also differs in for instance:

- a higher level of uncertainty
- a higher level of capital involved
- the vessel's value function

On the comparison between road and maritime transport, Hoff et al. (2010) adds that the biggest difference between maritime and road-based fleet planning is related to the scale. More specific the following differences are mentioned:

- vessels in maritime transport are bigger in size, while the number of vehicles in road-transport fleets are higher than in maritime fleets
- costs and revenues per vehicle are much lower for road-based transport
- even when considering the entire fleet, capital binding is much higher for the maritime industry
- the lead time for the maritime industry is much longer than for the automotive and truck industry and generally more comparable to the rail and aviation industry
- vessels are one-of-a-kind or client specific which is also the case for rail and aviation, while it is the contrary for the automotive and truck industry where there is more standardization
- the average lifetime of a vessel (decades) is much longer than for a truck (years)
- maintenance of a vessel takes longer, costs more and is less standardized compared to trucks

Regarding the modeling, maritime operations typically have a Pick-Up-and-Delivery structure with no depot, while road-based transportation usually has a Vehicle-Routing-Problem structure with a single depot and either pickups or deliveries only. Aforementioned differences between the modes, justify the need for different models for the modes (Hoff et al., 2010, Pantuso et al., 2014).

4.2.2. Basic Mathematical model for MFSMP

A general representation of the MFSMP in a mathematical model is presented by Pantuso et al. (2014). For these models the objective is commonly to minimize cost, an example of such an objective function for a basic case of MFSMP is provided in equation 4.1.

$$min \sum_{v \in V} C_v^F . y_v + \sum_{v \in V} \sum_{v \in R_v} C_{vr}^V . x_{vr} \tag{4.1}$$

Here V is the set of available vessel types and R_v is the set of routes which can be sailed by vessel v. Cost factors are included as C_v^F in the first term, which are the fixed costs to have vessel v in the fleet, and C_{vr}^V in the second term which are the variable cost to operate on route r with vessel v. The decision variables are y_v in the first term, or the number of vessels of type v to include in the fleet, and x_{vr} which represents the number of times route r will be sailed by vessel v in a given period.

For the feasibility of the model, constraints keep the decision variables within bounds. Constraints which are compatible with the objective function in equation 4.1 and keep track of the resources used, can be expressed as is done in equation 4.2. This constraint ensures that the time spent by the vessel to sail specific routes, Z_{vr}, is within the limits of total sailing time available given for instance the fleet size and available resources such as crew or fuel, Z.

$$\sum_{r \in R_v} Z_{vr} . x_{vr} - Z . y_v \leq 0, v \in V \tag{4.2}$$

Since MFSMPs often aim to align transportation demand with transportation supply coming from a fleet at minimal cost, constraints such as presented in equation 4.3 ensure that the demand is fully satisfied by the fleet. In this case it ensures that each port $i \in N$ is called at least D_i times during the planning horizon, whereby A_{ir} is set to 1 if the route is called and 0 otherwise. Subsequently vessels have to sail each route sufficiently to reach the demand by the ports D_i. If additionally to the frequency, the amount of goods or passengers to the various ports needs to be controlled, the constraint can be extended with Q_v which represents the capacity of vessel v for goods or passengers and let D_i be the demand of each port for goods or passengers. The equation can then be adapted to equation 4.4.

$$\sum_{v \in V} \sum_{r \in R_v} A_{ir}.x_{vr} \leq D_i, i \in N \tag{4.3}$$

$$\sum_{v \in V} \sum_{r \in R_v} A_{ir}.x_{vr}.Q_v \leq D_i, i \in N \tag{4.4}$$

Finally, Pantuso et al. (2014) mentions that the decision variables y_v and x_{vr} are restricted to take integer values. Depending on the application of MFSMP the variables may be more diverse and additional constraints can be added to the model. In the review on marine transportation in the current millennium by Christiansen et al. (2013), additional base models are provided to model the composition and deployment of vessel fleets for liner shipping. In these models it is also common to add the element of temporary outgoing vessels, for instance to markets with a temporary higher demand due to seasonal differences relative to the own market. In the objective function the revenue coming from chartered-out vessels are subtracted from the costs.

4.3. Maritime fleet planning in offshore wind O&M

Since this study focuses on the application of MFSMP for OTG, addressing literature in the field of MFSMP in the offshore wind industry, brings us closer to the core of this research. In the case wind turbines fail, in order to minimize loss production, the main cause of the failure has to be detected and repaired. In some cases the wind turbine components can be repaired on-site, but in other cases the components have to be taken to maintenance workshops off-site due to the lack of for instance material, tools and technicians on-site. The interesting question here is to determine the location, quantity and facilities of such maintenance accommodation sites (Besnard et al., 2013). These elements are also considered of significant interest for OTG, since OTG are also confronted with failures in a demanding offshore environment.

Based on the analysis for OWF by Shafiee (2015) it can be derived that the network of accommodation and workshop locations is dependent on:

1. the coverage of each maintenance accommodation or the location and number of platforms that are covered by each accommodation platform.
2. the distance and the associated travelling-time between the platforms and maintenance accommodation
3. the initial investment and operating cost of maintenance accommodation
4. the platform reliability which specifies the expected demand for repair

The review of research in the offshore wind industry by Shafiee (2015) has shown that little attention has been paid to the subject of maintenance accommodation location for OWF, let alone OTG. In the MSc thesis by De Regt (2012) this location problem of maintenance accommodation is presented as a "Weber" problem which minimizes the sum over the weighted distances to a given point. The scope was extended by Besnard et al. (2013) who not only looked at the location of accommodation in their mathematical model, but also the number of technicians, the choice of transfer vessels and the possibility of utilizing a helicopter. In the end the total model consists of an analysis of transportation strategy with different means of transportation, a queuing model for scheduling the maintenance activities, and an economic model for the maintenance support decisions (Besnard et al., 2013).

The maintenance support organization is an elementary part of the tactical operations of OWF (Besnard et al., 2013, Dewan, 2014). To execute the maintenance activities at OWF a certain number of specific vessels such as jack-up ships and crane ships are necessary for the transportation and replacement of components. Similarly, helicopters and/or work-boats are required to transport technicians to the site for the execution of the maintenance activities. These service ships and work-boats need to be allocated in sufficient numbers and with the necessary facilities on-board to enable timely and effective maintenance (Besnard et al., 2013).

In the overview by Besnard et al. (2013) it is stated that these maintenance support organizations and in particular the transport means for these maintenance support organizations have enjoyed a reasonable amount of research. Studies related to the aspects of transport means are for instance:

- A report published by Massachusetts Clean Energy Center (2017) which addresses the characteristics, capabilities, limitations and general availability of maintenance vessels to be used in the construction and maintenance of OWF
- Van de Pieterman et al. (2011) determined the optimum number of access vessels for an OWF consisting of 130 wind turbines in the Netherlands with a Fleet size model
- Gundegjerde and Halvorsen (2012) developed a stochastic optimization model to determine the optimal fleet size and composition for OWF. Here the optimal solution is determined based on factors such as: the failure rate of turbines, the charter rate of maritime vessels and helicopters, electricity prices and weather conditions
- In comparable work Halvorsen-Weare et al. (2013) proposed a model to determine the vessel fleet size for the maintenance activities of OWF. The studies by Dalgic et al. (2014), Joshi and Bolstad (2016), Stålhane et al. (2016), Zhang et al. (2014) also propose optimization models to determine the fleet size and composition for maintenance activities whereby the differences between the models is in e.g. the case the model is applied on, the inclusion of uncertainty and the inclusion of bases and transportation means such as vessels and helicopters
- A charter rate estimation model for jack-up vessels under various operational strategies, to complement the various MFSPM models aforementioned, proposed by Dalgic et al. (2013). Their model identified the most attractive charter periods among the jack-up vessels after which the seasonal influence on the charter rates was investigated
- McMillan et al. (2014) proposed a statistical forecasting method which targets the helicopter operations at OWF

Within the current body of literature on the logistic optimization for offshore industries, the share on offshore wind is thus extensive and continuing to grow. However, no literature could be found regarding the logistic optimization of the converter platforms in OTG networks. The following subsection will focus on the way uncertainty is addressed in the literature.

4.3.1. Uncertainty in MFSMP

The significant presence and impact of uncertainty in the offshore environment is underpinned in the work by Dalgic et al. (2014), Joshi and Bolstad (2016), Stålhane et al. (2016) and during the interviews with Algra (2017), Heinrich (2017a). However as stated by Dalgic et al. (2014), Fagerholt and Lindstad (2000), Hoff et al. (2010), Stålhane et al. (2016), Strømberg (2015) it is also one of the biggest challenges to include all sources of uncertainty in the models. The complexity of including uncertainty in MFSMP is also reflected in the limited amount of studies which take uncertainty into account sufficiently. Among the 37 publications reviewed by Pantuso et al. (2014), 27 articles deal with planning in a deterministic context. Of the 10 articles which do consider uncertainty, the majority does so by replacing parameter data with average or extreme values in otherwise deterministic models. This subsection will address how existing models in the field of MFSMP have addressed uncertainty.

Within the field of OR, stochastic programming (SP) and robust optimization are the most frequently applied to address uncertainty. Robust optimization considers uncertainty in deterministic means and sensitivity analysis is a means to determine to what extent optimal solutions would change if the base context data changes. The downside is that robust optimization still uses deterministic data and an uncertain future is not sufficiently taken into account in these models (Strømberg, 2015).

SP does take the uncertain future into account in the modelling, whereby its main premise is to model what might happen and how to handle each situation (Strømberg, 2015). According to Joshi and Bolstad (2016) SP can be traced back to 1955 when Dantzig introduced the recourse model on uncertainty in linear programming (Dantzig, 2010). SP can be characterized by: decisions made in discrete time steps, many potential values for decision variables and dealing with partially known distributions (Birge and Louveaux, 2011).

In the studies by Pantuso et al. (2015) and Pantuso (2014) a SP model is presented for the maritime fleet renewal problem, with the aim to investigate whether SP leads to better results than a deterministic model with average data. In the end the study did show better results for the SP model.

In the study on optimal policies for the operation of OSV fleets, Fagerholt and Lindstad (2000) accounted for uncertainty by including various scenarios in a robust optimization approach, e.g. on the operating hours of offshore installation and the minimum weekly visits required per offshore installation. This study was one of the first in the field of offshore supply operations, but the focus was more on the routing aspects of OSV, rather than the fleet compositions issues.

The approach deemed as most optimal by Pantuso et al. (2015) is applied for MFSMPs by Gundegjerde and Halvorsen (2012), Gundegjerde et al. (2015), Joshi and Bolstad (2016), Strømberg (2015) and Stålhane et al. (2016) in the form of multi-stage stochastic programming, often using a node formulation or scenario trees.

Another approach to cope with uncertainty is the use of simulation, hereby warranting for robustness to uncertain aspects such as weather (Strømberg, 2015). The simulation approach is applied for MFSMP by Halvorsen-Weare et al. (2012) where a significant role was also set apart for the routing aspect. The aim is to determine the optimal fleet composition of OSV and the associated optimal schedule for the weekly voyages or tours. For this supply vessel planning problem, comparable to a vehicle routing problem, the simulation approach consisted of a two-staged voyaged based model. In the first stage all candidate voyages are generated and in the second stage the voyage based model is solved with all the generated voyages from the first phase (Halvorsen-Weare et al., 2012). Fagerholt et al. (2010) also consider a similar approach whereby the strengths and weaknesses of optimization and simulation should balance each other out. Hereby they present a Monte Carlo simulation framework built around a short-term optimization model for decision support. The Monte Carlo simulation simulates the uncertainty in the parameters. A setback of this method is that it is not efficient in cases with a high variety of alternative fleets.

4.4. Combinatorial Optimization

The fleet optimization problem addressed in this thesis can be categorized as a combinatorial problem within the field of discrete optimization. This means that the solution space of the problem is a finite and discrete, but large, solution space whereby the decision variables take discrete values.

4.4.1. What is Combinatorial Optimization?

As previously mentioned the solution space of combinatorial problems is a discrete, finite, but big solution space. According to Papadimitriou and Steiglitz (1998) Combinatorial Optimization (CO) can be described as a form of discrete optimization which combines aspects from the field of combinatorics such as sets, subsets, combinations and permutations. The basic problem of combinatorics can be described as counting the number of elements in a finite set (Stanley, 1986). In addition, aspects from Graph Theory such as vertices, edges, paths, cycles and cuts are relevant for the field of CO.

The Travelling Salesman Problem (TSP) is one of the most famous problems within the field of CO. Moreover Scheduling and Timetable Problems are famous fields in which CO has a significant role. In their book, Lawler et al. (1985) present an extensive tour through the field of CO in its early days, applied on the TSP.

4.4.2. Solving Methods for Combinatorial Optimization

To solve problems in CO, the approaches can roughly be distinguished in two main categories:

1. The exact, complete or exhaustive algorithms: this approach searches the entire solution space and is guaranteed to find the optimal solution for a finite CO problem instance within bounded time (Papadimitriou and Steiglitz, 1998). Branch-and-Bound techniques fall under this category.
2. The approximate search methods: this line of solving approaches searches selected areas of the solution space. Under the approximate search methods, a distinction can be made between:

(a) constructive methods: solutions are generated from scratch, by adding elements to a partial solution, until a complete solution is established. The constructive algorithms are generally known as the faster algorithms, however solutions are generated of lower quality, relative to the local search methods.

(b) local search methods: starting from an initial solution the local search algorithm iteratively replaces the initial solution with improved solutions, found by structurally exploring the neighbourhood of the current solution.

(c) meta-heuristics: this is a new type of approximate search methods which tries to combine the previously mentioned basis heuristic methods on higher level search strategies in order to efficiently and effectively search the solution space. These metaheuristics include, but are not limited to, algorithms such as: Ant Colony Optimization, Evolutionary Computation, Genetic Algorithms, Iterated Local Search, Simulated Annealling and Tabu Search.

For the distinction between these search strategies, diversification and intensification are essential. The term diversification generally refers to the exploration of the solution space, whereas intensification refers to the exploration of the accumulated solution experience. Alliteratively the difference can be described as follows, diversification refers to the process of finding feasible solutions, while intensification refers to the process of proofing the optimality of already found feasible solutions.

Which solving algorithm is used depends on the goals which are aimed to be realized with the model, but also on the nature of the problem. Within CO, problems can be distinguished in NP-complete and NP-hard problems (Blum and Roli, 2003).

For NP-hard problems, no complete algorithms exist which can guarantee finding the optimal solution in polynomial time and exponential time would be necessary to find an optimal solution. Hence, for the feasibility, in terms of practical solving time, for NP-hard problems it is necessary to shift to the approximate algorithms. The trade-off between the exact and approximate methods is thus the sacrifice of finding the optimal solution, for the sake of finding good solutions in a significantly reduced amount of time (Blum and Roli, 2003).

4.5. Chapter Conclusion

Based on the challenges faced in the planning and execution of logistics for the operation and maintenance of OTG discussed in chapter 3 and 2, this chapter provided an overview of OR literature which tackles these challenges of fleet composition for other industries and and the maritime or offshore industry. After the literature study it can be stated that no application of MFSMP research exists for OTG and this forms a gap in literature. Hence, this study aims to develop and utilize MFSMP research for OTG. With the challenges for the OTG and the theoretical basis in this chapter in the development of models for MFSMP, the next chapter will elaborate on the development of the OptiFleet model for strategic OTG MFSMP.

5

Model Development

The model development is the subject which will be discussed in this chapter. Starting with the process model, an overview is provided of how the processes and activities around offshore platform O&M can be conceptually modelled. These processes and activities are subsequently incorporated in the model flow diagram, a schematic overview of the model components and its functioning. Finally, the various model modules and the mathematical model behind the MFSMP model called OptiFleet are elaborated.

5.1. Processes and activities in offshore substation platform O&M

In figure 5.1 the conceptual O&M transport process model is depicted, providing an overview on the activities and processes taking place in the O&M of offshore substation platforms. The aim of this overview is to improve the understanding of the reader for the processes which will be incorporated in OptiFleet.

The envisioned system surrounding the offshore logistics of substation platform O&M consists of several subsystems which together contribute towards the execution of reliable O&M in an cost efficient manner. This conceptual model can be presented after numerous interviews with logistic staff at TenneT Offshore GmbH, TenneT TSO B.V. and stakeholders in the maritime manufacturing industry.

The first system to address as the start of the decision process flow, is the O&M Planning System (OMPS) for the OTG. This system consist of the substation platforms and the relevant output for this study is the demand for maintenance activities coming from the platforms. The maintenance activities are required to prevent and fix failures occurring on platforms to maintain the operability of the platforms. This is discussed in more detail in section 3.2.

The maintenance demand generated by the platforms, has to be scheduled and planned in terms of date and necessary resources, and this is all done in the OMPS. To enable O&M planning, the information flow is of particular importance. Specifically the OMPS requires continuous provision of information on the availability of resources for the execution of maintenance. Resources for maintenance are broadly put, skilled technicians to conduct the activities and supporting crew, but also tools and spare-parts for the execution of maintenance.

The planning of maintenance, is to be followed by the execution of maintenance activities. For that to be possible, logistic and transportation services by means of maritime or airborne vessels are necessary. The planning of these logistic and transportation services are covered in the next sub-system, namely the Marine Dispatch Center (MDC). What the MDC does is essentially line up maintenance demand with available vessel and base capacity on an operational level. This results in a "maintenance transport dispatch plan" or MTDP. The MTDP consists of the following elements:

- **A pick-up and delivery schedule** which entails when the pick-up, transportation and delivery of crew and cargo should take place. The schedule includes the crew and cargo quantity needed to be transferred per platform.

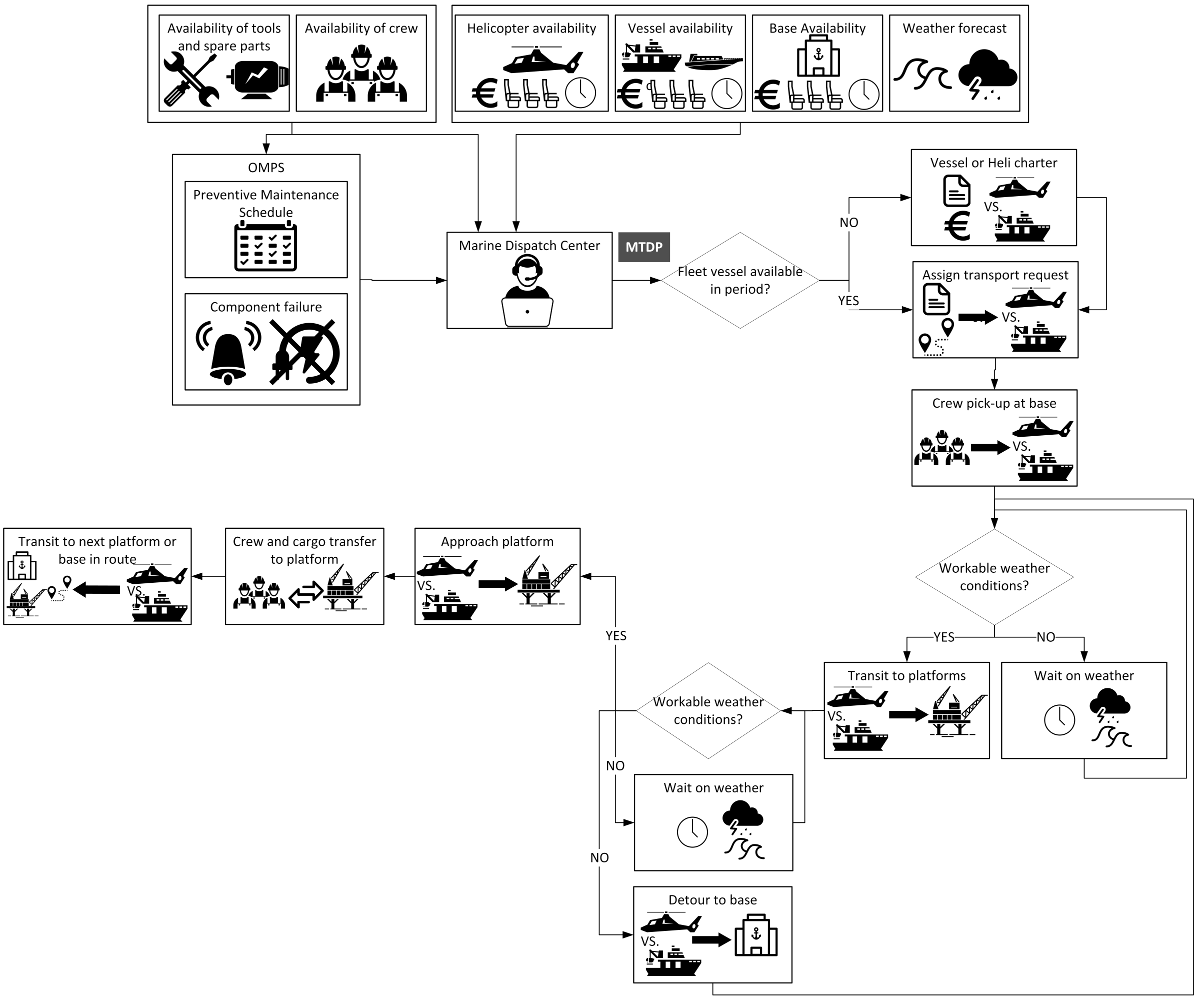


Figure 5.1: Conceptual processes behind the fleet operation for O&M of substation platforms

- **A sailing route** for the vessel to execute the maintenance schedule. If the schedule is generated with the demand of several platforms to be serviced within a certain period, the route takes this into account and includes a sequence of platform visits to minimize costs by consolidating transport volumes.
- **An allocation of a vessel or helicopter** to execute the generated route according to the schedule. This vessel allocation thus creates a transportation order for a specific vessel which can handle the distance of the platforms to be serviced, the expected weather conditions and the crew and cargo to be transferred. Note that the system should also be able to include a helicopter. It may be that the use of a helicopter is namely more economic, or plainly necessary for instance in the case of skilled labor, irregularities such as an emergency or in the case of persistent bad weather not allowing for crew access through the use of boats.

In order to produce the MTDP, the system requires embedded policies and ample data provision. The three fundamental policies, behind the MTDP are:

- **Demand based routing policy:** this entails that the system determines the transportation dispatch, vessel choice and routing, based on the O&M demand coming from the platforms. This to ensure that the service is fitted to the specific demand per platform.
- **Weather policy:** this entails that the weather conditions are taken into account when generating the MTDP. As mentioned in section 2.4, the weather, with respect to waves, visibility and precipitation, has a great impact on offshore vessel operations. This information on the weather, together with the vessel operational specifications, are used to determine whether vessels can sail and the transportation can proceed. After receiving the initial execution dates of maintenance from OMPS, the MDC can de-

cide to execute the activities if the weather allows for it. If the weather does not allow the operations, these can be rescheduled, by either postponing to wait for better weather or bringing the maintenance forward when the weather is acceptable and the resources, technicians and parts, for the execution of the maintenance activities are available. For this, a link has to be established with channels to receive meteorological data for the periods during which maintenance is planned, by the OMPS.

- **Vessel, helicopter and base availability policy:** in order to come up with a transportation schedule which is executable, it is necessary to know the availability of vessels, bases and helicopters either owned and operated by the client company or available for lease by third parties. This with regards to the time windows that vessels are available, or will become available, and operational characteristics such as: 1) the weather conditions under which the vessel can operate, 2) the fuel usage of the vessel and 3) the facilities on the vessel as specific clients may have specific wishes. For the MDC it is thus necessary to obtain information through links with the vessel market and the base market on the availability of vessels and bases on the market.

The information on the availability of transport means, the maintenance schedule and weather conditions form the input for the MDC to decides which vessel or helicopter should be allocated to support the O&M activities. The MDC allocates a vessel or helicopter which is operated through the TSO fleet, thus vessels on long-term (longer than 1 year) contracts, or short-term (1 day up to a month) charter contracts if those vessels are available and up to the weather conditions and requirements for the amount of crew and cargo. In the latter case, the MDC charters transport means on the spot market. Note that the choice for a short-term charter is only made if vessels are not available in the TSO fleet, for instance if all vessels in the long-term fleet are out on campaigns. To elaborate on this statement, for instance if a trip is required at two platforms near each other, the system will determine if the two platforms can be visited in one trip. Subsequently, MDC will determine if this is possible given the availability of the long-term vessels in the fleet. If this is not the case MDC will consider the possibility to charter a short-term vessel for that specific combination trip. The last option of a combined visit with a short-term vessel will only be proposed if this option yields lower costs compared to 1) the combined trip with a long-term vessel, but at a later or earlier time when the long-term vessel is available, or 2) the individual visit of the two platforms with the long-term vessel according to the availability if the long-term vessels. However, this depends on the necessity to conduct maintenance, which places constraints on the flexibility to postpone the execution of maintenance. Finally, as part of the transport mean allocation, the transport request is assigned to the chosen means of transportation.

The vessel or helicopter can subsequently proceed to pick-up the technicians and cargo at the port according to the pick-up and delivery schedule. After crew pick-up, the vessel or helicopter commences with the voyage towards the platforms according to the defined route and schedule. Having mentioned the operational policies, one of the most important requirements is with respect to the real-time monitoring of the data sources required for the operational policies. This is required to generate up to date MTDP which are convenient, agile and fast in reacting to to changing weather, demand or transport mean availability. For instance if during the trip the weather conditions change in such a way that normal vessel operation and platform access are not possible anymore, real-time route adjustments should be made. This route update can also be seen in figure 5.1. If en-route the vessel encounters unexpected bad weather conditions, affecting or preventing the vessel to sail or for platform access to be provided to the crew, the system considers several options:

- **Wait on weather:** In this case the vessel is ordered to wait on the weather to reach operable or workable conditions again before approaching the platform. This would be the choice if it is expected that the weather will clear up within the same weather window.
- **Detour to base:** In this case, usually when the weather is expected to remain bad for a period > 2 hours, the vessel is ordered to reroute towards a base for the temporary accommodation of crew. In the meanwhile the vessel could be utilized to service other areas with better weather conditions. This thus leads to maximum vessel utilization while the crew subject to crew change at a location under heavy weather is already offshore and close to the platform requiring maintenance, taking little time to get them to the platforms once the conditions improve.

An interesting aspect in the process of platform approach by the vessel to perform the crew change under specific weather conditions, is the crew change access method applicable on the specific vessel. Vessels equipped with "walk-to-work" systems can proceed with the crew change under more extreme weather conditions, while guaranteeing a safe and comfortable crew change. This compared to vessels applying alternative crane based access methods such as swing-roping. The type of access technology present on the vessel is thus a factor which should be taken into account already during the vessel allocation, to determine detailed crew change details and allowable weather changes.

If the weather and other conditions are within the operational conditions of the vessel and the safety regulation for the crew access, the vessel approaches the platform according to predefined offshore marine operational protocols. Once at the platform the delivery of the crew and cargo can take place and once the transfer is finished, the vessel can proceed with its route, either to other platforms or back to the base. Of course, when the system proposes a helicopter, the process is different compared to the use of vessels. The difference is not necessarily in the type and sequence of processes which occur, for instance both the vessel and helicopter need to pick-up crew, transport crew and deliver crew. The differences are for instance in the field of:

- **Geography:** vessels and helicopters operate from different type of facilities which may be at different locations.
- **Operational activities:** Vessels sail according to specific sailing routes which may have to be redirected around e.g. defence area's or area's with wind turbines. While helicopters also have defined routes, however these are more straight lined as they can fly over e.g. fishing areas.
- **Weather:** helicopters can operate under more extreme weather conditions than vessels.
- **Access type:** Vessels require extra equipment to provide the access, such as cranes on the platform for basket transfer or gangway systems, this also takes time. Helicopters do need a helipad on the platforms, however once landed, the access takes place quite fast.
- **Safety regulations:** helicopters and vessels operate under different regulatory frameworks, namely that of marine operations, on the one hand, and aviation on the other hand. Aviation regulation are not only different, but also more strict.

The aforementioned differences lead to varying attractiveness of the various options, depending on the case at hand. For instance in the case of irregular crew change, these are the specific crew-changes outside the standard periodical crew-change schedules consisting of for instance specially skilled engineers or technicians, a helicopter with its speed and flexibility may be the more attractive option. These differences and specific cases are taken into account in the model for when the choice has to be made between deploying boats or helicopters.

This process model is subsequently incorporated in the model flow diagram in section 5.3. But first in section 5.2 the different decisions that have to be made in the MFSMP model are discussed, including the respective levels they can be categorized in.

5.2. Levels of decision making in OptiFleet

In the proposed OptiFleet model, decisions are made on two-levels, namely the strategic and tactical level as is depicted in figure 5.2. With this distinction, the decisions made on the strategic level are assessed on their effectiveness by the tactical elements included.

On the strategic level, the decisions target a time-scale of between one and 20 years. In this strategic echelon the model determines which bases will facilitate the operations and which vessels will be used for the planning horizon of 20 years. Furthermore, the decision is made on how many of each vessel type should be included in the fleet via long-term leasing contracts. The aim of the strategic decisions are, in short, to establish a competent fleet at the lowest costs.

After the strategic level, decisions are made on a tactical level. These tactical decisions are made on a daily or weekly basis. In the optimization model, these tactical decisions enable the assessment of the strategic decision's quality. Essentially, in the tactical echelon, decisions are modeled which should lead to an optimal deployment of the fleet constituted in the strategic level. Hereby, by all means, this should occur in a way that the O&M needs are adequately satisfied. Hence, in the tactical level it will be determined which O&M activities should be supported with which vessel and from which base. For this allocation of vessel and base for a maintenance activity, the tactical level considers aspects such as: 1) the distance from base to the platforms and 2) the cost for the vessels and bases.

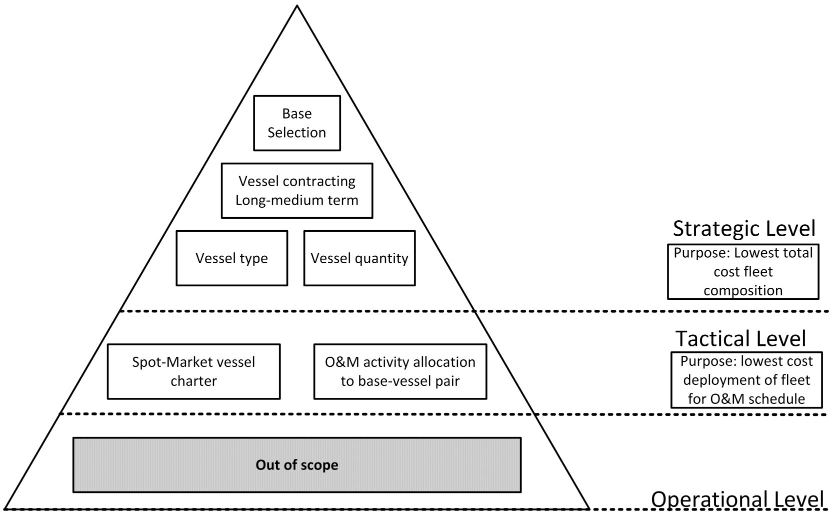


Figure 5.2: Schematic overview of the strategic and tactical decisions

The tactical assessment of the strategic decisions can be illustrated with the following example: when the strategic fleet planning results in a fleet with insufficient vessel capacity at a certain point in the planning horizon, e.g. an unexpected peak in platform failures, a tactical decisions is to acquire short-term vessels from the spot-market and execute the maintenance schedule as necessary.

Section 5.3 elaborates on how these decisions can be modelled and output can be generated on the optimal long-term fleet.

5.3. Model flow diagram

The center-piece of this study, is an optimization model addressing the fleet size and mix problem for an offshore substation platform network. However, this optimization model, called OptiFleet, is not the sole subject of this study. This optimization model is namely surrounded and supported by various modules which provide the optimization model of input with respect to the decision variables, but also the constraints. The modules provide structure to the modelling framework and provide a means to keep track of the information flow. The distinction in modules provides the flexibility to develop the model in components whereby simplifications and adjustments can be applied per component in a controlled manner. The division in modules is based on the findings regarding current logistics planning and the associated information flows at TSO TenneT. In addition, inspiration is drawn from the studies by Joshi and Bolstad (2016) and Gundegjerde and Halvorsen (2012).

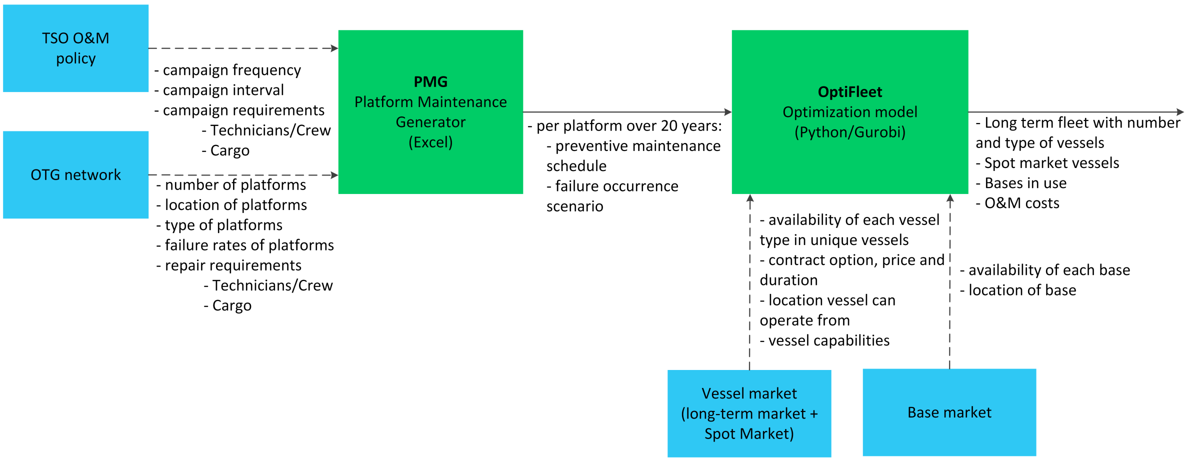


Figure 5.3: Schematic model process flow

In figure 5.3 a schematic overview of the model process flow is depicted. In this figure a distinction can be noticed between the modules, namely on the one hand, represented with the blue boxes are the data modules and in the green boxes the computational modules. The overall model thus consists of two computational modules, complemented with four data modules.

The data modules are providing the computational modules of input, see the dashed arrows. This input establishes the environment for the computational modules to execute calculations and yield results which contribute towards an efficient and effective fleet. The data modules are:

- **TSO O&M policy**: this module sets the value for the model parameters related to the characteristics of maintenance planning according to the policy of the TSO or the organization under study. TSO O&M policy targets parameters such as: 1) the frequency of maintenance on platforms which can be derived from the organization's risk assessments, and 2) the requirements for the transport and accommodation of technicians and cargo required for the maintenance activities, based on for instance the organization's safety culture.
- **OTG network**: the OTG network module provides data on the network of offshore platforms which are included in the case. The data addresses: 1) the number of platforms and their location, 2) the type of platforms and what failure rate is associated to the platforms and 3) requirements for technicians and cargo.
- **the vessel market**: the vessel market module contains data regarding the vessels (helicopters and ships) which are available on the market and can be acquired to execute the O&M activities on the given OTG network. The data is addressing various aspects of the vessels such as: 1) the contract under which they can be acquired, containing information on e.g. remuneration and the length of the lease agreement, 2) which type of vessels are available in terms of their operational characteristics, such as pax capacity, operable weather conditions, speed and fuel consumption, and 3) the location or ports these vessels may operate from.
- **the base market**: this data module is comparable to the vessel market module, but instead of vessels it provides data on the availability of bases.

The computational modules are characterized by computational functionality which make the model fit for use, namely provide strategic decision making support on the vessel fleet size and mix. The incorporated computational modules are:

- **PMG**: The Platform Maintenance Generator (PMG) creates the base demand for transportation services which have to be provided by the fleet. This is done by generating maintenance schedules. These maintenance schedules are generated from data coming in from the "OTG network" and "TSO O&M policy" data modules. More on how the PMG works can be found in section 5.4.
- **OptiFleet**: the OptiFleet optimization model is the component which, based on the base maintenance demand from the PMG, will determine which vessel fleet fits best with which maintenance scheme, leading to the lowest costs. The mathematical model behind OptiFleet and other aspects related to model development and implementation are discussed in section 5.6 and onward in this chapter.

After discussing the model flow diagram, the next section will discuss the PMG on how maintenance demand can be modelled, in more depth.

5.4. Modelling Maintenance Operations: PMG

As mentioned before the maintenance activities come down to preventive and corrective maintenance. The maintenance generator module is responsible for the generation of maintenance demand and this maintenance demand is the input for the optimization model to derive the fleet to handle this demand. Each platform within the case under study requires both preventive and corrective maintenance tasks to be executed, hence the maintenance generator creates both a demand for corrective and preventive maintenance. In the sub-sections below it will be discussed in which manner the maintenance demand is generated. Ultimately, how these activities can be included in the mathematical model is aimed to be described in this section.

5.4.1. Preventive maintenance activity generator

The activities in the category of preventive maintenance are assumed to be known in advance as they are usually also planned in advance, e.g. in the planning horizon prior to the operational year. Based on for instance the historic data it can be determined how often components have to be subject to preventive maintenance in order to prevent failures and prolong the lifetime of platforms. Furthermore, preventive maintenance is modelled as campaigns, whereby each campaign consists of several maintenance activities and is characterized by specific needs for: 1) number and type of maintenance technicians, 2) time required to conduct the campaign and the associated downtime, and 3) lifting capacity and deck space for tools and equipment required to execute the maintenance. For the strategic level of decision making supported by this model, the separate maintenance activities will be addressed, not individually, but as part of the campaign. These maintenance campaigns are common practice in the offshore wind sector, but also in the offshore oil&gas industry (Holst and Nystad, 2007, Liyanage, 2008, Sperstad et al., 2016).

Preventive maintenance is assumed to be only dependant on the amount and type of platforms. However, the variety in the type of platforms can significantly impact the maintenance needs as different platforms may require different maintenance activities with varying requirements for technicians, cargo and repair-time. A significant difference exists between cases with heterogeneous platforms (e.g. the Netherlands) and heterogeneous platforms (e.g. Germany).

The number of platforms directly influence the total demand for maintenance but also imply uncertainty in the demand on the long term. As the planning horizon of this study is 20 years, it is possible that within that horizon new platforms are added and existing platforms are decommissioned. Hence, this includes some uncertainty in the demand for preventive maintenance to be handled by the fleet within the planning-horizon.

For the platforms included in the model, various parameters are available to construct preventive maintenance schedules according to the policies of the TSO to which the model is applied. These parameters are:

- f_c: campaign frequency, this is how often a certain campaign should be executed during an operational year per platform.
- l_c: length of campaigns, this is the amount of time a campaign takes to be conducted, measured in days. The campaign length can be different for each campaign and also between platforms variety may exist.
- g_c: minimum gap between campaigns, this is a requirement which may be enabled for maintenance campaigns regarding the time separation between campaigns.

The procedure to generate the demand of preventive maintenance is as follows:

1. identify the required number and type of campaigns including their requirements for resources such as time, technicians and cargo, for each platform.
2. fill in the parameter values, f_c, l_c and g_c, for the scheduling of the campaigns for each platform.
3. assign each campaign to a starting date and based on the duration of the campaign, a sequence of time-periods (days), from start date to end date, is associated to each campaign. For this assignment, in addition to the campaign length, constraints also are in place for the interval between campaigns. It is important to mention that the campaigns are assigned for the season of summer and autumn, this coincides with the months of June, July, August, September, October, November and December in the Northern hemisphere. The motivation behind this assignment is based on the fact that wind-conditions for the generation of wind energy are ideal during the winter and spring, meaning that it is not desired to conduct maintenance and hence shut down platforms during these peak production seasons Wolfsturm (2017a). In section 5.5 it is explained how such campaign scheduling can occur.

After the plan for preventive maintenance is established in the planning horizon prior to the operational year, the plan can be executed in the operational year. However, due to the influence of external factors such as weather, waiting time on spare parts and the availability of technicians and transportation, the actual execution may deviate from the initial planning. Certain activities will take place according to the planning, while other activities may have to be postponed, take longer than planned or moved earlier than planned, however at all times it will occur within the specific operational year.

5.4.2. Corrective maintenance activity generator

On the contrary to preventive maintenance, the necessity for corrective maintenance is not known in advance. This necessity depends on the occurrence of failures and this is uncertain. For each platform, based on historic information, failure rates (R^f_{ai}) can be derived and with these failure rates, various failure scenarios can be constructed.

The likelihood of a specific failure scenario is not only dependant on the type of platform technology used, but also the policy regarding the preventive maintenance of the platforms. In figure 3.1, it could be seen that with decreasing efforts in preventive maintenance, the cost for corrective maintenance increases as the likelihood for failures to occur increases. It should be noted, that this relation between preventive and corrective maintenance will be taken into account. However, maintenance planning to the extent of detail where the scheduling is according to the cost minimization function, will be largely omitted as the study's focus is on supporting fleet size and mix decisions. Within this fleet size and mix model, the fleet solutions will mainly be tested on robustness to different scenarios addressing different demands for preventive and corrective maintenance, based on different trade-offs between these two types of maintenance activities. For instance a higher frequency of preventive maintenance directly influences the likelihood of the occurrence of a failure.

In reality there is a high variety in failures which can occur on a substation platform. This variety is the consequence of the different type of components on a platform, but also the possibility that parts and components are different between platforms. To simplify the modelling of the failure occurrence, the failure rates are aggregated to a platform level, rather than component level. On the strategic level in which the model features, the platform failure rate is assumed sufficient, as it represents the necessary input for the model to establish a fleet of vessels on a strategic level, with outreach to tactical uncertainty. The aggregated failure types are modelled in three classes, the three classes aim to represent the variety in failure types which impact on the need for resources. In other words, the three failure categories have different requirements for technicians, time to repair and cargo. The three categories of failures can be ranked from small to large, whereby the ranking is based on the amount of resources required. Furthermore the bigger, high-impact failures, of for instance a transformer, are rare. This subsequently implies that their failure rate is lower than for the smaller, low-impact, failures of for instance a switch or component associated to accommodation facilities rather than the converter circuit. The three categories of failure are: high-impact failures, medium-impact failures and small-impact failures.

For the maintenance generator to generate a demand for corrective maintenance, failures have to be simulated by means of the failure rate. This failure rate can be derived from Failure Mode, Effects and Criticality Analysis (FMECA) or Fault Tree Analysis (FTA) on the platform and their components. In addition to the operator of the transmission platforms, e.g. TenneT, these studies are produced by the manufacturers of the transmission platforms, parties such as ABB, Siemens and GE are relevant here.

The failure rate for each failure type a for platform i is R^f_{ia} and a number between 0 and 1. To generate the failure scenarios, the maintenance generator draws a number between 0 and 1 from a uniform distribution for each platform, failure type and time-period combination. If this number is smaller or equal to the R^f_{ia} the failure parameter is set to 1 and a failure of the corresponding type thus occurs for the platform f in the time-period p.

Once the failure variable is activated, the failure is linked to the required maintenance and a time-window is provided in which the repair should be conducted. The time-window is a sequence of days, starting from the day the failure occurred, to the day the repair is finished, or start period + repair_time in days.

5.5. Scheduling of O&M activities

In this section it will be discussed how the aforementioned maintenance activities, as a result of either preventive or corrective interventions, can be scheduled in time-windows over time. This information is relevant to generate routes which are at the basis of fleet composition decisions.

The planning and execution of both preventive and corrective maintenance activities is at the basis of the routes which have to be sailed by vessels or flown by helicopters. Not only does this maintenance planning and execution determine the routes of platforms visited during each journey, that is platform visits in a particular sequence, it also determines at which time these platforms need to be visited, how long each visit takes and what is delivered and picked up during each visit.

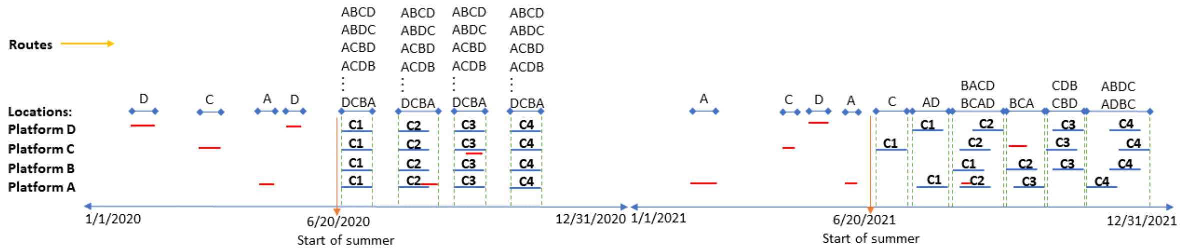


Figure 5.4: Scheduling of maintenance activities over platform A, B, C and D in 2020 and 2021

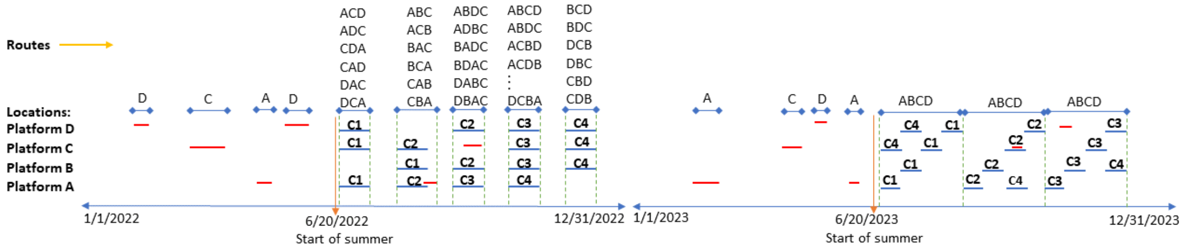


Figure 5.5: Scheduling of maintenance activities over platform A, B, C and D in 2022 and 2023

To explain this aspect, figure 5.4 and 5.5 exhibits some strategies on how the campaigns for preventive maintenance can be scheduled over a year. The example is for an instance with 4 platforms, platform A, B, C and D, and spread over 4 years. Assuming there are 4 preventive maintenance campaigns per year per platform, each taking two weeks. Preventive maintenance campaigns are indicated with the blue lines, while the red lines represent the execution of corrective maintenance as an result of failures. This example is comparable to maintenance strategies considered at TenneT and therefore, in this example, preventive maintenance is scheduled only for the summer and autumn months. The reasoning behind this choice lies in the fact that wind conditions are best during winter and spring, hence maintenance with associated downtime of the platforms would lead to higher production losses for the wind generators in winter and spring, compared to summer and autumn. On the other hand, due to the same reasoning, wind farm operators also desire to conduct maintenance during these summer and autumn months and this leads to a high demand for vessels and other material, which equals high cost on the spot-market. A prerequisite for successful execution of this summer-autumn strategy is that vessels are contracted timely on mid- to long term contracts, in order to guarantee vessel availability at low costs.

The example starts with the year 2020 and the preventive maintenance campaigns start in summer and continue in autumn. The 2020 strategy can be described as an approach which has very little coordination between maintenance planning and platform location, the start date for each campaign is the same for all platforms. For 2021 the coordination is even less, however there is more variance in the temporal planning, e.g. the start dates are not the same for platforms. These schedules are realized in a way where for each platform the maintenance is planned more or less independently from the other platforms and randomly spread over the 24-week period from summer to winter. The logistic strategy would have to be determined on a per platform basis, in a more reactive way and consolidating where the planning allows that. For instance in 2021, campaign 2 and 3 (C2 and C3) for platform A and B respectively can be combined in trips, while this is also possible for campaign 4 of all platforms in 2021. Above each campaign combination column, it is noted through which routes, platform sequences, that can be done. For 2020 much more routes are possible since the planned commencement of each campaign is on the same date. In 2021, the platform schedules possess much more temporal variation, different starting dates, and this limits the possibilities to combine logistics for platforms within a campaign column. These operations could be carried out with helicopters, CTV and PSV from an onshore base (port). In this strategy there is insufficient coherence between the platform schedules to consolidate transportation on OSV type of vessels. The planning for 2022 is comparable to that of 2021, but with more temporal variance in the distribution of the campaigns over time. It does share the characteristic of campaigns within the same 2-week block with the same start-time. Hence, also in 2022 many route options are possible as can be seen and the means of transportation would be in the same trend as 2020.

The maintenance schedule for 2023 provides an idea of how integrated planning could look like. This is planning integration of logistics and maintenance. The campaigns are planned in such a way that the end of a campaign for one platform, indicates the start of the campaign for the next platform. In this way logistics can be consolidated and multi-purpose accommodation vessels concepts like OSVs, where the vessel sets of from shore and cycles around the platforms to subsequently execute the campaigns at platforms, become attractive. From the mother vessel, daughter vessels e.g. CTVs can make trips to e.g. platform C, while the mother-vessel is at platform A for the execution of campaign 1 at platform A and campaign 4 at platform C, simultaneously.

In the strategic MFSMP model, the aim is to propose the optimal maritime fleet for the execution of long term maintenance and operations at the transmission platforms. This means that from the maintenance strategy, the maintenance planning and subsequent routes need to be satisfied by this long term fleet. As stated by Christiansen et al. (2007) it is not necessary to include the operational and detailed vessel routes in strategic MFSMP models. Consequently, the study does not include operational routes in detail either. The relevant aspects considered are: 1) the sequence of platform visits in platform clusters, 3) the maintenance campaigns in the journey, determining the vessel need and 3) the time platform visits need. Together these aspects form the characteristics of journeys and these journeys are aggregated to a long term picture. This long term picture, for instance over 20 years, entails the journeys required to satisfy maintenance demand of platform clusters and how often these journeys have to be sailed or flown. In the following section it is discussed how the vessels can be matched to the long term journey needs by means of the mathematical model.

5.6. Deterministic Mathematical model for OptiFleet

The mathematical model presented in this section forms the fundament of the OptiFleet model and will be implemented in a computer model for strategic MFSMP for OTG. All aspects regarding maintenance activities and the selection of vessels to support this maintenance discussed in the previous sections, are synthesized in the mathematical model. The model decision variables, objective function and the constraints to which these are subject to, are presented.

5.6.1. Indices

v	vessel or helicopter type
k	contract type for the medium- and long-term arrangements
s	contract type for the spot-market
b	base or port
f	offshore transmission platform
m	maintenance activity
p	period in the 20-year model planning horizon

5.6.2. Sets

V	set of vessel types, where each vessel type is linked to specific characteristics, $V : \{1, ..., \lvert V \rvert\}$
V^{mfs}	set of vessel types compatible with maintenance activity m at platform f, where $V^{mfs} \subseteq V$
V^{b}	set of vessel types compatible with base b, where $V^{b} \subseteq V, \quad \forall \text{b} \in B$
K	set of medium- and long-term contracts to acquire vessels

S	set of short-term contracts to acquire vessels from the spot-market
B	set of all bases, where each base is linked to its specific characteristics, $B:\{1,...,\lvert B\rvert\}$
F	set of all offshore transmission platforms, $F:\{1,...,\lvert F\rvert\}$
M	set of all maintenance activities to be executed, $M:\{1,...,\lvert M\rvert\}$
M_{fp}^{prev}	set of all preventive maintenance activities to be executed at platform f in year p, where $M_{fp}^{prev} \subseteq M$
M_{fp}^{corr}	set of all corrective maintenance activities to be executed at platform f in year p, where $M_{fp}^{corr} \subseteq M$
P	set of all time periods, years, in the given planning horizon, where $p_0 \in P$ is the first year and $p_e \in P$ is the last year in the planning horizon, $P:\{1,...,\lvert P\rvert\}$

5.6.3. Parameters

Cost parameters

C_{bp}^{FB}	Fixed cost for using base b during period p in [€/$period$]
C_{vkp}^{FV}	Fixed cost for acquiring vessel type v in the fleet on contract k in year p in [€/$period$]
C_{vs}^{DV}	Day-rate charter cost for a vessel of type v from the spot-market on contract s in period p, in [€/day]
C_v^O	Operational cost for vessel type v over 1-hour of operation in [€/$hour$]
C^S	Salary cost per crew member for every hour the employee is en-route in [€/$crew$/$hour$]
C_v^A	Accommodation cost per crew member per day when using vessel of type v in [€/$crew$/day]

Maintenance need parameters

$T_{mf}^{o\&m}$	The duration for maintenance activity m at platform f in $[days]$
$F_{mfp}^{o\&m}$	The frequency of maintenance activity m at platform f in period p, in $[frequency/period]$
$P_{mf}^{o\&m}$	The number of crew/technicians required to execute activity m at platform f, in $[crew]$
$L_{mf}^{o\&m}$	The lifting capacity required to execute activity m at platform f, in $[MT]$
$S_{mf}^{o\&m}$	The deck-space required for cargo transport to execute activity m at platform f, in $[m^2]$
$Z_{vbmfp}^{o\&m}$	number of trips vessel of type v needs to make to execute activity m at platform f from base b in year p, based on the maintenance requirements, relative to the vessel capabilities, in $[trips/activity]$

Vessel and base characteristics

R_v	The range of vessel type v per journey in $[NM]$
P_v	People/crew accommodation capacity of vessel type v, $[pax]$
L_v	The lifting capacity of vessel type v in $[MT]$
S_v	The deck-space of vessel type v in $[m^2]$
N_v	Operating speed of vessel type v in $[kn]$
G_v	Annual availability of vessel type v in $[days]$
P_b	People/crew accommodation capacity of base b in $[pax]$
K_{bv}	Vessel accommodation capacity of base b for each vessel type v in $[vessel/base]$
A_{bf}	Distance from base b to platform f in $[NM]$

B^{max}	the maximum number of bases to be utilized, in $[bases]$
D_k	Duration of contract k in $[years]$
Other	
T^{crew}_{max}	The maximum travel time for crew one-way in $[hours/trip]$

5.6.4. Decision variables

Strategic Decision variables

x_{bp}	1 if base b is used in year p, 0 otherwise
y_{vkp}	1 if vessel of type v is acquired on contract k in period p, 0 otherwise

Tactical Decision variables

q_{bvp}	1 if vessel of type v is utilized in combination with base b in period p, 0 otherwise
o_{vsp}	1 if vessel of type v is acquired on spot-market contract s in period p, 0 otherwise
c_{vbmfp}	1 if vessel of type v, is utilized to execute maintenance activity m at platform f in year p, 0 otherwise

5.6.5. Objective Function

The objective function captures the set of factors which together constitute the logistic cost of offshore operations for substation platforms, with a focus on the transportation of crew and cargo. This objective function will be subject to optimization and in this case the objective is to minimize the value of the objective function, in other words minimize costs.

$$\begin{aligned}
\textbf{MIN} \sum_{b\in B}\sum_{p\in P} C^{FB}_{bp}.x_{bp} + \sum_{v\in V^{mfs}}\sum_{k\in K}\sum_{p\in P} C^{FV}_{vkp}.y_{bvp} \\
+ \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M}\sum_{s\in S} c_{vbmfp}.T^{o\&m}_{mf}.o_{vsp}.C^{DV}_{vs} \\
+ \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M} \left(\left((C^{S}.P^{o\&m}_{mf}) + C^{O}_{v}\right).\frac{A_{bf}}{N_v}\right).Z^{o\&m}_{vbmfp}.c_{vbmfp} \\
+ \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M} \left((C^{A}_{v}.P^{o\&m}_{mf}.T^{o\&m}_{mf})\right).c_{vbmfp}
\end{aligned} \tag{5.1}$$

In thw objective function presented in eq. 5.1, the first line represents the fixed costs for remunerating operations from bases with a specific fleet. A more detailed decomposition of the first line is as follows:

- The first term in the first line represents the fixed costs to operate from a certain base b during year p.
- The second term represents the fixed costs for the acquisition of a vessel on either a 2-10 year long-term or 1-year medium-term contract. These contract costs are modeled as annual costs encompassing aspects such as the CAPEX financing, the vessel operation crew and vessel insurance.

The second line in the objective function addresses the vessels which are acquired from the spot-market on per-day spot-market contracts. Because the spot-market vessels are chartered on a per-day basis, the remuneration is included as a per-day charter rate which has to be paid on the days the vessels are used.

Hence, to determine the total spot-market costs, the multiplication with the length of each maintenance activity the vessel is set out to support is necessary.

The third and fourth line in the objective function represent the variable costs for the logistics required to support the execution of the maintenance activities m in M. For the third line, the variable logistic costs are divided in:

- Employee salary costs, which are incurred when crew is en-route to the platforms and not able to work. Here C^S is the average salary cost per employee per hour, [$€/crew/hour$], while $P_{mf}^{o\&m}$ is the size of the crew involved in maintenance activity m at platform f.
- Operational, or vessel sailing costs for e.g. fuel. This is represented with C_v^O for vessel type v per hour of operation, [$€/hour$] . For these operational costs, it is necessary to estimate the travel time per journey. This is accomplished via: $\dfrac{A_{bf}}{N_v}$, where A_{bf} represents the distance between base b and platform f and N_v represents the operational speed of vessel type v.

The variable costs in the third line accumulate over the annual journeys made for the execution of the maintenance schemes. One journey includes a trip from the base to the platform and a trip back to the base from the platform. Parameter $Z_{vbmfp}^{o\&m}$ includes the number of times this journey needs to be executed for each maintenance activity m, in order for the crew and cargo needs to be satisfied by the specific vessel type v used. Eq. 5.23 in the model preparation phase, calculates this parameter on the required number of journeys based on the number of crew and deck-space required per maintenance activity. Next, each journey has an average travelling time in hours which is derived from the distance between base and platforms and the vessel operational speed. Subsequently, journey travel time is multiplied with the sum of the vessel operational cost C_v^o and the employee salary cost C^S to constitute the "per journey costs". Ultimately, the required quantity a journey has to be sailed ($Z_{vbmfp}^{o\&m}$) is multiplied with "the per journey cost", resulting in the total journey costs.

Finally, in the fourth line the accommodation cost are represented. These accommodation costs, included on a €/PAX/day basis, are the cost made for all services and needs surrounding the accommodation of crew deployed on an offshore assignment. In this line, $P_{mf}^{o\&m}$ and $T_{mf}^{o\&m}$ represent, respectively, the number of crew and the time in days required to execute maintenance activity m at platform f.

Before heading to the constraints of the model, in the next sub-section a multiplication issue in the objective function will be addressed. This is namely the multiplication of two variables in the second line of the objective function and complicates the linearity of the model.

5.6.6. Linearization of terms in the objective function

It should be noted that the current multiplication between c_{vbmfp} and o_{vsp} in the third term of the objective function is mathematically incorrect, however due to the fact that both variables are binary and Gurobi accepts up to two binary variables in a multiplication which are automatically transformed to a linear formulation, it is possible to implement and run the model as originally stated. In this sub-section a method is proposed to mathematically correct for this non-linear relation in the objective function, namely by Linearization Reformulation Techniques (RLT).

The linearization techniques were first introduced by Bradley et al. (1977) for separable variables. The term separability entails that the variables can be separated by being present in different functions either within the objective function but also in the constraints. The LRT selected in this study is presented by Sherali and Tuncbilek (1992) for global optimization with not necessarily convex functions. A recent operationalization of this RLT was discussed during a conference talk by Fourer (2014), where strategies were discussed to cope with combinations of varying variable types in the non-linear term and how to substitute those with a new combination variable. Among these combinations, was the combination of two binary variables. This combination is relevant in this case as the two variables substituted are binary variables.

With the applied RLT, a substitution variable can be introduced, namely r_{vsbmfp}. This variable substitutes c_{vbmfp} and o_{vsp}, such that:

$$r_{vsbmfp} = c_{vbmfp}.o_{vsp} \tag{5.2}$$

In order for this substitution variable to be functional, additional constraints were required to be added to the model. See constraints 5.4 and 5.5. The objective function can thus be rewritten as:

$$\begin{aligned}\textbf{MIN} \sum_{b\in B}\sum_{p\in P} C^{FB}_{bp}.x_{bp} + \sum_{v\in V^{mfs}}\sum_{k\in K}\sum_{p\in P} C^{FV}_{vkp}.y_{bvp} \\ + \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M}\sum_{s\in S} r_{vsbmfp}.T^{o\&m}_{mf}.C^{DV}_{vs} \\ + \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M} \Big(\big((C^S.P^{o\&m}_{mf}) + C^O_v\big).\frac{A_{bf}}{N_v}\Big).Z^{o\&m}_{vbmfp}.c_{vbmfp} \\ + \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M} \big((C^A_v.P^{o\&m}_{mf}.T^{o\&m}_{mf})\big).c_{vbmfp}\end{aligned} \tag{5.3}$$

$$r_{vsbmfp} >= 0 \quad \forall \quad v \in V^{mfs}, b \in B, f \in F, p \in P, m \in M, s \in S \tag{5.4}$$

According to the RLT method, the combination variable should be bounded by a lower-bound of 0 (Fourer, 2014).

$$r_{vsbmfp} >= c_{vbmfp} + o_{vsp} - 1 \quad \forall \quad v \in V^{mfs}, b \in B, f \in F, p \in P, m \in M, s \in S \tag{5.5}$$

The constraint represented by eq. 5.5 ensures that the combination variable is set equal to 1 if either of the variables c_{vbmfp} and o_{vsp} take the value 1. Moreover, the subtraction with 1 ensures that the value of the combination variable is at most equal to 1. The following example illustrates this constraint: consider the scenario where $c_{vbmfp} = 0$, this means that $r_{vsbmfp} = c_{vbmfp}.o_{vsp} = 0$. The constraint subsequently force r_{vsbmfp} to take the value 0.

In an alternative scenario where $c_{vbmfp} = 1$ and $r_{vsbmfp} = c_{vbmfp}.o_{vsp} = o_{vp}$, the constraint ensures that $r_{vsbmfp} >= o_{vsp}$.

In the following sub-section the constraints for the implemented OptiFleet model will be addressed according to the category they can be associated to.

5.6.7. Constraints

For the feasibility of the model, constraints keep the decision variables within bounds. In this sub-section, the constraints of the OptiFleet model are categorized in constraints related to *the Maintenance demand and vessel-base coupling, the Vessel and Base Acquisition, Fleet Resource Management* and *Others*, and discussed individually.

Maintenance demand and vessel-base coupling

In this sub-section, the constraints presented target the generation of appropriate and sufficient maintenance support assignments, c_{vbmfp}, and associated to the maintenance support assignments, the appropriate vessel allocation and base selection.

$$\sum_{v\in V^{mfs}}\sum_{b\in B} c_{vbmfp} = F^{o\&m}_{mfp} \quad \forall \quad m \in M, f \in F, p \in P \tag{5.6}$$

In essence, the model aims to align logistic demand coming from the maintenance needs of the offshore platforms, with logistic supply coming from a fleet at minimal cost. The constraint as presented in equation

5.6 ensures that the maintenance demand $F^{o\&m}_{mfp}$ is fully satisfied by the maintenance activity assignments in c_{vbmfp}.

All maintenance activities, for each platform f in year p of both preventive and corrective nature, are grouped in the set of all maintenance activities M. Variable c_{vbmfp} represents the execution of maintenance activities via a maintenance activity assignment, to illustrate this, if c_{vbmfp} is equal to 1 for the index set vessel-A, base-A, maintenance-activity-A, platform-A, year-1, then the maintenance-activity-A at platform-A will be supported by vessel type vessel-A, from base-A in year-1. The sum of the supported maintenance activities of each type M, at each platform f and in each year p, over all vessel types and bases utilized, should thus be at least equal to the number of maintenance activities in M to ensure that all necessary maintenance activities are supported.

This constraint is addressed in the survey on fleet composition models by Pantuso et al. (2014), as an example of how conventional fleet optimization models treat demand satisfaction constraints given a certain fleet.

The following constraints target the appropriate allocation of vessels and selection of bases for the support of the maintenance activity assignments previously generated with c_{vbmfp}.

$$q_{bvp} = c_{vbmfp} \quad \forall \quad v \in V^{mfs}, b \in B, m \in M, f \in F, p \in P \tag{5.7}$$

q_{bvp} can be considered the vessel-to-base-pairing variable and constraint 5.7 ensures that if a vessel is allocated to a maintenance activity via a certain base in variable c_{vbmfp}, the base vessel coupling variable, q_{bvp} for that specific vessel-type and base combination, is enabled by taking the value 1.

$$c_{vbmfp}.A_{bf} \leq R_v \quad \forall \quad v \in V^{mfs}, b \in B, m \in M, f \in F, p \in P \tag{5.8}$$

Constraint 5.8 targets each individual journey and ensures that the specif journey is only selected if the journey distance, that is from the base to the platform-cluster and back, is below the maximum range (R_v) for the specific vessel type. Hence, variable c_{vbmfp} can only take the value 1 for a specific index-set $[vbmfp]$, if the base(b)-platform(f) link yields a distance less than the range of vessel type v in the index-set.

$$\frac{c_{vbmfp}.A_{bf}}{2.N_v} \leq T^{crew}_{max} \quad \forall \quad v \in V^{mfs}, b \in B, m \in M, f \in F, p \in P \tag{5.9}$$

The trip duration, where a trip is defined as a link either from the base to the cluster or back, can also be limited by a maximum travel time (T^{crew}_{max}) implied by the decision-maker on how long employees may be en-route per day. This constraint can be included with constraint 5.9. For instance TenneT applies a 2-hour travelling limit on one-way trips for their employees.

Vessel/base acquisition

The constraints addressed in this part ensure that the vessels or helicopters required to satisfy the maintenance demand, are indeed added to the fleet. The constraints can also be considered the fleet composition constraints.

$$x_{bp} >= q_{bvp} \quad \forall \quad p \in P, v \in V^{mfs}, b \in B \tag{5.10}$$

$$\sum_{k \in K} y_{vkp} + \sum_{s \in S} o_{vsp} >= \sum_{b \in B} q_{bvp} \quad \forall \quad p \in P, v \in V^{mfs} \tag{5.11}$$

First, constraint 5.10 ensures that bases selected in base-vessel combinations, through q_{bvp}, are added to the network accordingly. Whereas, constraint 5.11 ensures the acquisition of the necessary vessel types as utilized in q_{bvp}. Thus, if q_{bvp} is greater or equal to 1, meaning that vessel type v is utilized in combination with base b in year p, base b should be enabled and a vessel of type v should be made available in the fleet.

This corresponds to the variables x_{bp} taking the value 1, but also for y_{vkp} or o_{vsp} to take the value 1 according to the utilized vessel types either on respectively medium- or long-term contracts or from the spot-market.

$$\sum_{\alpha \in [p, MIN(p+D_k, P]} y_{vk\alpha} <= D_k \quad \forall v \in V^{mfs}, k \in K, p \in P \tag{5.12}$$

When the vessels or helicopters need to be contracted, constraint 5.12, ensures that the duration a vessel is under contract is complying with the duration of the specific contract, D_k.

$$\sum_{b \in B} x_{bp} \leq B^{max} \quad \forall \quad p \in P \tag{5.13}$$

Finally, constraint 5.13 allows for the decision maker to set a maximum on the number of bases to operate from.

Fleet resource management

After the fleet composition has occurred, it is necessary to include constraints which ensure that with the given fleet, the fleet allocation to support the maintenance activities, does not exceed the available resources.

$$\sum_{b \in B} \sum_{f \in F} \sum_{m \in M} (c_{vbmfp}.A_{bf}) \leq R_v.G_v.\big(\sum_{k \in K} y_{vkp} + \sum_{s \in S} o_{vsp}\big) \quad \forall \quad v \in V^{mfs}, p \in P \tag{5.14}$$

The constraint expressed in eq. 5.14 keeps track of the resources used. This constraint ensures that on an annual basis, the total distance operated by a vessel and/or helicopter is below what that vessel and/or helicopter is capable of per year. A comparable constraint for the resource management in terms of the range is mentioned by Pantuso et al. (2014) and in terms of the operation time by Joshi and Bolstad (2016).

First, the annual transportation time is calculated as the annual sum of the product between all maintenance activities to be executed via c_{vbmfp} and the distance between the base-platform link $b - f$ (A_{bf}).

The annual operational capability of the vessel is defined as the product between 1) the vessel availability (G_v) in days per year, 2) the maximum range of a vessel type for a single journey (R_v) and 3) the vessel types in the fleet on the various contract types (y_{vkp} and o_{vsp}).

$$\sum_{b \in B} \sum_{f \in F} \sum_{m \in M} (c_{vbmfp}.T^{o\&m}_{mf}) \leq \big(\sum_{k \in K} y_{vkp} + \sum_{s \in S} o_{vsp}\big).G_v \quad \forall \quad v \in V^{mfs}, p \in P \tag{5.15}$$

The constraint included with eq. 5.15 ensures that the vessel allocation for the support of maintenance activities complies with the number of days the vessel is available per year. This vessel availability (G_v) of each vessel type v expressed in days per year, is based on the weather in the area of operation and the capability of the vessel type to operate under certain weather conditions. The constraint implies that if the amount of maintenance activities can not be executed with one vessel within a year, additional vessels are acquired through y_{vkp} or o_{vsp}.

$$0 \leq \sum_{v \in V^{mfs}} q_{bvp} \leq x_{bp}.K_{bv} \quad \forall \quad b \in B, p \in P \tag{5.16}$$

The constraint in eq. 5.16 ensures that the vessels assigned to a base can be accommodated by that base, alternatively called the vessel constraint for bases. Here K_{bv} represents the capacity of each base in terms of how many vessels of type v can be accommodated.

$$\sum_{v \in V} q_{bvp}.P_v \leq x_{bp}.P_b \quad \forall \quad p \in P, b \in B \tag{5.17}$$

Subsequently, the constraint in eq. 5.17 ensures that the crew coming from the vessels assigned to operate from a certain base can be accommodated by that base. This is also called the base accommodation constraint, ensuring that the base in use has sufficient accommodation capacity (P_b) for the crew on the vessels assigned to that base.

Other

This sub-section addresses constraints which can not be directly placed under one of the previously discussed categories.

$$x_{bp} \in [0,1] \quad \forall \quad b \in B, p \in P \tag{5.18}$$

$$y_{vkp} \in [0,1] \quad \forall \quad v \in V^{mfs}, k \in K, p \in P \tag{5.19}$$

$$o_{vsp} \in [0,1] \quad \forall \quad v \in V^{mfs}, s \in S, p \in P \tag{5.20}$$

$$q_{bvp} \in [0,1] \quad \forall \quad b \in B, v \in V^{mfs}, p \in P \tag{5.21}$$

$$c_{vbmfp} \in [0,1] \quad \forall \quad v \in V^{mfs}, b \in B, m \in M, f \in F, p \in P \tag{5.22}$$

Finally, the constraints in eq. 5.18 till 5.22 impose the binary properties on the decision variables.

5.7. Mapping the decisions for the deterministic model

In order to incorporate uncertainty in the model, on an alternative way than the commonly applied stochastic optimization by e.g. Gundegjerde and Halvorsen (2012), Stålhane et al. (2016), the previously discussed optimization model is extended with a form of simulation. In particular the generation of scenarios for the maintenance schedules, both preventive and corrective, is generated with the uncertainty in failure rates, leading to different possible maintenance scenarios. For this approach, a general model flow diagram was discussed in section 5.3. This section provides an overview of how these decisions are made by the OptiFleet model in order to better grasp what is happening in the model. In the decision mapping in figure 5.6, it can be seen what the relation is between the decisions and how data is provided to the model as input towards the eventual optimal outcome consisting of an optimal fleet and the O&M costs associated to that fleet. Note that although these decisions are presented as sequential steps, the decision in OptiFleet are not made in a sequential manner.

5.7.1. Steps for model preparation

Model preparation: Platform clustering

The first step is the generation of clusters among the offshore transmission platforms. This implies that the platforms are grouped in clusters based on their proximity to each other and the spatial distribution. This step compensates for the initial weakness of the model where routing optimization is not taken into account. By clustering prior to the optimization steps, combined platform visits can be included.

Regarding the inclusion of routing, the findings from Christiansen et al. (2007), Pantuso et al. (2014) state that combinatorial fleet sizing and composition, in this case MFSMP, is more or less building further on a vehicle routing model where the routes are generated. However, the decision to omit detailed routing is in line with the arguments by Pantuso et al. (2014) on why detailed route choice modelling, in particular on the strategic level, is not necessary.

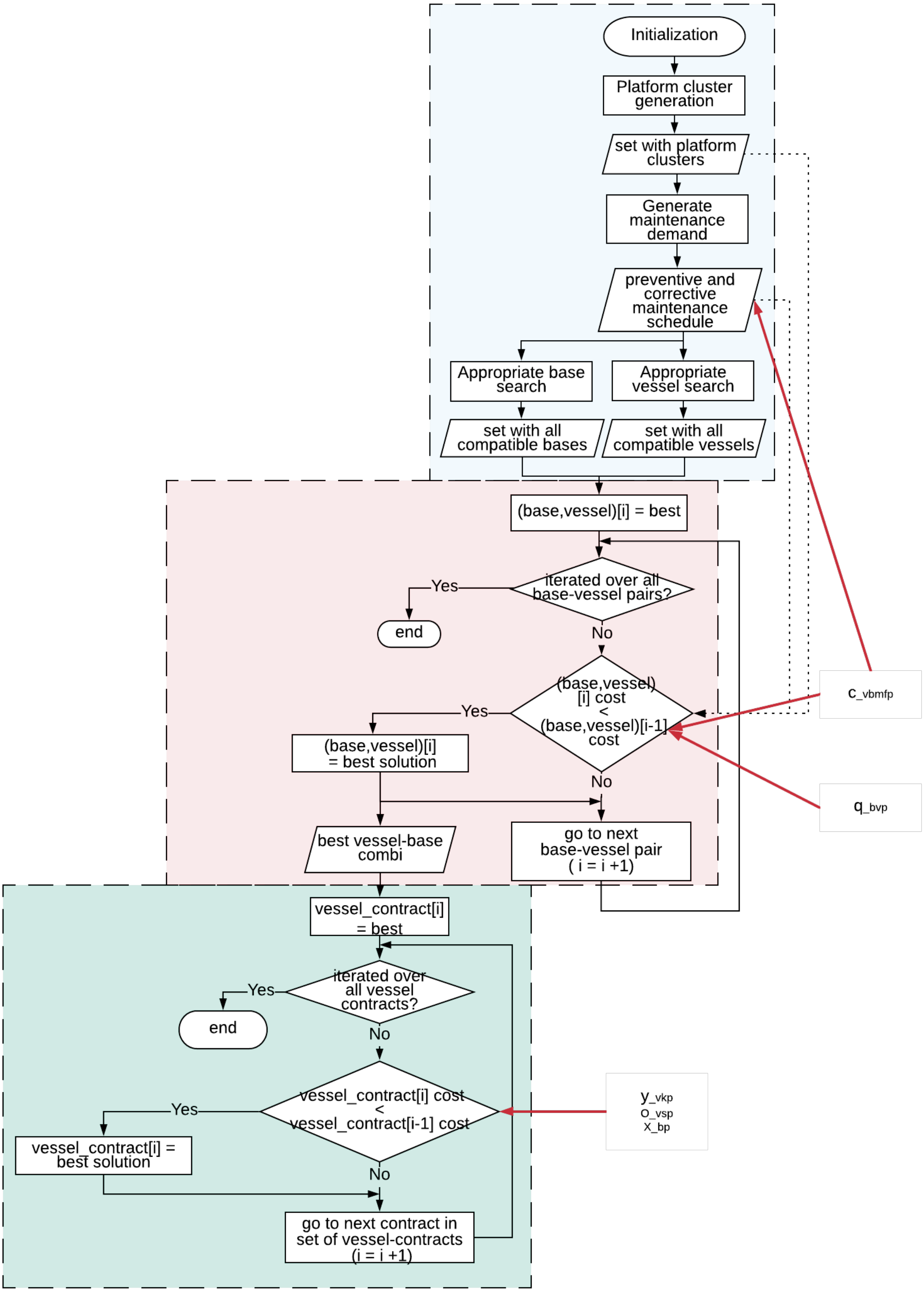


Figure 5.6: Process algorithm

The clusters of platforms will be considered as a single point in OptiFleet. The travel time between the platforms in a cluster can be neglected and the journey to the cluster can be considered a single journey from the base whereby the duration and needs concerning crew, lifting capacity and deck-space will be summed for the platforms in the cluster. The vessel could then interchangeably work on the platforms in a cluster.

The algorithm applied for the cluster forming is the DBSCAN algorithm. Along with e.g. the k-means algorithm, the DBSCAN algorithm can be applied to reduce spatial data sets for more effective analysis and improved visualization (Boeing, 2018). The choice for the DBSCAN algorithm was made, because it is stated by Boeing (2018) that the performance of the DBSCAN algorithm surpasses that of the more well-known k-means algorithm for spatial, longitude-latitude data. The DBSCAN algorithm, implemented via the scikit-learn package for python, clusters spatial data based on 1) the physical distance between points and 2) a minimum cluster size. For the cluster formation in this study it is assumed that the minimal cluster size entails one platform. This guarantees that the platforms outside the predefined neighbourhood, are included as a cluster which then consists of one platform. For the distance defining the neighbourhood of a platform, the assumption is made to work with a neighborhood radius of 10 km around each platform. This 10 km distance is considered to be a feasible range which supports the assumption of vessels working interchangeably between platforms in a cluster where intra-cluster transit is negligible.

Model preparation: Platform Maintenance generator

In this combined approach of simulation and optimization, the second step is the generation of the maintenance demand scenarios. This is done using the so called Platform Maintenance Generator (PMG) for the planning-horizon of 20 years. The timeline of 20 years is in line with the higher-end in the spectrum of long term lease agreements commonly set at 20 years, more or less also equal to the lifetime of a vessel and an offshore platform Dalgic et al. (2013). Furthermore, planning the fleet on a long time-horizon leads to a more robust fleet and a fleet in which the cost can be minimized by opting for medium- or long-term contracts instead of only the significantly more expensive vessels from the spot-market. In addition, the vessels from the spot-market have the added risk that the vessel may not always be available when needed because it is in use or needs significant mobilization time from the previous client or port. For these 20 years the PMG determines the maintenance demand, both preventive and corrective maintenance, resulting in a demand scheme for transportation services spread over 20 years.

Model preparation: Vessel filtering

With the maintenance scheme established through the PMG, the subsequent step is to narrow down the vessel set by eliminating vessel types which do not satisfy the maintenance demands. The aim of this filtering, in the pre-model stage, is to minimize constraints and calculation in the optimization model itself and subsequently realize improved performance.

For the vessel set filtering, the relevant categories of needs are the lifting requirement and the distance between the base and platforms. The motivation behind applying the lifting need and distance as vessel filtering criteria, is because on the contrary to the crew and deck-space needs where the number of journeys can be increased to satisfy the needs, the lifting needs cannot be satisfied by increasing the number of journeys. The only way to satisfy the lifting needs is when the vessel is equipped with the necessary equipment to execute these lifting operations accordingly. Whereas the only way to satisfy the distance criteria, is to utilize a vessel with sufficient range characteristics.

Model preparation: Journey frequency

With the filtered vessel set and the maintenance demand, the next step of the model preparation is to determine the required number of trips to satisfy each maintenance activity with the various vessel types. Again, the aim of this step in the model-preparation is to minimize the constraints and calculation in the OptiFleet model itself.

$$MAX\left(\frac{P^{o\&m}_{mf}}{P_v}, \frac{S^{o\&m}_{mf}}{S_v}\right) = Z^{o\&m}_{vbmfp} \quad \forall \quad b \in B, f \in F, m \in M, p \in P \tag{5.23}$$

Via $Z^{o\&m}_{vbmfp}$, eq. 5.23, calculates how often base-platform link bf needs to be sailed to satisfy the maintenance needs regarding the number of crew and the deck-space ($P^{o\&m}_{mf}$ and $S^{o\&m}_{mf}$) for all $m \in M$ with each $v \in V$. Here P_v represents the capacity of vessel type v for passengers, while S_v represents the deck-space for cargo. In short, this constraint ensures that the frequency with which a base-platform link is sailed is at least equal to the largest of either:

- $\frac{P^{o\&m}_{mf}}{P_v}$: the number of trips required to satisfy the crew number needs of maintenance activity m at platform f with vessel type v
- $\frac{S^{o\&m}_{mf}}{S_v}$: the number of trips required to satisfy the desired deck-space of maintenance activity m at platform f with vessel type v

To illustrate this, if maintenance activity A requires 50 crew members and 750 m^2 of deck-space and vessel type "B" offers capacity for 20 PAX and has deck-space equal to 400 m^2, then to satisfy the crew and cargo needs, vessel type B would have to make 3 and 2 trips respectively. The equation then ensures that the parameter $Z^{o\&m}_{vbmfp}$ is equal to 3, the largest of the required number of trips for crew and cargo.

Other external factors

As previously mentioned, various aspects, such as the weather, resulting in significant uncertainty are considered. Along with the maintenance demand created by a scheduled preventive campaign or a failure, a weather scenario based on the period and the location at which the maintenance takes place, is included. The weather scenarios, affect the annual availability of the vessel to execute transportation tasks and thus has an impact on the vessels to include in the fleet to sufficiently support the maintenance activities. The weather conditions are reflected in the annual availability percentage for each vessel type (G_v).

5.7.2. OptiFleet Search Strategy

After the model preparation steps in the blue demarcated box in figure 5.6, resulting in set of feasible vessel types and the trip frequencies, OptiFleet iterates over these vessel options to determine which yield the lowest cost for the maintenance schedule via variable c_{vbmfp}, see the red box in figure 5.6. These vessel options are vessels which are compatible with each other and could coexist in a fleet. The other relevant variable here is q_{bvp} or the vessel-base-pairing variable, which takes the value 1 for the option yielding the lowest costs.

The process within the demarcated box which is coloured green, are related to the decision variables through which OptiFleet determines the optimal vessel contract arrangements based on the vessels that need to be utilized. Here a vessel is either contracted on a long-term, medium-term or spot-market contract, respectively turning the variable y_{vkp} or o_{vsp} to take value 1 if the vessel is acquired on the corresponding contract. Eventually the contract yielding the lowest fixed costs over the total time-span is the optimal vessel contract.

It can be concluded that this search strategy is in line with the purpose of OptiFleet being a strategic support tool. This because the decisions are made bottoms-up, where first the maintenance demand is tested on all vessel possibilities available on the market, in order to subsequently make well argumented decisions for the vessel acquisition. This is opposite to existing approaches, such as from Halvorsen-Weare et al. (2013), where the primary decisions are made regarding the vessels and bases to only then test them with the demand coming from O&M.

5.8. Chapter conclusion

With the OptiFleet model and the corresponding model preparatory modules addressed elaborately in this chapter, the next step is to report on the model implementation and whether this implementation is according to the specifications and the mathematical model presented in this chapter. The proceeding chapter will thus address the model verification and the computational limitations of the model.

6

Model Implementation: Verification and Computational limitations

After elaborating on the model development in the previous chapter, this chapter will address the implementation of OptiFleet as a computer model. First, the model implementation will be verified and the verification is followed by the assessment of the computational limits of OptiFleet.

For the model verification, the model will be subjected to a serie of tests to determine whether OptiFleet is implemented according to the specifications and is generating the expected results.

For the computational limitation assessment, the model will be subject to a variety of input data to determine the bounds of the model. In other words, the computational limitations of OptiFleet are determined and a limit can be placed on the case size that can be dealt with by the model.

6.1. The implementation of OptiFleet and its components

The OptiFleet model is implemented in the object-based programming language Python 3.6, while the model solving is done using the Gurobi 8.0 Solver from Gurobi Optimization. To run the model a computer was used with following characteristics: Intel(R) Core(TM) i5-7200U CPU @ 2.50 GHZ and 4.00 GB RAM.

6.2. Model verification

The first implementation iterations of the OptiFleet model included tests which serve the purpose of model verification. In this section it will be discussed how the verification of OptiFleet is conducted and how model improvements could be applied based on the verification results.

To test the applicability of the model for the purpose of strategic decision support, model verification is an important step. Model verification is essentially the assessment of the model to determine if the model implementation is according to the specification and conceptual model. In the process of ensuring that the model is according to the specifications, the test allows for the modeller to eliminate errors in the implementation which lead to erroneous and unexpected behavior. Furthermore, the implementation is carried out in such a way that: 1) errors are prevented via a layered implementation where the implementation starts out simple and detail is added in layers, 2) phased verification tests are made possible via the modular implementation where input generation and model are separated to also test the model on different input sets and 3) internal verification mechanisms are included, for instance to decompose the objective function and to ensure that the sum of the different components of the optimal solution is equal to the value of the objective function.

The techniques applied for the verification of OptiFleet are methods initially developed for simulation models, see for instance Kleijnen (1995), Sargent (2013) and Duinkerken (2017) for examples of verification techniques. The choice to apply verification methods for simulation models for the verification of OptiFleet can be motivated by the absence of specialized verification techniques for Optimization Models. From the broad field of verification techniques a selection of the most relevant techniques constitute the Verification Experiment Design for this study, namely:

1. **Input check**: the input check ensures that the actual model input in terms of e.g. number of platforms, maintenance activities and vessel types is according to the specified cases. The input tests are carried out over the various input generators:
    (a) *targeting the clustering module*: the platforms represented in the clusters generated by the clustering module equals the sum of all platforms to be included in the case
    (b) *targeting the platform maintenance generator*: total maintenance activities equals the sum over all individual platform maintenance schemes, both preventive and corrective
    (c) *targeting the vessel input*: the workable vessel set is equal to (the initial input set of vessels - the vessels filtered out) due to insufficient range and lifting capacity characteristics
2. **Continuity test**: the Continuity test encompasses model runs with slight (5%) change in input parameter values for the cost factors, capacity factors of the vessels and bases and demand needs for maintenance activities. The finding here is that the model continues to generate output under the 5% parameter change. However, the output does change in terms of the vessels in the fleet. This will be further elaborated on in the sensitivity analysis in sub-section 7.2.2, where sensitivity runs are carried out on the parameter values leading to the most significant changes in model output, namely the vessel charter rates and the vessel operability.
3. **Extreme values tests**: extreme parameter values are used to derive whether the model behaves as expected under the extreme conditions. The findings here are:
    (a) the model solution contains the vessels with the highest capacity and operability characteristics when the charter costs are set to 0 for all vessel types on any contract.
    (b) when the logistic needs of the maintenance activities in terms of crew, deck-space and lifting-needs are set to 0, the model solution contains the vessels with the lowest capacity since these then yield the lowest total costs while satisfying the logistic needs equal to 0
    (c) when the base capacity is set to 0, for all bases, the model is infeasible since no bases are available with sufficient capacity to include in the solution. if the capacity of a certain base is set to 0, that particular base is not in the solution, regardless of having the lowest fixed and variable costs.
    (d) This test is also relevant to determine the boundaries, in terms of case size, within which the model is generating verified behavior in a reasonable solving time. More on this feature is discussed in sub-section 6.2.1 on the model limitations given the computational resources.
4. **Consistency checks**: the consistency test is carried out with counters build in to monitor whether a doubling in maintenance activities leads to an equal doubling in the number of trips.
5. **Verification with analytical results**: these test entail the comparison between hand-simulations and the computerized model on the output regarding the objective function for the total costs and the fleet composition. Since this category of tests has the dominant role in the model verification, the set-up and results of this test are addressed in more detail below. The verification with analytical results is carried out with the following goals:
    (a) *Objective function verification*: determine if the objective value, that is the value of the objective function for a specific solution, is according to the manually calculated cost for that solution. This thus ensures that the objective function is implemented according to the specifications as documented in the mathematical model.
    (b) *Model decision verification*: to determine for simple cases if the optimal solution as proposed by the computerized model is equal to the optimal solution as calculated analytically. This can thus be considered the verification test to determine whether the model decisions are indeed being made in favour of the lowest cost options.

In order to execute the verification with analytical results a number of test-cases are established varying in the number of platforms included, the number of maintenance activities, if either preventive and/or corrective maintenance are included, the charter- or contract costs and finally in set of included vessel types. An overview of these test-cases is presented below:

1. verification-test-case-1: 1 platform, 1 preventive maintenance activity/platform/year, 1 vessel type, normal long-term contract price and spot-market day-rate
2. verification-test-case-2: 1 platform, 1 preventive maintenance activity/platform/year, 2 vessel types, normal long-term contract price and spot-market day-rate
3. verification-test-case-3: 1 platform, 4 preventive maintenance activities/platform/year, 2 vessel types, normal long-term contract price and spot-market day-rate
4. verification-test-case-4: 2 platforms, 4 preventive maintenance activities/platform/year, 2 vessel types, normal long-term contract price and spot-market day-rate

Table 6.1: percentual difference in the costs between analytical and model results for the cost components

	verification-test-case-1	verification-test-case-2	verification-test-case-3	verification-test-case-4
# of platforms	1	1	1	2
# of maintenance activities	1	1	4	4
# of vessel types	1	2	2	2
Δ base cost [%]	0	0	0	0
Δ vessel cost [%]	0	0	0	0
$\Delta operationalcost$[%]	0	-3.18	-5.9	-2.73
Δ accommodation cost [%]	0	0	0	0
Δ total cost [%]	0	-0.18	-0.52	-0.21

For verification-test-case-1 where the optimal solution can be analytically determined rather simply due to the model input consisting of only 1 vessel-type, 1 platform with 1 maintenance activity and 1 port as base with shortest distance to the platform. The port operated from has a distance of 147,16 NM to the test platform and the single maintenance campaign annually requires 14 days of service-time and 30 crew-members. It is assumed that in case of a vessel charter from the spot-market on a day-rate, the vessel is chartered for the entire duration of the maintenance campaign, so in this case 14 days. This test-case subsequently results in an optimal solution consisting of 1 vessel of vessel type vessel-9 corresponding to a combination of an medium PSV for cargo and a medium CTV for crew, acquired from the spot-market for a day-rate of €20,506. The choice is made for day-rate charter from the spot-market since this option yields lower cost than the long-term lease, namely €5,741,680 for spot-market charter compared to €61,633,980 for 20 year long-term lease. This, while assuming the spot-market vessel is acquired and remunerated for 14 days per year since this is the length of the maintenance campaign, and the long-term lease would have to be remunerated for at least the entire year.

The implemented model also leads to vessel costs equal to €5,741,680, so this confirms that the calculation of vessel costs in the computerized model is according to the specifications. For this vessel concept, accommodation of crew takes place on the platform itself at a cost of 200 €/pax/day. The hourly wages amount to 160 €/employee/hour for the lost time during transit and the vessel operational cost amount to 623 €/hour. With these cost factors in mind, the analytical result for the vessel operational costs equals €638,456.90, while the computer model yields €638,456.90. In table 6.1 the percentual difference is presented between the analytical value and the computerized model value for the various cost components respectively. For the accommodation costs, the manual calculations result in accommodation costs of €1,680,000 and the computerized model also generates €1,680,000. The same can be said for the base utilization costs which are equal for the analytical and model results at €3,000,000. Hence, the total costs calculated manually and the value of the objective function of the computerized model for this test-case-1 is equal at €11,060,145. With this it can be concluded that all elements contributing to the total costs and represented in the objective function are implemented according to the specification.

For verification-test-case-2, two vessel types are taken into account. In addition to vessel-9 from verification-test-case-1, vessel-6 which corresponds to a medium OSV is now also included. The OSV is a vessel type which includes accommodation facilities on the vessel. With the analytical calculations to compare these two vessel types, the total costs are lower for vessel-9, namely €11,040,084.54 for vessel-9, compared to the €17,197,448.00 for vessel-6. These numbers are derived with the spot-market price for both vessel-types, which yield lower total costs relative to long-term contracts, given the utilization of the vessels for the case with 1 platform and 1 maintenance activity. Based on the lower total costs for vessel-9, this would thus indicate that the optimal solution includes vessel-9 over vessel-6. When looking at the optimal solution of the computer model, it can be confirmed that vessel-9 is acquired in the fleet from the spot-market.

Another observation is that for the test-cases with a larger scale compared to test-case-1, numerical differences occur between the analytical and computerized model results. These differences are ranging between -2.73% and -5.9% for the operational costs, whereby the calculated cost are generally lower than the computerized model costs. This may be explained by the rounding differences between the analytical and computerized model output and aggregation or simplification steps in the manual calculations, compared to the extensive iterations in the computerized model. When looking at the total costs, these differences decrease in magnitude, because the vessel costs are the most dominant contributor tot the total cost, and not the operational costs where the numerical differences occur.

6.2.1. Model computational limitations

In this subsection it will be discussed what the model limitations are, given the computer system mentioned in section 6.1. To do so OptiFleet is made subject to computational tests whereby 21 test-cases of varying size are set-up, to determine what the limitations are in terms of the necessary memory resources and solving time before it turns unreasonable to generate results. The test-cases vary in various aspects such as: the number of platforms, the number of maintenance activities and the number vessel types.

Optimality gap

Before heading to the results of the 21 test-cases, a brief introduction is provided on the *Optimality Gap* or *OG*. The OG is a measure to elaborate on the progress and result of the optimization run, it is a common measure used to monitor the extent to which a model can reach optimality. The OG is a convergence criteria which can be described as the difference between "the current best integer solution" and the "current lower bound". The current lower bound is the optimal solution of the model instance over which an relaxation has taken place. If this OG converges to 0, the solution represents the true global minimum or maximum and thus the optimal solution (Streiffert et al., 2005).

The 21 test-cases

In figure 6.1 it is visualized in what time an OG of 0.0% could be reached for the 21 test-cases when limiting the run to a solving-time of 300s. Note that in figure 6.1, on the x-axis the 21 test-cases are depicted in the order of increasing solving time. Moreover, next to the name of the test-case, it is depicted what the specific test-case entails in terms of the vessel types included (V), the number of platforms (P) and the total amount of preventive and corrective maintenance activities (M). All 21 test-cases are run with a set containing 5 marine bases. The 300s run-time specification means that if the specific case does not yield an optimal solution, that is an OG of 0%, the run is terminated at the 300s mark and the OG of the best result found within that time is reported. The aim of this test is twofold, first it is aimed to determine what case sizes can be handled with the OptiFleet model in its current implementation and the standard settings of the Gurobi Solver. Furthermore, these tests seek to provide information on which factors have the dominant influence on the model performance, or in other words which factors imply the largest limitation on the model to facilitate cases of increasing size.

Regarding the general goal to determine which case sizes can be handled by the model, figure 6.1 exhibits the cases in an order of increasing solving time. As can be seen, for all test-cases an optimal solution could be realized within the 300s time-limit. The test-case with the largest solving time is on the utmost right of the graph, namely test-case-21 which required 283.36s to reach optimality at an OG of 0.0%. In roughly the first half of the graph, an OG of 0.0% can be reached by OptiFleet in under 6.02s, this can be claimed for test-case 4, 1, 2, 3, 5, 7, 15, 6, 11, 12, 14, 8 and 9. The minimum solving time is reached for test-case-4 at 0.04s.

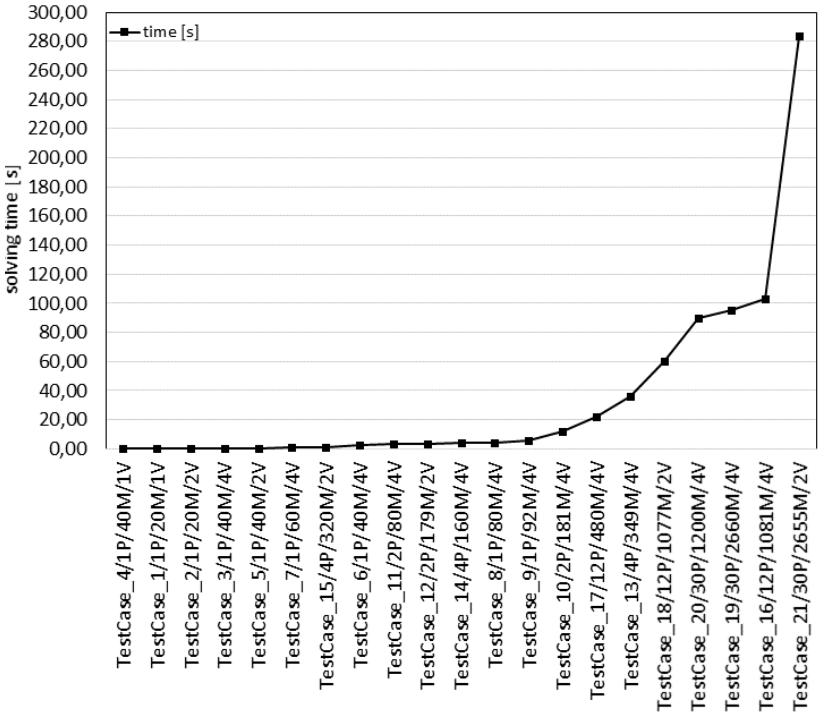


Figure 6.1: the solving-time for the 21 test-cases, run with a 300s time limit. The x-axis includes the composition of the test-case

The observed trend for the development of the solving time can be described as a trend showing the characteristics of an exponential growth, especially from test-case-10 onward. This thus entails that OptiFleet in its current implementation and with the standard settings for the Gurobi Solver, is capable to handle cases which are small, but also cases ranging up to the number of platforms which are desired to be included for the TenneT case-study to follow in chapter 7. The tested limit is at 30 platforms, 4 vessel types, 5 bases and 2,655 maintenance activities over a time-span of 20 years. The largest case to be included in the case-study in chapter 7, contains 24 platforms to represent the situation in the Dutch and German North Sea in 2030.

The second aim of this computational test is to determine which input has the most influence on the ability of the model to solve a case to optimality. Taking this question into account, and looking at the test-case order in figure 6.1, the conclusion can be drawn that the number of vessel types included in the model is the main contributor in the solving resources required for a case. In figure 6.1 it can namely be observed that for all test-cases in the exponentially increasing tail of the graph, the number of vessels is 2 or 4, these are the largest vessel sets included in the test cases.

After the number of vessel types, the number of platforms has the largest influence on the solving performance under standard solver settings. Of the 12 test-cases included with 2 or more platforms, 8 test-cases are on the exponential tail of the graph.

For a more complete overview, see appendix D where table D.1 depicts an overview of all test-cases, together with the input characteristics of the case and the resulting solving time. Additionally, appendix D includes graphs for the solving time of the test-cases in relation to the number of vessel types, the platforms and the number of maintenance activities, respectively in figure D.1, D.2 and D.3.

While this test covers the maximum platforms and bases included in the TenneT case-study, more vessel types will be included in the case-study than are included in the test-cases. This calls for a more detailed analysis of a model run in order to further optimize the performance and especially for cases with more vessel types. More on this is mentioned in sub-section 6.2.1, which entails measures to parameterize the solver such that it can smartly tackle larger case sizes.

Detailed run: monitoring the optimality gap and the bounds

After presenting the overall results for the 21 test-cases in the previous sub-section, this sub-section will address the detailed monitoring of the bands and the subsequent OG for one case. This with the aim to come up with a parameter set-up for the solver to cope with larger case sizes. The case studied in this sub-section achieved the highest solving time among all test-cases and can be summarized as containing 30 platforms, 4 preventive campaigns per platform annually with between 0 or 1 failures requiring corrective maintenance, 4 vessel types and 5 bases.

When running this case, with the default solver settings in Gurobi utilizing the Simplex algorithm together with Branch-and-Bound strategies, but without pre-solving, the model reached optimality in 141.1s. The progress of the solving process can be illustrated with the OG, see figure 6.2 for the plotting of the OG for both the run without presolve in the green line, and the run with presolve in the orange line. As mentioned before in sub-section 6.2.1, the OG is a convergence criteria which can be described as the difference between "the current best integer solution" and the "current lower bound". In this model instance with the test-case, the OG decreased from 100% to 36% in 128s. Hence, it took the remaining 13s for the OG to be reduced for the other 36% to 0.0%.

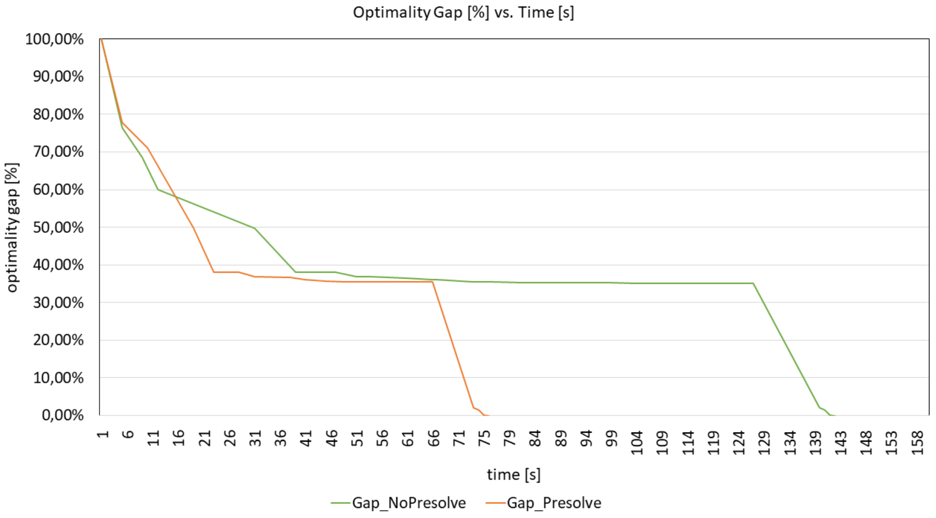


Figure 6.2: Optimality gap over time for the run without presolve in green and the run with presolve in orange

In figure 6.3 it can also be seen that the strongest convergence of the lower and upper bounds of the optimal solution takes place up to the 128s mark. The observation that little optimization progress is made between the 39s mark and the 128s mark, calls for measure to improve the optimization performance and increase the improvement of the OG in the mid-section of the run where currently little progress is made. This can thus be realized by adjusting the default Gurobi solver settings to fit the specific model more properly and subsequently realize improved solving performance.

Building upon this finding, experiments were run to determine the most suitable parameter setting for presolving, cutting planes strategies, heuristics and parallelism, but also model termination rules based on maximum solving time and the optimality gap (Gurobi Optimization, n.d.).

Model parameter settings

First, model presolving aims to reduce the problem size and strengthen the model formulation, or determine if the model is unbounded or unfeasible, among other by, but not limited to, eliminating redundant information and exploiting the model structure (Andersen and Andersen, 1995, Gamrath et al., 2015). Model presolving dates back to 1995 where the first commercial solvers such as, WHIZARD, OB1, OSL, Sciconic and CPLEX included some form of presolving (Andersen and Andersen, 1995). In these early days, presolving especially entailed scanning the data and model to discover and eliminate redundancy and non-zeros. A paper on the progress in model presolving by Gamrath et al. (2015) addressed three main types, namely: 1) a

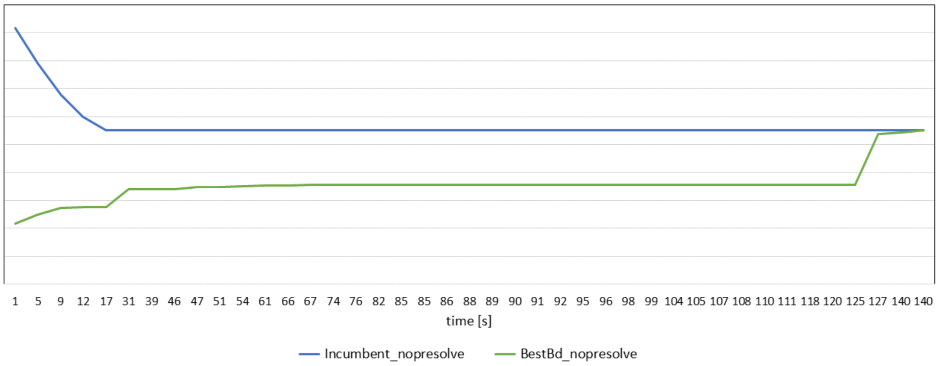


Figure 6.3: Lower bound vs. Upper bound over time without the application of presolve

method fixing continuous singleton columns and extending results known from duality fixing, this method is also mentioned by Andersen and Andersen (1995), 2) a method analyzing and exploiting pairwise dominance relations between variables and 3) a method that detects isolated sub-problems and solves them independently. All these methods perform differently under different data-sets, hence it depends on the data used which method should be chosen and also which solver is used.

Presolving in Gurobi combines the previously mentioned methods as follows (Gurobi Optimization, 2015):

- single-row and multi-row reductions which includes:
  - discard empty rows
  - discard redundant inequalities
  - remove coefficients with small impact
  - bound strengthening
  - coefficient strengthening for inequalities
  - parallel rows and sparsify
- single-column and multi-column reductions which includes:
  - discard fixed variables and empty columns
  - rounds bounds of integer variables
  - strengthen semi-continuous and semi-integer variables
  - dual fixing, substitution, and bound strengthening
  - parallel columns and dominated columns
- full problem reductions which includes:
  - symmetric variable substitution
  - probing (tentatively fixing variable values)
  - implied integer detection

Furthermore Gurobi presolve provides the user with tuning parameters to adjust presolving in terms of: 1) the presolve level, 2) enabling or disabling methods, e.g. disabling dual reductions, 3) the aggregation in presolve, 4) the presolve dependent row reductions, which eliminates linearly dependent constraints and 5) the number of passes allowed by presolve.

After the elaboration on the purpose of presolving, the following addresses the specific parameter setting in the Gurobi solver. The problem under study is an application of Mixed Integer Programming (MIP) and these models tend to get resource heavy rather fast (Blum and Roli, 2003). hence, in order to run near Real-Life cases, there is a necessity for smart solving methods.

To implement smart solving methods, which in particular target the memory used and the solving speed, means are provided by Gurobi Optimization in the Gurobi 9.0 Solver. Options are provided to the user to parameterize their desired solving method to suit the specific model. In order to retrieve feasible output in reasonable solving time, the following model parameter settings were applied (Gurobi Optimization, n.d.):

1. PreSolve:
   (a) Function: This parameter controls the presolve level in making the model smaller and improving the formulation by eliminating columns, rows, nonzero values and duplicates. This increases the

    ease with which the model can be solved
   - (b) Value: 1 – this is a moderate setting of presolve and leads to a tighter model with a moderate elimination strategy
2. PreSparsify:
   - (a) Function: Controls the sparsity reduction during presolve, which can significantly reduce the number of non-zero values in the presolved model
   - (b) Value: 1 – enables the sparsify option
3. TimeLimit:
   - (a) Function: Terminates the solving process when the predefined run-time is met
   - (b) Value: 3,600 seconds
4. NodeFileStart:
   - (a) Function: Enables the storage of nodes to the hard-disk when the amount of RAM memory to store nodes exceeds the specified parameter value. In other words, it divides the memory needs over the hard disk and RAM memory, instead of only on the RAM memory which is often limited (4GB in the computer used). Via this distributed storage, it is prevented that the computer runs out of memory prematurely, before generating feasible solutions.
   - (b) Value: 0.5 - after 0.5 GB of RAM usage, memory on the hard disk is also used.
5. MIPFocus:
   - (a) Function: Allows the modification of the high-level search strategies depending on the goals. By default, Gurobi searches for a balance between finding new feasible solutions and proving optimality of already found solutions.
   - (b) Value: 2 – this setting focuses the higher level search strategy to proof the optimality of a solution.
6. Cuts:
   - (a) Function: this parameter addresses the wide range of strategies deployed by the Gurobi solver for the Cutting Planes algorithms. In particular this parameter controls the aggressiveness of the cutting strategy.
   - (b) Value: 0 – this enables a moderate strategy for Cutting Planes
7. ImproveStartTime:
   - (a) Function: this parameter influences the high-level search strategy (MIPFocus) based on the solving time already passed. This can be explained in the following example: The initial high-level search strategy is set to find as much feasible solutions as possible, after a predefined point in solving time is met, the search strategy can be changed to focus on proving the optimality of solutions.
   - (b) Value: 20,000 seconds – after 20,000 seconds the high-level search strategy is changed to proof optimality to a even higher extent.

With these model parameters, the outcome of the test-case changes positively. In figure 6.2, it can be observed that for the run with the adjusted parameters, represented with the orange line, an OG of 0.0% is reached faster than in the run with the default parameters. After adjusting the parameters, the optimal solution is reached in 72.3s.

6.3. Chapter Conclusion

After the model is verified in this chapter and experiments are run to determine the model limits under default settings and how that can be improved to facilitate larger cases, the following chapter will apply the OptiFleet model and the knowledge from this chapter to answer the research questions for the case of TenneT in the German and Dutch North Sea.

7

Computational Study: The TenneT case & Results

The previous two chapters where devoted to discuss the development of the OptiFleet model and the corresponding data input components, the implementation of the model and concluded with the model verification and limitations.

In this chapter OptiFleet will be applied for the TenneT case. After this case is described, including the data used for this case, sub-case instances will be derived and based on this case and the associated sub-cases, OptiFleet will ultimately propose an optimal fleet solution for the TenneT case in the German and Dutch part of the North Sea.

7.1. Case description

In this section the case on which the model will be applied is discussed. This entails that the sub-cases which will be included in terms of the platforms, bases and vessels are presented. The source of case input data is also discussed in the subsections below.

7.1.1. Platforms and Bases

In figure 7.1 an overview is provided of the platform layout in the North Sea until 2023 for both Germany and the Netherlands. In total 14 platforms can be observed, 9 in the German North Sea and the other 5 in the Dutch North Sea. Of these 14 platforms, 7 are operational in 2018, 4 will be commissioned in 2019 and the final 3 will be commissioned between 2019 and 2022. For the longer term, the number of platforms will continue to grow. According to TenneT Holding B.V. (2017), the 5 Dutch platforms at an capacity of 700 MW each, good for a total of 3.5 GW, will increase to a number between 11 and 14 platforms to cope with the expected offshore wind generation capacity of between 7.5 GW and 10 GW in 2030. In Germany, the expected increase towards 2030 is less strong, resulting in 13 platforms in the German North Sea as the expected total in 2030.

This research is thus not limited to the offshore platform network in 2023, but also provides an outlook towards the situation in 2030. This temporal aspect captures the expected growth in the network, where as previously mentioned, at least a doubling is expected in the amount of platforms in the Dutch North Sea, whereas the increase is less strong for the German North Sea. The purpose of including the 2030 platform network in the study, is to determine what the impact is of platform network growth on the needs for logistics and subsequently provide recommendations on how the TSO can anticipate this network growth by means of a robust marine fleet. For an overview of how the offshore transmission network may look like in 2030, see figure 7.2.

In addition to the platforms, figure 7.1 presents the ports which are included in this study. These ports are

Figure 7.1: plot of the platform locations and bases in the North Sea according to the expectation till 2023

identified as feasible ports to operate from to support the logistic needs of the platforms in the North Sea (Wolfsturm, 2017a). In total 10 ports will be included, whereby 3 are located in the Netherlands, 6 in Germany and 1 in Denmark.

Figure 7.2: plot of the platform locations in the North Sea according to the expectation in 2030

With this information regarding the current and future platform network, six sub-cases are constructed for this case study. The six sub-cases are distinguished based on:

1. **the time**, to capture the difference in the network between 2023 and 2030 and enable recommendations on how to develop the fleet accordingly.
2. **the geographic distinction** between the German and Dutch North Sea to study the benefits of planning the Dutch and German grid in a integrated way, compared to two independent geographic areas.

For both 2023 and 2030 three sub-cases can be distinguished. The first sub-case addresses solely the transmission platforms in the German North Sea for 2023, DE-2023. The second case addresses the transmission platforms in the Dutch North Sea in 2023, NL-2023 and the third sub-case addresses the platforms in the German and Dutch North Sea in 2023 together, DE-NL-2023. The same distinction in sub-cases can also be made for 2030, leading to DE-2030, NL-2030 and DE-NL-2030, for a total of six sub-cases. Depending on the start-year of the sub-case being either 2023 or 2030, the OptiFleet model is run over 20 years of platform logistic needs. This means that the model will run for 2023 to 2043 for the 2023 sub-cases and 2030 to 2050 for the 2030 sub-cases. Note that for these model runs, the number of platforms does not change over the course of the 20 years. This 20 year run-time, is as mentioned before, in line with the lower-end of the expected vessel lifetime and with the higher-end of long-term vessel lease contracts which are close to vessel ownership in terms of duration (Robert, 2018). In figure 7.3 it is exhibited how the sub-cases relate to each other when looking at the the time and the number of platforms.

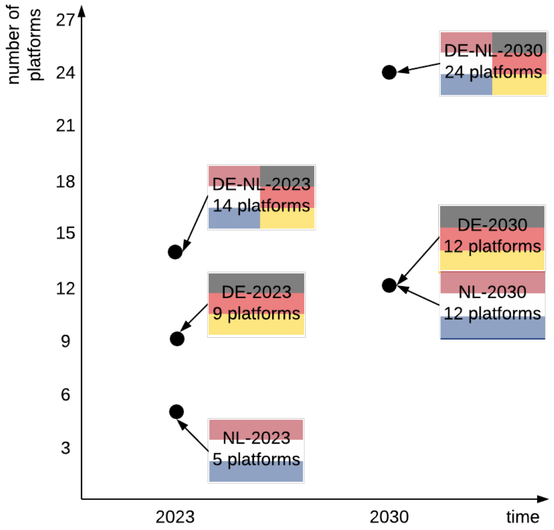


Figure 7.3: mapping of the sub-case instances

Before the sub-cases are applied in OptiFleet as model input, a clustering algorithm is run over the platforms first to establish platform clusters as described in sub-section 5.7.1. In table 7.1 the result of the clustering is exhibited. These clusters will be used to determine the maintenance need, aggregated per cluster.

Table 7.1: Results of platform clustering

	DE-2023	NL-2023	DE-NL-2023	DE-2030	NL-2030	DE-NL-2030	unit
number of sub-case platforms	9	5	14	12	12	24	[platforms]
platform neighborhood	10	10	10	10	10	10	[km]
minimum cluster size	1	1	1	1	1	1	[platforms]
number of sub-case clusters	6	3	9	7	8	15	[clusters]

7.1.2. Means of Transportation

The field of offshore wind energy, and consequently also the field of offshore transmission technology is fairly new. This implies that, compared to for instance the conventional offshore oil & gas industry, experience and good practices is not as widely documented and available. The same issue is also noted by earlier studies on vessel fleet models for offshore wind from e.g. Gundegjerde and Halvorsen (2012), Joshi and Bolstad (2016). Moreover, the vessel market is not transparent, hence vessel pricing information is not easily provided by vessel service providers and not widely available. Nevertheless, this research attempts to gather knowledge on the vessel market where possible, to enable economic analysis. The approach includes a literature study on the existing studies regarding fleet models for offshore wind, e.g. Dalgic et al. (2013, 2015b), Gundegjerde and Halvorsen (2012), Kaiser and Snyder (2010), Stålhane et al. (2016) and oil & gas e.g. Maisiuk and Gribkovskaia (2014b), Strømberg (2015). Furthermore, information is gathered through stakeholders in the vessel market, such as Damen Shipyards via interviews with Robert (2018), Robert and Bouma (2018).

It is important to note here, that the offshore grid operator will have access over detailed vessel data once releasing tenders to contract new vessels for instance. The data used in the current case, collected via literature and interviews, is far from complete and accurate, however it does provide an overview of a possible vessel market and how this information can be used for economic analysis on the long-term fleet planning. In short, the focus does not lie on analyzing the cost, but rather on how this model could be applied to performs the economic analysis with the available data.

In addition to the nontransparent vessel market, the difficulty to analyze vessels is challenging. For instance the OSVs come in a variety of shapes and sizes with different equipment on-board. In table 7.2 a brief overview is provided on the categories of vessels which are included in the further analysis. In section 2.2 more detailed information is provided on these vessel concepts. Taking into account all possible vessel options may also lead to the solution space of the optimization model to be too large, resulting in resource intensive models. This thus requires a selection of vessels as input to the model and note that OptiFleet includes a step in the model-preparation phase which discards vessels not satisfying the maintenance needs.

Table 7.2: Recap of transportation means

Vessel type	Conventional Vessel Market	Modern Vessel Market
Helicopter	small, fast, but expensive with strict safety regulations, dedicated for crew transit and transfer	bigger, faster and more comfortable, still dedicated for crew transit and transfer
CTV Crew Transfer Vessel	small, fast, but uncomfortable, dedicated for crew transit and transfer and heavily restricted by weather conditions	bigger, faster and more comfortable, still dedicated for crew transit and transfer and less restricted by weather conditions
PSV Platform Supply Vessel	multi-purpose vessels to supply the offshore structures of material and crew. Design may include e.g: accommodation, working space, deck-space and lifting capacity.	Vessel structure improved to maximize fuel efficiency and transportation capacity for both crew and cargo, while functionality is added such as helipads and daughter-vessels
OSV Operation Support Vessel also known as Accommodation Support Vessel	N/A	Large scale multi-purpose accommodation support vessels, also known as walk-to-work vessels, providing all facilities as offshore platforms (accommodation, helipad, working-space, daughter-vessels, deck-space, lifting capacity etc. depending on the design) and extended offshore endurance compared to PSV

Table 7.3: Vessel types to be included in the TenneT case study

vessel type	pax capacity [pax]	lifting capacity [MT]	deck-space [m^2]	max range [nm/trip]	endurance [days]	wave restriction [m]	vessel availability [days/year]	operating speed [kn]
vessel 1 CTV-M	15	0	10	100	1	2	150	25
vessel 2 CTV-L	60	0	240	600	1	2.5	250	35
vessel 3 Heli	15	0	4	490	1	-	250	150
vessel 4 PSV-M	0	2	500	6000	20	2.5	200	13
vessel 5 PSV-L	70	4	800	9000	25	3	250	12

vessel 6 OSV-M	50	2	250	8000	30	2.5	250	11.5
vessel 7 OSV-L	90	6	900	10000	40	3	300	13
vessel 8 PSV-M + Heli	15	2	500	6000	20	2.5	200	150
vessel 9 PSV-M + CTV-M	15	2	500	6000	20	2	250	25
vessel 10 OSV-M + CTV-M	15	3	500	8000	25	2	250	25
vessel 11 OSV-M + Heli	15	3	500	8000	25	2.5	280	150

After addressing the general vessel concepts included in the case-study in table 7.2, table 7.3 presents the specific vessel types and the associated characteristics. The choice on these vessels is made after consultation with logistics staff at TenneT and with Damen Shipyards on which concepts may fit the TenneT case(Robert and Bouma, 2018). In table 7.4 an overview is provided on which real-life vessel is used as example for each vessel concept included.

Table 7.4: Reference vessel per category

vessel type	vessel model	shipyard/manufacturer	source
vessel 1 CTV-M	20T CATAMARAN CREW TRANSFER VESSEL e.g. CWind Athenia	CTruk Boats	(CWind, n.d.)
vessel 2 CTV-L	DAMEN FAST CREW SUPPLIER 7011	Damen Shipyards	(Damen Shipyards, n.d.)
vessel 3 Heli	AGUSTA AW189	Agusta Westland	(GlobalAir, n.d.)
vessel 4 PSV-M	60M MPP AHTSF	South China Marine Ltd	(SeaBoats, n.d.)
vessel 5 PSV-L	PLATFORM SUPPLY VESSEL UT 755 XL e.g. C110 - HIGHLAND PRINCESS	Rosetti Marino	(Rosetti Marino, 2015)
vessel 6 OSV-M	DP GALYNA	Holland Shipyards	(Chevalier Floatels, n.d.)
vessel 7 OSV-L	ACCOMMODATION SUPPORT VESSEL 9020	Damen Shipyards	(Damen Shipyards, 2017)

Vessel Contract Rates

Each vessel which can be considered to be added to the fleet can be contracted on a long- or medium-term charter contract which varies in length. Furthermore, vessels can be available on the spot-market for short-term chartering. Detailed information on Marine Vessel Contracting can for instance be found in the thesis by Valbrek. The long term contracts range between 1 and 10 years and the medium term contracts have a duration of 1 year. From the spot-market, vessels can be chartered on a daily basis, with an assumed maximum of a year. For the vessels on long- and medium-term contracts, depending on the chosen contract, the vessel is available for the period stated in the contract and remuneration occurs on a annual basis for that period. These contract costs can be considered the fixed cost for having the vessel in the fleet on a contract. On the other hand, the spot-market vessels are remunerated on a utilization basis for the days these vessels are utilized (Dalgic et al., 2013). These vessel charter costs thus depend on the contract, whereby the long term contracts typically yield lower rates than the mid-term contracts, and the mid-term contracts on their turn yield lower rates than the short-term contracts when taking the day-rate equivalent costs for these contracts (Dalgic et al., 2013, Døsen and Langeland). The day-rate equivalent costs are incorporated to compare the long- and medium-term contracts, which are remunerated annually, with the spot-market arrangements which are remunerated on a daily basis. The day-rate equivalent is subsequently calculated by dividing the annual contract costs for long- and medium-term contracts over the annual days included in the contract.

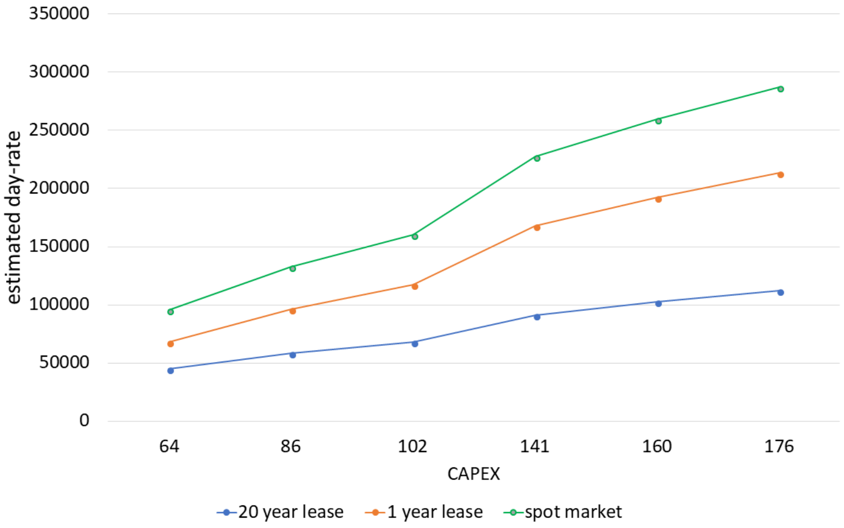


Figure 7.4: average day-rate estimation for jack-up vessels, adapted from (Dalgic et al., 2013)

In figure 7.4 the relation between estimated day-rates and the CAPEX for vessel acquisition is shown with a distinction in the contract type. This representation is for jack-up vessels, vessels which are typically used for wind-farm installation and maintenance of the larger scale. However, the same trend can be observed for other vessel types in the offshore wind industry (Dalgic et al., 2013, Døsen and Langeland). In this graph it can be observed that the difference in day-rates is significant between the three different contract types. The strength of the increase in day-rate, relative to the CAPEX, is also less strong for the long-term contracts, as compared to the mid- and short-term contracts. As can be observed, the difference in day-rates between the long-term contracts and the mid- and short-term contracts, increases as the CAPEX increases. This can be explained by the reduced risk to run without vessel revenue for the vessel owner when a vessel is contracted on the long-term to a client. In this way the vessel owner can provide lower day-rates (Døsen and Langeland).

Table 7.5: Overview of the contracts included in the TenneT case

contract type	duration	quantity [# of contracts]
short-term	1 day	360/year
medium-term	1 year	5
long-term	2 years - 20 years	5

Dalgic et al. (2013) also studied this relation relative to the different seasons in a year and could conclude that the difference in day-rate is significantly higher between mid-term and short-term contracts during summer. For the summer season, maintenance activity and thus vessel demand is high, as compared to the situation in winter when maintenance is not desired due to high production numbers.

In certain modern contracts, as a replacement for the conventional long- and medium-term contracts, a distinction in day-rates can be made between active day-rates, when the vessel is used, and idle-day rates, when the vessel is not used. This aims to maximize revenue for the vessel owner but also to incentivize efficient operation of the vessel (Robert and Bouma, 2018). Note that this distinction is not included in OptiFleet.

For the set of vessels which are included in the case-study, as previously presented in table 7.3, charter costs could be estimated. This is presented in table 7.6. Note that these are estimations as no concrete costs are available due to the non-transparent nature of the vessel market. Numbers are derived from previous studies such as Gundegjerde and Halvorsen (2012) for their case-study in the Norwegian market, Dalgic et al. (2015b), Stålhane et al. (2016) for the case of Great Britain, Dalgic et al. (2013) for the study on jack-up vessels, Kaiser and Snyder (2010) for the case on wind-farm installation vessels in the United States of America, Strømberg

(2015) for the study on PSVs in the Norwegian market, Maisiuk and Gribkovskaia (2014b) for the study on PSVs in different size classifications, but also through interviewing stakeholders such as Robert (2018), Robert and Bouma (2018) for their experiences as shipyard.

In addition to the day-rates and fixed contract costs charged to charter vessels, table 7.6 includes the vessel operational cost. The vessel operational cost can be described as the variable cost of vessels when deployed to sail out on a certain journey. Within these operational costs, fuel costs take the largest share. However, depending on the nature of the lease contract, costs can be added for among others, the vessel-operating crew (Maisiuk and Gribkovskaia, 2014b, Robert, 2018). The vessel operational cost in table 7.6 can be read as fuel costs and are determined based on fuel consumption information for vessels which can be placed among the vessel concepts included in the case and the market price for heavy- and medium fuel oil commonly used by these vessels. In table 7.4 an overview is provided on which real-life vessel is used as example for each included vessel concept and thus from which vessel operational costs are derived from.

Table 7.6: Cost estimation for vessels included in the case

vessel type	Vessel Operational Cost [€/hour]	Crew Accommodation Cost [€/pax/day]	Vessel Rates		
			Spot-market day-rate [€/day]	medium-term [€/year]	long-term [€/year]
vessel 1 CTV-M	170	200	4,791	1,261,416	720,000
vessel 2 CTV-L	383	200	11,977	3,153,540	1,800,000
vessel 3 Heli	2,034	200	9,093	2,394,168	1,366,560
vessel 4 PSV-M	453	200	12,000	3,159,492	1,803,397
vessel 5 PSV-L	955	100	18,000	4,739,238	2,705,096
vessel 6 OSV-M	219	100	23,955	6,307,080	3,600,000
vessel 7 OSV-L	716	100	47,910	12,614,160	7,200,000
vessel 8 PSV-M + Heli	2,487	200	21,093	5,553,659	3,169,957
vessel 9 PSV-M + CTV-M	623	200	16,791	4,420,908	2,523,397
vessel 10 OSV-M + CTV-M	389	100	28,746	7,568,496	4,320,000
vessel 11 OSV-M + Heli	2,253	100	33,048	8,701,248	4,966,560

Finally, accommodation cost are included for each vessel type in table 7.6. These cost entail what needs to be paid per crew member for catering and housing when deployed on a maintenance campaign. The value of the costs depends on the facility where crew stay during a campaign as this can be on the offshore platform or on certain vessels. In the TenneT case, where accommodation is currently provided on the platforms, a figure of 200 €/pax/day can be assumed for accommodation cost per pax per day as derived from a personal communication with Jan Heinrich at TenneT (June, 2018). As mentioned, accommodation can be provided on the vessel, however, not all vessel types provide accommodation for pax. The vessel types which do offer accommodation are: OSV-L, OSV-M and PSV-L, and accommodation cost for these vessels are assumed at 100 €/pax/day. This can be motivated by the premise that when OSV-L, OSV-M and/or PSV-L are utilized, crew stay on the vessel and accommodation facilities on the platforms could be decommissioned. The decommissioning of accommodation facilities on platforms, along with the elimination of the maintenance of these facilities and the consolidation of facilities and logistics to the vessels is the motivation behind the expected cost decrease.

Maintenance activities

Table 7.7: Preventive and Corrective maintenance activities

name	annual frequency	probability [%]	Logistic need				type
			duration [days]	crew required [#crew]	lifting need [MT]	deck-space required [m^2]	
campaign_a	1	-	14	30	4	500	Periodical preventive maintenance medium
campaign_b	1	-	14	20	4	400	Periodical preventive maintenance small
campaign_c	1	-	14	40	4	700	Periodical preventive maintenance large
campaign_d	1	-	14	30	4	500	Periodical preventive maintenance medium
failure_a	-	50	1	10	1	10	Small failure e.g. small mechanical or structural damage to critical components
failure_b	-	10	10	20	2	400	Medium failure e.g. medium mechanical or structural damage to critical components
failure_c	-	0.1	30	30	5	700	Large failure of critical components e.g. converter or cable

Note that for the maintenance activities presented in table 7.7, the distinction in small, medium and large relates to the scale of the logistic needs, rather than on the consequences of the maintenance activity or failure in terms of, for instance, platform downtime.

Furthermore, the failure rates from which the probability of failures requiring corrective maintenance are derived, are based on historic data and are thus expected failure rates. This forms a source of uncertainty in the actual demand for repairs. This uncertainty is enforced by the numerous "open-points" present on platforms between TenneT and third party suppliers and service providers. This is different per platform, since the platforms in the German OTG are not homogeneous and come from different consortia of manufacturers such as ABB and Siemens. This entails that the maintenance activities may vary between the platforms, but also for the individual platforms at different points in time. This variance affects the service time of the maintenance activity and the amount of technicians required per activity (Diekmann, 2018, Heinrich, 2017b).

Other Assumptions

In this subsection assumptions are discussed which can not be directly placed under the previously mentioned categories. These assumptions are implemented in the model parameters.

1. Aspects which are excluded:
    (a) Areal restrictions as to where vessels cannot operate are not included in the routes vessel operate on, the routes can be described as straight-lines between base and platform
    (b) TenneT platforms are usually open for supply and crew transfer from 7:00 to 19:00, in exceptional cases the time-window is extended to 20:00. This restriction could influence vessel operations on the tactical and operational level, but is not included in the strategic model
    (c) Ports to be used as bases also have opening hours, which may differ per port, but for the same reason as the previous point this aspect is also omitted

2. Aspects which are included:
    (a) From a significant wave height >= 3.5 meters no outboard work including delivery and pickups are executed
    (b) From a significant wave height >= 2 meters, crew transfer from boat transfer to the platform is restricted, assuming the use of traditional boat-landing and the absence of walk-2-work gangways which may increase this transfer criterion
    (c) Travel time with CTVs should not be higher than 4 hours per employee
    (d) The service time for crew and cargo pick-up and delivery for a single platforms is around 3 hours.

7.2. Results of the TenneT case study

After discussing the TenneT case and how data can be derived for this case in the previous sections, this section presents the results of the TenneT case. In the following section, the results will be presented for the 6 sub-cases: DE-2023, NL-2023, DE-NL-2023, DE-2030, NL-2030 and DE-NL-2030.

The first results to be presented are the realized optimality gaps with the associated solving time, in relation to the corresponding sub-case size. Afterwards, the fleet composition for the 6 sub-cases is discussed. Subsequently, sub-sections will present the cost performance analysis to address the economies of scale and the expected benefits of integrating Dutch and German logistics. Furthermore light is shed on the port selection, where it will be presented which ports are most suitable to operate from, for each sub-case.

Finally, the results will be proceeded by a sensitivity analysis on the model input parameters to determine the model robustness on the uncertainty in the assumptions made regarding the model input.

It should be noted again that a fair share of the data used for this case-study is from third parties or estimated from comparable cases in literature. This implies that the results do not reflect detailed and accurate costs for the real-life situation, but instead propose vessel fleet solutions which are optimal, given the data available. The resulting knowledge on how to use the model can be applied for detailed cost analysis, once the actual costs are known by the decision maker.

The following sub-sections dive deeper into the case results and will respectively present the fleet composition, the economic analysis and the the port selection.

7.2.1. OptiFleet output for the six sub-cases

The platform networks modelled for the 6 sub-cases and elaborated in sub-section 7.1.1, are summarized in table 7.8. This table also presents the size of the implemented sub-case in terms of the rows and columns, together with the time needed to solve the model and what optimality gap is associated to that model outcome.

Table 7.8: Overview of the case characteristics

sub-case	platforms		clusters		maintenance activities		columns	rows	time [s]	optimality gap [%]
	DE	NL	DE	NL	DE	NL				
DE-2023	9	0	6	0	587	0	67,804	100,471	63.31	0.00
NL-2023	0	5	0	3	0	474	35,212	51,444	43.17	0.00
DE-NL-2023	9	5	6	3	820	474	101,740	151,830	220.79	0.00
DE-2030	12	0	7	0	1,090	0	79,340	118,030	110.08	0.00
NL-2030	0	12	0	8	0	1,100	89,084	132,733	241.13	0.00
DE-NL-2030	12	12	7	8	1,090	1,100	166,028	248,836	534.54	0.00

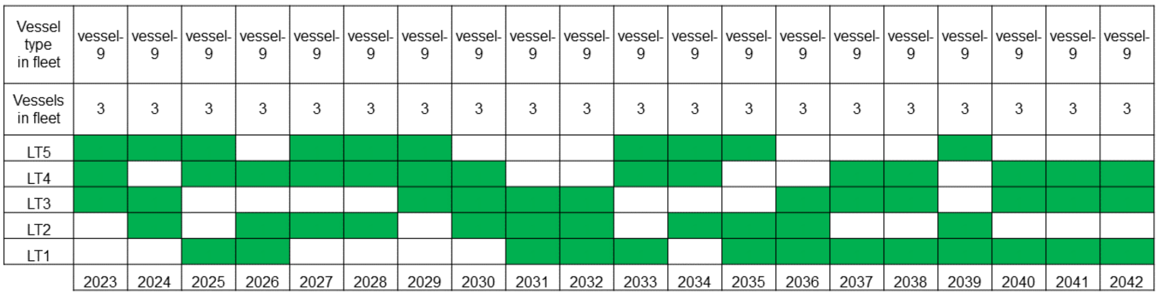
It can be stated that with the current implementation of OptiFleet and the settings for the Gurobi solver as mentioned in chapter 6, all 6 sub-cases can be solved to optimality with an OG of 0.00%. As mentioned in sub-section 6.2.1 for a solution to be accepted as the optimal solution of the problem, the OG needs to be 0.0% and to assume a sub-optimal solution as acceptable, the OG should generally be below 2%, depending on the size of the problem (Bixby and Rothberg, 2007, Gamrath et al., 2015). These results are also reached within reasonable time, the longest sub-case takes around 535s to be solved.

Results: Fleet composition

The Fleet Composition Tables (FCT) present the derived optimal fleet composition for the 6 sub-cases. The FCTs illustrated in figures 7.5 to 7.10, exhibit the following three aspects: 1) the type of vessel included in the fleet every year, 2) the number of vessels in the fleet every year, and 3) the contracts according to which the vessels are added to the fleet. By presenting this information, the FCTs aim to provide concise information on how OptiFleet proposes the fleet planning for TenneT over the time-span of 20 years for different platform networks.

DE-2023: Fleet composition

Sub-case DE-2023 can be considered the current state scenario for the offshore platform network in Germany, including the two platforms to be commissioned between 2019 and 2023. As mentioned before, the current situation logistics of the German OTG deploys helicopters for crew transportation to and from the platforms and once at the platforms the crew is accommodated on the platform itself. One objective of this study is to determine whether the marine vessel solutions are economically outperforming helicopters, given the platform network and maintenance strategy.



Vessel type in fleet	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9
Vessels in fleet	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
LT5	🟩	🟩	🟩		🟩	🟩	🟩				🟩	🟩	🟩				🟩			
LT4	🟩		🟩	🟩	🟩	🟩	🟩	🟩			🟩	🟩			🟩	🟩		🟩	🟩	🟩
LT3	🟩	🟩					🟩	🟩	🟩	🟩				🟩	🟩	🟩		🟩	🟩	🟩
LT2		🟩		🟩	🟩	🟩		🟩	🟩	🟩		🟩	🟩	🟩			🟩			
LT1			🟩	🟩					🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042

Figure 7.5: Fleet Composition Table for DE-2023

In the FCT for DE-2023 in figure 7.5 it can be seen that the chosen vessel in the fleet is of type "vessel-9". This is a combination of a PSV-M, a vessel dedicated for the transportation of cargo with no facilities for the accommodation of crew, and a CTV-M, a vessel dedicated for the transportation of crew. Together these two vessels thus provide in the logistic needs for the DE-2023 sub-case.

The selection is thus made for a solution other than the helicopter, entailing that in OptiFleet the use of ships outperforms the use of helicopters. Note that this is the case for the long-term fleet composition. On the short term, given uncertainty and irregularities, helicopters might still be necessary to be temporarily chartered. This could occur for instance if skilled labour needs to be transported to the platforms or for emergencies. In this scenario of an emergency or the immediate need for skilled labor, waiting on the vessel might be unfeasible and a helicopter is necessary.

In the FCT, the green cells indicate the contract on which the vessel is in the fleet. The green colour indicates that the contract is a long-term contract and in the first column, the terms LT1, LT2, LT3 etc. represent the individual contracts, long-term-1, long-term-2 etc. For instance long-term contract 1, LT1, is subsequently included on three instances. First for a duration of 2 years from 2025 to 2026, then for a duration of 3 years from 2031 to 2033 and finally for a duration of 8 years from 2035 to 2042. From the FCT it can be derived that the vessels are contracted on long-term contracts which vary in duration between 1 year and 5 years. When summing up the contracts for each year, it can be seen that annually 3 vessels of each type, PSV-M and CTV-M, are in the fleet on a long-term contract. This totals to 6 individual vessels in the fleet annually.

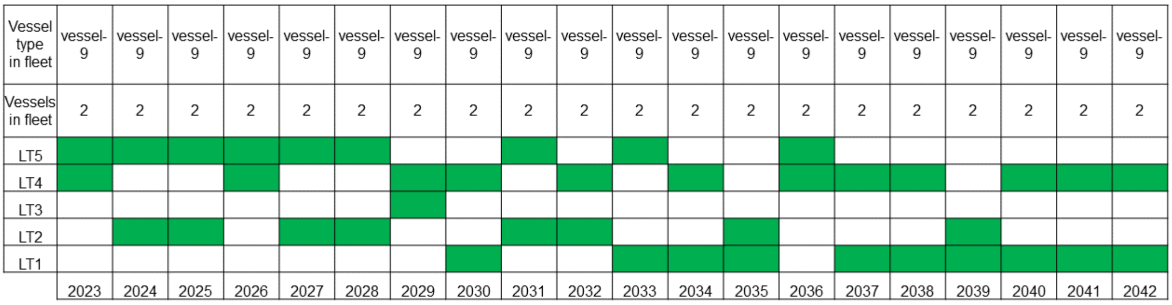
On the first glance, 6 vessels for a platform network of 9 platforms in sub-case DE-2023 can be considered as high. And this perhaps rises questions on the expected increase in efficiency as promised by OptiFleet. This can be explained by the constraints which are included to guarantee that maintenance is executed once planned in the case of preventive maintenance, or once a failure occurs in the case of corrective maintenance.

These constraints limit the flexibility in the contracting of vessels, and require that vessels are available at all times. If maintenance could be postponed, the number of vessels in the fleet could be lower since it would not be necessary to have ample vessel capacity available at all times. Maintenance could be postponed until vessel capacity is available again, instead of making sure to always have vessel capacity available.

Finally, based on the vessel fleet composition a recommendation can be made for the accommodation strategy. For DE-2023 the recommended fleet always consists of vessels without the facilities to accommodate crew on their stay offshore for longer periods, namely the vessel types PSV-M and CTV-M. As a result it can be concluded that the strategy relies on platform facilities for crew accommodation and the recommendation is to maintain the accommodation facilities on the platforms in the German grid.

NL-2023: Fleet composition

For the Dutch situation in 2023, NL-2023, the first observation from the FCT in figure 7.6 is that vessel type "vessel-9" is also the dominant vessel in the fleet, similar to DE-2023. However, instead of three vessels of each PSV-M and CTV-M in the fleet, as is the case for DE-2023, NL-2023 suffices with two vessels of each type. This is expected since NL-2023 has 5 platforms, compared to the 9 platforms in DE-2023.



Vessel type in fleet	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9
Vessels in fleet	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
LT5	🟩	🟩	🟩	🟩	🟩	🟩			🟩		🟩			🟩						
LT4	🟩			🟩			🟩	🟩		🟩		🟩		🟩	🟩	🟩		🟩	🟩	🟩
LT3							🟩													
LT2		🟩	🟩		🟩	🟩			🟩	🟩			🟩				🟩			
LT1								🟩			🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩
	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042

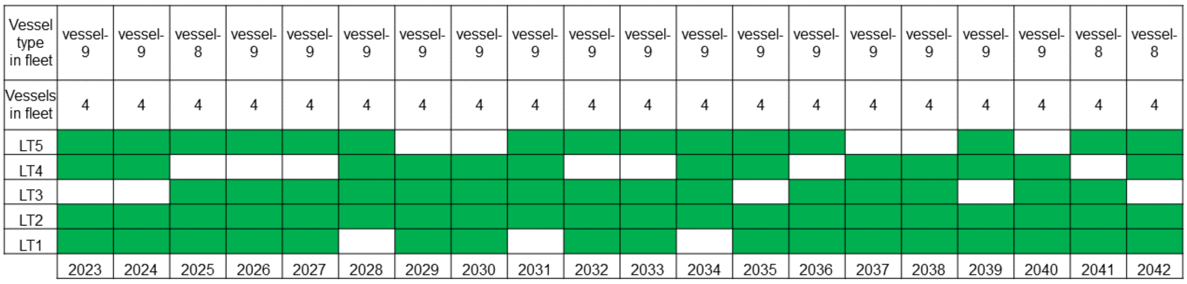
Figure 7.6: Fleet Composition Table for the NL-2023 sub-case

The medium PSVs and medium CTVs, are contracted on long-term contracts as is indicated by the green cells, ranging from a duration of one year up to a duration of 6 years.

Based on the vessel selection, where the fleet consists of vessels without facilities to accommodate crew for longer periods offshore, it can be concluded that the strategy relies on platform facilities for crew accommodation in the NL-2023 sub-case.

DE-NL-2023: Fleet composition

DE-NL-2023 represents the scenario where both the German and Dutch grid are considered as a single network for the long term fleet planning. The expectation is that in this integrated case, due to the economies of scale, possibilities arise to combine vessels for both grids, only hence increasing vessel utilization and reducing costs. The expected cost benefits will be further elaborated on in sub-section 7.2.1, as this sub-section only addresses the fleet composition.



Vessel type in fleet	vessel-9	vessel-9	vessel-8	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-9	vessel-8	vessel-8
Vessels in fleet	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
LT5	🟩	🟩	🟩	🟩	🟩	🟩			🟩	🟩	🟩	🟩	🟩	🟩			🟩		🟩	🟩
LT4	🟩	🟩				🟩	🟩	🟩	🟩			🟩	🟩		🟩	🟩	🟩	🟩		🟩
LT3			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩		🟩	🟩	
LT2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LT1	🟩	🟩	🟩	🟩	🟩		🟩	🟩		🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042

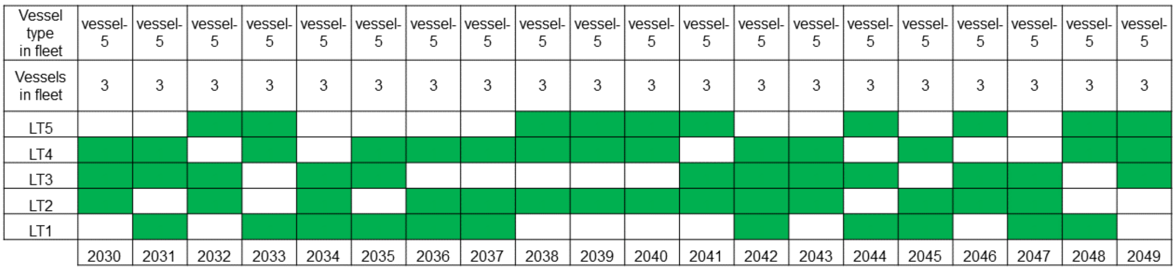
Figure 7.7: Fleet Composition Table for the DE-NL-2023 sub-case

It can be observed that also in the DE-NL-2023 sub-case, the fleet is dominated by the medium PSV. In addition, the medium PSVs are complemented with either medium CTVs, in "vessel-9", or helicopters in "vessel-8". Annually, four vessels are in the fleet and these vessels are added on long-term contracts. The long-term contracts in the integrated sub-case generally have a longer duration than in the separate DE-2023 and NL-2023 cases, in other words, there is less dispersion in the contracts. In the real-life vessel market this consistency in the long-term contracts may lead to even lower contract costs, because the risks for the vessel owner are reduced with the guarantee of its vessel being contracted for longer periods. This effect is not included in the current implementation of OptiFleet.

Based on the vessel selection, where the fleet consists of vessels without facilities to accommodate crew for longer periods offshore, it can be concluded that the strategy relies on platform facilities for crew accommodation in the NL-2023 sub-case.

DE-2030: Fleet composition

For the first sub-case in the 2030 category, DE-2030, OptiFleet generates a fleet dominated by the large PSV, "vessel-5". Compared to the DE-2023 sub-case, the choice is now made for the bigger vessel and due to the bigger vessel the total amount of vessels goes from 6, three PSV-M and three CTV-M for DE-2023, to three PSV-L for DE-2030.



Vessel type in fleet	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5
Vessels in fleet	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
LT5			🟩	🟩					🟩	🟩	🟩	🟩			🟩		🟩		🟩	🟩
LT4	🟩	🟩		🟩		🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩		🟩			🟩	🟩
LT3	🟩	🟩	🟩		🟩	🟩						🟩	🟩	🟩	🟩		🟩	🟩		🟩
LT2	🟩		🟩		🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩		
LT1		🟩		🟩	🟩	🟩	🟩	🟩					🟩		🟩	🟩		🟩	🟩	
	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049

Figure 7.8: Fleet Composition Table for the DE-2030 sub-case

The increase from 9 to 12 platforms in the German grid and the improved opportunities to cluster platforms can be pointed out as the main driver for the shift in vessel types and the subsequent number of vessels in the fleet. In the DE-2030 case, the average number of platforms in a cluster is 1.71, while that number is 1.5 for DE-2023.

Regarding the fleet capabilities for DE-2023, the large PSV is a multipurpose vessel which delivers capabilities such as significant deck-space, lifting capacity, crew accommodation capacity and the ability to accommodate operations with small to medium CTVs and helicopters through boat-landing facilities and helipads respectively. Characteristics which are very much in line with the modern OSV, however at significantly lower chartering cost. These chartering costs are lower for the PSV because these vessels have been in the market for decades and over time the costs to acquire and operate these vessels decreased, whereas the OSV solutions are new to the market and still in the early phases of operational diffusion within offshore companies. Moreover, there is an oversupply of these PSVs in markets all over the World, including the North Sea, and this presses down the prices for PSVs even further (Daleel, 2018).

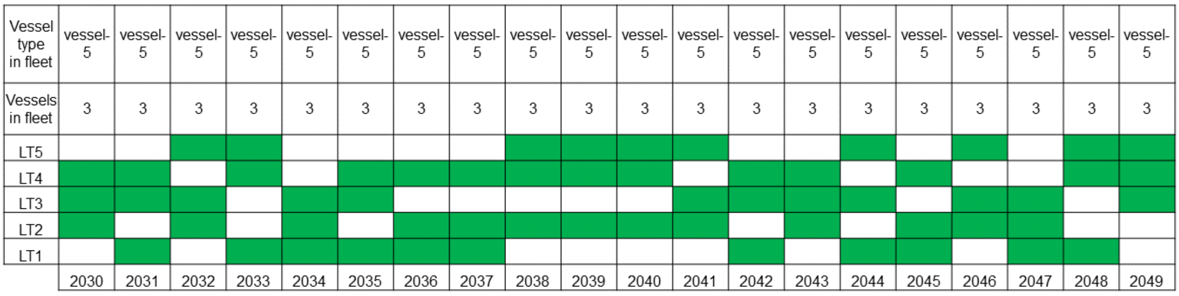
For DE-2030, the recommended accommodation strategy is to make the shift from platform based accommodation to vessel based floating accommodation of crew during the maintenance campaigns. This can be stated as a result of the vessel fleet composition which always consists of crew accommodation enabled vessels, namely the large PSV.

NL-2030: Fleet composition

When moving from the NL-2023 situation to the NL-2030 situation, it can be observed that the vessel fleet shifts from the PSV-M + CTV-M composition to a fleet consisting of the PSV-L, represented as vessel type "vessel-5' in the corresponding FCT in figure 7.9. Of these large PSVs, the fleet consists of three vessels, a fleet size which is on par with the German fleet.

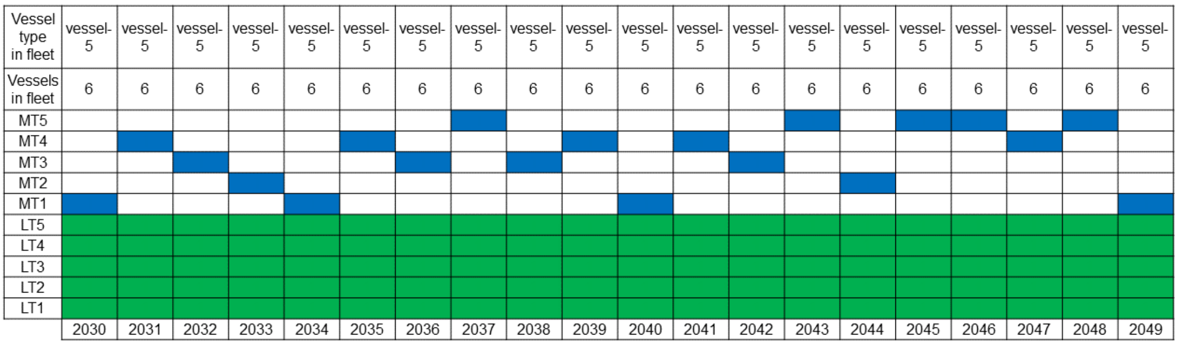
Regarding the accommodation strategy, based on the vessel fleet composition which always consists of crew accommodation enabled vessels, the large PSV, it can be concluded that the strategy also relies on floating vessel facilities for crew accommodation in the NL-2030 sub-case.

DE-NL-2030: Fleet composition



Vessel type in fleet	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5
Vessels in fleet	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
LT5			🟩	🟩					🟩	🟩	🟩	🟩			🟩		🟩		🟩	🟩
LT4	🟩	🟩		🟩		🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩		🟩			🟩	🟩
LT3	🟩	🟩	🟩		🟩	🟩						🟩	🟩	🟩	🟩		🟩	🟩		🟩
LT2	🟩		🟩		🟩		🟩	🟩	🟩	🟩	🟩	🟩		🟩		🟩	🟩	🟩		
LT1		🟩		🟩	🟩	🟩	🟩	🟩					🟩		🟩	🟩		🟩	🟩	
	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049

Figure 7.9: Fleet Composition Table for the NL-2030 sub-case



Vessel type in fleet	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5	vessel-5
Vessels in fleet	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
MT5								🟦						🟦		🟦	🟦		🟦	
MT4		🟦				🟦				🟦		🟦						🟦		
MT3			🟦				🟦		🟦				🟦							
MT2				🟦											🟦					
MT1	🟦				🟦						🟦									🟦
LT5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LT4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LT3	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LT2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LT1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049

Figure 7.10: Fleet Composition Table for the DE-NL-2030 sub-case

Finally, for the integrated approach in 2030, the combined fleet is proposed to be composed out of 6 large PSV vessels. Of these vessels, five vessels are contracted on long-term contracts as can be seen by the green cells in figure 7.10. The sixth vessel is contracted on 1-year mid-term contracts, indicated by the blue cells in the FCT. This can be explained by the modeled scarcity in long-term contracts, which are limited to 5 for each vessel type. After the long-term contracts for a certain vessel type run out, the model assesses the choice to either opt for a different vessel on a long-term contract, or the same vessel on a mid-term contract. The per year contract cost for a mid-term contract is higher than for a long-term contract, but despite the higher price, an additional large PSV on a medium-term contract is more economic than opting for another vessel on a long-term contract.

Regarding the accommodation strategy, based on the vessel fleet composition, where the fleet always consists of crew accommodation enabled vessels, the large PSV, it can be concluded that the strategy also relies on floating vessel facilities for crew accommodation in the DE-NL-2030 sub-case.

Synthesis of the fleet recommendation

In the previous sub-section, the fleet composition is individually addressed for each sub-case. This resulted in three sub-cases where medium PSVs in combination with a medium CTV are recommended to transport the cargo and crew respectively. These are the DE-2023, NL-2023 and DE-NL-2023 sub-cases. The sub-cases for the situation in 2030, namely DE-2030, NL-2030 and DE-NL-2030, are associated with a fleet recommendation consisting of the large PSV, a solution which integrates both cargo transportation and crew transportation and accommodation in an integrated vessel solution.

In short, it can thus be stated that for the platform network associated to the 2023 cases, the scale is not big enough to gain sufficiently from the integrated solution. For the 2023 case the recommendation is to maintain accommodation of the crew on the platforms and transport cargo with the PSV-M and crew with the CTV-M. In the meantime, the organization can learn and acclimatize to executing maintenance campaigns with maritime vessels instead of helicopters. Additionally, the organization is left with more time to prepare for the implementation of integrated vessel solutions with vessels such as the large PSV and OSVs.

On the other hand, the 2030 situation provides sufficient scale and clustering opportunities to make the shift to the integrated vessel solution as presented in the previous sub-section. After implementing the PSV-M + CTV-M concept for the 2023 cases, the organization should be ready to shift to the integrated vessel option in 2030.

Finally, the recommendation for vessel choice once opting for the strategy to integrate transportation and accommodation in a single vessel concept, is to acquire the large PSVs with comparable abilities as the OSVs. Due to the novelty of the OSVs these vessels are currently very high priced in the market and little operational experience exists. On the contrary, there is an oversupply in PSV vessels leading to low prices and a relatively easy inclusion of the vessel in the organization due to the ample operational experience with these vessels in the offshore industries (Daleel, 2018, Døsen and Langeland, Rosetti Marino, 2015).

After addressing the fleet composition in this sub-section, in the following sub-section an example of economic analysis will be presented based on the cost performance of the 6 sub-cases.

Results: cost performance

As mentioned in the introduction of this results section, OptiFleet will not be used for detailed cost analysis in this study due to lacking accurate data. However, with the available data and assumptions, an example of how cost analysis with OptiFleet could be performed is presented in this sub-section.

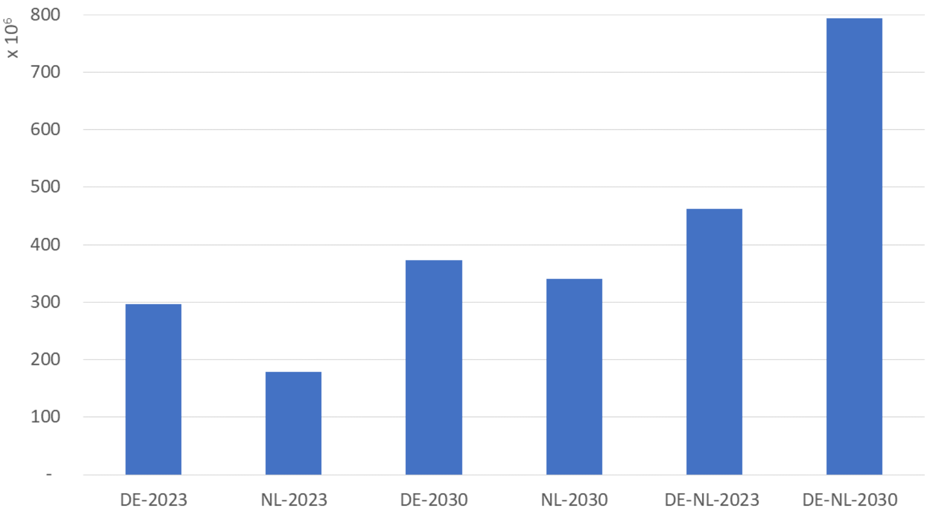


Figure 7.11: Total cost for the 6 sub-cases in [€]

First of all, the total costs in [€], are presented in figure 7.11 and in table 7.9. When comparing the total cost output for the German and Dutch sub-case separately, it can be observed that the total cost are significantly higher for the German grid than for the Dutch grid in 2023. This can be explained by the larger size of the German grid in 2023, resulting in higher maintenance needs. This difference is less significant for the DE and NL cases in 2030 where both grids consist of 12 platforms. Nevertheless, the total cost are less for the NL case than the DE case in 2030. One reason to explain this, is that the distance between platforms is smaller in the Dutch grid which leads to more efficient cluster forming to combine maintenance campaigns for platforms within a cluster. Moreover, the majority of the Dutch platforms are closer to shore than the German platforms and in addition to lower vessel operational costs due to less sailing time, this contributes to less travelling time for crew, resulting in less loss-time for which wages still need to be paid when the crew is en-route to and from platforms.

The highest total costs are associated to the integrated case in 2030, DE-NL-2030. This is also the largest case. When comparing the integrated cases for 2023 and 2030, that is DE-NL-2023 vs. DE-NL-2030, the number of platforms in 2030 is a factor 2 larger than in 2023. However, the total costs are less than twice as large for the 2030 case, this signifies the positive effect of economies of scale.

As discussed in the sections 7.1.2 and 5.6.5, the total cost consist of: 1) the base utilization costs, 2) vessel charter cost, either for vessels on long- and medium-term contracts or from the spot-market, 3) operational cost, these are the variable cost per hour of vessel operation, for instance the fuel costs but also crew wages for the time they are en-route from base to cluster and 4) the accommodation costs, the costs made to accommodate the crew once deployed on a maintenance assignment. The percentual contribution of each cost category to the total costs is presented in figure 7.12, where the bar-chart provides an overview of how these different cost posts, together compose the total cost.

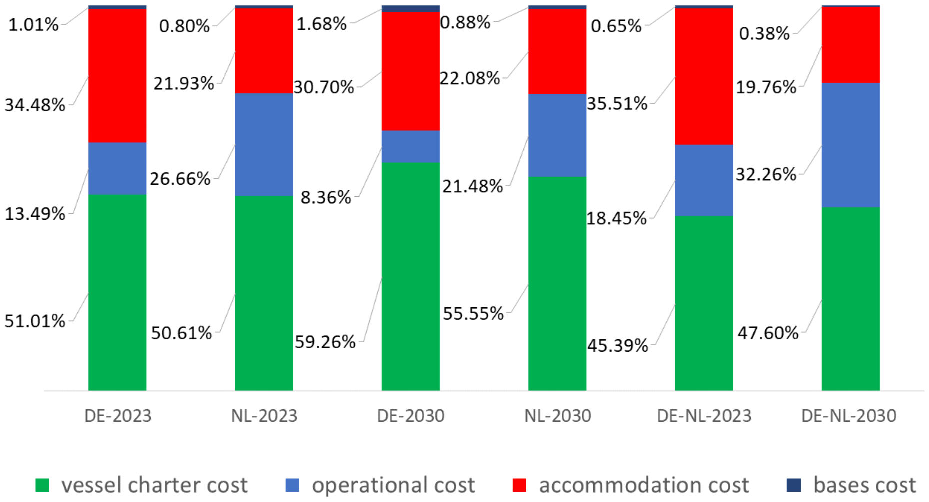


Figure 7.12: cost breakdown in [%] for the 6 sub-cases

The operational cost are percentually lower for DE, compared to NL, see figure 7.12. On the other hand the vessel charter cost are higher for DE and this can be explained by the larger fleet size for DE, compared to NL.

Furthermore, by observing the % documented in each cost category, it can be concluded that the total vessel costs are dominated by the vessel charter cost at 51.01%, 50.61%, 59.26%, 55.55%, 45.39% and 47.60% respectively for the 6 sub-cases. Based on this finding, and the fact that no accurate data was available for the vessel charter-rates, it is proposed to execute a sensitivity analysis with the vessel charter rates. This will be further elaborated in section 7.2.2.

Table 7.9: Cost break-down in [€] and the [%] change in cost between sub-cases

	DE-2023 [€]	DE-2030 [€]	Δ DE-2023 - DE-2030 [%]	NL-2023 [€]	NL-2030 [€]	Δ NL-2023 - NL-2030 [%]	DE-NL-2023 [€]	DE-NL-2030 [€]	Δ DE-NL-2023 - DE-NL-2030 [%]
total cost	296,786,035	373,328,982	26%	178,786,209	340,103,895	90%	461,809,436	793,796,822	72%
bases cost	3,000,000	3,000,000	0%	3,000,000	3,000,000	0%	3,000,000	3,000,000	0%
vessel contract cost	151,403,832	188,941,920	25%	105,940,966	188,941,923	78%	209,630,495	377,883,840	80%
vessel spot-market cost	0	0	0%	0	0	0%	0	0	0%
operational cost	40,036,204	99,531,058	149%	14,955,242	73,056,971	389%	85,206,940	256,096,982	201%
accommodation cost	102,346,000	81,856,000	-20%	54,890,000	75,105,000	37%	163,972,000	156,816,000	-4%

In table 7.9 it can also be observed that the operational cost increase as the cases increase in size, e.g. NL-2023 vs. NL-2030. This can be explained by the fact that with the larger cases, the network of platforms increase, this leads to more and longer journeys being made which require more fuel. In addition, more platforms means more maintenance and thus more crew. With the increasing journey times, the risk is that the loss-time of crew increases and this is reflected in en-route wages.

In the comparison between the 2023 and 2030 situation through table 7.9, for the OTG in Germany, from 2023 to 2030 a growth of 17% occurs in the number of platforms. However, the total costs increase with 26%. The largest increase in cost, in terms of the percentage, can be found in the operational cost with 149%. The same strong increase in total costs, largely contributed for by the vessel operational costs, can be observed for the NL sub-cases. On the other hand, a decrease in the accommodation cost can be observed for Germany and this can be motivated by the shift from platform accommodation to the vessel accommodation. This shift in accommodation strategy thus yields lower accommodation cost, but higher operational costs due to the vessel being offshore for longer periods.

For the Dutch network from 2023 to 2030, both the operational and accommodation costs increase due to the strong growth in the number of platforms in the Dutch grid with around 260%. The total costs subsequently increase with 90%.

When looking at the integrated DE-NL cases, an increase of 100% can be observed in the amount of platforms which need to be serviced in 2030, compared to 2023. On the other hand, the increase in costs is less at 72%. The accommodation cost are the cost category with the largest percentual increase here.

Results: cost saving as result of DE and NL grid integration

In this sub-section the focus lies on the specific cost comparison between approaching the German and Dutch grid separately in terms of fleet management, or as an integrated whole. The aim is to present the expected benefit in costs if the two offshore grids are integrated in the planning and deployment of the vessel fleet for maintenance.

The first comparison between the individual grid approach and the integrated grid approach can be addressed by means of the fleet size. If the Dutch and German OTG are considered as two separate and isolated logistic areas where vessels are exclusive to either the Dutch or German network, the fleet size equals three vessels for DE and two vessels for NL in 2023, while the fleet size increases to three vessels for both DE and NL in 2030. Hence, when summing up the DE and NL fleet, the total fleet size adds up to 5 vessels in 2023 and 6 vessels for 2030.

However, if the two networks are integrated for the 2023 situation in DE-NL-2023, it can be observed that less vessels are necessary relative to the isolated planning. For DE-NL-2023, at all times, four vessels are in the fleet and this is one vessel less than the sum of the DE and NL fleets in the isolated approach. This thus entails more efficient utilization of the vessels for the integrated approach.

Unlike DE-NL-2023, the integrated approach for 2030 exhibits no benefits with regards to a smaller fleet size. When combining the separate DE and NL fleets of DE-2030 and NL-2030 the total equals 6 vessels, while the proposed fleet for the integrated DE-NL-2030 is also equal to 6 vessels.

In tables 7.10 and 7.11 the cost performance is presented for the isolated and integrated approach for 2023 and 2030 respectively. In the fourth column the costs for DE and NL are summed up to get the total costs when the Dutch and German OTG are considered as separate systems in DE-2023, NL-2023, DE-2030 and NL-2030 respectively. These costs can subsequently be compared to the fifth column in which the costs are presented if the Dutch and German grid are considered in an integrated manner, respectively DE-NL-2023 and DE-NL-2030.

For the 2023 case, the results are in line with the expectations to achieve lower total costs for the integrated approach. In the integrated case DE-NL-2023, the total costs are 3% lower than in the separate case. It can be observed that for the integrated case, all cost factors are lower, except for the accommodation costs. The biggest cost benefit is reached for the vessel contract costs, these costs are 50% lower for the integrated approach. On the other hand, for the integrated case in 2023, the accommodation costs are 55% higher compared to the separated cases summed up. This largely cancels out the savings in the other cost categories, leading to a rather minimum benefit of integrated logistics.

Where the logistic integration leads to fair benefits for the 2023 case, the proposed logistic integration leads to higher costs for the 2030 situation. In table 7.11 the costs for the integrated approach are 11% higher than for the separate approach. The higher costs are especially caused by the high operational cost for the integrated approach.

Table 7.10: Cost comparison for the scenarios of treating DE and NL separately or integrated in 2023

	DE-2023 [€]	NL-2023 [€]	DE-2023 + NL-2023 [€]	DE-NL-2023 [€]	Δ DE-2023 + NL-2023 vs. DE-NL-2023 [%]	Δ DE-2023 + NL-2023 vs. DE-NL-2023 [%]
total cost	296,786,035	178,786,209	475,572,245	461,809,436	13,762,808	-3%
base utilization costs	3,000,000	3,000,000	6,000,000	3,000,000	-3,000,000	-50%
vessel charter cost	151,403,832	105,940,967	257,344,798	209,630,495	-47,714,303	-19%
operational cost	40,036,204	14,955,242	54,991,446	85,206,941	30,215,495	55%
accommodation cost	102,346,000	54,890,000	157,236,000	163,972,000	6,736,000	4%

Table 7.11: Cost comparison for the scenarios of treating DE and NL separately or integrated in 2030

	DE-2030 [€]	NL-2030 [€]	DE-2030 + NL-2030 [€]	DE-NL-2030 [€]	Δ DE-2030 + NL-2030 vs. DE-NL-2030 [%]	Δ DE-2030 + NL-2030 vs. DE-NL-2030 [%]
total cost	373,328,978	340,103,895	713,432,873	793,796,822	80,363,949	11%
base utilization costs	3,000,000	3,000,000	6,000,000	3,000,000	-3,000,000	-50%
vessel charter cost	188,941,920	188,941,924	377,883,840	377,883,840	0	0%
operational cost	99,531,058	73,056,972	172,588,030	256,096,982	83,508,953	48%
accommodation cost	81,856,000	75,105,000	156,961,000	156,816,000	-145,000.00	0%

In short, it can thus be stated that the model provides means to study the benefits of OTG integration to a certain extent, but the results are not as expected. The following can be proposed to improve the results and bring them closer to the expected and desired behavior: *include a maintenance planning mechanism with combined vessel routes.* This would align and coordinate the periods when maintenance should be carried out on the platforms in combined campaigns. Subsequently, the combined maintenance campaigns can be connected to optimal vessel routes which combines platform campaigns in more detail as currently occurs in OptiFleet. Ultimately this adjustment should lead to decreased costs due to the optimization of the vessel utilization with combined campaigns in optimal routes. This is an aspect which would require extending the model with an increased tactical level and the addition of operational decisions.

Results: harbour selection

A unique functionality of OptiFleet, compared to existing fleet composition models, is the ability to determine which harbour to use as base for the offshore operations, given the network of platforms and the maintenance demand. OptiFleet namely includes means to model the base utilization cost, but also accounts for the distance between the harbours and the platforms. In figure 7.13 it is depicted which harbours are utilized in each sub-case.

Note that the constraint is enabled that at max *three* harbours may be used in the optimal solution. This is assumed to be a manageable number of harbours to operate from. Operating from too many harbours would result in high costs for customs, material handling and storage. These extra costs and efforts may cancel the gains in operational cost and travel time from the distance to platform minimization.

Furthermore, it is assumed that it should be possible to change the base of operation annually. Taking these two points into account, the base-utilization is mapped in figure 7.13, for each sub-case

The harbour of Delfzijl is the designated harbour to support maintenance activities in the German grid for

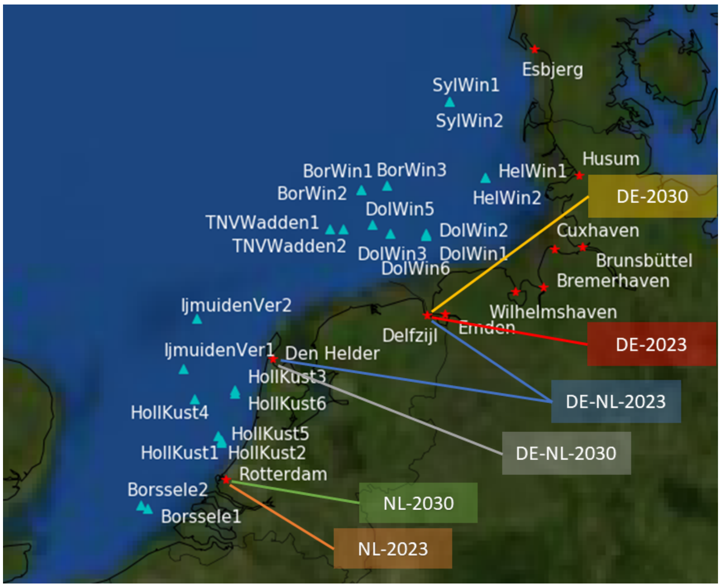


Figure 7.13: This map exhibits the ports utilized in the optimal solution for each sub-case

DE-2023 and DE-2030. In the study by Wolfsturm (2017b) to determine the shortest route along the platforms in Germany, Delfzijl is likewise recommended for operations in the West-cluster. This recommendation is thus solely based on the minimum sum of distances between the harbour and the platforms to execute the maintenance campaigns at the platforms on an annual basis.

Moreover, the recommendation for Delfzijl is made based on the assumption that a harbour has to be chosen in a green field situation and this implies that no existing operations or infrastructure is assumed from any particular harbour. However, the German grid is currently being supported from the harbour in Emden with material handling and storage facilities in place in Emden. When these costs for customs, material handling and storage would be taken into account, the harbour selection possibly could shift towards Emden. Hence, maintaining operations for the German grid from Emden could be justified, also because when opting for the harbour in Emden over Delfzijl, the vessel operational costs increase with a mere 6.4%. This 6.4% cost saving based on the shorter distances from Delfzijl relative to Emden, could be cancelled out by the costs for material handling and storage which could be saved with the existing operations from Emden.

For the Dutch sub-cases, NL-2023 and NL-2030, OptiFleets recommends operations from the Port of Rotterdam. Note that the cost for the utilization of a port are assumed to be equal for all ports, in reality the larger ports such as the port of Rotterdam might have significantly higher costs to operate from than the smaller ports. This distinction could lead to a different recommendation than the port of Rotterdam for the Dutch operations.

Finally, when looking at the harbour selection for the integrated cases, DE-NL-2023 operates from Delfzijl and Den Helder. The harbour in Den Helder is proposed for the years where the maintenance needs are temporarily higher for the Dutch grid, namely the years of 2023 and 2024 when several new Dutch platforms are commissioned. The Platform Maintenance Generator models higher maintenance needs in the beginning years of new Dutch platforms due to the possible presence of inexperience, challenges and problems during the start-up period of new platforms. On the other hand DE-NL-2030 selects the harbour in Den Helder as the designated port to support logistics for each year in the 2030 to 2050 horizon.

7.2.2. Sensitivity analysis on input parameters

The data used to generate the results presented in the previous sub-section is lacking completeness and accuracy, whereby assumptions were necessary. To determine what the influence of these assumptions are, and how the model output changes in relation to changes in these parameters will be discussed in this sub-section. From sub-section 7.2.1 and 7.2.1 it could be derived that the vessel rates and the accommodation costs contribute for over 70% in the total costs meaning that these two cost factors are pivotal for the fleet composition. Subsequently, in this sensitivity analysis these two cost factors will be subject to the analysis.

The analysis regarding the vessel rates is twofold, first the vessel rates will be subject to random changes between -10% and 10% to determine what market price fluctuations entail for the fleet. Second, it will be determined at what price level the OSV solutions become attractive enough to include in the fleet over the older PSVs.

The second part of the analysis will address the vessel availability and the accommodation rate assumed for the accommodation of crew in the floating vessel. The question here is to determine whether a 10% increase and decrease in the assumption on vessel accommodation rates changes the recommended accommodation strategy.

Fleet sensitivity to vessel charter cost

When running the random fluctuations between -10% and 10% for the vessel rates, see table 7.12 for the specific changes, the main finding is that changes do occur in the fleet composition, compared to the static cost table used in the previous sub-sections. However, these changes only occur for the 2023 sub-cases. With the static data NL-2023, DE-2023 and DE-NL-2023 depend on a combination between a medium PSV and a medium CTV, after the changes in the vessel rates these sub-cases, except NL-2023, adapt the large PSV. Recall that this large PSV is a crew accommodation enabled vessel, hence the accommodation strategy shifts from platform accommodation to accommodation on the floating vessel for the 2023 sub-cases.

Table 7.12: percentual change in the vessel rates, applicable for the spot-market, medium-term and long-term rates

vessel type	sensitivity Δ
vessel 1: CTV-M	-4.85%
vessel 2: CTV-L	-8.43%
vessel 3: Heli	7.82%
vessel 4: PSV-M	-2.92%
vessel 5: PSV-L	-3.14%
vessel 6: OSV-M	-7.03%
vessel 7: OSV-L	-0.52%
vessel 8: PSV-M + Heli	2.45%
vessel 9: PSV-M + CTV-M	-3.89%
vessel 10: OSV-M + CTV-M	-5.94%
vessel 11: OSV-M + Heli	0.40%

The second objective of the cost parameter sensitivity analysis is to determine the price level at which the OSV solution becomes economically attractive to select over the PSVs. For the DE-2030 sub-case, the OSV solution come into the picture after the rate decreases with around 30%. For the rates of OSVs to decrease this significantly the OSV will need time on the market and more parties opting for these vessels. When the cases increase in size the point at which OSV become economic require a less strong decrease in the price. For DE-NL-2023, the OSV comes into the picture when the price drops with 25%. Finally, for the 2030 sub-cases, which are all by definition larger than the 2023 sub-cases, a rate decrease of around 14% is sufficient to replace the large PSVs with OSVs. The bigger the cases turn, the more benefit can be derived from the lower operational costs of the OSV and this compensates for the higher vessel contracting rates.

Accommodation strategy sensitivity

The second aspect of the sensitivity analysis is to assess the sensitivity of the accommodation strategy to changes in the assumption on the floating vessel accommodation costs. For the accommodation costs on the platforms, data could be derived from TenneT, however, for the floating vessel accommodation costs no data was available and an initial 100 €/crew member/day is assumed.

Respectively the vessel accommodation costs were first decreased with 10% and then increased with the same percentage. For the scenario, with a 10% decrease in the vessel accommodation costs a clear shift occurs in the accommodation strategy for the 2023 sub-cases. Where the initial cost of 100 €/crew member/day resulted in platform accommodation, costs of 90 €/crew member/day leads to the adoption of the large

PSV with on-board crew accommodation for DE-2023 and DE-NL-2023. For NL-2023 the combination of a medium PSV and CTV is maintained. On the other hand, the 10% increase in the vessel accommodation costs does not lead to shifts in the accommodation strategy, compared to the 100% initial scenario.

Sensitivity to vessel availability

When the vessel availability increases with 10%, no significant differences can be observed between the fleet composition. However, for the 10% reduction in the available days, the fleet becomes vulnerable. For the 2023 sub-cases, the fleets are still dominated by the combination of the medium PSV with the medium CTV, while for the 2030 sub-cases the fleets are dominated by the large PSV. However, occasionally it can be observed that the fleet is expanded with vessels boasting higher vessel availability on medium-term contracts. These vessels with the higher availability are the OSVs. This could be explained by the fact that in this reduction of vessel availability, it occurs more often that the available days of the PSVs are below the annual requirement and the more capable OSVs are necessary.

Recommendations based on the sensitivity analysis

From the findings derived from the previously addressed sensitivity analysis the following recommendations can be proposed for the decision maker:

- Fluctuations in the vessel rates significantly impact the fleet selection for the 2023 cases. A mere decrease in the costs of large PSVs makes these vessels even more attractive and an option to opt for in the 2023 cases, in addition to the 2030 cases. With the current oversupply in PSV vessels and the strong negotiating position of the clients (Daleel, 2018), it is recommended that TenneT negotiated the lowest possible rates for the large PSV and this could enable an early adoption of these vessels in 2023 instead of 2030.
- Moderate reductions in the vessel availability of e.g. the older large PSVs, makes the fleet vulnerable for harsh weather conditions if these vessels are selected in the fleet. This would require the addition of more capable vessels on expensive shorter term contracts for the seasons with harsh weather conditions. With this finding, it is recommended to conduct detailed weather analysis and thoroughly test the vessel capabilities on the likely weather scenarios in a way which is more detailed than in this study.
- In addition to detailed information on vessel rates, it is important to retrieve detailed information on rates for crew accommodation on the vessels. Moderate 10% reductions in the assumed costs already shifted the accommodation strategy from platform accommodation to vessel accommodation for the German grid in 2023. The recommendation is to gather detailed information on the crew accommodation on vessels, e.g. from parties already operating with vessel accommodation such as Ørsted and Siemens-Gamesa with their OSV concepts (offshoreWIND.biz, 2018, Østensjø Rederi, 2018). With this information, the adoption of vessel accommodation could already be implemented in 2023 instead of 2030, first with large PSVs and eventually with OSVs.
- For the OSV vessels to be economically attractive compared to the PSV, significant rate drops are necessary, ranging from 30% for DE-2023 to 14% for DE-NL-2030. For OSV to drop in costs that significantly, a bigger market and more adopters are necessary and this will take time. Hence, the recommendation is to take advantage of the oversupply in PSVs and opt for these vessels instead, up to the point that OSVs drop is price sufficiently. Moreover, the recommendation is to conduct detailed vessel analysis to determine how benefits of the OSV which are difficult to express in costs, for instance crew travelling and accommodation comfort and reduced emissions, can be included in the comparison between the vessel concepts.

With the presentation of the results from the application of OptiFleet on the TenneT case in the previous sub-sections, the thesis is nearing its conclusion. In the next chapter the thesis will finally be concluded.

8

Conclusion and Future Work

The research presented in this thesis on Maritime Fleet Management for the Offshore Transmission Grid (OTG) in Germany and the Netherlands has the objective to develop a model which can be utilized to provide decision-support to the decision maker in the strategic management and planning of its maritime fleet for the execution of OTG maintenance. For this model, methods from the field of Operations Research are applied. Heading towards the conclusion of this study, this chapter readdresses the research questions mentioned in chapter 1. For the main- and sub-research question a concise answer will be provided, based on the knowledge gained during this study.

Subsequently, the chapter proceeds with recommendations on possible future work which addresses the limitations of OptiFleet and builds further on the body of knowledge developed with this study.

8.1. Answers for the research questions

In chapter 1 the main research question was introduced and since then has been the leading question aimed to be answered with this research. The research question was introduced as follows:

> *To what extent can an optimal Marine Fleet Size and Mix established via integrated planning of the transport and accommodation strategy, minimize costs for the maintenance of the offshore substations in Germany and the Netherlands?*

The main research question can be further specified in 7 sub-research questions. Together these questions should ultimately contribute towards answering the main research question and close the identified research gap which targets the lack of knowledge on long-term maritime fleet management for OTG. In the following paragraphs these sub-questions will be answered, and ultimately the section will be concluded with an answer on the main research question.

8.1.1. What aspects of the offshore transmission grid drive the demand and challenges for offshore logistics?

An important aspect of this study was to determine and document what aspects of the OTG are driving the logistic challenges faced by TSOs. These aspects were identified and addressed in chapter 2 and 3. One of the most essential findings is that the novelty of the technology involved in OTG is a major driver behind the logistic challenges. In particular for the TenneT case, the fact that these platforms are the first of its kind in the world, makes it inevitable that challenges will arise in the learning process regarding the optimal maintenance strategy and logistics planning.

Moreover, the offshore environment in itself is challenging and also a new environment for the TSO as they only got involved in the offshore environment around 2008 in Germany. Before that year, all TSO operations where onshore where the conditions and characteristics regarding the transmission technology, the weather, transportation means and infrastructure are drastically different.

To add to the complexity due to the novelty of the platforms, a large number of parties is involved in the operation and maintenance of these platforms. The most important here being: Technicians and engineers of the TSO, technicians and engineers of the platform manufacturer, technicians and engineers of third party service providers and employees from service providers responsible for support services such as catering and accommodation. All these people, including cargo and tools to execute maintenance need to be scheduled and transported to the platforms and back in a coordinated way to enable the timely and correct execution of maintenance.

Finally, the importance of these offshore platforms for the provision of electricity to the German, and in the near future, Dutch market can be considered a driver of the requirement for high quality and fast logistics. The offshore substation platforms can be considered as hubs in the network of wind farms, which connect the wind farms to shore. Once failures of a platform occur, the connected wind farms cannot deliver power to the consumers anymore. Hence, a strategy should be in place where preventive maintenance prevents these failures as much as possible, and if a failure occurs, corrective maintenance is initiated immediately and down-time is minimized. Hereby it is important to get crew and material to the platforms fast and according to specifications, for the maintenance to be executed timely and reliably.

8.1.2. How can these drivers develop with the expected growth in offshore wind capacity and innovation in offshore transmission technology?

In 2019 the OTG in Germany consisted of 9 HVDC platforms, this will increase towards an estimated 13 platforms in 2030. On the Dutch side the 5 HVAC platforms which will be brought into operation between 2019 and 2023, will increase towards a number between 11 and 14 platforms in 2030 (TenneT Holding B.V., 2017). In short, the scale will continue to grow and this directly influences the demand for offshore logistics to guarantee the reliability of the OTG by means of timely maintenance. When considering this growth in the OptiFleet model, for the German grid, the total estimated costs for offshore logistics increases with 26% from 2020 to 2023 for a growth in the number of platforms equal to 44%. While for the Dutch case, the cost increase is 90% for a growth in the number of platforms equal to 160%. This is reached with logistic optimization by means of a cost efficient fleet as proposed by OptiFleet.

The expectation is that the novelty of the offshore transmission technology will turn to be less of a challenge in the future as experience is gained and lessons are learned. On the other hand, the operation of these platforms will proceed towards the unmanned phase and this innovation poses new challenges in terms of:

- *reaction time when a failure occurs:* in the case of unmanned platforms, this is the case once the Dutch platforms are operational and the direction which the German grid is moving towards in the near future, crew is not permanently on the platforms and logistics will need to evolve to even higher standards. Hereby, the reaction time to get material and personnel on the platform, after a failure, will be more important than in the current situation where personnel and material is permanently on the platform (Algra, 2017, Heinrich, 2017b)

- *travelling comfort:* currently personnel of offshore platforms are used to be accommodated on the platforms permanently and only be transported by helicopter before and after the shift. The unmanned situation requires more frequent travelling for crew from shore to platforms and between platforms for the execution of maintenance. This implies that the transportation means should provide an environment which stimulates productivity with at least the same level of comfort compared to the platform accommodation facilities

The weather will continue to be an uncertain, but critical driver behind the logistic needs in the future. In particular with the shift from helicopters to vessels which are more weather dependant, there is a need to take the knowledge from this study on the fleet composition and study on an operational level what the fleet availability would be, given detailed weather data on each platform in the network.

8.1.3. What are relevant performance measures and how can these be implemented in the model objective function?

From interviews with the OTG experts at TenneT, it could be concluded that the main aim is to reduce the cost of platform maintenance, while the reliability of the OTG must be guaranteed at all times. Currently the total maintenance cost per platform are estimated to be around 20 million €/year, and this needs to be reduced to a figure below 10 million €/year ultimately to comply with standards from the regulatory authority and pressure from society (Heinrich, 2017a).

Regarding the reliability, the critical performance measure is the overall grid availability, measured in the % of the annual time that the OTG is able to transmit power from the offshore wind-parks to the consumers on shore. OptiFleet captures this availability requirements by including constraints which force all indicated maintenance activities, both preventive and corrective, to be executed immediately and not postponed to match cheaper vessel availability. This means that when a failure occurs, at all times the decision will be made to head out and repair the failure immediately, therefore limiting downtime to a minimum.

The downtime per platform, that is the time during which an individual platform is not operable due to failure or maintenance, is a measure used to address the individual contribution of each platform to the OTG availability. To this downtime a cost factor can be attached, resulting in the downtime costs. These are the cost with which the TSO can be penalized if the platform is out for longer than the time as documented in the regulations. How the down-time costs can be modelled is proposed in appendix B.2.

In terms of the objective function, which is presented in section 5.6.5, all objectives are expressed in monetary costs. To be more specific, the objective function represents total maritime logistics cost and consists of: 1) the costs for the utilization of the selected bases or harbours, 2) the charter costs for the vessel either on a long-term contract or in a day-rate from the spot-market, 3) the operational costs to operate the vessel, e.g. fuel costs, but also personnel wages for the time they are en-route, and finally 4) the accommodation costs for crew, consisting of catering-, working- and sleeping facilities either on the platform or the floating vessel.

The subject of logistics for the offshore platforms also includes costs for material handling and storage, and personnel training when helicopters are used, however these costs are not included in the objective function.

8.1.4. What are possible alternatives for the manning strategy, accommodation strategy and transport strategy of OTG?

In this study various alternatives are identified and explored with regards to the manning strategy, accommodation strategy and the transport strategy. First, for the manning strategy it is explored what unmanned operations, as alternative to the permanently manned platforms, imply for the logistic needs for the platforms.

For the accommodation strategy, the alternative to accommodation on the platforms is found in accommodation aboard the floating vessel. In the latter scenario, accommodation facilities on the platform become surplus to requirement and can be decommissioned to reduce cost even further, while accommodation is consolidated on the vessels. Note however, that for this solution, the modern vessels known for their multipurpose characteristics that enable a variety of functionality, such as people accommodation and catering facilities, facilities for daughter vessel or helicopter operations and facilities to transport and move cargo are necessary. Under this category the Operations Support Vessels (OSV) and the larger and more modern Platform Supply Vessels (PSV) can be found.

Finally, for the transport strategy, a close link exists to the manning strategy and the accommodation strategy. This is why transport means are considered which can support both unmanned platforms and accommodation aboard the vessel. Maritime concepts taken into account are: Crew Transfer Vessels (CTV), Platform Supply Vessels (PSV), Operation Support Vessels (OSV) and helicopters. All in different sizes, with different operational capabilities and in different combinations assuming operability from various harbours in the Netherlands, Germany and Denmark.

8.1.5. What external factors imply constraints on the fleet management for OTG?

External factors which are identified as being able to place constraints on the decisions for strategic fleet management are:

- *The harsh weather offshore* is of compelling significance for the crew change industry. For vessel transport and crew transfer there are two dominant weather influences posing operational constraints, namely: wave conditions and wind speed (Halvorsen-Weare and Fagerholt, 2017). Wave conditions are generally described by two parameters, the significant wave height (Hs) and the mean zero-crossing wave period (Tz). Together they form the wave conditions of a certain sea state, during which the climate is considered constant for any period of three hours (Cerda-Salzmann, 2004)
- *Maritime and aviation regulation* which have strict rules and procedures on the allowed means for crew transport and transfer technology allowed to be used under specific weather conditions
- *The vessel market* as it can imply constraints on which vessels are available for contracting and on the period the vessel can be contracted

8.1.6. What internal policies imply constraints on the fleet management for OTG?

Internal factors which are identified as being able to place constraints on the decisions for the strategic fleet management are:

- *platform facilities* can place constraints on the transport means used. For instance the lack of a helipad on the Dutch platforms, eliminates the use of helicopters to transport crew to the Dutch platforms, unless the helicopter is used in combination with a vessel which is equipped with a helipad
- *internal policy on operable weather conditions.* For instance under the current policy, crew transfer by CTV is not allowed for a wave-height higher than 2m
- *employees may add requirements*, for instance on what they consider as maximum travel time by vessel. This places restrictions on the application of optimal vessel routing which combines platforms in a journey and reduces costs as a result, but at the same time increases travel time. Requirements can also be made for the facilities and level of comfort they desire on the vessels

8.1.7. How can the robustness of the fleet be guaranteed for different scenarios of platform quantity, platform location and maintenance philosophy?

The answer to this sub-question lies in the analysis whereby the OptiFleet model runs over various sub-cases. The sub-cases are based on the geographic distribution of platforms in the North Sea and the difference in the number of platforms between 2023 and 2030: 1) DE-2023: all platforms in the German North Sea in 2023, 2) DE-2030: all platforms in the German North Sea in 2030, 3) NL-2023: all platforms in the Dutch North Sea in 2023, 4) NL-2030: all platforms in the Dutch North Sea in 2030, 5) DE-NL-2023: the combined situation with platforms in the German and Dutch North Sea in 2023 and 6) DE-NL-2030: the combined situation with platforms in the Germany and Dutch North Sea in 2030. From this sub-case analysis it can be concluded that the vessel selections which fits all sub-cases best is vessel type "vessel-5" and this corresponds to a large PSV. See section 7.2.1 for the detailed output by OptiFleet. The large PSV is the designated vessel for the 2030 sub-cases, whereas the combination of a medium PSV with a medium CTV is proposed for the 2023 sub-cases. However, the sensitivity analysis in sub-section 7.2.2 showed that a mere decrease in the costs of large PSVs makes these vessels more attractive and an option to opt for in the 2023 cases, in addition to the 2030 cases.

Regarding the number of vessels, the model output showed varying vessel fleet sizes from 2 vessels for the Dutch case in 2023 to 6 vessels for the integrated case in 2030. These vessels were all contracted on the less flexible, but least expensive long term contracts. A recommended measure to add flexibility while maintaining the low cost of long-term contracts is to take advantage of the strong position clients have in the PSV market with oversupply and include early-termination clauses in the contracts (Daleel, 2018, Valbrek). These early-termination contracts would allow, in this case TenneT, to terminate the existing contracts and flexibly opt for new vessels and contracts which are more attractive at that point in time, hence this flexibility enhances the robustness of the fleet management.

8.1.8. Overall conclusion

After addressing each sub-research question individually in the previous sub-section, this sub-section presents the overall conclusion based on the overarching research question. In short it can be concluded that operations research provides the necessary means to study the economic benefits of integrated fleet planning and support decision making for long term strategic fleet planning. These strategic decisions cover not only the geographic and organizational integration of the German and Dutch Grid, but also the integration of different logistic aspects, namely: vessel type selection, vessel contracting, accommodation strategy and maintenance strategy. However, for the model to be put to use effectively, it is necessary to acquire accurate and detailed data on, in particular, the vessel charter rates and the crew accommodation rate as these cost categories contributes for over 70% in the total logistic costs addressed by this study. This research did not sufficiently manage to gather all this data, hence the model could not be applied for detailed cost analysis. However, analysis was conducted with approximated data from literature, stakeholders and TenneT, and with this output conclusions could be drawn for the direction in which strategic logistic decisions could be made in the years to come. For the detailed results of the OptiFleet model for the 6 sub-cases, see chapter 7.

After OptiFleet was conducted over the six sub-cases, the following can be concluded and recommended to TenneT:

- *Fleet composition.* For the situation in 2023, the combination of a medium PSVs with a medium CTV is recommended to transport the cargo and crew respectively. On the other hand, the situation in 2030 is recommended to be operated with the large PSVs, a solution which integrates both cargo and crew transportation in an integrated vessel solution. In short, the motivation can be given by the insufficient scale of the platform network associated to the 2023 cases, subsequently the 2023 situation cannot gain sufficiently from the integrated solution. On the other hand, the 2030 situation provides sufficient scale and clustering opportunities to make the shift to the integrated vessel solution.
- *Fleet size* the fleet size required to sufficiently meet the logistic demand by the different sub-cases is as follows:
    - DE-2023: three vessels of each PSV-M and CTV-M
    - NL-2023: two vessels of each PSV-M and CTV-M
    - DE-NL-2023: four vessels of each PSV-M and CTV-M
    - DE-2030: three vessels of type PSV-L
    - NL-2030: three vessels of type PSV-L
    - DE-NL-2030: six vessels of type PSV-L
- *PSV over OSV*, due to its lower cost, as compared to the newer OSV with comparable characteristics, the large PSV is selected over the OSV by OptiFleet. Due to the novelty of the OSVs these vessels are currently very high priced in the market and little operational experience exists. On the contrary, there is an oversupply in PSV vessels leading to low prices and a relatively easy inclusion of the vessel in the organization due to the ample operational experience with these vessels in the offshore industries (Daleel, 2018, Døsen and Langeland, Rosetti Marino, 2015).

  For the OSV vessels to be economically attractive compared to the PSV, significant rate drops are necessary, ranging from 30% for DE-2023 to 14% for DE-NL-2030. For OSVs to drop in costs that significantly,a bigger market and more adopters are necessary and this will take time. Hence, the recommendation is to take advantage of the oversupply in PSVs and opt for these vessels instead, up to the point that OSVs drop is price sufficiently.

  However, it is necessary to dive into the operational aspects of the two vessel types in a detailed manner to make the final decision. Especially benefits of the OSV which are difficult to express in costs, e.g.

travelling and accommodation comfort and reduced emissions, should be included in the comparison between the vessel concepts.

- *Vessel contracting*, all vessels are recommended to be contracted on the less flexible, but least expensive long term contracts. A recommended measure to add flexibility while maintaining the low cost of long-term contracts is to take advantage of the strong position clients have in the PSV market with oversupply and include early-termination clauses in the contracts (Daleel, 2018, Valbrek). These early-termination contracts allow, in this case TenneT, to terminate existing contracts and flexibly opt for new vessels and contracts which are more attractive at that point in time.
- *Maritime vessels over helicopters*, the vessel selection clearly conveys that the helicopter is not part of the long-term fleet. This supports the decision of TenneT to make the shift away from helicopters, to vessels out of safety and economic reasons. Note that this is the case for the long-term fleet composition. On the short term, given uncertainty and irregularities, helicopters might still be necessary to be temporarily chartered. For instance if skilled labour needs to be transported to the platforms or for emergencies and when the vessels in the fleet are already en-route. In this scenario, heading back to the coast for the pick-up of the specially skilled technicians is not considered economic and a helicopter might be necessary. In addition to the helicopters, vessels other than the large low-speed vessels can be utilized. The alternative to the helicopter for these irregular, high speed operations is the CTV. Opting for the CTV, makes the helipads on the platform not needed and allows for the decommissioning of the helipads on the platforms leading to more cost reductions.
- *Accommodation strategy 2023.* For the 2023 case the recommendation is to maintain accommodation of the crew on the platforms and transport cargo with the PSV-M and crew with the CTV-M. In the meantime, the organization can gain experience and acclimatize to executing maintenance campaigns with maritime vessels instead of helicopters. Additionally, the organization is left with more time to prepare for the implementation of integrated vessel solutions with vessels such as the large PSV and OSVs.
- *Accommodation strategy 2030.* For the 2030 situation, given the specific characteristics of the recommended large PSV as a multi-purpose vessel which can transport both crew and cargo, accommodate crew on-board and boast other facilities to support offshore operations, the recommendation is to make the shift from platform accommodation to floating vessel accommodation of crew.
- *Importance of vessel charter rates.* Vessel charter costs contribute for an average of 52% in the logistic cost. This implies that for detailed cost analysis it is absolutely critical to derive detailed and accurate vessel charter cost from the market, before making decisions. This data could be derived via the tenders, launched once the desired requirements for the desired transport mode are determined in the field of crew capacity, deck-space, lifting capacity, accommodation facilities, vessel operability or availability (days per year that the vessel can be operated) and crew transfer capability (days per year that the crew can be transferred from vessel to platform and vice-versa). The latter two are dependant on the weather conditions.
- *Benefits from geographic integration.* Regarding the geographic integration of the German and Dutch grid with a single fleet approach, this entails that both grids are considered as a single grid for the fleet planning, the results are not as expected. Where major benefits where expected if grids are geographically and organizationally integrated, OptiFleet shows small (3%) benefits for the case in 2023. However, the model generates higher costs for the integrated cases in 2030. On the contrary to the economic benefits which are not as expected for the integrated approach, OptiFleet does provide output which indicates that a leaner fleet, that is a fleet with less vessels, is possible in the integrated approach. This, compared to the sum of the individual Dutch and German fleets.

  In short, it can thus be stated that the model provides means to study the benefits of OTG integration to a certain extent, but the results are not as expected. The following can be proposed to improve the results and bring them closer to the expected and desired behavior: include a maintenance planning mechanism with combined vessel routes. More on this is discussed in the recommendations in subsection 8.3.

The OptiFleet model can be considered to be a relevant tool to support the strategic decisions regarding the future logistic operations, where different platform networks and maintenance strategies can be tested to determine the appropriate fleet composition, base utilization and accommodation strategy. However, the model is limited to predominantly the strategic level and partially the tactical level. After readdressing the relevance of this study in the next section, section 8.3 will propose recommendations on how the model could be further developed to improve functionality and applicability in real-life cases.

8.2. Societal and Scientific relevance

This research is conducted with contributions in both the societal and scientific field. The societal relevance of this research lies in the contribution to the realization of reliable and cost efficient O&M for OTG, by means of integrated fleet mix and size decision making, to enable further increase in renewable offshore wind capacity at low costs and high availability. Hence, the aim of this study is to learn from the rapid and unprecedented growth of offshore wind power in Germany , and subsequently the rapid and unprecedented growth of OTG, and propose a model which can help the TSO in Germany and TSOs around the world to plan and operate their OTG cost effectively. More specifically, this model should provide decision support to decision makers within TSOs when planning the fleet management in terms of the size of the vessels and the mix of vessel types in the fleet.

The scientific relevance of this research lies in the belief that developing a model and literature on the logistic optimization of OTG is necessary for TSOs around the world, to provide decision support on logistics which should lead to cost effective operations or the best possible return on investments. As stated before in for instance chapter 4, models do already exist for wind farms. This is also elaborated in section 4.3, however the existing model apply targeted or dedicated approaches on parts of the problem. The scientific motivation for this thesis, is that an integrated approach resulting in a holistic model, has potential to improve the existing knowledge on offshore vessel fleet optimization. The holistic approach entails the integration of vessel fleet decisions, maintenance strategy decisions and manning strategy decisions for offshore transmission platforms.

8.3. Recommendations for future work

From the identified knowledge gap it can be derived that there is a need for the knowledge which is aimed to be generated with this research. Moreover, stakeholders in the offshore industry, such as TSO TenneT at which this study was conducted and marine shipyards showed great interest in this study when these stakeholders were approached for the gathering of data. The research is thus a necessary step in the direction of optimized offshore logistics for OTG, but on the other hand, the study has its limitations. These limitations prevent the study to close all knowledge gaps in the field of offshore maritime fleet planning. In this final section, recommendations are presented on how this study can be taken as a starting point for future work, in order for the body of knowledge to be further developed.

First, it is recommended for the model to be extended with full-fledged tactical decisions and the operational decisions related to the day-to-day execution of maintenance where crew related aspects and the weather gain importance. Conducting weather analysis and coupling that with the vessel operability will provide detailed information on the vessel deployment and determine whether the decisions made on strategic level, e.g. on the number of vessels, are accurate enough.

In addition to weather data, the operational model is recommended to include heterogeneous platforms. In OptiFleet it is currently assumed that all platforms are identical and have the same characteristics in terms of logistic needs for the maintenance activities. Failure probability is also assumed to be the same for all platforms. In reality this is not the case, and it is believed that it is relevant to study how heterogeneous platforms influence logistics and the fleet management.

Third, it is recommended to include a detailed maintenance planning and scheduling mechanism with combined vessel routes in the OptiFleet model on an operational level. This could improve the ability of the model to reduce operational costs and be more fit for analysis of the integrated DE-NL cases. The maintenance planning mechanism should align and coordinate the periods, day-to-day and hourly, when maintenance should be carried out on the platforms in combined campaigns, taking into account the available vessels and possible routes along the platforms. The maintenance planning should thus go further, than the per year aggregate maintenance planning currently implemented in OptiFleet. Ultimately this adjustment should lead to decreased costs due to the optimization of the vessel utilization with combined campaigns in optimal routes.

The extension of the model to the operational level, is recommended to be executed with a stochastic approach to take into account the uncertainty. Hence, it is recommended to implement stochastic optimization, especially since this method is proven to be applicable to take uncertainty into account over various scenarios in maritime fleet planning (Gundegjerde and Halvorsen, 2012, Joshi and Bolstad, 2016). Note that a possible extension of the OptiFleet model to a stochastic model is presented in appendix B.

For the model to be fully functional in generating output for real-life cases, it is recommended to gather detailed and accurate data on vessel charter rates and costs for the accommodation of crew on floating vessels. In general there is a great need for this data, as very little exist in literature about this vessel market which lacks transparency.

In addition to lacking vessel cost data, it is recommended to thoroughly study the vessel characteristics which cannot directly be expressed in monetary units, e.g. the facilities on the vessel and how these contribute to the travelling comfort for crew and the emissions of the vessels. In line with this lacking data, it is recommended to TenneT to start a study on the employee specific requirements and acceptance of the vessel solutions. The vessel acceptance knowledge coming from this study should further aid the decision process on selecting vessels for the long-term fleet.

With the aforementioned model extensions and gathered detailed data, the model will be highly specialized and extensive that commercial solvers may not proof to be feasible anymore. Hence, this calls for specialized solving algorithms which are fitted for the Mixed Integer Programming approach in combination with Stochastic Optimization.

Finally, it is recommended to TenneT, that if knowledge from the model wants to be optimally utilized in the strategic fleet planning, there is a need to integrate the model in the asset management and risk analysis activities of TenneT Offshore. Input and output from the models for asset management and risk analysis are recommended to be interactively utilized with the input and output for OptiFleet. In this way risk analysis on for instance platform failure rates can be adjusted based on the vessel fleet characteristics proposed by OptiFleet and on its turn OptiFleet can adjust the fleet based on the updated platform failure rates. Integration of the model in the greater organization is expected to be the best way to gain support for the application of the model and subsequently realize cost effective and reliable fleets for an equally reliable and cost-effective Offshore Transmission Grid.

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A

Code script

A.1. Platform clustering

```python
"""
Created on Sun May 20 13:58:45 2018

@author: devin
"""


import pandas as pd, numpy as np, matplotlib.pyplot as plt, time
from sklearn.cluster import DBSCAN
from sklearn import metrics
from geopy.distance import great_circle
from shapely.geometry import MultiPoint


# define the number of kilometers in one radian# defin
kms_per_radian = 6371.0088

# load the data set
df = pd.read_excel("C:/Users/devin/Dropbox/TIL thesis/python/new beginnings/ultima_vez/platforms_TenneT_NS_DE_2023.xlsx", encoding='utf-8')
df.head()

# represent points consistently as (lat, lon)
coords = df.as_matrix(columns=['lat', 'lon'])
print(coords)

# epsilon is the distance around a platform forming its neighbourhood, converted to radians for use by haversine
epsilon = 10 / kms_per_radian

start_time = time.time()
db = DBSCAN(eps=epsilon, min_samples=1, algorithm='ball_tree', metric='haversine').fit(np.radians(coords))
cluster_labels = db.labels_

# get the number of clusters
num_clusters = len(set(cluster_labels))

# print the outcome
message = 'Clustered {:,} points down to {:,} clusters, for {:.1f}% compression in {:,.2f} seconds'
print(message.format(len(df), num_clusters, 100*(1 - float(num_clusters) / len(df)), time.time()-start_time))

# turn the clusters in to df, where each element is a cluster of points
clusters = pd.Series([coords[cluster_labels==n] for n in range(num_clusters)])
cluster_size = [len(i) for i in clusters]
print(cluster_size)
print(clusters)
```

```python

def get_centermost_point(cluster):
    centroid = (MultiPoint(cluster).centroid.x, MultiPoint(cluster).centroid.y)
    centermost_point = min(cluster, key=lambda point: great_circle(point, centroid).m)
    return tuple(centermost_point)

centermost_points = clusters.map(get_centermost_point)

# unzip the list of centermost points (lat, lon) tuples into separate lat and lon lists
lats, lons = zip(*centermost_points)

# from these lats/lons create a new df of one representative point for each cluster
rep_points = pd.DataFrame({'lon':lons, 'lat':lats, 'cluster_set':clusters})
print(rep_points)

#rep_points.replace([[54.354167000000004, 6.025],[53.996667, 7.74],[55.063333, 7.241667],[55.451667, 6.74]],['platform_1','platform_2','platform_3','platform_4'])

# pull row from original data set where lat/lon match the lat/lon of each row of representative points
# that way we get the full details like city, country, and date from the original dataframe
rs = rep_points.apply(lambda row: df[(df['lat']==row['lat']) & (df['lon']==row['lon'])].iloc[0], axis=1)

rs['cluster_set'] = cluster_size

rs.to_excel('C:/Users/devin/Dropbox/TIL thesis/python/new beginnings/ultima_vez/platforms_TenneT_NS_DE_2023_cluster.xlsx', encoding='utf-8')
rs.tail()

# plot the final reduced set of coordinate points vs the original full set
fig, ax = plt.subplots(figsize=[10, 6])
rs_scatter = ax.scatter(rs['lon'], rs['lat'], c='#99cc99', edgecolor='None', alpha=0.7, s=120)
df_scatter = ax.scatter(df['lon'], df['lat'], c='k', alpha=0.9, s=3)
ax.set_title('Full data set vs DBSCAN reduced set - platforms_TenneT_NS_DE_NL_2030')
ax.set_xlabel('Longitude')
ax.set_ylabel('Latitude')
ax.legend([df_scatter, rs_scatter], ['Full set', 'Reduced set'], loc='upper right')
plt.show()
```

A.2. Platform Maintenance Generator - PMG

```python
"""
Created on Mon May 21 13:04:10 2018

@author: devin
"""

# -*- coding: utf-8 -*-
"""
Created on Wed Jan 24 16:51:08 2018

@author: devin
"""
import random
import math
from collections import defaultdict
from gurobipy import *
import pprint
import numpy as np
import matplotlib.pyplot as plt
import seaborn as sns
import pandas as pd
import plotly.plotly as py
import plotly
import plotly.figure_factory as ff
from pandas import ExcelWriter
import time
import datetime
from openpyxl import Workbook
wb = Workbook()

from xlrd import open_workbook

############Platform cluster import
bookPlatform = open_workbook('C:/Users/devin/Dropbox/TIL thesis/python/new beginnings/ultima_vez/platforms_TenneT_NS_DE_2023_cluster.xlsx')
sheetPlatform = bookPlatform.sheet_by_index(0)

# read header values into the list
keysPlatform = [sheetPlatform.cell(0, col_index).value for col_index in range(0,6)]
#print(keysPlatform)

platforms_data = {}
for row_index in range(1, sheetPlatform.nrows):
    platforms_data[sheetPlatform.cell(row_index,1).value] = {keysPlatform[col_index]: sheetPlatform.cell(row_index, col_index).value
                 for col_index in range(0,6)}

#print(platforms_data, len(platforms_data))
#print(platforms_data.keys())

platforms = [i for i in platforms_data.keys()]

#list with failure likelihood, necessary for looping to link with platform-failure tuple
#failure_ps = ['p_a','p_b','p_c']

#time definition
start_year = 2023
end_year = 2043

start_time = start_year
end_time = end_year

periods = [i for i in range(start_time,end_time)]
#len(periods)

period = ()
platform = ()
failure_type = ()
platform_and_failure_type = ()
```

```
m = () #maintenance bundle
s = () #maintenance schedule

################################################################################
###corrective maintenance generator##############################GOED##############################

f_types,repair_t,num_crew,deckm2,lift,prob = multidict({"failure_a": [1,10,10,1,0.5],
                                                       "failure_b": [10,20,400,2,0.1],              # inspection, monitoring
                                                       "failure_c": [30,30,700,5,0.001]})


#all failures


list_of_CORRmaint_platforms = {}
for platform in platforms:
    for period in periods:
        for failure_type in f_types:
            list_of_CORRmaint_platforms[(platform,failure_type,period)] = platforms_data[platform]['cluster_set'] * prob[failure_type]
#print(list_of_CORRmaint_platforms)

def failure_generator(a, b):
    failure_generator_term = random.uniform(a,b)
    return failure_generator_term

CorrMaintNeedsPlatformPeriod = {x: 1 if list_of_CORRmaint_platforms[x] >= failure_generator(0, 1) else 0
                                for x in list_of_CORRmaint_platforms}
#print(CorrMaintNeedsPlatformPeriod)
#print(sum(CorrMaintNeedsPlatformPeriod.values()))

#take only the elements in which a failure occurs
Filter_PeriodsWithCorrMaint = {key:value for key, value in CorrMaintNeedsPlatformPeriod.items()
if CorrMaintNeedsPlatformPeriod[key] == 1}
#print(Filter_PeriodsWithCorrMaint)
Tuple_Platform_CorrType_Period = list(Filter_PeriodsWithCorrMaint)
#print("--------------------------------------------------------------------------------------------")
#print("Tuple_Platform_CorrType_Period",Tuple_Platform_CorrType_Period,len(Tuple_Platform_CorrType_Period))
#
#repair_time_platform_failure_ID = ()
Dict_Platform_CorrType_Reqs = {}
for item in Tuple_Platform_CorrType_Period:
    platform_failure_ID = list(item)
    a = item[2] # a is the period in which the failure occurs
    platform_failure_ID_edit = platform_failure_ID[:]
    repair_time_platform_failure_ID = repair_t[platform_failure_ID_edit[1]]
    platform_failure_ID_tuple = tuple(platform_failure_ID_edit)
    Dict_Platform_CorrType_Reqs[platform_failure_ID_tuple] = [repair_t[platform_failure_ID_edit[1]],
                                num_crew[platform_failure_ID_edit[1]] * platforms_data[platform_failure_ID_edit[0]]['cluster_set'],
                                deckm2[platform_failure_ID_edit[1]] * platforms_data[platform_failure_ID_edit[0]]['cluster_set'],
                                lift[platform_failure_ID_edit[1]],
                                1]
#print("list with corrective interventions")
#print(Dict_Platform_CorrType_Reqs, len(Dict_Platform_CorrType_Reqs))

################################################################################

#preventive maintenance
###parameters
Rprev_campaign_lenght = 14 #each campaign takes a fixed amount of 14 days
Rprev_campaign_freq = 4 #4 prev maintenance campaigns take place per year
Rgap_between_prev_campaign = 30 #30 day gap between maintenance campaigns

Camps,repair_t,num_crew,deckm2,lift,start = multidict({"CampA": [14,30,500,4,start_year],
                                                       "CampB": [14,20,500,4,start_year],              # inspection, monitoring
```

```
                                                       "CampC": [14,40,700,4,start_year],           # inspection, monitoring, replacement large
                                                       "CampD": [14,30,400,4,start_year]
                                                      })


Dict_Platform_PrevType_Reqs = {}

#print(start['CampA'],start['CampA'] + datetime.timedelta(years=1))

#define planning horizon for base year in terms of begin and start period for each campaign, taking into account seasons
#add uncertainty to these baeyear periods and derive for each year up to 2040.

for year in periods:
    for platform in platforms:
        for M_camp in Camps:
            if year == start_year:
                execution_year = start[M_camp]
            else:
                if year <= end_time:
                    execution_year = year
            platform_campaign = (platform,M_camp,execution_year)
            Dict_Platform_PrevType_Reqs[platform_campaign] = [repair_t[platform_campaign[1]]*platforms_data[platform_campaign[0]]['cluster_set'],
                         num_crew[platform_campaign[1]] * platforms_data[platform_campaign[0]]['cluster_set'],
                         deckm2[platform_campaign[1]] * platforms_data[platform_campaign[0]]['cluster_set'],
                         lift[platform_campaign[1]],
                         1]
#print("list with campaigns")
#print(Dict_Platform_PrevType_Reqs, len(Dict_Platform_PrevType_Reqs))

###preventive maintenance
df_prev_main = pd.DataFrame(
         {"maintenance_campaign":[],
         "repair_time":[],
         "num_crew":[],
         "deckspace":[],
         "lifting":[],
         "activated":[]},
         index = []
        )

for i in Dict_Platform_PrevType_Reqs.keys():
    s = pd.Series([i,
                  Dict_Platform_PrevType_Reqs[i][0],
                  Dict_Platform_PrevType_Reqs[i][1],
                  Dict_Platform_PrevType_Reqs[i][2],
                  Dict_Platform_PrevType_Reqs[i][3],
                  Dict_Platform_PrevType_Reqs[i][4]],
    index=["maintenance_campaign","repair_time","num_crew","deckspace","lifting","activated"])
    df_prev_main = df_prev_main.append(s, ignore_index=True)

df_prev_main.set_index("maintenance_campaign", inplace=True)
#print(df_prev_main)

# Create a Pandas Excel writer using XlsxWriter as the engine.
writer = pd.ExcelWriter('C:/Users/devin/Dropbox/TIL thesis/python/new beginnings/ultima_vez/maintenance_all/PrevMaint_DE_2023.xlsx', engine='xlsxwriter')

# Convert the dataframe to an XlsxWriter Excel object.
df_prev_main.to_excel(writer, sheet_name='Sheet1')

# Get the xlsxwriter objects from the dataframe writer object.
workbook  = writer.book
worksheet = writer.sheets['Sheet1']

####corrective maintenance
df_corr_main = pd.DataFrame(
```

```
         {"corrective_maintenance":[],
         "repair_time":[],
         "num_crew":[],
         "deckspace":[],
         "lifting":[],
         "activated":[]},
         index = []
        )


for i in Dict_Platform_CorrType_Reqs.keys():
    s = pd.Series([i,
                  Dict_Platform_CorrType_Reqs[i][0],
                  Dict_Platform_CorrType_Reqs[i][1],
                  Dict_Platform_CorrType_Reqs[i][2],
                  Dict_Platform_CorrType_Reqs[i][3],
                  Dict_Platform_CorrType_Reqs[i][4]],
    index=["corrective_maintenance","repair_time","num_crew","deckspace","lifting","activated"])
    df_corr_main = df_corr_main.append(s, ignore_index=True)

df_corr_main.set_index("corrective_maintenance", inplace=True)
#print(df_corr_main)

# Create a Pandas Excel writer using XlsxWriter as the engine.
writer2 = pd.ExcelWriter('C:/Users/devin/Dropbox/TIL thesis/python/new beginnings/ultima_vez/
     maintenance_all/CorrMaint_DE_2023.xlsx', engine='xlsxwriter')

# Convert the dataframe to an XlsxWriter Excel object.
df_corr_main.to_excel(writer2, sheet_name = 'Sheet1')

# Get the xlsxwriter objects from the dataframe writer object.
workbook  = writer.book
worksheet = writer.sheets['Sheet1']
```

A.3. OptiFleet

```
"""
Created on Thu May 24 12:03:03 2018

@author: devin
"""

import random
import math
import collections
from gurobipy import *
import pprint
import numpy as np
import matplotlib.pyplot as plt
import seaborn as sns
import pandas as pd
import ast
from xlrd import open_workbook


def make_data():

#    #General parameters
    kMAX = 3 #maximum number of bases in use
    hour_salary = 160 #salary per hour of engineering crew
    max_travel_time = 24 #limit on travel time for crew, as per company policy
    #timeline
    start_year = 2023
    end_year = 2043
    years = [i for i in range(start_year,end_year)]
    len(years)

    vessel_contracts, contract_duration = multidict({
        'l_term_1': 20,
        'l_term_2': 5,
        'l_term_3': 4,
        'l_term_4': 2,
        'l_term_5': 3,
        'm_term_1': 1,
        'm_term_2': 1,
        'm_term_3': 1,
        'm_term_4': 1,
        'm_term_5': 1
        })

    spot_contracts, spot_X = multidict({
        's_term_1': 1, #day
        's_term_2': 1, #day
        's_term_3': 1, #day
        's_term_4': 1, #day
        's_term_5': 1  #day
        })
    ############vessel price import
    VesselCostBook = open_workbook('C:/Users/devin/Dropbox/TIL thesis/python/new beginnings/ultima_vez/
     vessel cost estimations.xlsx')
    sheetVesselCost = VesselCostBook.sheet_by_name('ACC')


#dictionary with all possible vessel types
    vessels, v_pax, v_lift, v_deckm2, v_endurance, v_speed, v_cost_hour, v_cost_cap, v_availibility,
     v_cost_a = multidict({
            'vessel_1': [30, 0, 10, 100, 25, sheetVesselCost.cell(17, 1).value, {'l_term_1':(
     sheetVesselCost.cell(17, 5).value), 'm_term_1':(sheetVesselCost.cell(17, 4).value), 's_term_1':(
     sheetVesselCost.cell(17, 3).value),'l_term_2':(sheetVesselCost.cell(17, 5).value), 'm_term_2':(
     sheetVesselCost.cell(17, 4).value), 's_term_2':(sheetVesselCost.cell(17, 3).value),'l_term_3':(
     sheetVesselCost.cell(17, 5).value), 'm_term_3':(sheetVesselCost.cell(17, 4).value), 's_term_3':(
     sheetVesselCost.cell(17, 3).value),'l_term_4':(sheetVesselCost.cell(17, 5).value), 'm_term_4':(
     sheetVesselCost.cell(17, 4).value), 's_term_4':(sheetVesselCost.cell(17, 3).value),'l_term_5':(
     sheetVesselCost.cell(17, 5).value), 'm_term_5':(sheetVesselCost.cell(17, 4).value), 's_term_5':(
     sheetVesselCost.cell(17, 3).value)}, 150, 200],
```

```
        'vessel_2': [60, 0, 240, 600, 35, sheetVesselCost.cell(18, 1).value, {'l_term_1':(
sheetVesselCost.cell(18, 5).value), 'm_term_1':(sheetVesselCost.cell(18, 4).value), 's_term_1':(
sheetVesselCost.cell(18, 3).value), 'l_term_2':(sheetVesselCost.cell(18, 5).value), 'm_term_2':(
sheetVesselCost.cell(18, 4).value), 's_term_2':(sheetVesselCost.cell(18, 3).value),'l_term_3':(
sheetVesselCost.cell(18, 5).value), 'm_term_3':(sheetVesselCost.cell(18, 4).value), 's_term_3':(
sheetVesselCost.cell(18, 3).value),'l_term_4':(sheetVesselCost.cell(18, 5).value), 'm_term_4':(
sheetVesselCost.cell(18, 4).value), 's_term_4':(sheetVesselCost.cell(18, 3).value),'l_term_5':(
sheetVesselCost.cell(18, 5).value), 'm_term_5':(sheetVesselCost.cell(18, 4).value), 's_term_5':(
sheetVesselCost.cell(18, 3).value)}, 250, 200],  #CTV-L
        'vessel_3': [15, 0, 4, 490, 150, sheetVesselCost.cell(19, 1).value, {'l_term_1':(
sheetVesselCost.cell(19, 5).value), 'm_term_1':(sheetVesselCost.cell(19, 4).value), 's_term_1':(
sheetVesselCost.cell(19, 3).value),'l_term_2':(sheetVesselCost.cell(19, 5).value), 'm_term_2':(
sheetVesselCost.cell(19, 4).value), 's_term_2':(sheetVesselCost.cell(19, 3).value),'l_term_3':(
sheetVesselCost.cell(19, 5).value), 'm_term_3':(sheetVesselCost.cell(19, 4).value), 's_term_3':(
sheetVesselCost.cell(19, 3).value),'l_term_4':(sheetVesselCost.cell(19, 5).value), 'm_term_4':(
sheetVesselCost.cell(19, 4).value), 's_term_4':(sheetVesselCost.cell(19, 3).value),'l_term_5':(
sheetVesselCost.cell(19, 5).value), 'm_term_5':(sheetVesselCost.cell(19, 4).value), 's_term_5':(
sheetVesselCost.cell(19, 3).value)}, 250, 200], #heli
        'vessel_4': [15, 5, 500, 6000, 13, sheetVesselCost.cell(20, 1).value, {'l_term_1':(
sheetVesselCost.cell(20, 5).value), 'm_term_1':(sheetVesselCost.cell(20, 4).value), 's_term_1':(
sheetVesselCost.cell(20, 3).value),'l_term_2':(sheetVesselCost.cell(20, 5).value), 'm_term_2':(
sheetVesselCost.cell(20, 4).value), 's_term_2':(sheetVesselCost.cell(20, 3).value),'l_term_3':(
sheetVesselCost.cell(20, 5).value), 'm_term_3':(sheetVesselCost.cell(20, 4).value), 's_term_3':(
sheetVesselCost.cell(20, 3).value),'l_term_4':(sheetVesselCost.cell(20, 5).value), 'm_term_4':(
sheetVesselCost.cell(20, 4).value), 's_term_4':(sheetVesselCost.cell(20, 3).value),'l_term_5':(
sheetVesselCost.cell(20, 5).value), 'm_term_5':(sheetVesselCost.cell(20, 4).value), 's_term_5':(
sheetVesselCost.cell(20, 3).value)}, 200, 200],  #PSV-M
        'vessel_5': [70, 4, 800, 9000, 12, sheetVesselCost.cell(21, 1).value, {'l_term_1':(
sheetVesselCost.cell(21, 5).value), 'm_term_1':(sheetVesselCost.cell(21, 4).value), 's_term_1':(
sheetVesselCost.cell(21, 3).value),'l_term_2':(sheetVesselCost.cell(21, 5).value), 'm_term_2':(
sheetVesselCost.cell(21, 4).value), 's_term_2':(sheetVesselCost.cell(21, 3).value),'l_term_3':(
sheetVesselCost.cell(21, 5).value), 'm_term_3':(sheetVesselCost.cell(21, 4).value), 's_term_3':(
sheetVesselCost.cell(21, 3).value),'l_term_4':(sheetVesselCost.cell(21, 5).value), 'm_term_4':(
sheetVesselCost.cell(21, 4).value), 's_term_4':(sheetVesselCost.cell(21, 3).value),'l_term_5':(
sheetVesselCost.cell(21, 5).value), 'm_term_5':(sheetVesselCost.cell(21, 4).value), 's_term_5':(
sheetVesselCost.cell(21, 3).value)}, 250, 100],  #PSV-L
        'vessel_6': [60, 4, 250, 8000, 11.5, sheetVesselCost.cell(22, 1).value, {'l_term_1':(
sheetVesselCost.cell(22, 5).value), 'm_term_1':(sheetVesselCost.cell(22, 4).value), 's_term_1':(
sheetVesselCost.cell(22, 3).value),'l_term_2':(sheetVesselCost.cell(22, 5).value), 'm_term_2':(
sheetVesselCost.cell(22, 4).value), 's_term_2':(sheetVesselCost.cell(22, 3).value),'l_term_3':(
sheetVesselCost.cell(22, 5).value), 'm_term_3':(sheetVesselCost.cell(22, 4).value), 's_term_3':(
sheetVesselCost.cell(22, 3).value),'l_term_4':(sheetVesselCost.cell(22, 5).value), 'm_term_4':(
sheetVesselCost.cell(22, 4).value), 's_term_4':(sheetVesselCost.cell(22, 3).value), 'l_term_5':(
sheetVesselCost.cell(22, 5).value), 'm_term_5':(sheetVesselCost.cell(22, 4).value), 's_term_5':(
sheetVesselCost.cell(22, 3).value)}, 250, 100],  #OSV-M
        'vessel_7': [90, 6, 900, 10000, 13, sheetVesselCost.cell(23, 1).value, {'l_term_1':(
sheetVesselCost.cell(23, 5).value), 'm_term_1':(sheetVesselCost.cell(23, 4).value), 's_term_1':(
sheetVesselCost.cell(23, 3).value), 'l_term_2':(sheetVesselCost.cell(23, 5).value), 'm_term_2':(
sheetVesselCost.cell(23, 4).value), 's_term_2':(sheetVesselCost.cell(23, 3).value),'l_term_3':(
sheetVesselCost.cell(23, 5).value), 'm_term_3':(sheetVesselCost.cell(23, 4).value), 's_term_3':(
sheetVesselCost.cell(23, 3).value),'l_term_4':(sheetVesselCost.cell(23, 5).value), 'm_term_4':(
sheetVesselCost.cell(23, 4).value), 's_term_4':(sheetVesselCost.cell(23, 3).value), 'l_term_5':(
sheetVesselCost.cell(23, 5).value), 'm_term_5':(sheetVesselCost.cell(23, 4).value), 's_term_5':(
sheetVesselCost.cell(23, 3).value)}, 300, 100],  #OSV-L
        'vessel_8': [15, 5, 500, 6000, 150, sheetVesselCost.cell(24, 1).value, {'l_term_1':(
sheetVesselCost.cell(24, 5).value), 'm_term_1':(sheetVesselCost.cell(24, 4).value), 's_term_1':(
sheetVesselCost.cell(24, 3).value),'l_term_2':(sheetVesselCost.cell(24, 5).value), 'm_term_2':(
sheetVesselCost.cell(24, 4).value), 's_term_2':(sheetVesselCost.cell(24, 3).value),'l_term_3':(
sheetVesselCost.cell(24, 5).value), 'm_term_3':(sheetVesselCost.cell(24, 4).value), 's_term_3':(
sheetVesselCost.cell(24, 3).value),'l_term_4':(sheetVesselCost.cell(24, 5).value), 'm_term_4':(
sheetVesselCost.cell(24, 4).value), 's_term_4':(sheetVesselCost.cell(24, 3).value),'l_term_5':(
sheetVesselCost.cell(24, 5).value), 'm_term_5':(sheetVesselCost.cell(24, 4).value), 's_term_5':(
sheetVesselCost.cell(24, 3).value)}, 200, 200],  #heli+PSV-M
        'vessel_9': [15, 5, 500, 6000, 25, sheetVesselCost.cell(25, 1).value, {'l_term_1':(
sheetVesselCost.cell(25, 5).value), 'm_term_1':(sheetVesselCost.cell(25, 4).value), 's_term_1':(
sheetVesselCost.cell(25, 3).value),'l_term_2':(sheetVesselCost.cell(25, 5).value), 'm_term_2':(
sheetVesselCost.cell(25, 4).value), 's_term_2':(sheetVesselCost.cell(25, 3).value),'l_term_3':(
sheetVesselCost.cell(25, 5).value), 'm_term_3':(sheetVesselCost.cell(25, 4).value), 's_term_3':(
sheetVesselCost.cell(25, 3).value),'l_term_4':(sheetVesselCost.cell(25, 5).value), 'm_term_4':(
sheetVesselCost.cell(25, 4).value), 's_term_4':(sheetVesselCost.cell(25, 3).value), 'l_term_5':(
sheetVesselCost.cell(25, 5).value), 'm_term_5':(sheetVesselCost.cell(25, 4).value), 's_term_5':(
```

```
     sheetVesselCost.cell(25, 3).value)}, 250, 200],  #CTV-M+PSV-M
             'vessel_10': [15, 4, 500, 8000, 25, sheetVesselCost.cell(26, 1).value, {'l_term_1':(
     sheetVesselCost.cell(26, 5).value), 'm_term_1':(sheetVesselCost.cell(26, 4).value), 's_term_1':(
     sheetVesselCost.cell(26, 3).value),'l_term_2':(sheetVesselCost.cell(26, 5).value), 'm_term_2':(
     sheetVesselCost.cell(26, 4).value), 's_term_2':(sheetVesselCost.cell(26, 3).value),'l_term_3':(
     sheetVesselCost.cell(26, 5).value), 'm_term_3':(sheetVesselCost.cell(26, 4).value), 's_term_3':(
     sheetVesselCost.cell(26, 3).value),'l_term_4':(sheetVesselCost.cell(26, 5).value), 'm_term_4':(
     sheetVesselCost.cell(26, 4).value), 's_term_4':(sheetVesselCost.cell(26, 3).value),'l_term_5':(
     sheetVesselCost.cell(26, 5).value), 'm_term_5':(sheetVesselCost.cell(26, 4).value), 's_term_5':(
     sheetVesselCost.cell(26, 3).value)}, 250, 100],  #CTV-M+OSV-M
             'vessel_11': [15, 4, 500, 8000, 150, sheetVesselCost.cell(27, 1).value, {'l_term_1':(
     sheetVesselCost.cell(27, 5).value), 'm_term_1':(sheetVesselCost.cell(27, 4).value), 's_term_1':(
     sheetVesselCost.cell(27, 3).value),'l_term_2':(sheetVesselCost.cell(27, 5).value), 'm_term_2':(
     sheetVesselCost.cell(27, 4).value), 's_term_2':(sheetVesselCost.cell(27, 3).value),'l_term_3':(
     sheetVesselCost.cell(27, 5).value), 'm_term_3':(sheetVesselCost.cell(27, 4).value), 's_term_3':(
     sheetVesselCost.cell(27, 3).value),'l_term_4':(sheetVesselCost.cell(27, 5).value), 'm_term_4':(
     sheetVesselCost.cell(27, 4).value), 's_term_4':(sheetVesselCost.cell(27, 3).value),'l_term_5':(
     sheetVesselCost.cell(27, 5).value), 'm_term_5':(sheetVesselCost.cell(27, 4).value), 's_term_5':(
     sheetVesselCost.cell(27, 3).value)}, 280, 100]  #heli+OSV-M
             })

#List of bases
#    load: max base cap for pax,
#    cost: cost for operating the base type

    bases, b_pax, b_vessel, b_cost_ops, b_cost_cap, latb, lonb, b_cost_a = multidict({
              'DenHelder': [2000, 3, 1, 150000, 52.96269, 4.79358, 0], #port@Husum/pax high since
     accommodation on platforms/cost includes platform accommodation
              'Emden': [2000, 3, 5, 150000, 53.3384, 7.18716, 0], #port@Emden/pax high since accommodation
     on platforms/cost includes platform accommodation
              'Cuxhaven': [2000, 3, 1, 150000, 53.87176, 8.70889, 0], #port@Husum/pax high since
     accommodation on platforms/cost includes platform accommodation
              'Brunsb ttel': [2000, 3, 5, 150000, 53.88905, 9.09423, 0], #port@Emden/pax high since
     accommodation on platforms/cost includes platform accommodation
              'Delfzijl': [2000, 3, 5, 150000, 53.32762, 6.93285, 0], #port@Emden/pax high since
     accommodation on platforms/cost includes platform accommodation
              'Wilhelmshaven': [2000, 3, 1, 150000, 53.52254, 8.16157, 0], #port@Husum/pax high since
     accommodation on platforms/cost includes platform accommodation
              'Rotterdam': [2000, 3, 1, 150000, 51.94366, 4.15117, 0], #port@Husum/pax high since
     accommodation on platforms/cost includes platform accommodation
              'Husum': [2000, 3, 1, 150000, 54.47162, 9.03994, 0], #port@Husum/pax high since accommodation
      on platforms/cost includes platform accommodation
              'Esbjerg': [2000, 3, 5, 150000, 55.47107, 8.4255, 0], #port@Emden/pax high since
     accommodation on platforms/cost includes platform accommodation
              'Bremerhaven': [2000, 3, 5, 150000, 53.56384, 8.55114, 0] #port@Emden/pax high since
     accommodation on platforms/cost includes platform accommodation
             })

    allowed_b_v_combis = [('DenHelder','vessel_1'),('DenHelder','vessel_2'),('DenHelder','vessel_3'),('
     DenHelder','vessel_4'),('DenHelder','vessel_5'),('DenHelder','vessel_6'),('DenHelder','vessel_7'),('
     DenHelder','vessel_8'),('DenHelder','vessel_9'),('DenHelder','vessel_10'),('DenHelder','vessel_11'),
                            ('Delfzijl','vessel_1'),('Delfzijl','vessel_2'),('Delfzijl','vessel_3'),('
     Delfzijl','vessel_4'),('Delfzijl','vessel_5'),('Delfzijl','vessel_6'),('Delfzijl','vessel_7'),('
     Delfzijl','vessel_8'),('Delfzijl','vessel_9'),('Delfzijl','vessel_10'),('Delfzijl','vessel_11'),
                             ('Rotterdam','vessel_1'),('Rotterdam','vessel_2'),('Rotterdam','vessel_3'),('
     Rotterdam','vessel_4'),('Rotterdam','vessel_5'),('Rotterdam','vessel_6'),('Rotterdam','vessel_7'),('
     Rotterdam','vessel_8'),('Rotterdam','vessel_9'),('Rotterdam','vessel_10'),('Rotterdam','vessel_11'),
                              ('Emden','vessel_1'),('Emden','vessel_2'),('Emden','vessel_3'),('Emden','
     vessel_4'),('Emden','vessel_5'),('Emden','vessel_6'),('Emden','vessel_7'),('Emden','vessel_8'),('
     Emden','vessel_9'),('Emden','vessel_10'),('Emden','vessel_11'),
                               ('Wilhelmshaven','vessel_1'),('Wilhelmshaven','vessel_2'),('Wilhelmshaven','
     vessel_3'),('Wilhelmshaven','vessel_4'),('Wilhelmshaven','vessel_5'),('Wilhelmshaven','vessel_6'),('
     Wilhelmshaven','vessel_7'),('Wilhelmshaven','vessel_8'),('Wilhelmshaven','vessel_9'),('Wilhelmshaven'
     ,'vessel_10'),('Wilhelmshaven','vessel_11'),
                                ('Bremerhaven','vessel_1'),('Bremerhaven','vessel_2'),('Bremerhaven','
     vessel_3'),('Bremerhaven','vessel_4'),('Bremerhaven','vessel_5'),('Bremerhaven','vessel_6'),('
     Bremerhaven','vessel_7'),('Bremerhaven','vessel_8'),('Bremerhaven','vessel_9'),('Bremerhaven','
     vessel_10'),('Bremerhaven','vessel_11'),
                                 ('Cuxhaven','vessel_1'),('Cuxhaven','vessel_2'),('Cuxhaven','vessel_3'),('
     Cuxhaven','vessel_4'),('Cuxhaven','vessel_5'),('Cuxhaven','vessel_6'),('Cuxhaven','vessel_7'),('
     Cuxhaven','vessel_8'),('Cuxhaven','vessel_9'),('Cuxhaven','vessel_10'),('Cuxhaven','vessel_11'),
```

```
                                ('Brunsb ttel','vessel_1'),('Brunsb ttel','vessel_2'),('Brunsb ttel','
     vessel_3'),('Brunsb ttel','vessel_4'),('Brunsb ttel','vessel_5'),('Brunsb ttel','vessel_6'),('
     Brunsb ttel','vessel_7'),('Brunsb ttel','vessel_8'),('Brunsb ttel','vessel_9'),('Brunsb ttel','
     vessel_10'),('Brunsb ttel','vessel_11'),
                                ('Husum','vessel_1'),('Husum','vessel_2'),('Husum','vessel_3'),('Husum','
     vessel_4'),('Husum','vessel_5'),('Husum','vessel_6'),('Husum','vessel_7'),('Husum','vessel_8'),('
     Husum','vessel_9'),('Husum','vessel_10'),('Husum','vessel_11'),
                                ('Esbjerg','vessel_1'),('Esbjerg','vessel_2'),('Esbjerg','vessel_3'),('
     Esbjerg','vessel_4'),('Esbjerg','vessel_5'),('Esbjerg','vessel_6'),('Esbjerg','vessel_7'),('Esbjerg',
     'vessel_8'),('Esbjerg','vessel_9'),('Esbjerg','vessel_10'),('Esbjerg','vessel_11')]

    #############################



    ############Platform cluster import
    bookPlatform = open_workbook('C:/Users/devin/Dropbox/TIL thesis/python/new beginnings/ultima_vez/
     clusters/platforms_TenneT_NS_DE_NL_2023_cluster.xlsx')
    sheetPlatform = bookPlatform.sheet_by_index(0)

    # read header values into the list
    keysPlatform = [sheetPlatform.cell(0, col_index).value for col_index in range(0,6)]

    platforms_data = {}
    for row_index in range(1, sheetPlatform.nrows):
        platforms_data[sheetPlatform.cell(row_index,1).value] = {keysPlatform[col_index]: sheetPlatform.
     cell(row_index, col_index).value
                  for col_index in range(0,6)}

    platforms = [i for i in platforms_data.keys()]

    ############Corrective maintenance import
    bookCorr = open_workbook('C:/Users/devin/Dropbox/TIL thesis/python/new beginnings/ultima_vez/
     maintenance_all/CorrMaint_DE_NL_2023.xlsx')
    sheetCorr = bookCorr.sheet_by_index(0)

    # read header values into the list
    keysCorr = [sheetCorr.cell(0, col_index).value for col_index in range(sheetCorr.ncols)]
#
    corr_maintenance = {}
    for row_index in range(1, sheetCorr.nrows):
        corr_maintenance[ast.literal_eval(sheetCorr.cell(row_index,0).value)] = {keysCorr[col_index]:
     sheetCorr.cell(row_index, col_index).value
                         for col_index in range(1,sheetCorr.ncols)}

    ############Preventive maintenance import
    bookPrev = open_workbook('C:/Users/devin/Dropbox/TIL thesis/python/new beginnings/ultima_vez/
     maintenance_all/PrevMaint_DE_NL_2023.xlsx')
    sheetPrev = bookPrev.sheet_by_index(0)

    # read header values into the list
    keysPrev = [sheetPrev.cell(0, col_index).value for col_index in range(sheetPrev.ncols)]

    prev_maintenance = {}
    for row_index in range(1, sheetPrev.nrows):
        prev_maintenance[ast.literal_eval(sheetPrev.cell(row_index,0).value)] = {keysPrev[col_index]:
     sheetPrev.cell(row_index, col_index).value
                         for col_index in range(1,sheetPrev.ncols)}

    total_maintenance_needs_list = {**prev_maintenance,**corr_maintenance}

#Create a list with maintenance activities
    total_maintenance_list = {}
    for (platform,maint_type,period) in total_maintenance_needs_list.keys():
        total_maintenance_list[platform,maint_type,period] = 1

    maintenance_name = []
    for i in total_maintenance_needs_list.keys():
        if i[1] not in maintenance_name:
            maintenance_name.append(i[1])
```

```
    def distance(lat1, lon1, lat2, lon2):
        radius = 6371 # km of earth radius
        dlat = math.radians(lat2-lat1)
        dlon = math.radians(lon2-lon1)
        a = math.sin(dlat/2) * math.sin(dlat/2) + math.cos(math.radians(lat1)) \
            * math.cos(math.radians(lat2)) * math.sin(dlon/2) * math.sin(dlon/2)
        l = 2 * math.atan2(math.sqrt(a), math.sqrt(1-a))
        k = radius * l * 0.539957
        return k

    #straightlight base-platform distances in km
    B_P_distances = {}
    for base in bases:
        for platform in platforms:
            lat1 = latb[base]
            lon1 = lonb[base]
            lat2 = platforms_data[platform]['lat']
            lon2 = platforms_data[platform]['lon']
            B_P_distances[(base,platform)] = distance(lat1, lon1, lat2, lon2) * 2
    print(max(B_P_distances.values()))
    for i in B_P_distances.values():
        if i == max(B_P_distances.values()):
            for l in B_P_distances.keys():
                if B_P_distances[l] == i:
                    print(l, B_P_distances[l])

    #vessel check
    vessels_comp_OM = {}
    vessels_comp = []
    for vessel in vessels:
        for i in total_maintenance_needs_list:
            if v_lift[vessel] >= total_maintenance_needs_list[i]['lifting'] :
                vessels_comp_OM[i] = vessel
                vessels_comp.append(vessel)
    vessels_comp = set(vessels_comp)


    allowed_b_v_combis_comp = [i for i in allowed_b_v_combis if i[1] in vessels_comp]

    #create a list with the maintenance assignments
    maintenance_vessel_base_list = {}
    for base in bases:
        for vessel in vessels_comp:
            for (platform,maint_type,period) in total_maintenance_needs_list.keys():
                if (base,vessel) in allowed_b_v_combis:
                    maintenance_vessel_base_list[base,vessel,platform,maint_type,period] = max(math.ceil(
     total_maintenance_needs_list[(platform,maint_type,period)]['num_crew']/v_pax[vessel]),
                        math.ceil(total_maintenance_needs_list[(platform,maint_type,period)]['deckspace'
     ]/v_deckm2[vessel]))

    return (bookPlatform,sheetPlatform,keysPlatform,platforms_data,corr_maintenance,bookPrev,sheetPrev,
     keysPrev,prev_maintenance,
            bookCorr,sheetCorr,keysCorr,total_maintenance_needs_list,total_maintenance_list,
     vessels_comp_OM,
            vessels_comp,allowed_b_v_combis_comp,hour_salary,max_travel_time,start_year,
            end_year,years,vessel_contracts,contract_duration,vessels,v_pax,v_lift,v_deckm2,
            v_endurance,v_speed,v_cost_hour,v_cost_cap,v_availibility,v_cost_a,bases,b_pax,
            b_vessel,b_cost_ops,b_cost_cap,latb,lonb,b_cost_a,allowed_b_v_combis,B_P_distances,kMAX,
            platforms,maintenance_name,maintenance_vessel_base_list,spot_contracts)


def OptiFleet(bases,years,vessels_comp,allowed_b_v_combis,vessel_contracts,platforms,
 total_maintenance_list,maintenance_name):
    """
    parameters:
        sets for the variables:
            bases
            years
            vessels_comp: list with compatible vessels
            vessel_contracts
            platforms
```

```
        objective parameters:
            b_cost_cap
            v_cost_cap_l
            v_cost_cap_m
            v_cost_cap_s
            hour_salary
            num_crew
            v_cost_hour
            b_cost_ops
            B_P_distances
        constraints:
            f = frequency of maintenance

            ------------------------keep updating here-------------------
    """

    model = Model('OptiFleet2')
    #######definition of model variables
    x,y,q,c,o,r = tupledict(),tupledict(),tupledict(),tupledict(),tupledict(),tupledict()

 ########################Variables for vessel and base acquisition
    for base in bases:
        for period in years:
            x[base,period] = model.addVar(vtype = 'B', name = 'x(%s,%s)'%(base,period))

    for vessel in vessels_comp:
        for contract in vessel_contracts:
            for period in years:
                y[vessel,contract,period] = model.addVar(vtype = 'B', name = 'y(%s,%s,%s)'%(vessel,
     contract,period))

    for vessel in vessels_comp:
        for period in years:
            for contract in spot_contracts:
                o[vessel,contract,period] = model.addVar(vtype = 'B', name = 'o(%s,%s,%s)'%(vessel,
     contract,period))

#######################Variable to link bases to vessels - in het rapport q
    for base in bases:
        for vessel in vessels_comp:
            for period in years:
                if (base,vessel) in allowed_b_v_combis:
                    q[base,vessel,period] = model.addVar(vtype = 'B', name = 'k(%s,%s,%s)'%(base,vessel,
     period))

 ######################Variables for linking supply to demand, with z = trip frequency and c = execution
     of maintennance act

    for base in bases:
        for vessel in vessels_comp:
            for (platform,maint_type,period) in total_maintenance_needs_list.keys():
                if (base,vessel) in allowed_b_v_combis:
                    c[base,vessel,platform,maint_type,period] = model.addVar(vtype = 'B',
                     name = 'c(%s,%s,%s,%s,%s)'%(base,vessel,platform,maint_type,period))

    for vessel in vessels_comp:
        for contract in vessel_contracts:
            for period in years:
                r[vessel,contract,period] = model.addVar(vtype = 'I', name = 'r(%s,%s,%s)'%(vessel,
     contract,period))


    model.update()

    L = [model.getVars()]

    #######definition of model constraints
    ###link supply to demand

    for (platform,maint_type,period) in total_maintenance_needs_list.keys():
        model.addConstr(quicksum(c[base,vessel,platform,maint_type,period]
```

```
        for base in bases
        for vessel in vessels_comp) == total_maintenance_needs_list[platform,maint_type,period]['activated'],
        "DemandTotal(%s,%s,%s,%s,%s)"%(base,vessel,platform,maint_type,period))

###    ###vessel below availibility

    for vessel in vessels_comp:
        for period in years:
            model.addConstr(quicksum(c[base,vessel,platform,maint_type,period] *
                                     B_P_distances[(base,platform)]
            for base in bases
            for platform in platforms
            for maint_type in maintenance_name
            if (base,vessel,platform,maint_type,period) in c)
            <=
            (v_endurance[vessel] *
             v_availibility[vessel] *
             (quicksum(y[vessel,contract,period] for contract in vessel_contracts) +
              (quicksum(o[vessel,contract,period] for contract in spot_contracts)))),
            'vessel_endurance_per_year')

    for vessel in vessels_comp:
        for period in years:
            model.addConstr(quicksum(c[base,vessel,platform,maint_type,period] *
                                     total_maintenance_needs_list[platform,maint_type,period]['repair_time']
            for base in bases
            for platform in platforms
            for maint_type in maintenance_name
            if (base,vessel,platform,maint_type,period) in c)
            <= (v_availibility[vessel] *
                (quicksum(y[vessel,contract,period] for contract in vessel_contracts) +
                 (quicksum(o[vessel,contract,period] for contract in spot_contracts)))),
            'vessel_availibility_per_year')

    for base in bases:
        for vessel in vessels_comp:
            for platform in platforms:
                for maint_type in maintenance_name:
                    for period in years:
                        if (base,vessel,platform,maint_type,period) in c:
                            model.addConstr(c[base,vessel,platform,maint_type,period] *
                                                    B_P_distances[(base,platform)]
                                                    <= v_endurance[vessel],
                            'vessel_endurance_per_trip')
#
###    ####pair bases to vessels
###
    for base in bases:
        for vessel in vessels_comp:
            for platform in platforms:
                for maint_type in maintenance_name:
                    for period in years:
                        if (base,vessel) in (allowed_b_v_combis):
                            if (base,vessel,platform,maint_type,period) in c:
                                model.addConstr(q[base,vessel,period] ==
                                                c[base,vessel,platform,maint_type,period], 'vessel_base_pairing_maintenance')
##
###
###    ###ensure base and vessel availibility and acquisition
###    #base only in base-vessel pairs when paid for (x=1) and vessel is available (y=1)
##
    for period in years:
        for vessel in vessels_comp:
            model.addConstr((quicksum(y[vessel,contract,period] for contract in vessel_contracts) +
                             quicksum(o[vessel,contract,period] for contract in spot_contracts)) >= quicksum(q[base,vessel,period] for base in bases), 'Vessel_Acq')

    for period in years:
```

```
        for vessel in vessels_comp:
             for base in bases:
                 model.addConstr(x[base,period] >= q[base,vessel,period], 'Base_Acq')
##
###
    for vessel in vessels_comp:
        for period in years:
            for contract in vessel_contracts:
                model.addConstr(quicksum(y[vessel,contract,period2] for period2 in range(period,min(period+contract_duration[contract],max(years)))) <=
                                contract_duration[contract], 'contract_lenght')
#
###
#    ####base capacity for vessels
    for period in years:
        for base in bases:
            model.addConstr(quicksum(q[base,vessel,period]
            for vessel in vessels_comp
            if (base,vessel) in allowed_b_v_combis) <= b_vessel[base], 'BaseCapVessel')

#    ####base pax capacity
    for period in years:
        for base in bases:
            model.addConstr(quicksum(q[base,vessel,period] * v_pax[vessel]
            for vessel in vessels_comp
            if (base,vessel) in allowed_b_v_combis) <= b_pax[base] * x[base,period], 'BaseAccommodationPax' )
#
#    ###Bases in use
    for period in years:
        model.addConstr(quicksum(x[base,period] for base in bases) <= kMAX, "MaxBasesInUse")
#
#
#    ###routes below max travel time
    for (base,vessel,platform,maint_type,period) in c:
        for contract in vessel_contracts:
            model.addConstr((c[base,vessel,platform,maint_type,period] *
                             B_P_distances[(base,platform)]) / (v_speed[vessel] * 2) <= max_travel_time,
                            'max_personnel_travel_time')

    ##Objective functions
    obj1_fixedC_base = quicksum(x[base,period] * b_cost_cap[base] for base in bases
                            for period in years)

    obj5_fixedC_vessel = quicksum(y[vessel,contract,period] * v_cost_cap[vessel][contract] for vessel in vessels_comp
                              for contract in vessel_contracts
                              for period in years)

    obj2_SpotCharter_vessel = quicksum(c[base,vessel,platform,maint_type,period] *
                                   o[vessel,contract,period] *
                                   total_maintenance_needs_list[platform,maint_type,period]['repair_time'] *
                                   v_cost_cap[vessel][contract] for base in bases
                                   for vessel in vessels_comp
                                   for platform in platforms
                                   for maint_type in maintenance_name
                                   for period in years
                                   for contract in spot_contracts
                                   if (base,vessel,platform,maint_type,period) in c)

    obj3_varC = quicksum(c[base,vessel,platform,maint_type,period] *
                     maintenance_vessel_base_list[base,vessel,platform,maint_type,period] *
                     ((((hour_salary *
                        total_maintenance_needs_list[platform,maint_type,period]['num_crew']) +
                        v_cost_hour[vessel]) *
                        (B_P_distances[(base,platform)]/v_speed[vessel]))) for base in bases
                                   for vessel in vessels_comp
                                   for platform in platforms
                                   for maint_type in maintenance_name
                                   for period in years
```

```
                                                    if (base,vessel,platform,maint_type,period) in c)

    obj4_acc = quicksum(c[base,vessel,platform,maint_type,period] *
                          total_maintenance_needs_list[platform,maint_type,period]['num_crew'] *
                          (b_cost_a[base] + v_cost_a[vessel]) *
                          total_maintenance_needs_list[platform,maint_type,period]['repair_time'] for base
     in bases
                                                   for vessel in vessels_comp
                                                   for platform in platforms
                                                   for maint_type in maintenance_name
                                                   for period in years
                                                    if (base,vessel,platform,maint_type,period) in c)

    model.setObjective(obj1_fixedC_base + obj2_SpotCharter_vessel + obj3_varC + obj4_acc +
     obj5_fixedC_vessel, GRB.MINIMIZE)

    model.update()
    model.__data = x,y,q,c,o,r
    return model

if __name__ == "__main__":
    (bookPlatform,sheetPlatform,keysPlatform,platforms_data,corr_maintenance,bookPrev,sheetPrev,keysPrev,
     prev_maintenance,
             bookCorr,sheetCorr,keysCorr,total_maintenance_needs_list,total_maintenance_list,
     vessels_comp_OM,
             vessels_comp,allowed_b_v_combis_comp,hour_salary,max_travel_time,start_year,
             end_year,years,vessel_contracts,contract_duration,vessels,v_pax,v_lift,v_deckm2,
             v_endurance,v_speed,v_cost_hour,v_cost_cap,v_availibility,v_cost_a,bases,b_pax,
             b_vessel,b_cost_ops,b_cost_cap,latb,lonb,b_cost_a,allowed_b_v_combis,B_P_distances,kMAX,
             platforms,maintenance_name,maintenance_vessel_base_list,spot_contracts) = make_data()
    model = OptiFleet(bases,years,vessels_comp,allowed_b_v_combis,vessel_contracts,platforms,
     total_maintenance_list,maintenance_name)
    model.Params.TuneCriterion =  0
    model.Params.Presolve = -1
    model.Params.PreSparsify = -1
    model.Params.TuneOutput = 2
    model.Params.DualReductions = 1
    model.Params.TimeLimit = 3600
    model.Params.NodefileStart = 0.5
    model.Params.MIPFocus = 0
    model.Params.Cuts = -1
    model.Params.ImproveStartTime = 3600
    model.optimize()


    status = model.Status

    x,y,q,c,o,r = model.__data

    vessel_support = {(base,vessel,platform,maint_type,period):c[base,vessel,platform,maint_type,period].X
                      for (base,vessel,platform,maint_type,period) in c
                      if c[base,vessel,platform,maint_type,period].X > 0}

    vessels_acquired_l_m = [(vessel,contract,period,y[vessel,contract,period].X) for (vessel,contract,
     period) in y if y[vessel,contract,period].X != 0]

    vessels_acquired_spot = [(vessel,contract,period,o[vessel,contract,period].X) for (vessel,contract,
     period) in o if o[vessel,contract,period].X != 0]

    bases_in_use = [(base,period) for (base,period) in x if x[base,period].X > 0]


    vessel_base = {(base,vessel,period): q[base,vessel,period].X
                   for (base,vessel,period) in q
                   if q[base,vessel,period].X != 0}

    base_cost = quicksum(x[base,period].X * b_cost_cap[base] for (base,period) in x if x[base,period].X !=
      0)

    vessel_m_l_cost = quicksum(y[vessel,contract,period].X * v_cost_cap[vessel][contract] for vessel in
     vessels_comp
```

```
                                  for contract in vessel_contracts
                                  for period in years)

    operational_cost = quicksum(c[base,vessel,platform,maint_type,period].X *
                                maintenance_vessel_base_list[base,vessel,platform,maint_type,period] *
                                ((((hour_salary *
                                    total_maintenance_needs_list[platform,maint_type,period]['num_crew']) +
                                    v_cost_hour[vessel]) *
                                    (B_P_distances[(base,platform)]/v_speed[vessel]))) for base in bases
                                                for vessel in vessels_comp
                                                for platform in platforms
                                                for maint_type in maintenance_name
                                                for period in years
                                                if (base,vessel,platform,maint_type,period) in c)

    spot_market_vessel_costs = quicksum(c[base,vessel,platform,maint_type,period].X *
                                        o[vessel,contract,period].X *
                                        total_maintenance_needs_list[platform,maint_type,period]['repair_time'] *
                                        v_cost_cap[vessel][contract] for base in bases
                                        for vessel in vessels_comp
                                        for platform in platforms
                                        for maint_type in maintenance_name
                                        for period in years
                                        for contract in spot_contracts
                                        if (base,vessel,platform,maint_type,period) in c)

    accommodation_cost = quicksum(c[base,vessel,platform,maint_type,period].X *
                        total_maintenance_needs_list[platform,maint_type,period]['num_crew'] *
                        (b_cost_a[base] + v_cost_a[vessel]) *
                        total_maintenance_needs_list[platform,maint_type,period]['repair_time'] for base in bases
                                        for vessel in vessels_comp
                                        for platform in platforms
                                        for maint_type in maintenance_name
                                        for period in years
                                        if (base,vessel,platform,maint_type,period) in c)

    number_vessel_contract = [((vessel,contract,period),r[vessel,contract,period].X) for (vessel,contract,period) in r if r[vessel,contract,period].X != 0]


    print("optimal value:", model.ObjVal)
    print('---------------')
    print(base_cost + vessel_m_l_cost + spot_market_vessel_costs + operational_cost + accommodation_cost)
    print('---------------')
    print("Optimal value bases=",base_cost)
    print('---------------')
    print('optimal value spot market vessels=', spot_market_vessel_costs)
    print('---------------')
    print("Optimal value vessels long and mid term=", vessel_m_l_cost)
    print('---------------')
    print("Optimal value operations=",operational_cost)
    print('---------------')
    print('accommodation cost=',accommodation_cost)
    print('---------------')
    print("Bases in use:", bases_in_use)
    print('---------------')
    print("vessels acquired long and med term:",vessels_acquired_l_m)
    print('---------------')
    print("vessels acquired spot:",vessels_acquired_spot, len(vessels_acquired_spot))
    print('---------------')
    print('---------------')
    print("Base-Vessel combination:",vessel_base, len(vessel_base), sum(vessel_base.values()))
    print('---------------')
    print("Number of vessels and contracts:",number_vessel_contract)
    print(model.Status)

    model.printQuality()

```

```
    model.write("OptiFleet4-output.sol")

"""

    ...: Plotting

    ...: """

Maintenance_list = pd.DataFrame(
        {'year':[],
         'maintenance_list':[],
         '#prev':[],
         '#corr':[],
         '#AnnualTrips':[]},
         index = [])


list_maint_p = []

ij = 0
for i in platforms:
    ij = ij + platforms_data[i]['cluster_set']
#    print(ij)

for x in list_maint_p:
    s_n = pd.Series([x[0],x[1],ij,len([i for i in x[1] if 'failure_' in i]),x[2]],
                     index=['year','maintenance_list','#prev','#corr','#AnnualTrips'])
    Maintenance_list = Maintenance_list.append(s_n, ignore_index=True)

# Define a function for a grouped bar plot

def groupedbarplot(x_data, y_data_list, y_data_names, colors, x_label, y_label, title):
    _, ax = plt.subplots()
# Total width for all bars at one x location
    total_width = 1
# Width of each individual bar
    ind_width = total_width / len(y_data_list)
# This centers each cluster of bars about the x tick mark
    alteration = np.arange(-(total_width/2), total_width/2, ind_width)

  # Draw bars, one category at a time
    for i in range(0, len(y_data_list)):
          # Move the bar to the right on the x-axis so it doesn't
          # overlap with previously drawn ones
        ax.bar(x_data + alteration[i], y_data_list[i], color = colors[i], label = y_data_names[i], width = ind_width)
        ax.set_ylabel(y_label)
        ax.set_xlabel(x_label)
        ax.set_title(title)
        ax.legend(loc = 'upper right')

# Call the function to create plot

groupedbarplot(x_data = Maintenance_list['year']
               , y_data_list = [Maintenance_list['#prev'], Maintenance_list['#corr'], Maintenance_list['#AnnualTrips']]
               , y_data_names = ['prev_maint', 'corr_maint', '#AnnualTrips']
               , colors = ['#539caf', '#7663b0', 'r']
               , x_label = 'year'
               , y_label = '# of maintenance activities'
               , title = 'number of maintenance activities per year')


# do IIS
print('The model is infeasible; computing IIS')
model.computeIIS()
if model.IISMinimal:
    print('IIS is minimal\n')
else:
    print('IIS is not minimal\n')
    print('\nThe following constraint(s) cannot be satisfied:')
```

```

for c in model.getConstrs():
    if c.IISConstr:
        print('%s' % c.constrName)
```

B

Proposal for model expansion

B.1. A possible extension to OptiFleet: the stochastic model

A case could be made for the upgrade of the model towards a stochastic model to cope with the great amount of uncertainty in long term maritime vessel fleet planning. This can be justified by the outcome of reviews on models on fleet management by Dalgic et al. (2015a), Hoff et al. (2010) where the lacking inclusion of uncertainty was one of the main issues with modern fleet management models for the long term. As Fagerholt et al. (2010), Gundegjerde and Halvorsen (2012), Joshi and Bolstad (2016) portrayed, stochastic optimization is one of the options to cope with the uncertainty. Stochastic optimization can thus be a replacement for the combination approach of simulation and optimization assumed in the deterministic model previously discussed in 5.6 In this section it will be discussed how this thesis proposes stochastic optimization for MFSMP.

In the deterministic model it is assumed that the values of all parameters are known in advance. However, how realistic is it to assume that the values of all parameters are known in advance and do not change in the course of the operational period of e.g. three years? Hence strategic and tactical uncertainty are included in the model. If this inclusion would be done in the classical way of constructing decision trees, the result would be a decision tree which explodes in terms of complexity and computational needs Kaut et al. (2014). To prevent this computational infeasibility, Kaut et al. (2014), propose a method to cope with the different timescales and uncertainty in a model. This method is called the multi-level approach for stochastic optimization.

As applied by Gundegjerde and Halvorsen (2012), Joshi and Bolstad (2016), Stålhane et al. (2016), Strømberg (2015) multi-stage stochastic optimization is currently among the most popular methods to deal with both uncertainty and multi-level decisions. For the stochastic model the idea is to specify the decisions on the various levels (strategic and tactical, see figure 5.2) over three stages. At every stage new information becomes available and the possibility exist to make recourse decisions. In other words, on the contrary to conventional optimization where decisions are made based on deterministic global information available at the start of the model, stochastic information divides the information provision, and associated uncertainty, over stages, much more in line with reality where not all information is available at the beginning of a process, but rather information becomes available as time goes on and previous decisions play out their affect.

More specifically, the here-and-now decisions in the first node are the long term infrastructure related decisions on the number and type of bases to use along with the vessels to acquire on long term contracts, see figure B.1. This is done with information available on the maintenance demand coming from the preventive maintenance schedules of the platforms in operation at that point in time.

After the first stage decisions, the second stage decisions can be considered recourse decisions, whereby the decisions made in the first stage can be corrected for if it turns out that for instance the demand coming from the preventive schedule, added with the demand coming in from corrective maintenance to address platform failure, can not be met with the vessel acquired on a long term contract as a strategic decision. The recourse decision would then be to add a vessel coming in from the spot market on a short term contract. Relevant information coming available in the second stage is thus the failure information of the platforms and the rates for spot vessels.

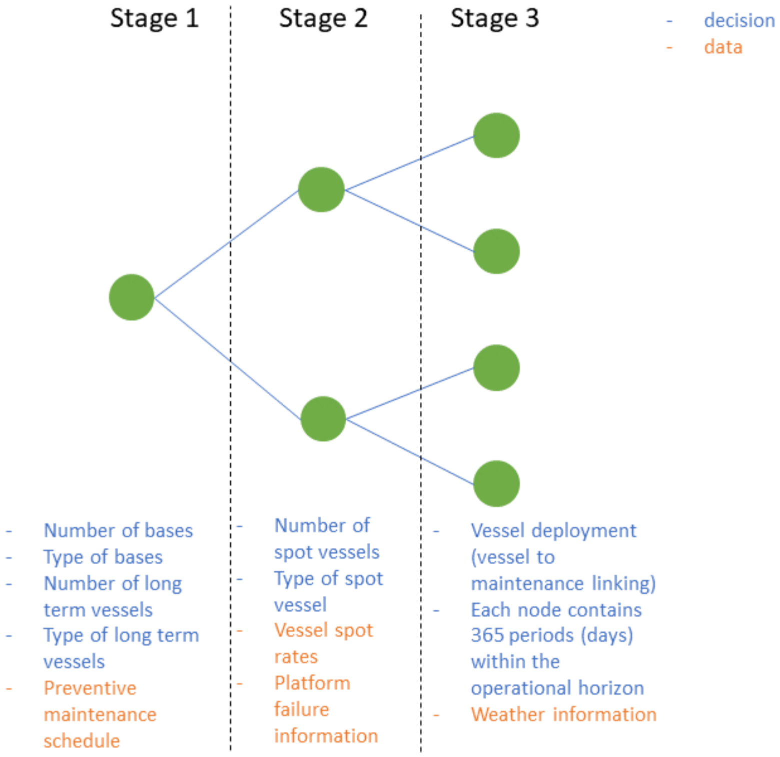

Figure B.1: Scenario tree

B.1.1. Proposal stochastic mathematical model

Indices

v	type of vessel
b	type of base (substation platform, harbour or offshore station)
a	maintenance activity id
m	maintenance bundle
s	maintenance scheme
p	operational time period
l	lease term
i	platform at which O&M activities are to be executed
a	category of preventive maintenance

Parameters

C^{F}_{bp}	Fixed cost for using base b during period p
C^{FL}_{vp}	Fixed cost for having vessel of type v in the fleet on a long term lease contract
C^{FM}_{vp}	Fixed cost for having vessel of type v in the fleet on a medium term lease contract
C^{FS}_{vp}	Fixed cost for having vessel of type v in the fleet on a short term charter contract
C^{O}_{vbsip}	Operational costs for vessel V operating from base b to support maintenance scheme s at platform i during period P
C^{D}_{aip}	Downtime cost of executing maintenance activity a at platform i during period p

N_{si}^p	The number of maintenance activities of preventive nature in maintenance scheme s
N_{ai}^p	Total number of preventive maintenance activities a which should be performed at platform i
C_a^{PP}	Penalty cost for not executing preventive maintenance activity a during the planning horizon
C_a^{PC}	Penalty cost for not executing corrective maintenance activity a during the planning horizon
$K_b^V v$	Vessel accommodation capacity of base b for each vessel type v
K_v^P	People accommodation capacity of vessel v
K_b^P	People accommodation capacity of base b
E_b	1 if base b must be used in the optimal solution, e.g. a base that is already operated from or owned by the decision-maker, 0 otherwise
E_{bv}	the number of vessels of vessels v at base b that must be used, e.g. if these vessels are owned or in contract by the decision maker at the start of the planning horizon in the model
M_{vp}^S	Available vessels of type v on the spot-market for short term charters
M_{vl}^M	Available vessels of type v on the market for a medium-term lease over lease period l
M_v^L	Available vessels of type v on the market for a long-term lease
S_s^{MD}	amount of technicians and crew required to execute maintenance scheme s
S_b^{MA}	amount of technicians and crew available at base b during period p

Decision variables

Strategic Decision variables - first stage

u_{bp}	1 if base of type b is used in period p, 0 otherwise
x_{bv}^L	number of vessels of type v, operating from base b on a long term lease
x_{bvl}^M	number of vessels of type v, operating from base b on a medium term lease over lease term l

In the first stage of decision making, one of the first aspects to make a decision upon is the use of bases. It needs to be decided whether offshore or onshore bases are used and whether those are static or dynamic bases, along with the capacity and capabilities of the base. This is captured in the decision variable u_{bp}, a binary variable on whether a base available on the market is used or not. Simultaneously with the decision on the base, the decision maker needs to consider the vessels to use together with the chosen bases. Vessels which will be acquired on long term contracts are part of the stage 1 decision making echelon and are represented by the variables x_{bv}^L and x_{bvl}^M.

Tactical Decision variables - second stage

x_{bvl}^S	number of vessels of type v, operating from base b on a short term lease (charter) over lease-term l

In the second stage, variable x_{bvp}^S specifies the amount and type of short-term, spot market, vessels which need to be acquired to cope with unanticipated demand coming from platform failures or irregularities with preventive maintenance.

Tactical Decision variables - third stage

y_{vbsip}	number of vessels of type v, operating from base b to execute scheme s at platform i in period p
l_{aivbp}	1 if corrective maintenance activity a at platform i is supported by

vessel of type v operating from base b in period p, 0 otherwise.

w^C_{aip} 1 if corrective maintenance activity a at platform i is not executed during period p, 0 otherwise

w^P_{ai} number of preventive maintenance activities of type a at platform i which are not executed in the planning horizon.

Finally, in the third stage, after information becomes available on weather related aspects and the demand is known in the form of maintenance schedules for both preventive and corrective maintenance, the vessels can be deployed over the maintenance demand. The decision variable y_{vbsip} is elementary in this stage as it specifies the vessel to maintenance schedule deployment, based on w^C_{aip} and w^P_{ai} which specify whether the maintenance activities on the schedule will be supported.

Objective Function

The objective function captures a general set of factors which together constitute the logistic cost of offshore operations for substation platforms. This objective function will be subject to optimization and in this case the objective is to minimize the value of the objective function, in other words minimize costs.

$$\begin{aligned}
\textbf{MIN} \sum_{b\in B}\sum_{p=1}^{P} C^F_{bp} * u_{bp} + \sum_{v\in V}\sum_{b\in B}\sum_{p=1}^{P} C^{FL}_{vp} * x^L_{bv} + \sum_{v\in V}\sum_{b\in B}\sum_{p=1}^{P} C^{FM}_{vp} * x^M_{bvl} \\
+ \sum_{n\in N_1} Pn\left[\sum_{v\in V}\sum_{b\in B}\sum_{p=1}^{P} C^{FS}_{vp} * x^S_{bvp}\right] \\
+ \sum_{n\in N_2} Pn\Bigg[\sum_{b\in B}\sum_{v\in V}\sum_{p=1}^{P}\sum_{s\in S}\sum_{i\in I} C^O_{vbsip} * y_{vbsip} + \sum_{a\in A}\sum_{i\in I}\sum_{v\in V}\sum_{b\in B}\sum_{p=1}^{P} C^D_{aip} * l_{aivbp} \\
+ \sum_{m\in M}\sum_{i\in I}\sum_{v\in V}\sum_{b\in B}\sum_{p=1}^{P} C^D_{aip} * y_{vbsip} * N_{si} \\
+ \sum_{a\in A}\sum_{i\in I}\sum_{p=1}^{P} C^{PP}_a * w^P_{ai} + \sum_{a\in A}\sum_{i\in I}\sum_{p=1}^{P} C^{PC}_a * w^C_{aip}\Bigg]
\end{aligned}$$

Note that in the objective function the three stages can also be identified. The first-stage aspects are captured in the first three elements of the objective function. This is followed by the second-stage aspects in line 2 of equation B.1.1, where the P_n represents the probability of the scenario in the particular stage. Finally, line 3, 4 and 5 represent the stage 3 aspects of the model, again multiplied with the probability of the scenario.

Information on the specific element in the objective function:

In this objective function, B.1.1, the 1st and 2nd line represent the costs for the acquisition, lease or chartering of vessels and bases in terms of the fixed and investment costs. The 1st term targets the the fixed costs if base b is used during period p. The 2nd, 3rd and 4th term respectively represent the fixed costs for vessel v on a long term lease, medium term lease or short term charter.

The 3rd line in the objective function represents the variable cost for the operation of a vessel to support O&M activities at platforms, e.g. fuel costs, labor cost for crew en-route and maintenance of the vessel. As mentioned before the cost parameter C^O_{vbsip} includes the cost for both the sailing or flying of a ship or helicopter, but also the time the vessel spends at the platform while supporting the O&M activities.

The costs related to downtime of platforms are accounted for in the 4th line of the objective function. This respectively for the corrective maintenance activities in the 6th term, and the preventive activities in the 7th term.

Finally the 5th line of the objective function, contains the elements related to the penalty cost of delay or postponement of O&M activities. The 8th term expresses the costs made for preventive maintenance activities are delayed or cancelled in the planning horizon of one year. The 9th term addresses the penalty cost for corrective maintenance that is not supported.

Constraints

In this subsection, the constraints will be presented, according to the stage of the model which they are relevant in.

1st stage constraints

$$0 \leq x^L_{vb} + x^M_{vbl} + x^S_{vbp} \leq K^V_{bv} \tag{B.1}$$

To ensure that the vessels assigned to a base can be accommodated by that base, also called the vessel constraint for bases. This constraint does not include the pax capacity for accommodation yet, it strictly looks at the number of vessels of each specific type assigned to a base and the number if vessels of that specific type which can be facilitated by that particular base K^V_{bv}.

$$u_{bp} \geq E_b \tag{B.2}$$

$$x^L_{vb} + x^M_{vbl} \geq E_{bv} \tag{B.3}$$

Constraint B.2 and B.3 ensures that the t_0 includes vessels and bases which are in use at the beginning of the planning horizon. So if vessels and bases are in use before the model will propose a optimal fleet, this optimal fleet also includes the vessels and bases already in use.

$$\sum_{b \in B} x^M_{vbl} \leq M^M_{vl} \tag{B.4}$$

$$\sum_{b \in B} x^L_{vb} \leq M^L_v \tag{B.5}$$

Constraint B.4 and B.5 ensure that vessels to be included in the proposed optimal fleet are indeed available on the market for the corresponding vessel. The markets are also divided according to the vessel lease term, namely long-term, medium-term and short-term markets. In the 1st stage, only the long-term and medium-terms contracts are considered, while the short-term market is relevant for the 2nd stage.

2nd stage constraints

$$\sum_{b \in B} x^S_{vbp} \leq M^S_{vp} \tag{B.6}$$

Constraint B.6 is thus the short-term counterpart of constraint B.4 and B.5 and applicable in the 2nd stage where also information on platform failure becomes available and it will be determined, as a recourse decision, whether extra vessel capacity is necessary to cope with the demand.

3rd stage constraints

$$(x^L_{vb} * K^P_v) + (x^M_{vbl} * K^P_v)(x^S_{vbp} * K^P_v) \leq (u_{bp} * K^P_b) \tag{B.7}$$

The constraint in equation B.7 focuses on the accommodation of the crew. It ensures that the crew coming from the vessels assigned to a base can be accommodated by that base, also the base accommodation constraint. In other words it assures vessels are deployed in a way that the base from which the vessel operates has sufficient accommodation capacity for the crew on the vessels assigned to that base.

$$(N_{si} * y_{vbsip}) + w^P_{ai} = N_{ai} \tag{B.8}$$

$$l_{aivbp} + w^C_{aip} = 1 \tag{B.9}$$

The constraints marked as equation B.8 and B.9 are included to assure that all preventive and corrective maintenance activities are executed in the planning horizon. In addition, when considering the 8th and 9th term of the objective function, maintenance which is postponed outside the operational horizon will be subject to penalty costs. For instance, in B.9, if the corrective maintenance on schedule is postponed, in addition to the accumulating downtime cost, the penalty cost will be enabled as w^C_{aip} will take the value 1.

If the preventive maintenance activity is not executed within the operational year, this will lead to the decision-maker being penalized. Postponement of maintenance entails a difference between the maintenance plan and the actual execution of the preventive maintenance. If the activities of type a executed according to the plan at platform i in period p are described as w_{ai}, then $a_{ai} - w_{ai} = w^P_{ai}$, where w^P_{ai} represents the activities which are postponed to the next period.

Penalizing postponement of maintenance is a way to implement in the model that it is highly undesirable to postpone maintenance to the next year. Based on the intolerance of the decision-maker for the postponement of maintenance by a year, the height of the penalty can be determined. If it is somewhat allowed to postpone maintenance, the penalty will be low, while the penalty will have an extremely high value if it is not tolerated to postpone maintenance at all. It may also be that the penalty cost are different per maintenance type, for instance the penalty cost of corrective maintenance can be much higher since the impact of failure and postponing the repair of that failure is arguably much more severe than postponing preventive maintenance.

$$\sum y_{vbsip} * S^{MD}_m \leq S^{MA}_b * u_{bp} \tag{B.10}$$

Since each base is assumed to accommodate a specific number of technicians, constraint B.10 is in place to ensure that the crew assigned per vessel to conduct O&M activities does not exceed the crew available on the bases from which the vessels operate. Furthermore, the constraint ensures that vessels only operate from bases which are in use in that time period.

$$\sum y_{vbsip} \geq x^L_{vb} + x^M_{vbl} + x^S_{vbp} \tag{B.11}$$

Comparable to the previous constraint where the crew availability is addressed, constraint B.11 addresses the vessel availability at the bases from which vessels operate. It ensures that sufficient vessels are available, that is acquired or leased by the decision-maker, to execute the maintenance schedule over the operational horizon.

$$\left(\sum\sum N^p_{si} * y_{vbsip}\right) - l_{aivbp} = 0 \tag{B.12}$$

To ensure that each maintenance task is linked to a specific vessel and period, constraint B.12 is included.

B.2. A possible extension to OptiFleet: Down-time costs

An important aspect which is strongly influenced by maintenance is the downtime of platforms. Downtime, in short, is the time a platform is not operating, hence it is not possible for the electricity generated to be transported to shore where the consumers are, leading to production losses for the wind farm operators. Platform downtime occur for instance when failures of components occur which hamper the operability of the platform, or when maintenance needs to be conducted. It is critical that this downtime is minimized and as predictable as possible, in other words the platforms need to be reliable. For the downtime to be minimized, the failures occurring at platforms should be prevented as much as possible as these failures may lead to significant downtime of the platforms. To reach this, timely and thorough preventive maintenance is necessary. The following presents a way in which these down-time costs can be included in the model by means of equation B.13.

Parameters related to corrective maintenance:

R^f_{mf}	annual failure rate of category m at platform f
T^a_{mf}	time to wait on the availability of parts for activity m at platform f
T^w_{mf}	time to wait on operable weather window for activity m at platform f
T^t_{fvm}	transit time to platform f with vessel v for activity m
T_{mf}	duration of repair activity m at platform f

Parameters related to preventive maintenance:

F^{pi}_{mf}	annual frequency of preventive maintenance of category m at platform f
T_{mf}	duration of preventive intervention m at platform f
o_{mf}	outage due to preventive intervention m at platform f variable, 1 if intervention leads to downtime, 0 otherwise
t^D_{mf}	downtime due to activity m at platform f

Parameters related to the platform availability:

t^D_f	total downtime of platform f
t^{Dmax}_f	downtime limit at platform f

$$t^D_i = \Big(\sum_{m \in M} \sum_{f \in F} R^f_{mf} * (T^a_{mf} + T^w_{ai} + T^t_{iva} + T^{re}_{ai}) \Big) + \Big(\sum_{a \in A_p} F^{pi}_{ai} * o_{ai} * T^{pi}_{ai} \Big) \tag{B.13}$$

If $t^D < t^{Dmax}$ no down-time cost are made, however if $t^D \geq t^{Dmax}$, the down-time costs start to increase up to the point that the failure is repaired and the platform is operational again.

Penalty cost, for excessive downtime and the subsequent loss of production for wind farm operators, are determined by the regulatory authority and embedded in the energy law. As can be seen the penalty costs are dependent on the downtime of the platform and thus the reliability of the platform. In the current German regime of legislation for offshore transmission, the TSO has a required reliability of 92% per year. This comes down to an allowed downtime, t^{Dmax}, of 700.8 hours per year. However, in all cases, downtime up to 10 days do not have to be financially compensated by the TSO in Germany, but if the down exceeds those 10 days, the TSO is charged with the loss productions.

DNV GL (2014), state in their report on the lessons learned for the British offshore wind sector, that TenneT is experiencing average cost of between €1.6 million and €3.2 million per day, depending in the wind-farms connected to the platform.

C

Clustering Images

Table C.1: an overview of all platforms included in the study for both the German and Dutch Offshore Grid. The platforms with an asterisk behind the year service should begin, are the platforms for which the commissioning year is not yet known and an assumption is made

number	name	start of service	lat	lon	part of cluster	country
1	BorWin1	2018	54.354167	6.025000	BorWin2	DE
2	BorWin2	2018	54.355000	6.025000	BorWin2	DE
3	BorWin3	2019	54.388333	6.371337	BorWin3	DE
4	DolWin1	2018	53.996667	6.923333	DolWin6	DE
5	DolWin2	2019	53.978333	6.923333	DolWin6	DE
6	DolWin3	2018	53.996670	6.421667	DolWin3	DE
7	DolWin5	2020*	54.068700	6.171700	DolWin5	DE
8	DolWin6	2023*	53.979000	6.924000	DolWin6	DE
9	HelWin1	2018	54.451667	7.740000	HelWin2	DE
10	HelWin2	2018	54.451667	7.736667	HelWin2	DE
11	SylWin1	2018	55.063333	7.241667	SylWin1	DE
12	SylWin2	2023*	55.063000	7.239000	SylWin1	DE
13	Borssele1	2019	51.698333	3.056667	Borssele2	NL
14	Borssele2	2019	51.726667	2.965000	Borssele2	NL
15	HollKust1	2021	52.320000	4.043330	HollKust5	NL
16	HollKust2	2022	52.258333	4.085000	HollKust5	NL
17	HollKust3	2023*	52.679000	4.271000	HollKust6	NL
18	HollKust4	2025*	52.629000	3.716000	HollKust4	NL
19	HollKust5	2025*	52.280000	4.084000	HollKust5	NL
20	HollKust6	2030*	52.700667	4.270000	HollKust6	NL
21	IjmuidenVer1	2030*	52.884000	3.555000	IjmuidenVer1	NL
22	IjmuidenVer2	2030*	53.304667	3.741000	IjmuidenVer2	NL
23	TNVWadden1	2030*	54.035	5.584	TNVWadden1	NL
24	TNVWadden2	2030*	54.035	5.770000	TNVWadden2	NL

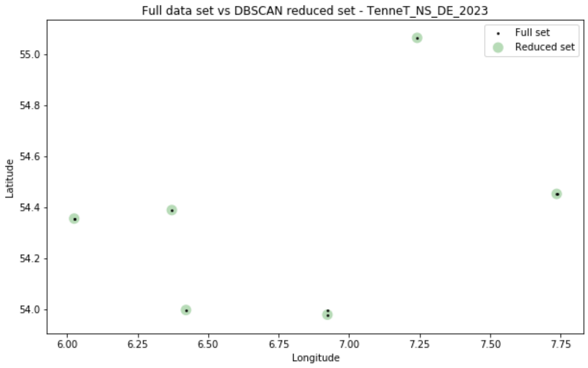

Figure C.1: Clustering of the platforms in the DE-2023 case from 9 to 6

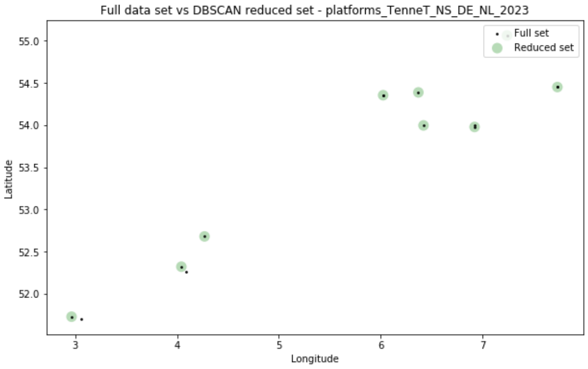

Figure C.2: Clustering of the platforms in the DE-NL-2023 case from 9 to 6 in DE and 5 to 3 in NL

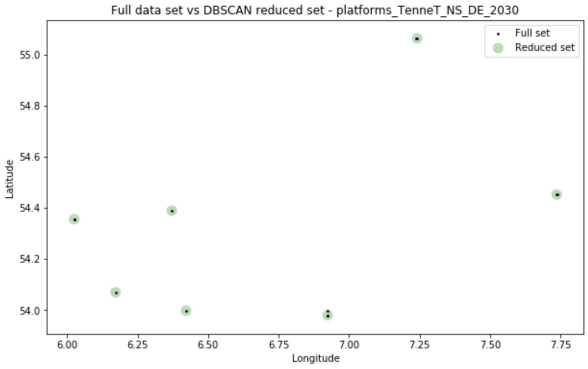

Figure C.3: Clustering of the platforms in the DE-2023 case from 12 to 7

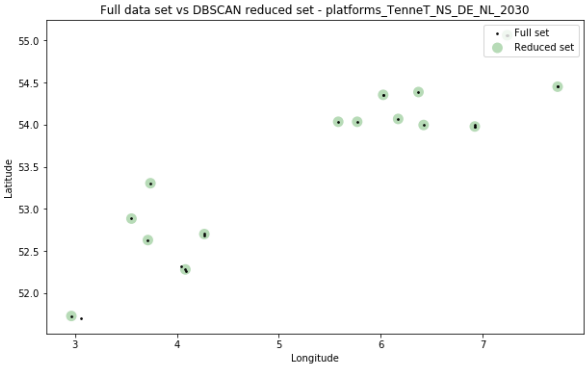

Figure C.4: Clustering of the platforms in the DE-NL-2023 case from 12 to 7 in DE and 12 to 8 in NL

D

Verification table

Table D.1: Overview of the 21 test-cases, the composition and results

Name	platforms	prev	corr	tot_maintenance	vessels	optimality gap [%]	time [s]
TestCase_1	1	20	0	20	1	0.00	0.06
TestCase_2	1	20	0	20	2	0.00	0.11
TestCase_3	1	20	0	20	4	0.00	0.20
TestCase_4	1	40	0	40	1	0.00	0.04
TestCase_5	1	40	0	40	2	0.00	0.20
TestCase_6	1	40	0	40	4	0.00	2.48
TestCase_7	1	60	0	60	4	0.00	1.04
TestCase_8	1	80	0	80	4	0.00	3.78
TestCase_9	1	80	12	92	4	0.00	6.02
TestCase_10	2	160	21	181	4	0.00	11.73
TestCase_11	2	80	0	80	4	0.00	3.03
TestCase_12	2	160	19	179	2	0.00	3.45
TestCase_13	4	320	29	349	4	0.00	35.96
TestCase_14	4	160	0	160	4	0.00	3.77
TestCase_15	4	320	0	320	2	0.00	1.15
TestCase_16	12	960	121	1081	4	0.00	102.71
TestCase_17	12	480	0	480	4	0.00	22.32
TestCase_18	12	960	117	1077	2	0.00	60.17
TestCase_19	30	2400	260	2660	4	0.00	94.92
TestCase_20	30	1200	0	1200	4	0.00	89.54
TestCase_21	30	2400	255	2655	2	0.00	283.36

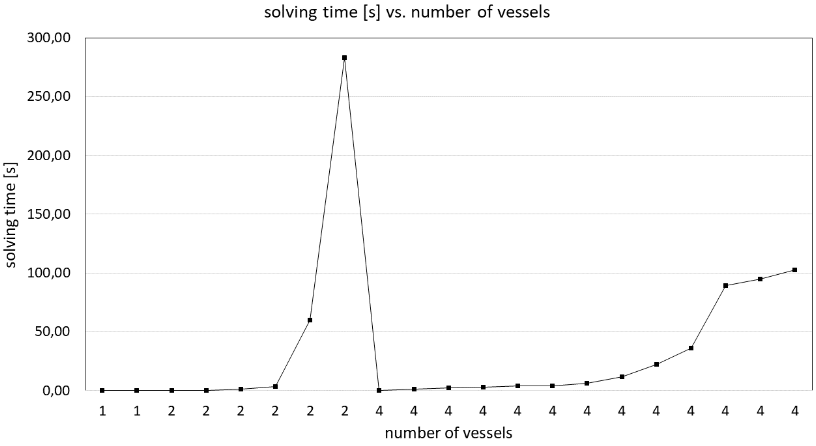

Figure D.1: Solving time of the various test cases, plotted against the number of vessel types

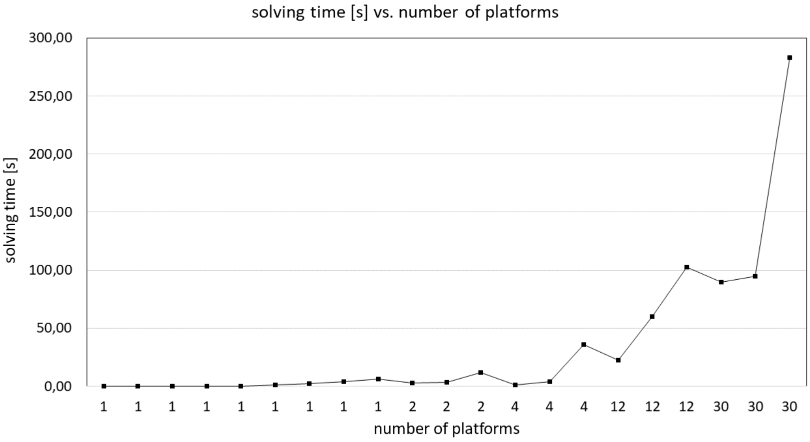

Figure D.2: Solving time of the various test cases, plotted against the number of platforms

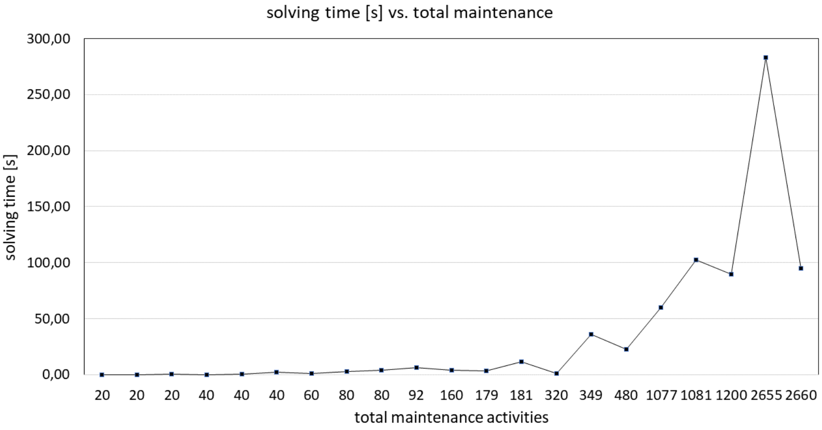

Figure D.3: Solving time of the various test cases, plotted against the number of maintenance activities