Scientific article accompanying the MSc thesis for Transport Infrastructure & Logistics

Marine Fleet Optimization for Offshore Substation Maintenance: An application for the German and Dutch Offshore Transmission Grid

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Abstract
To convey the energy coming from offshore wind-farms to the end-users, a network of offshore transmission platforms with sub-sea cables is in place, functioning as the supply chain for electricity. This research addresses the development of an optimization model, OptiFleet, which targets the problem of vessel fleet management to perform the transportation of crew and cargo to and from the platforms. OptiFleet provides strategic decision support to the Transmission System Operator on the optimal accommodation and transportation strategy. In particular the model aims to generate an optimum fleet size and mix, this is the number and the type of vessels in the fleet to support the platform maintenance campaigns.

Keywords
decision support systems, operations research, maritime transportation, fleet size and mix, long-term planning

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Introduction

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 [1].

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 by reducing Greenhouse gas emission by means of replacing fossil based energy with renewable energy. To convey 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 [2] [3]. High costs are induced by, among others, extreme wind and wave conditions, limiting the deployment of transportation means needed to access offshore structures such as the transmission platforms. These access related aspects can constitute to about 84% of OWF operating cost [3]. 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 [3, 4].

The reliability of the OTG is critical, as an unavailable OTG implies production losses for all connected OWF [5]. 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.

This research addresses the development of an optimization model, OptiFleet, which targets the problem of vessel planning to perform the transportation of crew and cargo to and from the platforms, necessary for the maintenance of the platforms. OptiFleet provides strategic decision support to the Transmission System Operator on the optimal accommodation and transportation strategy. In particular the model aims to generate a optimum fleet size and mix, this is the number and type of vessels in the fleet necessary to support the platform maintenance campaigns. To exhibit the functionality of the model, OptiFleet is applied on the case of TenneT TSO B.V. This case entails the offshore transmission platforms in both the Dutch and German North Sea.

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.

This paper is organized as follows: The transport logistics problem is described in Section 1. In Section 2 relevant literature is discussed. The model development is described in Section 3, with the mathematical model in Section 4. Subsequently, Section 5 presents the results of the computational study of the case and Section 6 concludes the paper.

1. Problem description

The aforementioned OTG consist of two main elements: submarine transmission cables and offshore converter substations. In figure 1, such an OTG is schematically presented with its components and the associated function. Within the blue framework, lies the scope of OTG. Transmission System Operators or TSOs are the organizations which operate these OTGs. In Germany, the case under study, the TSO responsibilities are in the hands of TenneT TSO GmbH [6].

For the execution of offshore substation maintenance activities, 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 a subject worth studying. 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 [8]. 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 [8, 9].

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 ConklindeDecker. This while the cost of vessels range from 3,000 $/day, to 35,000$/day, depending on the type of vessel and contract type TenneTAccesNL. 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 GundegHalvor. 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.

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.

2. literature

2.1 Maritime fleet planning

Maritime fleet planning is the exact application of combinatorial fleet sizing and composition for the maritime industry. Both [10, 11] conducted surveys on the existing literature in the field of maritime fleet planning, whereby the latter focused on publications in the current millennium and the first broadens the scope to all publications on the subject. G. Dantzig and D. Fulkerson [12] 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.

The specific focus on the Maritime Fleet Size and Mix Problems (MFSMP) has its own challenges because there are significant differences with the other modes of transportation. [10] state that not only are there operational differences, but the maritime industry also differs from the road transportation industry in for instance: 1) a higher level of uncertainty, 2) a higher level of capital involved and 3) the vessel's value function.

A general representation of the MFSMP in a mathematical model is presented by [10]. For these models, the objective is usually to minimize cost, an example of such an objective function for a basic and general is provided in eq. 1.

$$min \sum_{v \in V} C_v^F .y_v + \sum_{v \in V} \sum_{v \in R_v} C_{vr}^V .x_{vr} \tag{1}$$

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 representing the variable cost to operate on route r with vessel v.

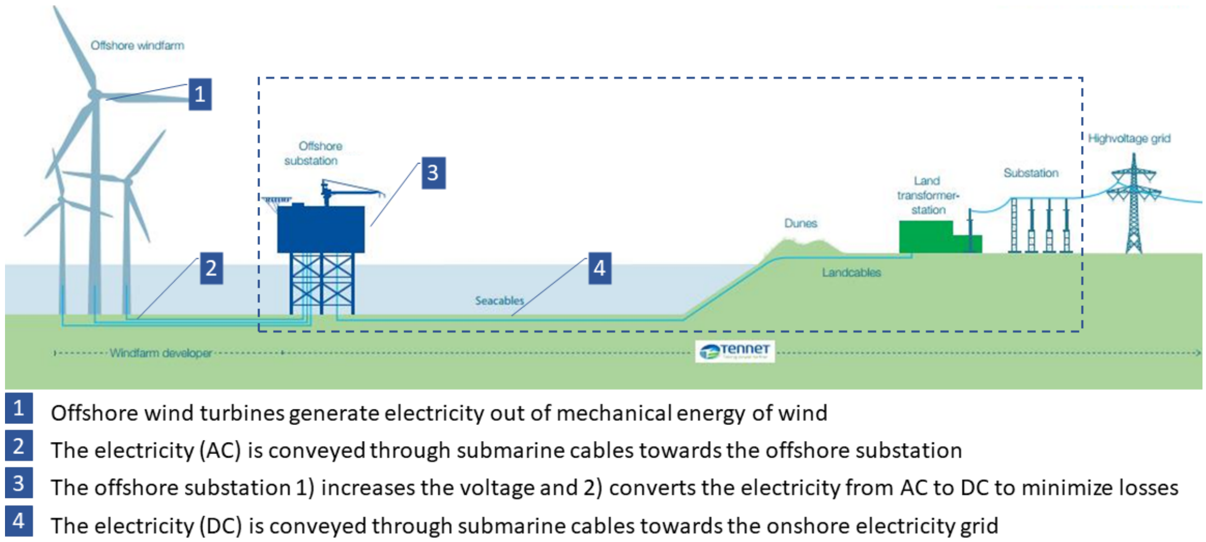

Figure 1. Schematic overview of an OTG, adapted from [7]

The decision variables are y_v in the first term, or the amount 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.

For the feasibility of the model constraints keep the decision variables within bounds. Constraints which are compatible with the objective function in eq. 1 and keep track of the resources used, are for instance eq. 2. This constraint ensures that the time spent by the vessel to sail specific routes, Z_{vr}, is within the limits of the total sailing time available given for instance the fleet size and available resources such as crew or fuel, Z.

$$\sum_{r \in R_v} Z_{vr}.x_{vr} - Z.y_v \leq 0, v \in V \tag{2}$$

Since MFSMPs are often aiming to align transportation demand with transportation supply coming from a fleet at minimal cost, constraints such as presented in eq. 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, also 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 eq. 4.

$$\sum_{v \in V} \sum_{r \in R_v} A_{ir}.x_{vr} \leq D_i, i \in N \tag{3}$$

$$\sum_{v \in V} \sum_{r \in R_v} A_{ir}.x_{vr}.Q_v \leq D_i, i \in N \tag{4}$$

Finally, [10] 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.

2.2 Maritime fleet planning in offshore wind O&M

When 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 [13]. 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 [14] it can be derived that the network of accommodation and workshop locations is dependent on:

1. the coverage of each maintenance accommodation, e.g. 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 a maintenance accommodation
4. the platform reliability which specifies the expected demand for repair

The review of research in the offshore wind industry by [14] 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 [15] this location problem of maintenance accommodation is presented as a ”Weber” problem which minimized the sum over the weighted distances to a given point. The scope was extended by [13] 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 [13].

Studies related to the aspects of transport means within the maintenance support organizations are for instance:

1. A report published by [16] addresses the characteristics, capabilities, limitations and general availability of maintenance vessels to be used in the construction and maintenance of OWF.
2. [17] determined the optimum number of access vessels for an OWF consisting of 130 wind turbines in the Netherlands with a Fleet size model.
3. [18] 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 vessel and helicopters, electricity prices and weather conditions.
4. In comparable work [19] proposed a model to determine the vessel fleet size for the maintenance activities of OWF. The studies by [20, 21, 22, 23] also propose optimization models to determine the fleet size and composition for maintenance activities whereby the differences between the models are 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.
5. A charter rate estimation model for jack-up vessels under various operational strategies, to complement the various MFSPM models aforementioned, is proposed by [24]. Their model identified the most attractive charter periods among the jack-up vessels after which the seasonal influence on the charter rates were analyzed.
6. [25] 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.

2.3 Uncertainty in MFSMP

It was mentioned by [22, 20, 21] and during the interviews with [26, 27] that uncertainty in the offshore environment is inevitable. However as stated by [28, 29, 30, 22, 21] it is also one of the biggest challenges to include all uncertainty in the models. The complexity of including uncertainty in MFSMP can also be reflected in the limited amount of studies which take uncertainty into account sufficiently. Among the 37 publications reviewed by [10], 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 averages or extreme values in otherwise deterministic models. This subsection will address how existing models in the field of MFSMP have addressed uncertainty up to now.

Within the field of OR, stochastic programming (SP) and robust optimization are most commonly applied to address uncertainty. Here Robust optimization considers uncertainty in deterministic means and sensitivity analysis is a common used means to determine to what extent optimal solutions would change if the base 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 [30].

SP does take the uncertain future into account, whereby its main premise is to model what might happen and how to handle each situation [30]. SP can be characterized by: 1) decisions made in discrete time steps, 2) many potential values for decision variables, 3) having expected values in the objective, and 4) dealing with partially known distributions [31]. For examples of such models the reader is referred to [32, 33, 18, 34, 30, 20, 22].

Another approach to cope with uncertainty is the use of simulation, hereby warranting for robustness to uncertain aspects such as weather [30]. The simulation approach is executed on the subject of MFSMP by [35] where a significant role was also set apart for the routing aspect. [36] also consider a similar approach whereby the strengths and weaknesses of optimization and simulation should balance each other out by applying a Monte Carlo simulation framework.

After addressing the state of the art in fleet planning literature, the next section addresses the development of OptiFleet.

3. Model development

3.1 Final scope of the model

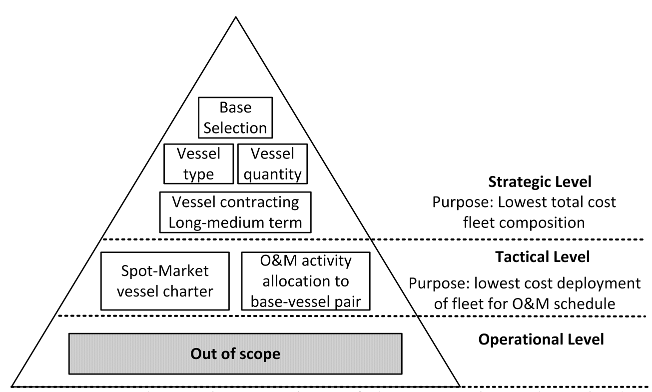

Figure 2. Schematic overview of the strategic and tactical decisions

In the proposed OptiFleet model decisions are made on two-levels, the strategic and tactical level, as depicted in figure 2. The decisions made on the strategic level are assessed on their short- to mid-term effectiveness by the decisions on the tactical level.

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.

3.2 Model flow diagram

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 [20, 18].

In figure 3 a schematic overview of the model process flow is depicted and in this figure 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 **??**.

4. Mathematical model

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

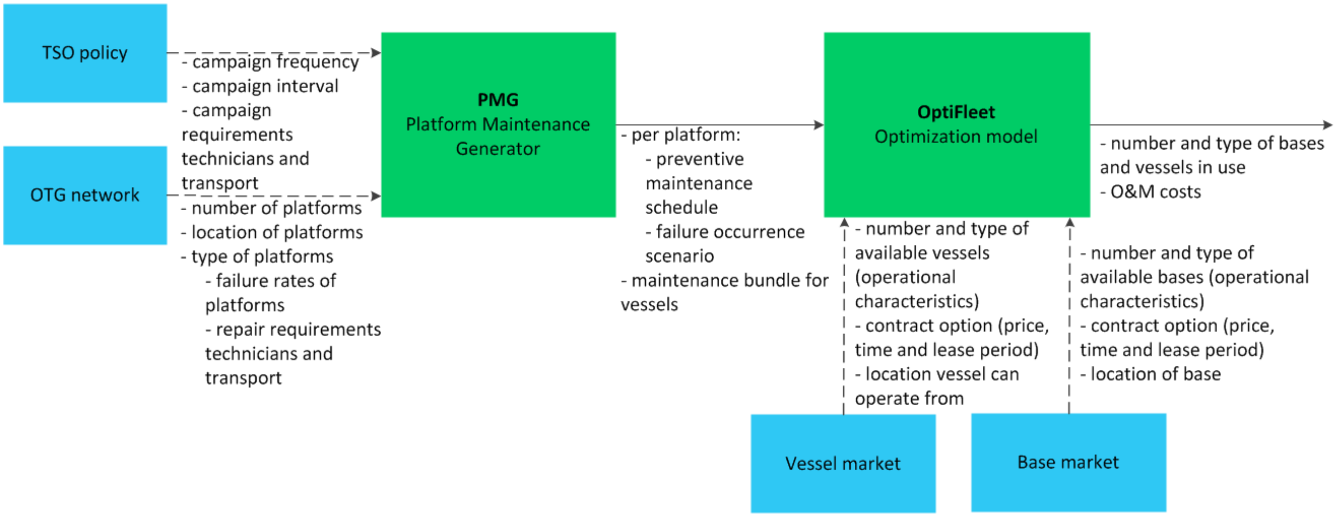

Figure 3. Schematic model process flow

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.

4.1 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

4.2 Sets

V set of vessel types, where each vessel type is linked to specific characteristics, $V: \{1,...,|V|\}$

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 $V^b \subseteq V, \quad \forall b \in B$

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, $B: \{1,...,|B|\}$

F set of all offshore transmission platforms, $F: \{1,...,|F|\}$

M set of all maintenance activities to be executed, $M: \{1,...,|M|\}$

M^{prev}_{fp} set of all preventive maintenance activities to be executed at platform f in year p, where $M^{prev}_{fp} \subseteq M$

M^{corr}_{fp} set of all corrective maintenance activities to be executed at platform f in year p, where $M^{corr}_{fp} \subseteq M$

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, $P: \{1,...,|P|\}$

4.3 Parameters

Cost parameters

C^{FB}_{bp} Fixed cost for using base b during period p in $[€/period]$

C^{FV}_{vkp} Fixed cost for acquiring vessel type v in the fleet on contract k in year p in $[€/period]$

C^{DV}_{vs} Day-rate charter cost for a vessel of type v from the spot-market on contract s in period p, in $[€/day]$

C^{O}_{v} 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^{A}_{v} Accommodation cost per crew member per day when using vessel of type v in $[€/crew/day]$

Maintenance need parameters

$T^{o\&m}_{mf}$ The duration for maintenance activity m at platform f in $[days]$

$F^{o\&m}_{mfp}$ The frequency of maintenance activity m at platform f in period p, in $[frequency/period]$

$P^{o\&m}_{mf}$ The number of crew/technicians required to execute activity m at platform f, in $[crew]$

$L^{o\&m}_{mf}$ The lifting capacity required to execute activity m at platform f, in $[MT]$

$S^{o\&m}_{mf}$ The deck-space required for cargo transport to execute activity m at platform f, in $[m^2]$

$Z^{o\&m}_{vbmfp}$ 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 $[hours/trip]$

4.4 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

4.5 Objective Function

$$\begin{aligned}
\textbf{MIN} & \sum_{b\in B}\sum_{p\in P} C^{FB}_{bp}.x_{bp} + \sum_{v\in V^{mfs}}\sum_{k\in K}\sum_{p\in P} C^{FV}_{vkp}.y_{bvp} \\
& + \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M}\sum_{s\in S} c_{vbmfp}.T^{o\&m}_{mf}.o_{vsp}.C^{DV}_{vs} \\
& + \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M} \Big(\big((C^S.P^{o\&m}_{mf}) + C^O_v\big).\frac{A_{bf}}{N_v}\Big). \\
& Z^{o\&m}_{vbmfp}.c_{vbmfp} \\
& + \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M} \big((C^A_v.P^{o\&m}_{mf}.T^{o\&m}_{mf})\big).c_{vbmfp}
\end{aligned} \tag{5}$$

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.

In the objective function presented in eq. 5, 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 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 to fifth 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 $P^{o\&m}_{mf}$ 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^O_v 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: $\frac{A_{bf}}{N_v}$, 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 $Z^{o\&m}_{vbmfp}$ 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. In the model preparation phase, this parameter is calculated on 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 fifth 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.

4.6 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 [37] 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 [38] for global optimization with not necessarily convex functions. A recent operationalization of this RLT was discussed during a conference talk by [39], 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:

$$r_{vsbmfp} = c_{vbmfp}.o_{vsp} \tag{6}$$

In order for this substitution variable to be functional, additional constraints were required to be added to the model. See constraints 8 and 9. The objective function can thus be rewritten as:

$$\begin{aligned}
&\textbf{MIN} \sum_{b\in B}\sum_{p\in P} C_{bp}^{FB}.x_{bp} + \sum_{v\in V^{mfs}}\sum_{k\in K}\sum_{p\in P} C_{vkp}^{FV}.y_{bvp} \\
&+ \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M}\sum_{s\in S} r_{vsbmfp}.T_{mf}^{o\&m}.C_{vs}^{DV} \\
&+ \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M} \Big(\big((C^S.P_{mf}^{o\&m}) + C_v^O\big).\frac{A_{bf}}{N_v}\Big). \\
&Z_{vbmfp}^{o\&m}.c_{vbmfp} \\
&+ \sum_{v\in V^{mfs}}\sum_{b\in B}\sum_{f\in F}\sum_{p\in P}\sum_{m\in M} \big((C_v^A.P_{mf}^{o\&m}.T_{mf}^{o\&m})\big).c_{vbmfp}
\end{aligned} \tag{7}$$

$$r_{vsbmfp} >= 0 \quad \forall \quad v\in V^{mfs}, b\in B, f\in F, p\in P, m\in M, s\in S \tag{8}$$

According to the RLT method, the combination variable should be bounded by a lower-bound of 0 [39].

$$r_{vsbmfp} >= c_{vbmfp} + o_{vsp} - 1 \quad \forall \quad v\in V^{mfs}, b\in B, f\in F, p\in P, m\in M, s\in S \tag{9}$$

The constraint represented by eq. 9 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.

4.7 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.

4.7.1 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.

$$\sum_{v\in V^{mfs}}\sum_{b\in B} c_{vbmfp} = F_{mfp}^{o\&m} \quad \forall \quad m\in M, f\in F, p\in P \tag{10}$$

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 10 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 pantuso2014survey, 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}.

$$q_{bvp} = c_{vbmfp} \quad \forall \quad v \in V^{mfs}, b \in B, m \in M, f \in F, p \in P \tag{11}$$

q_{bvp} can be considered the vessel-to-base-pairing variable and constraint 11 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.

$$c_{vbmfp}.A_{bf} \leq R_v \quad \forall \quad v \in V^{mfs}, b \in B, m \in M, f \in F, p \in P \tag{12}$$

Constraint 12 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.

$$\frac{c_{vbmfp}.A_{bf}}{2.N_v} \leq T^{crew}_{max} \quad \forall \quad v \in V^{mfs}, b \in B, m \in M, f \in F, p \in P \tag{13}$$

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 13. For instance TenneT applies a 2-hour travelling limit on one-way trips for their employees.

4.7.2 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.

$$x_{bp} >= q_{bvp} \quad \forall \quad p \in P, v \in V^{mfs}, b \in B \tag{14}$$

$$\sum_{k \in K} y_{vkp} + \sum_{s \in S} o_{vsp} >= \sum_{b \in B} q_{bvp} \quad \forall \quad p \in P, v \in V^{mfs} \tag{15}$$

First, constraint 14 ensures that bases selected in base-vessel combinations, through q_{bvp}, are added to the network accordingly. Whereas, constraint 15 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.

$$\sum_{\alpha \in [p, MIN(p+D_k, P]} y_{vk\alpha} <= D_k \quad \forall v \in V^{mfs}, k \in K, p \in P \tag{16}$$

When the vessels or helicopters need to be contracted, constraint 16, ensures that the duration a vessel is under contract is complying with the duration of the specific contract, D_k.

$$\sum_{b \in B} x_{bp} \leq B^{max} \quad \forall \quad p \in P \tag{17}$$

Finally, constraint 17 allows for the decision maker to set a maximum on the number of bases to operate from.

4.7.3 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.

$$\sum_{b \in B} \sum_{f \in F} \sum_{m \in M} (c_{vbmfp}.A_{bf}) \leq R_v.G_v.\left(\sum_{k \in K} y_{vkp} + \sum_{s \in S} o_{vsp}\right) \quad \forall \quad v \in V^{mfs}, p \in P \tag{18}$$

The constraint expressed in eq. 18 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 pantuso2014survey and in terms of the operation time by joshi2016heuristics.

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}).

$$\sum_{b\in B}\sum_{f\in F}\sum_{m\in M}(c_{vbmfp}.T^{o\&m}_{mf}) \leq \big(\sum_{k\in K} y_{vkp} + \sum_{s\in S} o_{vsp}\big).G_v \quad \forall \quad v\in V^{mfs}, p\in P \tag{19}$$

The constraint included with eq. 19 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}.

$$0 \leq \sum_{v\in V^{mfs}} q_{bvp} \leq x_{bp}.K_{bv} \quad \forall \quad b\in B, p\in P \tag{20}$$

The constraint in eq. 20 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.

$$\sum_{v\in V} q_{bvp}.P_v \leq x_{bp}.P_b \quad \forall \quad p\in P, b\in B \tag{21}$$

Subsequently, the constraint in eq. 21 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.

4.7.4 Other

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

$$x_{bp} \in [0,1] \quad \forall \quad b\in B, p\in P \tag{22}$$

$$y_{vkp} \in [0,1] \quad \forall \quad v\in V^{mfs}, k\in K, p\in P \tag{23}$$

$$o_{vsp} \in [0,1] \quad \forall \quad v\in V^{mfs}, s\in S, p\in P \tag{24}$$

$$q_{bvp} \in [0,1] \quad \forall \quad b\in B, v\in V^{mfs}, p\in P \tag{25}$$

$$c_{vbmfp} \in [0,1] \quad \forall \quad v\in V^{mfs}, b\in B, m\in M, f\in F, p\in P \tag{26}$$

Finally, the constraints in eq. 22 till 26 impose the binary properties on the decision variables.

5. Computational Study: The TenneT DE and NL case

In this section the case on which the model will be applied will be discussed. 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.

5.1 Case description

5.1.1 Platforms and Bases

Figure 4. Map of the offshore platforms in 2023

In figure 4 an overview is provided of the platform layout in the North Sea until 2030, and the ports from logistics can be supported. 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 other 3 will be commissioned between 2019 and 2022. For the longer term, the number of platforms will continue to grow. According to [40], the 5 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.

For each year, 2023 and 2030, three sub-cases can be distinguished. The first 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 both the platforms in the German and Dutch North Sea in 2023, 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. The model will run for 2023 to 2043 for the 2023 sub-cases and 2030 to 2050 for the 2030 sub-cases, hence the run-time is 20 years. Note that for these model runs, the number of platforms does not change over the course of the 20 years. This 20 years run-time, is in line with the lower-end of the expected vessel lifetime and also with the higher-end of long-term vessel lease contracts which are close to vessel acquisition in terms of duration [41]. In figure 5 it is exhibited how the sub-cases relate to each other when looking at the the time and the number of platforms.

Before the sub-cases are applied in OptiFleet as model input, a clustering algorithm is run over the platforms first to establish platform clusters which represent the combination of platforms for a journey. In table 4, for each sub-case, the result of the clustering step can be seen when looking at the difference between the number of platforms in the 2nd and 3rd column, and the number of clusters in the 4th and 5th column. These clusters will be used to determine the maintenance need, aggregated per cluster.

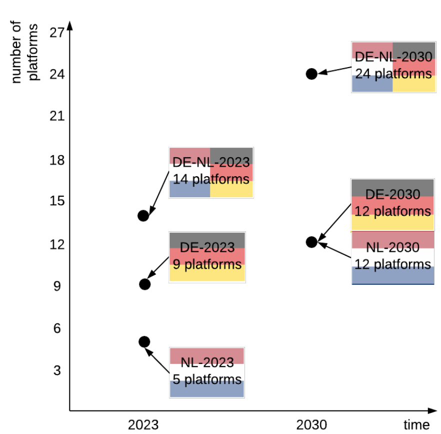

Figure 5. mapping of the case instances

5.1.2 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. [18, 20]. 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. [18, 22, 24, 42, 43] and oil & gas e.g. [30, 44]. Furthermore, information is gathered through stakeholders in the vessel market, such as Damen Shipyards via interviews with [41, 45].

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. 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. In table 1 an overview is provided of all vessel types taken into account for the TenneT case.

5.1.3 Vessel Contract Pricing

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 [46]. 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 [24]. 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 [47, 24]. 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

Table 1. Overview of the included vessel types

Vessel type	Vessel Operational Cost [€/hour]	Crew Accommodation Cost [€/pax/day]	Spot-market day-rate [€/day]	Medium-term contract prince [€/year]	Long-term contract price [€/year]	pax capacity [pax]	Lifting capacity [MT]	Deckspace [m^2]	Vessel availability [days/year]	Operating speed [kn]
vessel 1 CTV-M	170	200	4,791	1,261,416	720,000	15	0	10	150	25
vessel 2 CTV-L	383	200	11,977	3,153,540	1,800,000	60	0	240	250	35
vessel 3 Heli	2034	200	9,093	2,394,168	1,366,560	15	0	4	250	150
vessel 4 PSV-M	453	200	12,000	3,159,492	1,803,397	0	2	500	200	13
vessel 5 PSV-L	955	100	18,000	4,739,238	2,705,096	70	4	800	250	12
vessel 6 OSV-M	219	100	23,955	6,307,080	3,600,000	60	3	500	250	11.5
vessel 7 OSV-L	716	100	47,910	12,614,160	7,200,000	90	6	900	300	13
vessel 8 PSV-M + Heli	2487	200	21,093	5,553,659	3,169,957	15	2	500	200	150
vessel 9 PSV-M + CTV-M	623	200	16,791	4,420,908	2,523,397	15	2	500	250	25
vessel 10 OSV-M + CTV-M	389	100	28,746	7,568,496	4,320,000	15	3	500	250	25
vessel 11 OSV-M + Heli	2253	100	33,048	8,701,248	4,966,560	15	3	500	280	150

costs for long- and medium-term contracts over the annual days included in the contract.

In studies on the vessel-charter rates by [24, 47, 48] a significant difference between rates for long-term contracts, medium-term contracts and spot market contracts is identified, whereby the height of the rate is mainly dependant on the vessel CAPEX and on the season. During summer, vessel rates are generally higher, when maintenance activity and thus vessel demand is high, compared to the situation in winter when maintenance is not desired due to high production numbers [24]. For the North-Sea market this difference can be averaged down to 75.20% between long-term and medium-term contracts and 36.73% between medium-term contracts and day-rates from the spot-market. The estimated rates for the different vessel types are included in table 1, while in table 2 it is presented how many contracts for each vessel type and of each type of vessel charter is included.

Table 2. contracts included

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

The vessel rates included in table 1 are estimations as accurate costs are not available due to the non-transparent nature of the vessel market. Numbers are derived from previous studies such as [18] for their case-study in the Norwegian market, [22, 42] for the case of Great Britain, [24] for the study on jack-up vessels, [43] for the case on wind-farm installation vessels in the United States of America, [30] for the study on PSV in the Norwegian market, [44] for the study on PSVs in different size classifications, but also through interviewing stakeholders such as [41, 45] for their experiences as shipyard.

Table 1 also includes the vessel operational cost, which 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 [41, 44]. The vessel operational cost in table 1 are determined based on fuel consumption information for vessels types included in the case and the market price for heavy- and medium fuel oil commonly used by these vessels.

Finally, accommodation cost are included for each vessel type in table 1. 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.

5.1.4 Maintenance Activities

For the maintenance activities, see table 3, the distinction in maintenance type relates to the scale of the logistic needs, rather than the consequences of the maintenance activity or failure in terms of, for instance, platform downtime.

Table 3. Preventive and Corrective maintenance activities

name	probability of annual occurrence [%]	Logistic need				
		duration [days]	crew required [#crew]	lifting need [MT]	deck-space required [m^2]
campaign_a	100	14	30	4	500
campaign_b	100	14	20	4	400
campaign_c	100	14	40	4	700
campaign_d	100	14	30	4	500
failure_a	50	1	10	1	10
failure_b	10	10	20	2	400
failure_c	0.1	30	30	5	700

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 [49, 9].

5.1.5 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.

5.2 Results of the TenneT case study

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.

It should be noted again that many of the data derived for this case is from third parties or estimated from comparable cases in literature. This entails that the results will not yield detailed costs for the actual case, but will propose vessel fleet solutions which may proof to be optimal under the data available. This should lead to knowledge on how to use the model for detailed cost analysis when the actual costs are known by the decision maker.

5.2.1 OptiFleet output for the six sub-cases

The platform networks are summarized in table 4. In addition to the size of the sub-case, the table presents the size of the sub-case implementation in OptiFleet, together with the time needed to solve the case to optimality and what optimality gap is associated to that model outcome.

It can be stated that with the current implementation of OptiFleet and the setting for the Gurobi solver, all 6 sub-cases can be solved to optimality as can be derived from an Optimality Gap (OG) of 0.00% for all 6 sub-cases. 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 [50, 51]. This also occurs within reasonable time, the longest sub-case takes around 535s to be solved.

Results: Fleet composition and size

In this sub-section the resulting fleet composition for the 6 sub-cases under the TenneT case, derived with OptiFleet, will be presented. This is done with table 5 which exhibit three aspects, namely: 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 fleet composition tables aim to provide concise information on how OptiFleet proposes the fleet planning for TenneT over the time-span of 20 years in different platform networks.

Fleet composition The first aspect to address regarding the results is the fleet composition for the 6 sub-cases. For the situation in 2023, in both DE and NL, the combination of a medium PSVs, for the transportation of cargo, with a medium CTV, for the transportation of crew, is recommended. On the other hand, the situation in 2030 is recommended to be

Table 4. Overview of the case characteristics and results

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

Table 5. fleet composition results

	vessel type	fleet size	long-term contract	medium-term contract	spot-market
DE-2023	vessel-9 Medium PSV + Medium CTV	3	✓	x	x
NL-2023	vessel-9 Medium PSV + Medium CTV	2	✓	x	x
DE-NL-2023	vessel-9 Medium PSV + Medium CTV or Helicopter	4	✓	x	x
DE-2030	vessel 5 Large PSV	3	✓	x	x
NL-2030	vessel 5 Large PSV	3	✓	x	x
DE-NL-2030	vessel 5 Large PSV	6	✓	✓	x

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

On the first glance, 3 vessels of each PSV-M and CTV-M, 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.

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 [48, 47, 52].

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 [48, 46]. 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.

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.

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 subsection.

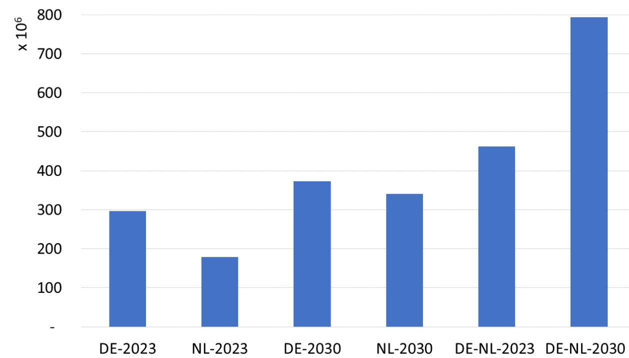

Figure 6. Total cost for the 6 sub-cases in [€]

First of all, the total costs in [€], are presented in figure 6 and in table 6. When comparing the total cost output for the German and Dutch sub-case separately, the larger size of the German grid leads to total cost that are significantly higher than for the Dutch grid in 2023. 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 and this can be explained by the smaller distance between platforms 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, 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 earlier discussed, 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, where the bar-chart provides an overview of how these different cost posts, together compose the total cost.

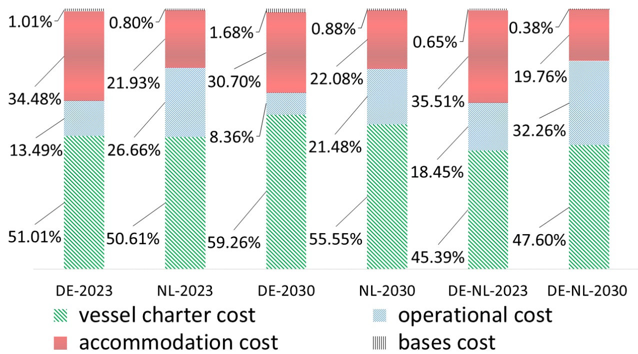

Figure 7. cost breakdown in [%] for the 6 sub-cases

By observing the % documented in each cost category, it can be concluded that the total vessel costs are dominated by the vessel charter cost 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 recommended to execute a sensitivity analysis with the vessel charter rates, to determine the change in fleet composition with price fluctuations.

In table 6 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 equal 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 6, 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 area 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 and to present the expected benefit in costs if the two offshore grids are integrated.

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.

In tables 7 and 8 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. 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.

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 mere benefits for the 2023 case, the proposed logistic integration leads to higher costs for the 2030 situation. In table 8 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.

In short, it can thus be stated that the model provides means to study the benefits of OTG integration to a certain

Table 6. 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%
accommo-dation cost	102,346,000	81,856,000	-20%	54,890,000	75,105,000	37%	163,972,000	156,816,000	-4%

Table 7. 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 8. 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%

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 in the recommendations for future work in sub-section 6.2.

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 8 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 8, for each sub-case

The harbour of Delfzijl is selected to support maintenance activities in the German grid for DE-2023 and DE-2030. In the study by [53] to determine the shortest route along the platforms in Germany, Delfzijl is likewise recommended for

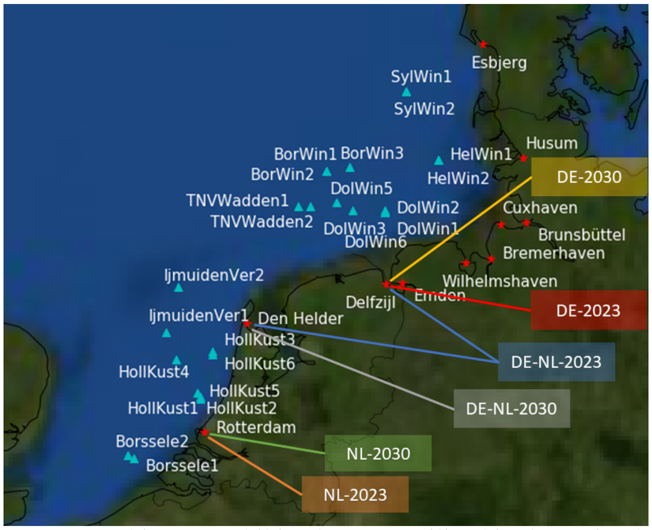

Figure 8. This map exhibits the ports utilized in the optimal solution for each sub-case

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.

6. Conclusion & Future work

6.1 Conclusion

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. With this output, conclusions could be drawn for the direction in which strategic logistic decisions could be made in the years to come. Hereby the main findings are:

- The decision by TenneT to make the shift away from helicopter, towards maritime vessels, can be partially justified by OptiFleet. In all case-experiments, the vessel solutions were proven to be economically more efficient than helicopters, on the strategic level.
- The vessel combination of a medium PSV for cargo and a medium CTV for crew is recommended for the 2023 situation and the large PSV, which integrates both cargo and crew transportation and accommodation, is recommended for the 2030 situation. In line with this vessel recommendation, the accommodation recommendation is to maintain platform based accommodation until 2023 and towards 2030 make the gradual shift to floating vessel based accommodation.
- Vessels to be added to the TenneT fleet are recommended to be added on long-term contracts, however with the inclusion of early-termination clauses. These early-termination clauses provide flexibility to adjust the fleet proactively, while benefiting from low cost for long-term deals. Due to the strong position of clients in a market with an oversupply of PSVs, these clauses can be negotiated.

In the following sub-section, based on the main limitations of OptiFleet, recommendations are made to improve the model and further build on the body of knowledge for offshore OTG maritime fleet size and mix.

6.2 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. 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.

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 [18, 20].

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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