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Designing a decision-support tool for the operational phase of an offshore wind farm installation project

Design Project
MSC Industrial Engineering and Management

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Van Oord
Marine ingenuity

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Abstract

Offshore wind energy is increasingly important in the current global market and accounted for a record 10% share of the total wind energy capacity growth in 2019. Van Oord is currently leading the way in this transition towards renewable energy, for which it is working on the installation of multiple offshore wind farms. Van Oord's current approach to creating a planning for their complex offshore wind farm installation projects is by means of simulations in FlexSim, which is commercial-off-the-shelf software. Van Oord is currently in the R&D phase of an in-house simulation tool, but does not yet have an operational tool which can be used to optimise the planning of complex marine installation projects.

In this design project, a decision-support tool (DST) has been developed, which is able to optimise the remainder of the planning of the 'Saint-Brieuc project' during the operational phase. The Saint-Brieuc project is an offshore wind farm installation project near the French coast. Van Oord will install 63 foundations, starting from 1 March 2021 and finishing in August 2022. The DST is focused on the second half of the Saint-Brieuc project, starting from the moment when a decision has to be made whether to stay operational or initiate the winter break and go idle due to poor weather conditions.

The DST is able to incorporate the actual status of the project and the most recent weather forecast, including its uncertainty. In the DST, installation cycles consisting of 90 unique activities that all have specific durations, weather windows and weather limits have been incorporated. It is concluded that the DST has been successfully developed and its high accuracy and optimality have been proved.

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1. Introduction

Wind energy is one of the most promising technologies to produce sustainable and renewable energy. In 2019, wind farms with a total capacity of approximately 60 Gigawatts were constructed worldwide, expanding the global wind power market to a total of 650 Gigawatts. Offshore wind accounted for 10% of new installations, making 2019 the year with the highest increase in offshore wind capacity to date (REN21, 2020).

The increase in offshore wind capacity worldwide has several reasons. At sea, winds are typically more stable and stronger, resulting in higher energy production per installed unit. Furthermore, wind turbines can be larger at sea, since it is easier to transport very large components compared to the installation process of an onshore wind turbine. Constructing an offshore wind farm also has the advantage of eliminating visual and noise impact. Offshore wind turbines are also able to harvest energy more effectively, since there is less turbulence. Lastly, due to lower wind-shear at sea, the towers of the wind turbines can be shorter. Besides these advantages, there is also one main disadvantage: the realisation of an offshore wind farm is more costly. The marine foundations and integration into the electrical grid are expensive. Additionally, large and highly specialised, and therefore expensive, vessels and resources are required for the installation of an offshore wind farm. Moreover, the installation process is highly restricted due to weather conditions (Bilgili, Yasar and Simsek, 2011; Kaldellis and Apostolou, 2017).

1.1. Van Oord

Van Oord is a maritime contracting company from The Netherlands, that is specialised in dredging, land reclamation and constructing offshore wind farms. Van Oord is currently leading the way in the energy transition towards renewable energy, for which it is working on the installation of multiple offshore wind farms (*Van Oord,* 2020b). As an example, Van Oord has recently been awarded a Transportation and Installation contract for the installation of the foundations for an offshore wind farm on a project site 16.3km off the French coast, the Saint-Brieuc project (*Van Oord,* 2020c). According to *OG Monitor* (2020), this is a $2.7 billion project, of which Van Oord is responsible for the transportation and installation of the foundations of the wind turbines.

Van Oord usually tenders for either a Balance of Plant (BoP) contract or a Transportation and Installation (T&I) contract. BoP contracts include the design, procurement and installation of every component of an offshore wind farm, apart from the generating unit. T&I contracts include only part of the installation process of the offshore wind farm, multiple contractors are responsible for different activities. Therefore, predetermined installation dates under a T&I contract often allow limited float and delays of the installation works that Van Oord is responsible for will have a negative impact on other contractors, due to which liquidated damages need to be paid.

1.2. Complexity of offshore wind farm installation projects

The operational phase of offshore wind farm installation projects is comprised of many complex activities. Working on complex marine installation works brings complexity due to the fact that the installation takes place in a very dynamic and possibly turbulent environment (Thomsen, 2014). All activities of the installation process have a specific duration and many activities are weather restricted. These weather restrictions are represented by unique limits per activity with respect to four different characteristics of the weather (Table 1). To further clarify the fourth characteristic in Table 1: the wave peak period corresponds to the fastest time it takes for two consecutive waves to pass through the same point, during an observed time window.

Table 1: Relevant weather characteristics

Uw at 10m [m/s]	Wind speed at 10 metres above the surface
Uc [m/s]	Surface current speed
Hs [m]	Significant wave height
Tp [s]	Wave peak period

Due to the unique composition of the soil at the locations at which an offshore wind turbine should be installed, specific drilling times and processes need to be determined. Moreover, the cycle of installation activities is different at every location. The foundations to be installed consist of three pin piles which will be put into large wells which will be drilled to predetermined depths. Thereafter, a three-legged jacket will be put on top of these three pin piles (Figure 1).

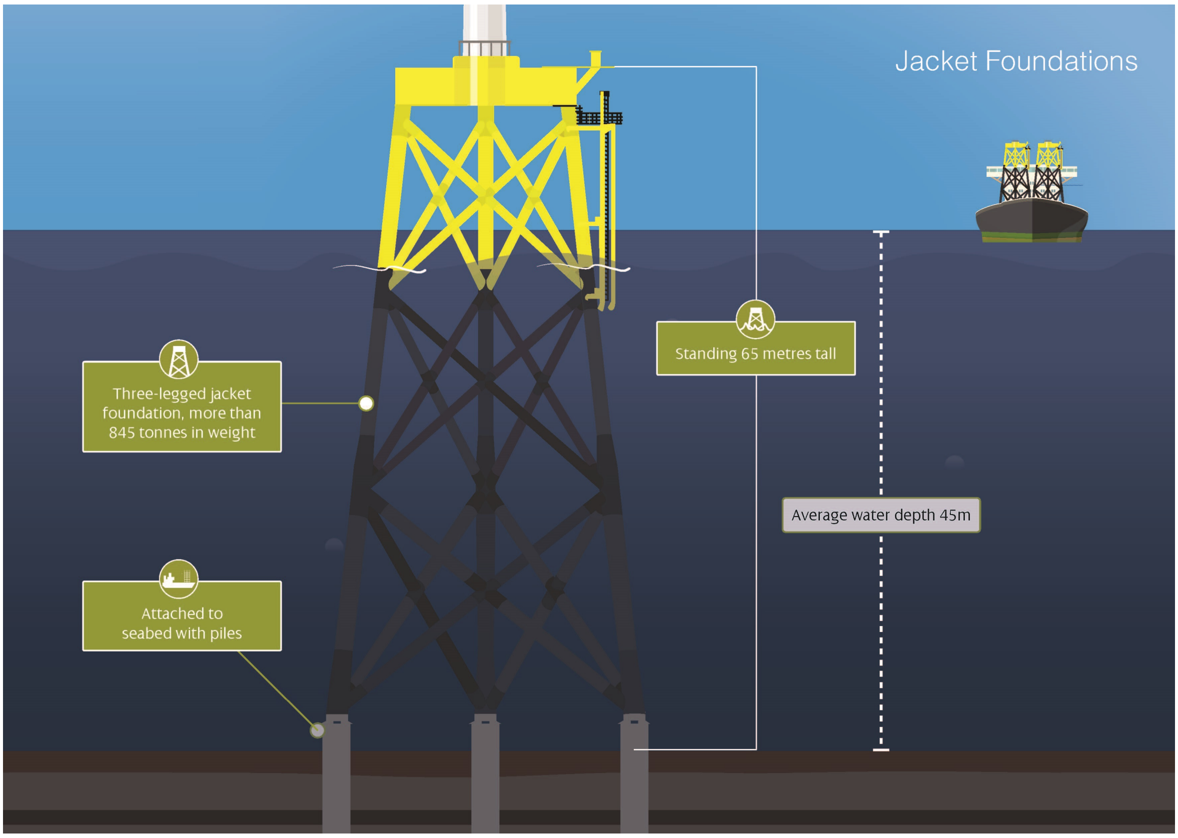

Figure 1: Jacket foundation of offshore wind turbine (*Van Oord,* 2020a)

Skilled personnel, specialized installation vessels, large components and marshalling ports are required to construct an offshore wind farm. Long before the operational phase of the project has started, delivery dates of components for specific locations need to be agreed upon with suppliers. These components will be transported to the marshalling port, at which the components can be partially assembled. The components are either directly loaded onto the installation vessel or loaded onto a less expensive Platform Supply Vessel, which transports the components to the installation vessel. This can be done to ensure that the total operational time of the expensive installation vessel is reduced.

1.3. Planning of offshore wind farm installation projects

Not only the operational phase of the installation process is comprised of complex tasks, the planning of the projects is also highly complex. The unpredictability of the weather, especially in the long-term, makes it difficult to plan the execution of the project. Van Oord has two approaches to modeling the complex logistics challenges of their projects.

Firstly, the planning department of Van Oord makes use of commercial-off-the-shelf software, FlexSim (*FlexSim* 2020), which is used to simulate the execution of projects in order to create a feasible planning. All activities are modelled into FlexSim in great detail and in a specific order, such that the execution of the project can be simulated over historic weather data. This can be done with a data set which is comprised of 20 years of historic weather data. In this way, an overview of potential outcomes is obtained and different strategies can be validated by means of these simulations. Thereafter, a long-term plan is created.

Secondly, Van Oord is currently working together with the Delft University of Technology to develop a simulation-engine based on the open-source Python toolbox SimPy (*Simpy,* 2020). The resulting open-source simulation-engine for maritime cases is OpenCLSim (*OpenCLSim,* 2020), to which Van Oord adds proprietary interfaces for the Wind and Dredging business units.

The aforementioned tools are used to assist the planning department during the planning phase of their projects, before the operational phase of the project has started. By means of simulation-based tools it is possible to very accurately simulate the execution of a project with different (initial) conditions. However, to find the best solution out of many possibilities, simulation-based approaches are impractical. This is mainly due to the fact that all possibilities need to be explored in order to find the best solution. In FlexSim, exploring different possible outcomes of a project is a fully manual exercise, due to which it is difficult to easily obtain insights into many different possible outcomes of the project. By means of OpenCLSim, all possible outcomes of a project can be evaluated more conveniently. However, since an optimisation tool is not yet included in OpenCLSim, it explores all possible strategies and logs their performance. Every individual simulation in FlexSim takes several seconds. A wind farm installation project that consists of 9 locations has $9! = 362,880$ possible installation sequences. Therefore, if one simulation takes e.g. 5 seconds, exploring all possible configurations takes three weeks. This constitutes Van Oord's main motivation for exploring optimisation-based decision-making.

Updating the status of the project in the simulation tools and running new simulations is currently a time-consuming and manual task. The result is that the planning engineers are always behind the actual situation and end up administering the progress of the project instead of providing timely strategy updates to the project. Correspondingly, Van Oord does not yet have a tool which enables them to perform optimisations during the execution phase of their projects based on its current status and the latest weather forecast. Inevitably, long-term plans are interfered by dynamic weather conditions and certain activities will have gone faster or slower than planned. Therefore, a mechanism is required for dynamic adjustments and short-term control, which is able to react in just a few days or hours.

1.4. State of the art

According to Vis and Ursavas (2016), only a few approaches in literature deal with the installation process of offshore wind farms, whereas a lot more research has been conducted towards the scheduling of maintenance activities. The few approaches that do focus on the installation process, have been very recently conducted. For example, at the International Ocean and Polar Engineering Conference in 2018, 90 articles were devoted to offshore wind, of which only a single one focused on the overall installation process (Jathe et al., 2019).

It can be said that in the field of optimisation-based decision making for offshore wind farm installation projects, there is still a lot to be explored. This research will contribute to the advancement of optimisation-based decision making in the offshore wind industry.

1.5. Outline of this report

In the next chapter, the problem context of this research is thoroughly analysed. The main findings of an extensive literature research are stated in Chapter 3. In Chapter 4, the design of the artifact that is created throughout this research is discussed. Subsequently, the results of this research are shown in Chapter 5. The discussion of the results and the limitations of the artifact developed, along with recommendations for future development, are given in Chapter 6. The concluding remarks of this research are stated in Chapter 7.

2. Problem context

In this chapter, the problem statement of this research is stated. Furthermore, the system, scope and interest of the stakeholders are defined in order to adequately identify the goal of this research and formulate the corresponding research questions. This chapter is concluded by an overview of the methods and tools that are used throughout this research.

2.1. Problem statement

The aforementioned lack of a tool which is able to perform optimisations during the operational phase of a wind farm installation project forms the basis of this research. The derived problem statement is formulated as follows:

Van Oord does not yet have an operational tool that is able to optimise the planning of offshore wind farm installation projects based on their status and the latest weather forecast

The problem owner is the Estimating & Engineering (E&E) department of Van Oord, since this is the department that is, among other tasks, responsible for the simulations and planning of projects. Throughout this report, the planning of an offshore wind farm installation project refers to the planning of the main installation vessel, since Van Oord usually uses only one installation vessel.

2.2. System description and scope

Van Oord currently uses the commercial software FlexSim as a simulation tool to assist decision-makers during the planning phase of their projects. Internal requirements come from the project itself, whereas the simulations can be performed over historic and location specific weather data which Van Oord has of many years. Subsequently, the long-term planning of the project is created before the actual installation phase starts. The first part of the operational phase is not within the scope of this research, namely the phase of the installation process before the winter break (Figure 2).

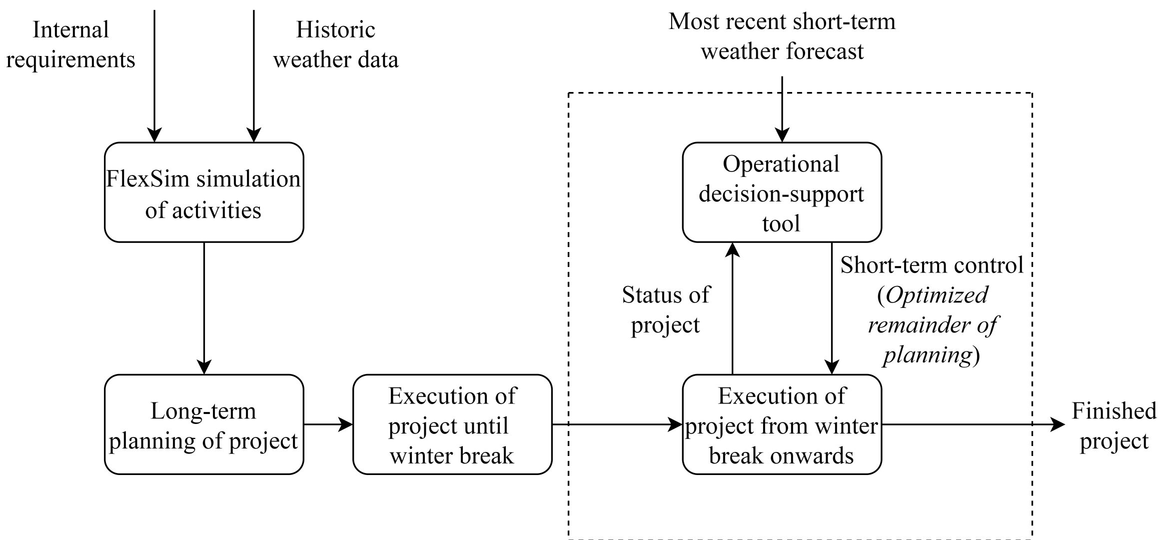

Figure 2: The planning procedures of the Saint-Brieuc project with the focus of this research in the dashed box

During the initial planning of the project, no short-term weather forecast could be used and only multiple scenarios could be analysed by means of different sets of weather data over the past years. Ideally, during the execution phase of a project a decision-support tool (henceforth referred to as DST) exists which is able to incorporate the most recent weather forecast and the status of the project, since both are very likely to deviate from the expected. This project is focused on the operational phase of the Saint-Brieuc project, starting from the moment when it has to be decided whether to initiate the winter break or continue operations. The winter break is a period of several months, usually from October until February, during which the installation vessel goes idle due to unworkable weather conditions. However, the exact moment at which the winter break should be initiated is variable and dependent on the status of the project, the weather forecast and associated cost of being operational, stand-by or idle. The costs of being stand-by are the costs when the vessel is not installing a foundation, but is waiting for improved weather conditions. The costs of being idle are the significantly lower costs that are incurred when the vessel is in the harbour and the operational crew is not mobilised.

2.3. Stakeholder analysis

A stakeholder analysis has been performed in order to identify the key stakeholders that have an interest in the challenges that this project addresses. To successfully complete this project, the stakeholders and their needs are determined via several meetings with the relevant stakeholders. The identified stakeholders and their stakes are described in the following sections.

2.3.1. Van Oord

Van Oord is the company for which this project is executed and is responsible for the installation of several offshore wind farms. The stake of Van Oord in this project is the influence that the tool to be designed will ultimately have on the planning during the execution phase of their projects. Their requirement is that the DST should be generic in the sense that the concepts of the DST should be applicable to other wind farm installation projects. Furthermore, the DST should reduce the probability of not finishing (part of) a project in time, which usually results in costly liquidated damages, which are predefined fines. Ultimately, the outcome of this project strengthens Van Oord's competitive advantage. Within Van Oord, several more specific stakeholders are identified, which are elaborated upon below.

2.3.1.1 Planning engineer

The planning engineers within Van Oord are currently using static tools to simulate projects well in advance in order to create a well-thought-out planning. Their stake in this project is the potential change that the outcome of this project might have on their daily tasks during the operations of a project. The DST would make their job more dynamic, since it requires more involvement throughout the execution phase of projects by re-optimising and adjusting the remainder of the schedule. Their daily tasks would shift from a reactive attitude towards a proactive attitude.

2.3.1.2 Data engineer

The data engineers within Van Oord are currently involved in many projects regarding the transition towards data-driven decision making. Their stake in this project is the potential to use and further develop the DST. Furthermore, their stake is the desire to ultimately have one piece of software which is able to assist project teams during the tender phase as well as the operational phase. The resulting requirement of the data engineers is compatibility with the simulation tool that is currently under development, OpenCLSim.

2.3.1.3 Project team

The project team within Van Oord are the employees that are responsible for the execution of the installation of the offshore wind farms. Their stake in this project is the influence that the DST will have on their daily tasks. The decision that will ultimately be made based on the outcome of the DST will determine which actions they will perform at what moment. Their requirement is that the DST does not result in riskier activities, boundaries should not be pushed due to the outcome of the DST. Thus, the DST should ensure that safety regulations are always taken into account.

2.3.2. Clients

The requirement of the clients of Van Oord is that projects are finished on time and in the right manner. If not, large predefined fines might be issued. The stake of the clients in this project is the interest that they have in an increased chance of finishing a project on time, or finishing the project even earlier. The earlier a project is finished, the earlier the client can start generating energy.

2.3.3. Suppliers and partners

The introduction of the DST might have an influence on Van Oord's future demand from their suppliers and partners. Their requirement is that no impossible deliveries are to be expected as a result of the planning that the DST suggests. It is possible that in close co-operation with suppliers and partners a more robust inventory is required in the harbour, since the DST could suggest changes in the short-term planning which would not be possible if the required materials are still to be supplied.

2.4. Goal

The problem context, problem statement, the system and scope of this research have been described in the previous sections. This has, along with a stakeholder analysis, led to the formulation of the goal of this project according to the SMART criteria (Doran, 1981). The goal is formulated as:

Design a decision-support tool which is able to reduce the costs of an offshore wind farm installation project by providing short-term control during its operational phase. This should be done by optimising the planning from the winter break onwards, based on the latest weather forecast and status of the project. This research should be completed within five months.

As stated in the previous section, the DST should be generic in the sense that the concepts of the DST should be applicable to other wind farm installation projects. Large parts of the installation procedures are the same for different wind farm installation projects, but there are also several unique characteristics and procedures. Therefore, the DST requires minor changes to be used for another project.

This project is considered a success when the DST is be able to optimise the remainder of the planning during the operational phase of the project, based on the costs of being operational, stand-by and idle. To do so, the project requirements, current status of the project and the latest weather forecast have to be incorporated. Furthermore, the complexity of the installation process of the Saint-Brieuc project needs to be adequately captured into the DST. Thus, installation durations per location should be similar to the durations obtained from FlexSim, for any part of the historic weather data set.

2.5. Research questions

In order to solve the problem and achieve the goal of this research, the following research question has been determined:

How can an operational decision-support tool be designed to ultimately reduce the costs of wind farm installation projects?

Several interconnected subquestions are formulated in order to acquire necessary information to answer the main research question. The subquestions are divided into knowledge questions (KQ), design questions (DQ) and validation questions (VQ). The subquestions are formulated as:

- KQ: What are the exact project requirements for the Saint-Brieuc project?
- KQ: How can the uncertainty of the weather forecast be quantified?
- DQ: In what way should historic weather data be used to represent the weather beyond the scope of the weather forecast?
- DQ: How should the remainder of the planning of the project be optimised?
- VQ: Are the calculated installation durations similar to the durations determined by FlexSim for every location and any historic weather data set?
- VQ: Is the planning suggested by the decision-support tool actually optimal?

2.6. Methods and tools

Throughout this research, the three cycle approach by Alan Hevner (Figure 3) is used as the guiding framework (Hevner, 2007). This framework is used, since it ensures that important aspects such as the requirements of the environment, the actual design of an innovative artifact and a contribution to the knowledge base are addressed. The relevance cycle sets the design science research up with an application context that provides requirements for the design and acceptance criteria for the evaluation of the results. Thus, all project requirements, as well as requirements for the DST, are explored and used as input for the design cycle.

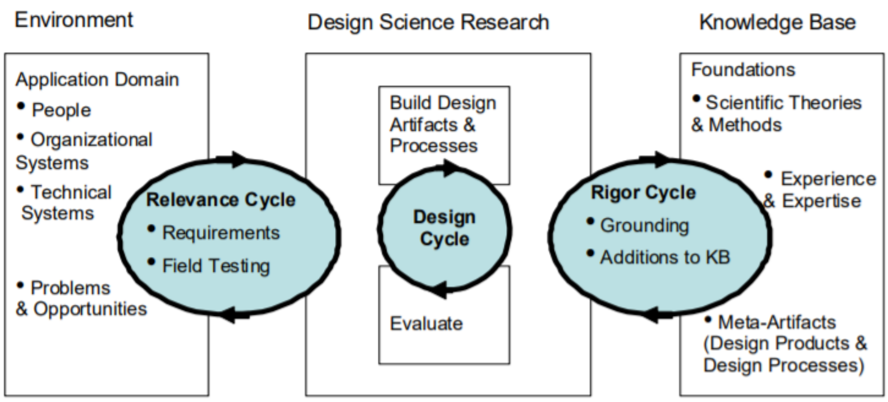

Figure 3: Design Science Research Cycles (Hevner, 2007)

The rigor cycle ensures that scientific expertise and foundations are drawn from the knowledge base for the design of the DST. The state-of-the-art and existing artifacts and processes in the relevant scientific field are evaluated in order to support the development of the DST. Furthermore, the knowledge base is referenced to ensure that this project results in novel research contributions.

Throughout the design cycle there is a continuous iteration between the core activities of design of the artifact, its evaluation and subsequent feedback to further refine the design. Thus, the requirements for the design are the input coming from the relevance cycle, which is gathered by means of many meetings with the relevant stakeholders. Furthermore, the theories for the design and evaluation of the artifact are obtained from the rigor cycle by means of an extensive literature research.

Throughout this research, all modeling is be performed in Python. One of the reasons for using Python is the fact that it is the programming language that is used throughout Van Oord. Thus, by developing the DST in Python, it will be more convenient for Van Oord to provide inputs to and use the output of the DST. Developing the DST in Python also gives Van Oord the opportunity to implement it into the open-source engine that they are working on: OpenCLSim. Furthermore, the fact that renowned optimisation software such as Gurobi, CPLEX and XPRESS can be readily used within Python, is another reason for its use (Gurobi Optimization, LLC, 2020; IBM, 2020; FICO Xpress Optimizer, 2020).

3. Literature research

Research on available literature is performed to gain knowledge and useful insights into the research problem. Firstly, prior studies of analogous concepts are investigated. Other topics that will be elaborated upon are mathematical optimisation methods for construction scheduling, linear and mixed-integer programming software and solvers, and uncertainty of weather forecasts.

3.1. Existing research on optimisation of offshore wind farm installation projects

As has been stated in Section 1.4, little research has been performed on the optimisation of operations planning of offshore wind farm installation projects. In this section, the state-of-the-art is briefly summarised.

Vis and Ursavas (2016) propose a simulation-based decision-support tool in order to evaluate several preassembly strategies and assess the impact of these strategies on the overall project performance. Ait-Alla et al. (2017) propose a discrete event, multi-agent simulation model, in order to investigate the impact of several installation concepts on the overall logistics costs. The main concept that is investigated in this research is the feeder concept, where a cheaper transport vessel will provide the required materials to the expensive installation vessel, such that the installation vessel is only responsible for the actual installation activities. Muhabie et al. (2018) propose a discrete-event simulation approach that includes the analysis of vessel characteristics, assembly scenarios and environmental conditions. The focus of their model is on evaluating the overall project lead time of different strategies. Irawan, Jones and Ouelhadj (2017) propose a multi-objective optimisation model for the scheduling of the installation of an offshore wind farm project. Their mathematical model involves two objectives that it aims to minimise, namely the total installation cost and completion date. Their model also incorporates constraints such as the availability of vessels and weather conditions.

According to Rippel et al. (2019), the existing literature has several drawbacks. First of all, most approaches combine the installation of the offshore wind farm into one installation project, whereas usually the installation of the foundations, top structures and cables are carried out sequentially by multiple companies. Another drawback is the fact that most approaches aggregate the weather conditions into discrete classes. However, the installation of a foundation or top structure consists of many activities that each have their own duration and limits, most approaches consider this as one installation activity.

According to Jathe et al. (2019), long-term plans are interfered by dynamic weather conditions or the fact that activities might have gone faster or slower than expected. Therefore, a mechanism is required for dynamic adjustments and short-term control, which is able to react in just a few days or hours. A model is proposed that combines optimisations with short-term control by means of a method from control theory, namely the model predictive control scheme (Lars and Jürgen, 2011). The aim of the model is to obtain a trade-off between the high reactivity of the short-term control and optimality of mid- to long-term plans, whilst also minimising the risk that changing weather conditions impose. The optimisation problem in the proposed model can be implemented as a MILP (Mixed Integer Linear Program). Furthermore, the model predictive control scheme combines closed-loop control, that retrieves the status of the project, and open-loop model-based optimisations in order to determine optimised plans for a longer planning horizon. The approach also incorporates dynamic weather conditions and the uncertainties of weather forecasts.

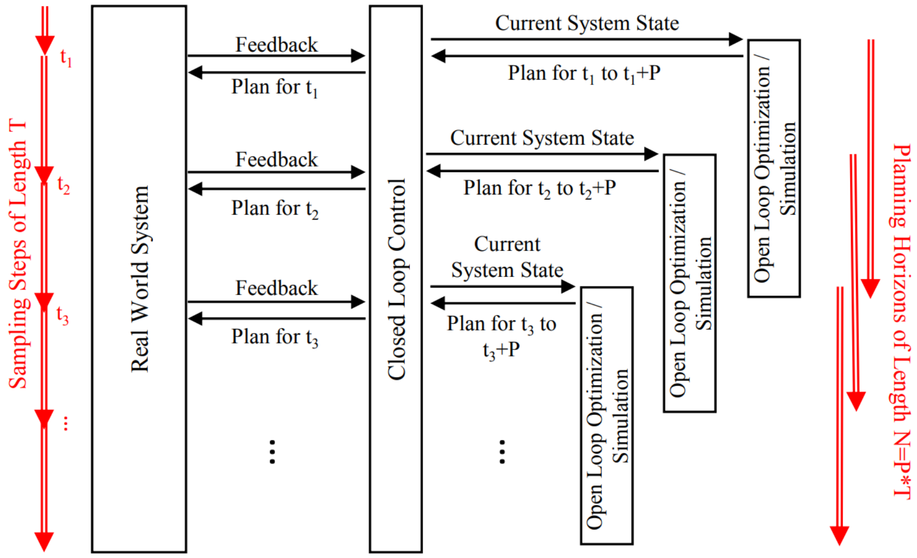

Figure 4: Model predictive control scheme (Rippel et al., 2019)

In Figure 4, the approach of the model predictive control scheme can be seen. At any moment in time, the current state of the project is used as input for the open-loop optimisation, which optimises the planning for a planning horizon of length $P \cdot T$. Subsequently, the first T part of the optimised planning is executed, where T is the length of the sampling step. For example, if T is 5 days and $P = 4$, the planning is optimised over a period of 20 days and the first 5 days of the resulting planning are executed. This process is repeated until the project is completed.

3.2. Mathematical optimisation methods for onshore construction scheduling

A lot of research has been conducted on optimisation of onshore construction schedules. By means of a variety of approaches, several models have been developed, such as linear programming, integer programming, dynamic programming, genetic algorithms, neural networks, particle swarm optimisations and ant colony optimisations (Senouci and Mubarak, 2016). In essence, the aim of these models is to reduce the total time or costs of a project. For onshore construction scheduling problems, taking data on weather into account is not very relevant. For that reason, the only literature available on construction scheduling which takes the weather conditions into account, is research on offshore construction projects. For the optimisation of the planning of offshore installation projects, most models use (mixed-integer) linear programming.

Linear programming is a technique in which complex relationships are modelled through linear functions in order to find optimal points. Linear programs are usually formulated as

$$\begin{aligned} \min_{x} \quad & c^T x \\ \text{s.t.} \quad & Ax \leq b \\ & LB \leq x \leq UB, \end{aligned} \tag{1}$$

where the aim is to minimise the objective function, which consists of a known vector of coefficients c and vector of decision variables x. Furthermore, b is a known vector of coefficients and A is a known matrix of coefficients. The constant coefficients are usually referred to as the parameters of the model. The inequalities $Ax \leq b$ and $LB \leq x \leq UB$, are the restrictions which are referred to as the constraints (Hillier and Lieberman, 2015). Lastly, the decision variables x are restricted by a lower bound (LB) and an upper bound (UB).

3.3. Linear and mixed-integer programming software and solvers

The three most renowned optimisation software programs are CPLEX, Gurobi and XPRESS (Mittelmann, 2020). Anand, Aggarwal and Kumar (2017) have performed a comparative analysis in which they assessed how well they are able to handle a variety of constraints and objectives. Their main conclusion is that the appropriateness of the solver depends on the nature of the problem that is to be optimised. It is not possible to estimate which solver is the best for a specific problem, but Gurobi is generally perceived to be the fastest solver (Jablonsk et al., 2015; Mittelmann, 2017; Mittelmann, 2020). However, as all comparative analyses show, the performance of the solvers varies between different tested problems.

3.4. Uncertainty of weather forecast

The atmosphere is a chaotic fluid by nature, which is highly sensitive to initial conditions. That, combined with an incomplete depiction of the actual state of the atmosphere, results in weather forecast uncertainty (Gill, 2008). For many applications, forecasts are only considered useful if an estimate of the uncertainty can be assigned to them. Unfortunately, the connection between forecast uncertainty and initial atmospheric fields are nonlinear and non-trivial, and effective methods to diagnose it have not been proposed at this time (Scher and Messori, 2018). The best method to provide an estimate of the uncertainty is to create an ensemble of numerical simulations. For example, the Dutch national weather service provides a confidence estimate by running 51 simulations, each with different initial conditions (*KNMI,* 2020). A graphical representation of the forecast of the wind speed obtained from all 51 simulations can be seen in Figure 5, which represents the forecast for De Bilt in The Netherlands on September 12, 2020.

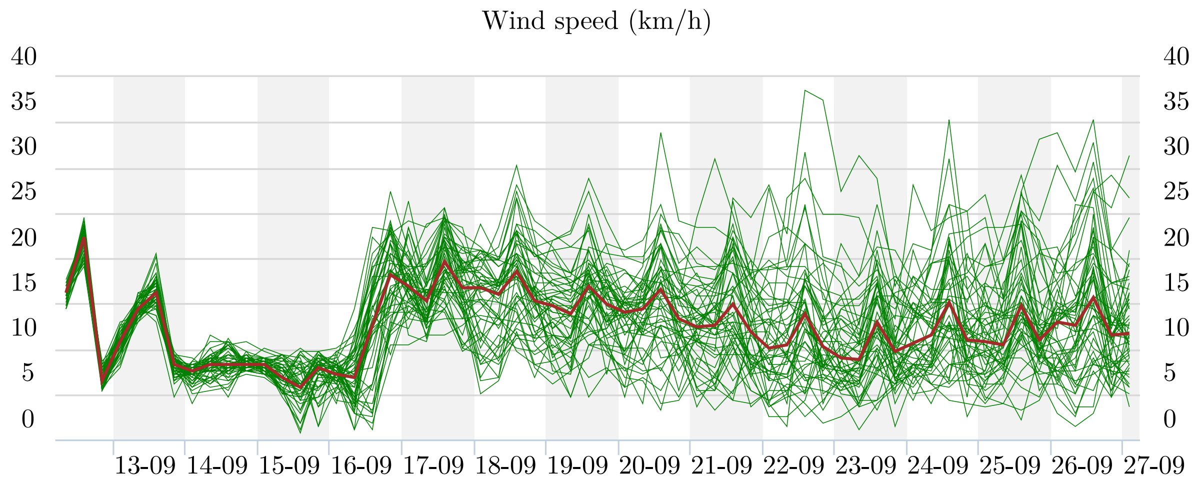

Figure 5: Wind speed forecast by 51 unique simulations (*KNMI,* 2020)

4. Description of the design

In this chapter, the design of the DST is described. Firstly, the sequence of activities and requirements of the project are discussed. Secondly, the handling of the weather (forecast) is clarified. Thirdly, the calculation of the duration of installing any location at any possible starting hour is discussed. This chapter is concluded by the explanation of the linear program that has been developed.

4.1. Sequence and complexity of activities

In this section, the installation sequence of the Saint-Brieuc project is described. In total, there are 63 locations at which Van Oord has to perform installation activities. At one location, Van Oord will install the foundation of the offshore substation, which is the system that collects and exports the generated power through specialised cables. However, the installation of the offshore substation is not within the scope of this research, since it will be installed long before the winter break. The remaining 62 locations will all be incorporated into the model, since it is highly desirable to be able to optimise any set of locations that still have to be installed, if unexpected changes occurred.

The remaining 62 locations can be divided into four different groups. Firstly, 53 locations will be installed whilst the installation vessel, the Aeolus, is jacked up on its four legs throughout the entire installation sequence. In Figure 6, the Aeolus can be seen whilst being jacked up on its four legs.

Secondly, at 9 locations, part of the installation process will be performed whilst the Aeolus is floating. The reason for this is that the lifting radius is limited, due to the weight of the drilling template. Furthermore, the seabed at these locations has many rocky ridges or other seabed hazard due to which the Aeolus cannot jack up close enough to be able to lift the drilling template into position. Therefore, it is required that the Aeolus lifts the drilling template whilst floating, after which the Aeolus moves to the closest location where it is able to jack up in order to perform the subsequent activities.

Lastly, at 11 locations a sacrificial casing needs to be installed, which is a second tubular member which is installed around the pin pile. Due to a thick soft overburden layer at these locations, additional lateral stability to the foundation is required, which is provided by the sacrificial casing. This is done at 9 out of the 53 locations which will be installed whilst the Aeolus is jacked up and at 2 out of the 9 locations at which the Aeolus is partially floating.

Figure 6: The installation vessel of the Saint-Brieuc project, the Aeolus (*Van Oord,* 2020d)

The rest of this section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.1.1. Locations at which the Aeolus is fully jacked up

This section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.1.1.1 Sail to location

This is the first activity of the installation process. The Aeolus has to sail from the location at which it just finished the installation process to the next location at which a foundation will be installed. In the DST the duration of sailing between two locations is set to 30 minutes.

4.1.1.2 Jack up

This section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.1.1.3 Lift template to seabed

This section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.1.1.4 Drilling and grouting operations

This section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.1.1.5 Retrieve template

This section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.1.1.6 Retrieve GLAs

This section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.1.1.7 Jack down

This section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.1.2. Locations at which the Aeolus is partially floating

This section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.1.3. Sacrificial casing

This section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.2. Project requirements

Besides the complete installation sequence that has been clarified in the previous section, the project also has several requirements which will be discussed in this section.

4.2.1. Duration, weather window and limits

For every activity of the installation cycle, Van Oord's engineers have determined its specific duration in minutes. Furthermore, the engineers have determined weather windows, which range from being the same as the duration of the activity to being nine times longer than the duration of the activity. The weather windows imply that an activity can only be commenced if the limits of that activity are not exceeded for the entire weather window. Almost all activities that have to be performed have a limit on one or more of the four relevant characteristics of the weather: wind speed at 10m above the surface [m/s], surface current speed [m/s], significant wave height [m] and peak period [s]. If the limits of an activity are not exceeded for its entire weather window, the activity will be performed and will last the predetermined duration. The durations, weather windows and limits of the activities are not shown, due to confidentiality. Also, stating these would add little value to the report.

4.2.2. Drilling times and windows

Van Oord's engineers have calculated the time that the drilling operations will take at every location, based on the local composition of the soil. Furthermore, the engineers have calculated two specific weather windows for the drilling operations. For drilling to a depth of 16 meters, a specific weather window and corresponding limiting significant wave height have been determined. For drilling deeper than 16 meters, another specific weather window and limiting significant wave height have been determined.

The rest of this section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.2.3. Seabed

The composition of the seabed at half of the locations has been classified as rock, the other half as sand. The difference that this makes is that the limits of the significant wave height and peak period are different for the jacking up and down activities. Therefore, this needs to be incorporated into the model.

4.2.4. Tool change

Van Oord's engineers have determined nine locations at which a tool change needs to take place. Once the drilling activity has finished, the drill will be removed, after which the drill bit is renewed.

The rest of this section is not included in the university-version of this report due to confidentiality of the discussed matter.

4.2.5. Installation sequence of locations

Van Oord's engineers have also determined that the first 40 locations that will be installed, should have a short temporary casing. A temporary casing is used to stabilise the drilled excavation and is removed during or after the placement of fluid concrete. The choice has been made to first install the shorter temporary casings, since these are easier to handle and put less stress on the drilling template, due to which the progress of the project is increased early on.

Furthermore, Van Oord has noticed that the transfers from the PSV are slowing down the installation process at locations that require a sacrificial casing. Therefore, it will be investigated what can be done in order to prevent the Aeolus from being slowed down by the PSV. Most likely, a second PSV will be used during the installation of the locations that require a sacrificial casing. For that reason, a requirement is that all sacrificial casing locations should be installed as one group, such that the second PSV will be required for the shortest possible time.

4.2.6. Delivery sequence

Based on the long-term planning that has been made for the project, suppliers have been informed in what order the materials for the locations should be delivered. The materials of 44 locations will be delivered before the winter break, whereas the materials for the other 18 locations will be delivered during the winter break. This will be considered in the model, since it limits the choice of locations to install before going into the winter break.

4.2.7. Factoring in breakdowns and delays

As has been mentioned before, Van Oord's engineers have determined a specific duration for every activity. Furthermore, 10% extra time should be factored into the duration due to anticipated breakdowns and delays.

4.2.8. Metocean location

Van Oord's engineers have divided all locations into two groups based on metocean data. Out of all 62 locations, 33 are considered to be in the Southern area, whereas 29 are in the Northern area. This distinction is made, since in the Northern area the weather is typically worse than in the Southern area. This is mainly due to the fact that the Northern area is farther away from shore and the Southern area is to a certain extent covered by land.

4.3. Weather handling

Since the model will optimise the remainder of the planning starting from the moment at which the winter break might be initiated, the model should take all subsequent months into account. Thus, from October until August, which is when the project should be finished. However, since the weather is already highly unpredictable in a time period of weeks, it is even more unpredictable in a time period of months. Therefore, an average year needs to be determined which will be used to represent the weather which can be expected in the long-term. To do so, multiple FlexSim simulations of different installation sequences have been run over all 20 years of which the weather data is available. Furthermore, a data analysis of the four characteristics of the weather has been performed on Python for all 20 years of which the weather data is available. This, together with the results of the FlexSim simulations, has led to the conclusion that 1993 was 'the most average year' in terms of weather.

At any moment in time, it should be possible to load the weather forecast into the DST. To do so, the uncertainty of the weather forecast should be considered, as has been explained in Section 3.4. A thorough literature research has been performed and many websites of meteorological institutions have been consulted. Unfortunately, no accurate data on the uncertainty of the forecast of the four relevant characteristics of the weather can be found. Presumably, the main reason for this is that the uncertainty is not a constant factor, but differs from time to time and also per location. Therefore, there are two options. The first option is to discuss with the supplier of the weather forecasts to include a prediction of the certainty of the forecast over time. Another option is to buy a lot of historic forecasts of both locations which are relevant for this project, the Northern and Southern region which have been described in Section 4.2.8. Subsequently, these historic forecasts can be compared to the actual weather data. Since both options are costly, these options are left for the engineers of the Saint-Brieuc project to explore further and decide whether or not they believe it is worth it. Furthermore, the comparative analysis of the historic forecasts to the actual weather data is, possibly, worthy of a whole new study and too large to include in this already large research.

The approach that has been used in this research, is obtained from (Lütjen et al., 2019), who also developed an operational model for scheduling activities of an offshore wind farm installation project. Their model has many differences compared to the model that is developed in this research. One of which is the incorporation of variable durations of activities, based on the condition of the weather. To do so, the uncertainty of the weather forecast was quantified. The forecasted value of any of the four characteristics of the weather is denoted by μ. Furthermore, the average value of the characteristic over the forecasted period is denoted by μ^*. The uncertainty of the weather t hours into the future is denoted by $\delta(t)$, which starts at $\delta(0) = 0$ and reaches 0.25 at 168 hours into the future. From there, it quickly increases to 0.65 at 336 hours into the future and 0.95 at 504 hours into the future. The forecast is adjusted by taking the expected value and adding the average value multiplied by the uncertainty: $forecast_{char}(t) = \mu + \mu^* \cdot \delta(t)$ where *char* represents any of the four relevant characteristics of the weather.

During a meeting with a coastal and metocean engineer from Van Oord, it was clarified that the maximum length of a forecast that can be purchased is 15 days. For that reason, and the assumption that the uncertainty is slightly higher than what is used in their publication, the uncertainty that was spread out over three weeks is now spread out over two weeks. The aforementioned $\delta(t)$ and a fictitious forecast of the significant wave height with the determined uncertainty interval are plotted (Figure 7). In order to determine whether an activity can be commenced or not, the upper bound of the uncertainty interval is used and should be below the relevant limit.

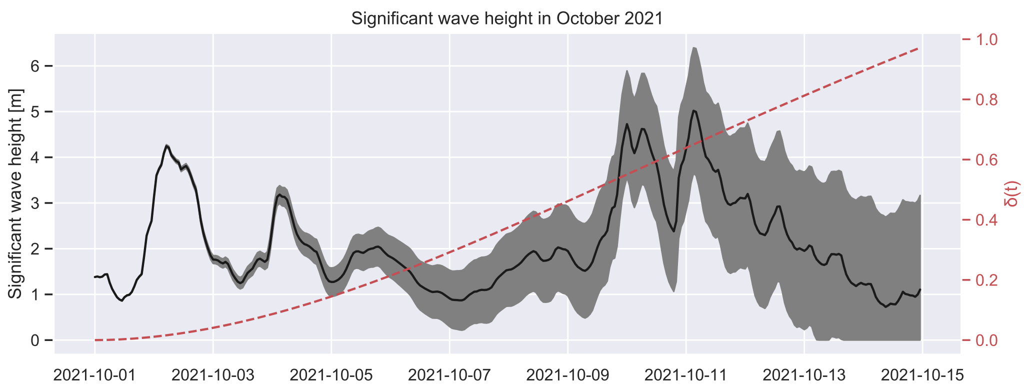

Figure 7: Fictitious forecast of the significant wave height, including uncertainty

The historic weather data of 20 years has a one hour resolution, whereas most weather forecasts that can be purchased have a three hour resolution. In order to ensure that the duration calculations, which will be clarified in the next section, can handle activities that have durations rounded to the minute, linear interpolation is applied to the historic weather data and forecast to obtain weather data with a one-minute resolution.

4.4. Decision-support tool

The sequence and complexity of the installation activities, the project requirements and weather handling that have been clarified in the previous sections, have all been used for the development of the DST. The DST consists of two parts. The first part of the DST is the calculation of the duration of starting the installation process of any location at every possible starting hour. The output of this part of the DST is used as input for the second part. The second part of the DST is the optimiser, which consists of a linear program that minimises the total costs of the remainder of the project whilst taking the current status of the project and the latest weather forecast into account.

No useful literature has been found in which real-life projects are modelled with similar project requirements and the same kind of complexity as this research aims for. Therefore, the two parts of the DST have been uniquely developed for this project and will be elaborated upon in the next sections.

4.4.1. Duration calculation

The model developed is able to calculate for any starting hour how long it would take to complete the installation of any location. In this case, the determined average year, 1993, is used. For every hour in 1993, the model cycles through all activities, taking all the aforementioned project requirements into account. The development of this model has been a long and complex process, during which many meetings with an engineer of the project and comparisons with the FlexSim model took place.

Furthermore, before the optimisation can be started, the weather forecast and its uncertainty needs to be implemented. At any moment in time, the weather forecast can be loaded into the model, after which the model will calculate the durations of starting during any hour of the forecast period, for every location. This, combined with the duration of starting at any hour of the average year, will be the input of the optimiser. An example of this input has been created (Table 2 and Figure 8), in which the duration of starting the installation process of a specific location at a specific starting hour can be seen. The 62 locations of the Saint-Brieuc project are referred to as B01, B02, etc. The empty cells in the table do not mean that it is not possible to start installing a specific location at that hour, it simply means that starting at that hour does not make sense, since the installation process of that location will finish at the same time if you start at a later hour, as can also be seen in the pseudocolor plot.

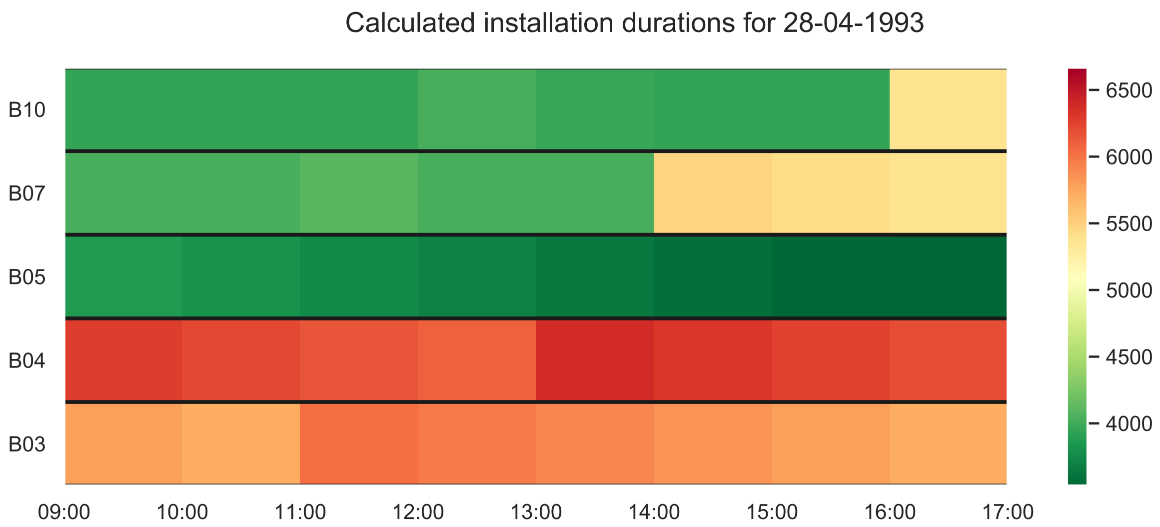

Figure 8: Pseudocolor plot of calculated durations (in minutes) per starting hour

Table 2: Example of calculated durations (in minutes) per starting hour

Starting time	B03	B04	B05	B07	B10
28-04-1993 09:00				4043	6280
28-04-1993 10:00	5730			4043	
28-04-1993 11:00				4099	
28-04-1993 12:00		6100		4043	6441
28-04-1993 13:00				4043	
28-04-1993 14:00			3585		
28-04-1993 15:00			3533		6548
28-04-1993 16:00	5734	6201	3533	5370	

A pseudocolor plot has also been created of the same locations for March and April 1993 (Figure 9). It can be seen that there is a period of bad weather, due to which it takes a long time to complete the installation process of the locations if the installation is started in the beginning of March. Furthermore, it can be seen that all locations have varying installation durations and also vary slightly from one another.

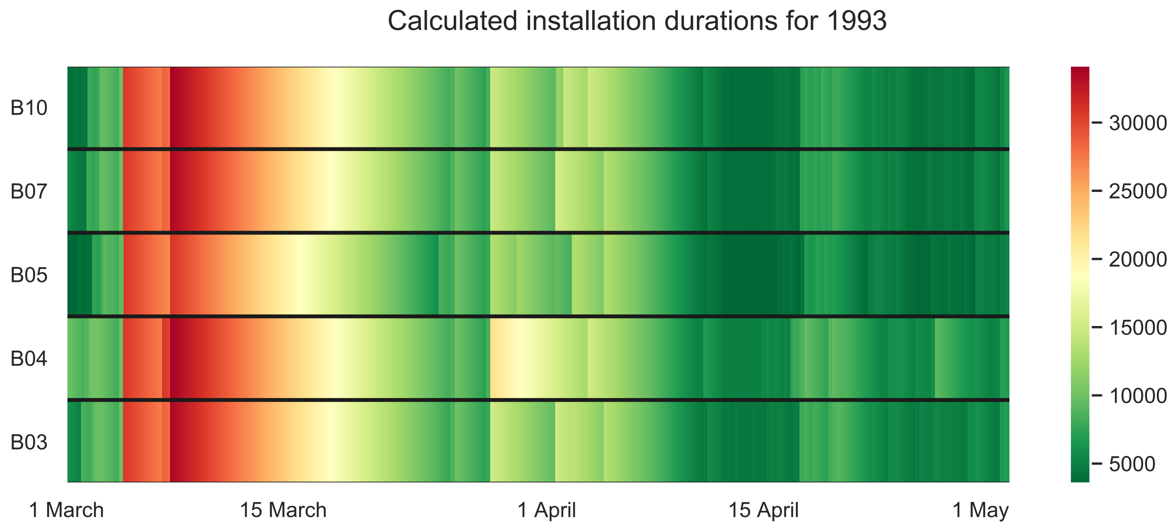

Figure 9: Pseudocolor plot of two months of calculated durations (in minutes) per starting hour

The development of the model that is able to calculate the installation duration of every location for any starting hour has been a continuous process between the relevance cycle, design cycle and rigor cycle: having many meetings with an engineer of the project, drawing knowledge from relevant literature and comparing the developed model and its output with the FlexSim model and its output. In the next section, the final results of a comparison between the calculated durations of the developed model and the FlexSim model are shown.

4.4.1.1 Validation of duration calculation

To validate the calculation of the installation duration of the DST, 16 locations have been simulated in FlexSim and the starting times and durations have been logged. For the same 16 locations, the durations that the DST calculates for the exact same starting times have also been logged. The sequence of locations has been set to ascending order, from B01 until B62. During the first couple of locations, extra PSV activities are performed, which are not considered in the DST. However, this is not an issue, since the DST is developed to be used from the winter break onwards. For that reason, in the comparison the first 8 locations are not considered and the comparison is started at location B09. Since it is a time-consuming process to accurately determine the starting times and durations in FlexSim, and also run the duration calculation of the DST at the exact same starting time, no more than 16 locations are considered.

In the range from location B09 until B27, three locations - B12, B26 and B23 - are not considered in the comparison due to the fact that these locations require a sacrificial casing. As has been mentioned in Section 4.2.5, Van Oord will ensure that the Aeolus is not slowed down by the PSV during the installation of locations that require a sacrificial casing. Therefore, the PSV operations that do not require the crane of the Aeolus are not considered in the DST. In FlexSim, these operations are still taken into account and lead to considerable delays of the Aeolus. For this reason, locations that require a sacrificial casing have not been considered in the duration comparison. However, the durations until and after the PSV operations calculated by the DST have been thoroughly compared with the FlexSim model. It is concluded that the accuracy of the DST for the calculation of the duration of the installation process of locations that require a sacrificial casing, disregarding the PSV delay, is similar to the results that can be seen in Table 3.

Table 3: Duration calculation comparison between FlexSim and the DST

Location ID	Jacked [Y/N]	Starting time	FlexSim [h]	DST [h]	Difference [h]
B09	Y	28-04-1993 03:45	114.25	109.92	-4.33
B10	Y	02-05-1993 22:00	106.33	106.32	-0.02
B11	Y	07-05-1993 08:20	114.17	116.42	2.25
B13	N	16-05-1993 15:00	77.75	83.63	5.88
B14	N	19-05-1993 20:45	112.50	112.22	-0.28
B16	Y	31-05-1993 20:00	113.92	113.87	-0.05
~~B17~~	~~Y~~	~~05-06-1993 13:55~~	~~122.25~~	~~190.20~~	~~67.95~~
B18	Y	10-06-1993 16:10	170.83	170.33	-0.50
B19	Y	17-06-1993 19:00	103.50	103.45	-0.05
B20	Y	22-06-1993 02:30	123.50	123.55	0.05
B21	Y	27-06-1993 06:00	69.00	70.72	1.72
B22	Y	30-06-1993 03:00	76.92	76.72	-0.20
B24	Y	08-07-1993 15:20	72.00	66.97	-5.03
B25	Y	11-07-1993 15:20	97.58	99.37	1.78
B26	N	15-07-1993 16:55	274.33	274.20	-0.13
B27	Y	27-07-1993 03:15	91.75	91.65	-0.10
Average difference [h]		0.07			
Average deviation [h]		1.52			

The difference in duration for B17 is very large. The reason for this is that activity *2.8 Remove drill* and activity *2.9 Install pile - Incl GLA* are not modelled as consecutive operations in FlexSim. This small mistake in FlexSim usually does not result in noteworthy differences. However, in some cases this leads to notable differences, since finding a weather window for two consecutive activities is more restrictive than finding a weather window for two sequential activities. In some occasions, FlexSim is able to find a workable weather window, whilst the DST only finds a weather window (much) later due to the more restrictive nature of consecutive operations. For this reason, location B17 is not considered in the comparison of the durations.

The average difference of the 15 considered locations is 0.07 hours, which is approximately 4 minutes. Furthermore, the average deviation is 1.52 hours. When the calculated duration is compared for many locations and many starting moments, an average deviation of 1.5 hours is expected if the DST is accurate. This is due to the fact that at every other location the casing teeth need to be replaced, which is resembled by activity *2.16*. Since this needs to be done three times, once for every drill, and takes 1 hour each, the total extra duration if the casing teeth are replaced at a certain location is 3 hours. However, during the calculations of the durations for every location at any starting hour, the installation sequence is not yet known. Therefore, the replacement of the casing teeth has been included at every location, but for half its original duration. For that reason, the average deviation should be 1.5 hours if the DST calculates the durations accurately. The fact that the average deviation in Table 3 is very close to the expected 1.5 hours, even though it is based on only 15 comparisons, could be a coincidence, but could also prove the accuracy of the DST. Either way, the accuracy of the DST is high.

4.4.2. The optimiser

In order to optimise the remainder of the planning, a linear program has been created of which the main concept has been explained in Section 3.2. The main input of this linear program is the calculated duration of completing the installation of any location, at any starting hour. The objective of the optimisation is to minimise the costs of the installation process. There are three different types of costs in this project, namely the cost of being operational, stand-by and idle. As has been stated in Section 4.2.5, all 11 locations that require a sacrificial casing should be installed as one group. Lastly, one change has been made to the requirement that the first 40 locations should have a short temporary casing. This has been changed to the first 44 locations that will be installed requiring a short temporary casing. The main reason for this is that this change results in a much faster optimisation. The parameters, decision variables and formulation of the linear program are discussed below.

Parameters

- loc — Location, where $loc \in \{1, 2, .., L\}$
- $sacr$ — Locations that require a sacrificial casing, where $sacr \in \{sacr_1, sacr_2, .., sacr_{11}\}$
- $nonsacr$ — Locations that do not require a sacrificial casing, where $nonsacr \in \{nonsacr_1, nonsacr_2, .., nonsacr_{L-11}\}$
- $D_{loc,k}$ — Duration (in hours) if installation of specific location is started at hour k
- D_1 — Discretisation of the duration representing one hour
- K — Last considered hour
- F — Hour that represents 01-03-2022 00:00
- $C_{operational}$ — Hourly cost when Aeolus is operational

- $C_{standby}$ Hourly cost when Aeolus is stand-by
- C_{idle} Hourly cost when Aeolus is idle
- $lookahead$ Look-ahead to determine if Aeolus is idle: 336 hours
- M Large value

Decision variables

- $Y^{start}_{loc,k}$ Binary, 1 if installation of specific location has started at hour k, 0 otherwise
- Y^{busy}_{k} Binary, 1 if vessel is busy at hour k, 0 otherwise
- Y^{idle}_{k} Binary, 1 if vessel is idle at hour k, 0 otherwise
- $Y^{ba}_{nonsacr,sacr}$ Binary, to ensure that every non sacrificial casing location is installed either before or after the group of sacrificial casing locations
- Y Binary, to ensure that every non sacrificial casing location is installed either before or after the group of sacrificial casing locations

LP formulation

The objective of the optimisation is to minimise the total costs of the project. This is achieved by setting the objective function to

$$\begin{aligned} \text{minimise} \quad & \sum_{k=1}^{K}\sum_{loc=1}^{L} Y^{start}_{loc,k} \cdot D_{loc,k} \cdot C_{operational} + \Big(\sum_{k=1}^{K} Y^{idle}_{k} + lookahead\Big) \cdot D_1 \cdot C_{idle} \\ & + \Big(T - \Big(\sum_{k=1}^{K} Y^{idle}_{k} + lookahead\Big) \cdot D_1 - \sum_{k=1}^{K}\sum_{loc=1}^{L} Y^{start}_{loc,k} \cdot D_{loc,k}\Big) \cdot C_{standby}, \end{aligned} \tag{2}$$

where T is the hour at which the project is finished and a *lookahead* of two weeks is used, which ensures that the Aeolus is deemed to be idle if it is stand-by for two weeks or more. This will be clarified further by means of the relevant constraints.

The first set of constraints ensures that T is larger than every *installation starting time + duration*, for all locations. In this way, T denotes the finishing time of the project.

$$T \geq \sum_{k=1}^{K} Y^{start}_{loc,k} \cdot (k + D_{loc,k}), \qquad \forall\ loc. \tag{3}$$

The following set of constraints ensures that every location is installed exactly once

$$\sum_{k=1}^{K} Y^{start}_{loc,k} = 1, \qquad \forall\ loc. \tag{4}$$

The following set of constraints ensures that at every hour, the vessel is either starting the installation of a location, busy installing a location, idle or stand-by. The vessel is stand-by if it is not starting an installation, is not operational and is not idle. This will be incorporated in other constraints.

$$\sum_{loc=1}^{L} Y^{start}_{loc,k} + Y^{busy}_{k} + Y^{idle}_{k} \leq 1, \qquad \forall\ k. \tag{5}$$

To ensure that the vessel is *busy* for the duration of the activity, due to which another activity cannot be started, the following constraint is constructed. **Note:** $(D_{loc}^{act} - 1)$ is used, since 1 hour of the duration is already accounted for in $Y_{loc,k}^{start}$.

$$\sum_{t=k+1}^{k+D_{loc,k}} Y_t^{busy} \geq Y_{loc,k}^{start} \cdot (D_{loc,k} - 1), \qquad \forall\ k, \forall\ loc. \tag{6}$$

To ensure that the binary decision variable Y_k^{busy} can only be 1 if and only if the vessel is busy, the following constraint is constructed

$$\sum_{k=1}^{K} Y_k^{busy} = \sum_{k=1}^{K} \sum_{loc=1}^{L} Y_{loc,k}^{start} \cdot (D_{loc,k} - 1). \tag{7}$$

The vessel is considered to be idle if it is stand-by for two weeks or more. Therefore, a look-ahead window of 336 hours is used in the following sets of constraints and . The large value - M - that is used in the next constraints is incorporated to ensure that the relevant decision variable is forced to the right value depending on the values of the other parameters and decision variables.

$$\sum_{t=k}^{k+336} \left(Y_t^{busy} + \sum_{loc=1}^{L} Y_{loc,k}^{start} \right) + M \cdot Y_k^{idle} \geq 1, \qquad \forall\ k \in \{1, .., F - lookahead - 1\}. \tag{8}$$

$$\sum_{t=k}^{k+336} \left(Y_t^{busy} + \sum_{loc=1}^{L} Y_{loc,k}^{start} \right) + M \cdot Y_k^{idle} \leq M, \qquad \forall\ k \in \{1, .., F - lookahead - 1\}. \tag{9}$$

The following constraint is constructed to ensure that the vessel cannot go idle from March 1st onward

$$\sum_{t=k}^{K} Y_t^{idle} = 0, \qquad \forall\ k \in \{F, .., K\}. \tag{10}$$

The last set of constraints is constructed to ensure that all sacrificial casing locations are installed as one group

$$\sum_{k=1}^{K} Y_{nonsacr,k}^{start} \cdot D_{loc,k} - \sum_{k=1}^{K} Y_{sacr,k}^{start} \cdot D_{loc,k} + M \cdot Y_{nonsacr,sacr}^{ba} \geq 0, \qquad \forall\ nonsacr, \forall\ sacr. \tag{11}$$

$$\sum_{k=1}^{K} Y_{nonsacr,k}^{start} \cdot D_{loc,k} - \sum_{k=1}^{K} Y_{sacr,k}^{start} \cdot D_{loc,k} + M \cdot Y_{nonsacr,sacr}^{ba} \leq M, \qquad \forall\ nonsacr, \forall\ sacr. \tag{12}$$

$$\sum_{loc=sacr_1}^{sacr_{11}} Y_{nonsacr,loc}^{ba} = 11, \cdot Y \qquad \forall\ nonsacr. \tag{13}$$

5. Results

In this chapter, the initial conditions of the optimisations are explained. Thereafter, the results that the optimiser can produce are shown and clarified. Furthermore, the results of the optimiser are validated by means of a brute force comparison.

5.1. Optimisation settings

Several choices have been made before the optimisation was run. First of all, it is assumed that the current date is 1 October 2021, which is the date at which the winter break is officially planned. Furthermore, Van Oord expects to finish 36 ± 4 locations before 1 October 2021. For the optimisations, the worst case scenario is chosen such that the optimiser is tested for the largest problem that it potentially has to solve. Thus, it is assumed that 32 locations have been installed and 31 locations still need to be installed. The 31 remaining locations are determined by the installation sequence that Van Oord will use until the winter break. The characteristics of the remaining 31 locations can be seen in Appendix A.

The optimisations have been performed for two different weather forecasts. First of all, the weather data from 1 October 1994 until 14 October 1994 has been used as forecast, to which the uncertainty explained in Section 4.3 has been applied. From a data analysis in Python and simulations in FlexSim, it is obtained that these two weeks in 1994 were average to good in terms of the weather. Secondly, the weather data from 1 October 2000 until 14 October 2000 has been used, since these two weeks were one of the worst out of all 20 years of the historic data.

As has been discussed in Section 4.4.2, the first 44 locations should have a short temporary casing. Thus, if 32 locations have been installed, the next 12 locations should have a short temporary casing. In Appendix A, 13 locations with a short temporary casing can be seen. However, location B08 also requires a sacrificial casing and, as has been explained in Section 4.2.5, the 11 locations that require a sacrificial casing should be installed as one group. Therefore, B08 is not part of the first 12 locations.

5.2. Optimisation with average weather forecast

For this optimisation, the weather data from 1 October 1994 until 14 October 1994 is used as forecast, to which the aforementioned uncertainty has been applied. The results of the optimisation can be seen in Appendix B. Furthermore, a plot of the optimal planning is created (Figure 10).

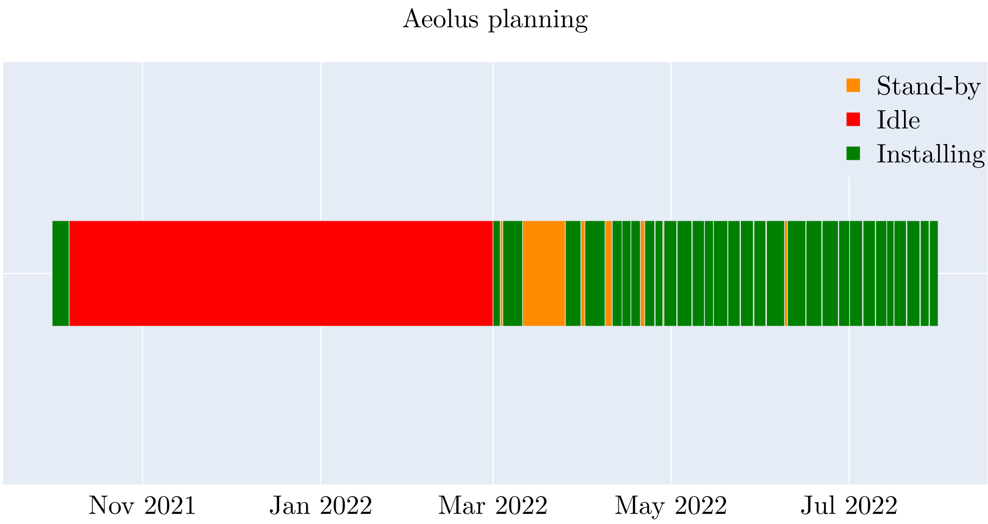

Figure 10: Planning of the optimisation performed with an average weather forecast

It can be seen that the optimiser scheduled location B54 on 1 October 2021, after which the winter break is commenced and the Aeolus goes idle until 1 March 2022. Another notable result of the optimiser is that it has not scheduled any locations from 11 March 2022 until 25 March 2022. The reason for this is the fact that during this time period in 1993, the wave peak period was higher than 12 seconds, which can be seen in Figure 11. As has been explained in Section 4.3, the weather data of 1993 is used to represent the weather that can be expected in the long term. Since every location has multiple activities of which the limit of the wave peak period is 12 seconds, no installations could be performed during these two weeks and the Aeolus was stand-by.

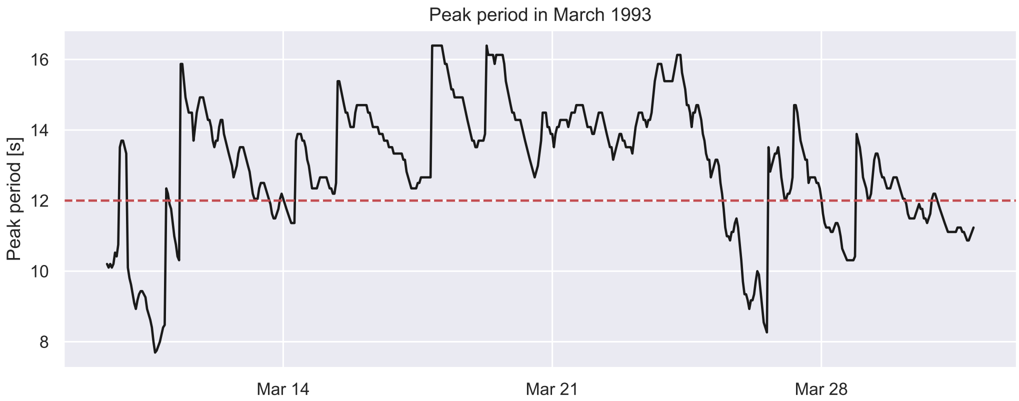

Figure 11: Plot of wave peak period in March 1993, red dashed line is the limit

Furthermore, it can be seen in Appendix B and Figure 10 that the Aeolus spends more time being stand-by in March and April than in the months thereafter. This corresponds to the fact that the weather is much better from May onwards. Thus, the Aeolus barely spends any time being stand-by and almost all available time is utilised by installation activities.

5.3. Optimisation with bad weather forecast

For this optimisation, the weather data from 1 October 2000 until 14 October 2000 is used as forecast, to which the aforementioned uncertainty has been applied. The results of the optimisation can be seen in Appendix C. Furthermore, a plot of the optimal planning is created (Figure 12).

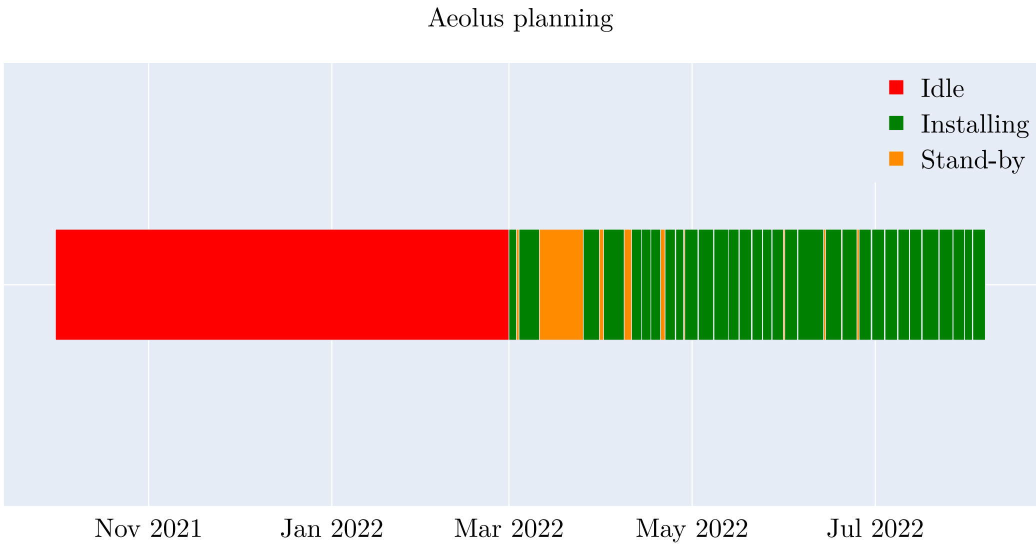

Figure 12: Planning of the optimisation performed with a poor weather forecast

It can be seen that the optimiser has not scheduled any locations to be installed before initiating the winter break. It turns out that in this case it is not possible to install a location due to the poor weather forecast. Another option is that it was possible to install a location before the winter break, but that it would take (much) longer compared to the installation duration during a period of better weather. In that case, the long term benefit of having to install one location fewer after the winter break, does not outweigh the extra cost of staying operational in order to install one more location before initiating the winter break.

By comparing the results from Appendix B and Appendix C, it can also be concluded that optimiser made the right decision to install a location before initiating the winter break for the average weather forecast, since the costs are **Confidential** less compared to the case where no location was installed before the winter break.

5.4. Validation of the optimiser

In order to validate that the output of the optimiser is actually optimal, a brute force has been performed over all possible configurations. The brute force approach calculates the performance of all possibilities, thereby bypassing the use of an optimiser. Nine locations have been used for this validation, since this already has $9! = 362,880$ possible configurations and increasing the amount of locations any further leads to extremely long brute force times. Hence, the reason an optimiser is needed in the first place. The DST and the brute force have both used the nine locations and their durations per starting hour as input, starting from 1 March 1993. A table has been created with the optimal result of the DST (Table 4). From all 362,880 calculations of the brute force approach it is also concluded that there is exactly one optimal solution. It is concluded that the optimisation function of the DST is fully functioning, since the DST and the brute force both find the exact same optimal solution out of all 362,880 possible solutions.

Table 4: Optimisation result of nine locations to compare with brute force result

Location ID	**Start**	**End**	**Duration [h]**	**Stand-by until start [h]**
B60	01-03-2022 00:00	03-03-2022 12:00	60	0
B54	04-03-2022 08:00	11-03-2022 03:00	163	20
B09	25-03-2022 18:00	31-03-2022 03:00	129	351
B32	01-04-2022 12:00	08-04-2022 09:00	165	33
B48	10-04-2022 20:00	14-04-2022 05:00	81	59
B53	14-04-2022 05:00	17-04-2022 06:00	73	0
B33	17-04-2022 06:00	20-04-2022 12:00	78	0
B21	21-04-2022 23:00	25-04-2022 09:00	82	35
B38	25-04-2022 13:00	28-04-2022 04:00	63	4
Total hours operational			**894**	
Total hours stand-by			**502**	
Total costs			**Confidential**	

6. Discussion

Throughout this research, a decision-support tool has been developed which is able to optimise the remainder of the planning of an offshore wind farm project. More specifically, the DST is designed to be used from the moment at which a decision has to be made about initiating the winter break or staying operational. Firstly, the DST imports the latest weather forecast and applies a gradually increasing uncertainty factor to it. Secondly, the DST calculates the duration of installing every remaining location at any future starting hour, whilst taking all the project requirements into account. The resulting durations at all possible starting hours are used as input for the optimiser, which optimises the remainder of the planning based on three different cost types: idle costs, stand-by costs and operational costs.

In this chapter, the results of this research are discussed. Furthermore, the limitations of the DST and corresponding recommendations for the further development are given.

6.1. Main results

The most promising result of this research is the fact that the DST has been developed in such a way that at any moment in time, the latest weather forecast can be imported. Thereafter, the most optimal installation sequence is determined on the basis of which a decision can be made with regards to what location to install next or if the Aeolus should go idle. This result has been achieved by successfully developing the two parts of the DST that have been described in Section 4.4, which will be elaborated upon in the next paragraphs.

One interesting result of this research is the successfully developed optimiser. The optimiser takes three different types of costs into account: operational costs, stand-by costs and idle costs. Furthermore, the optimiser takes specific project requirements into account with regards to the installation sequence: the first 44 locations should have a short temporary casing and the 11 locations that require a sacrificial casing should be installed as one group, as has also been explained in chapter 4. The validity of the output of the optimiser has been proved and it is concluded that the optimiser has been developed successfully.

Another interesting result of this research is the fact that the possibility of very accurately modelling a large and complex installation project into Python is proved. In this research, an offshore wind farm installation project - the Saint-Brieuc project - has been modelled in which approximately 90 unique activities have been incorporated. These 90 activities are not only sequential activities, but also parallel and consecutive without allowed interruptions. At 53 locations the Aeolus will be fully jacked up for the entire installation process, whereas at 9 locations the Aeolus is floating for part of the installation process. At 9 out of the 53 locations at which the Aeolus is fully jacked up and at 2 out of the 9 locations at which the Aeolus is partially floating, a sacrificial casing needs to be installed. This sacrificial casing is a second tubular member which is installed around the pin pile, because extra lateral stability to the foundation is required due to a thick soft overburden layer at these locations.

Almost every activity has specific limits regarding the four relevant characteristics of the weather: significant wave height, peak period, wind speed at 10 meters above the surface and the surface current speed. For every activity, the limits of these four characteristics may not be exceeded by the forecasted weather during a predefined weather window. If this is not the case, the activity can be commenced for a predefined duration. Furthermore, for every location specific drilling times, windows and limits have been determined by Van Oord's engineers. These drilling characteristics have been determined based on the composition of the soil. Additionally, at some locations a tool change is needed, which requires additional activities to be performed. Lastly, the seabed has been divided into two seperate groups, rock and sand, due to which several activities have specific limits depending on the type of the seabed.

To ensure that the results of the optimiser have the potential to be useful, it is important that the durations that the DST calculates for every location and starting hour are accurate. If this is not the case, the results of the optimisation function of the DST are not useful. It is concluded that all project requirements have been successfully incorporated in the DST and the accuracy of the duration calculation of the DST is high.

Lastly, compared to the existing literature that has been explored in Section 3.1, this research has managed to accurately model the entire complexity of a wind farm installation project, whereas existing literature mostly simplifies the installation process. In the existing relevant literature, at most 11 activities have been used, whereas in this research 90 unique activities have been incorporated. Furthermore, most articles in the relevant literature focus on optimizations before the installation phase of the project has started, whereas in this research an operational model has been developed that can be used throughout the installation phase of a wind farm installation project. The DST that has been developed in this research can use the status of the project and latest weather forecast at any moment in time in order to optimise the remainder of the planning of the project. In this way, the DST acts as a fully operational tool which is able to provide dynamic adjustments and short-term control at any moment in time.

6.2. Limitations of the DST and recommendations for further development

Due to the size and complexity of the Saint-Brieuc project and the development of the duration calculation and optimisation functions of the DST, not every aspect of the DST has been fully developed and researched upon. This also leads to two current limitations of the DST, which will be discussed below. Additionally, in order to eliminate the limitations of the DST, recommendations for further development are given.

First of all, the incorporation of the uncertainty of the weather forecast has been implemented similarly to a recent publication of another offshore wind farm installation optimisation problem by Lütjen et al. (2019). However, ideally, the (un)certainty of the weather forecast is bought from the meteorology institution which also supplies the weather forecast. Alternatively, many historic weather forecasts for the locations of the Saint-Brieuc project can be bought and compared to the actual historic weather. In this way, information on the accuracy of the weather forecast over time can be obtained. Both options would presumably improve the predictive quality of the DST. However, it is up to the engineers of the Saint-Brieuc project to determine the best option.

The second limitation of the DST is the handling of the weather that can be expected beyond the scope of the weather forecast, in the long term. In this research, through multiple simulations in FlexSim and data analysis in Python, an average year in terms of the weather has been determined. However, there are two other options that could have been better, but were not performed due the time limit of this research.

One option is to determine an average year based on the historic weather data. This can be done by performing 20 seperate optimisations, one for every year of the historic weather data. From these optimisations the completion dates of the project for every year can be compared in order to determine what year(s) are average in terms of performance. The resulting year can be used to represent the weather in the long-term which is used in the DST. This option has not been used, since the calculation of the durations for every location and every starting hour of a year takes approximately half a day to run. Furthermore, running the optimisation usually takes anywhere from half a day up to a full day. For that reason, performing the calculations and optimisations for all 20 years would take approximately 20 to 30 days. Unfortunately, running a code for so many days was not an option due to the time constraint of this research and the limited availability of computers.

Another option would be to, once the DST is operational, run 20 different optimisations simultaneously every time a new optimal planning needs to be obtained. Every optimisation makes use of a different year of the historic weather data. Hence, the suggested installation sequence, and most importantly the suggested location to install next, can be compared for every year of the historic weather data. In this way, the certainty of the suggestion made by the DST can be based on the results of the 20 optimisations. This option was not tested, due to the same reason as mentioned in the previous paragraph.

7. Conclusion

Throughout this research, the development of a novel and useful decision-support tool for the operational phase of an offshore wind farm installation project has been guided by one main research question and six related sub-questions. The main research question throughout this research was:

How can an operational decision-support tool be designed to ultimately reduce the costs of wind farm installation projects?

The approach to acquiring an answer to the main research question has been to further investigate into the six sub-questions that are stated in Section 2.5. The approach to obtaining an answer to these sub-questions will be briefly summarised in the next paragraph.

Throughout this research, the exact requirements of the Saint-Brieuc project have been thoroughly discussed with an engineer of Van Oord via multiple meetings. Furthermore, for the handling of the weather forecast and historic weather data, relevant literature and meteorology institutions have been consulted, as well as several discussions with Van Oord's engineers. The development of the optimiser has been based on relevant literature on linear programming as well as experience in developing optimisation models. Lastly, the performance of the DST has been validated by means of a thorough comparison to the FlexSim model of the Saint-Brieuc project as well as a comparison to the result of a brute search, which was used to find the optimal solution of a small-scale problem.

The performance of the DST has proven to be very accurate compared to FlexSim. Furthermore, the output of the DST, which is provided by the optimiser, has also proven to be optimal. Hence, it is concluded that throughout this research a decision-support tool for the Saint-Brieuc project has successfully been developed. Notwithstanding, it is recommended to Van Oord to further develop the DST in order to improve the usefulness of its output. Additionally, this research proved that it is possible to accurately model a complex installation project in Python, due to which potentially FlexSim is no longer required for project planning. Moreover, the concepts used in the DST for the Saint-Brieuc project can also be applied to other wind farm installation projects. To extend the applicability of the DST to more projects than just the Saint-Brieuc project, small changes will be required in order to adjust the DST to the specific characteristics of another project. Additionally, by means of the DST optimisations can be performed during the operational phase of the project, which is not possible in FlexSim.

To ultimately conclude this research, it is recommended that Van Oord further develops the DST and incorporates it into their in-house Python simulation engine, OpenCLSim. It is also recommended that Van Oord further investigates the possibilities of transitioning more towards optimisation-based decision making instead of simulation-based decision making, since this researched has proved the usefulness of one of the many possibilities in this field.

References

Ait-Alla, Abderrahim et al. (2017). "A study of new installation concepts of offshore wind farms by means of simulation model". In: *The 27th International Ocean and Polar Engineering Conference.* International Society of Offshore and Polar Engineers.

Anand, Rimmi, Divya Aggarwal and Vijay Kumar (2017). "A comparative analysis of optimization solvers". In: *Journal of Statistics and Management Systems* 20.4, pp. 623–635.

Bilgili, Mehmet, Abdulkadir Yasar and Erdogan Simsek (2011). "Offshore wind power development in Europe and its comparison with onshore counterpart". In: *Renewable and Sustainable Energy Reviews* 15.2, pp. 905–915.

Doran, George T (1981). "There's a SMART way to write management's goals and objectives". In: *Management review* 70.11, pp. 35–36.

FICO Xpress Optimizer (2020). *FICO Xpress Optimizer Reference Manual.* URL: `https://www.fico.com/en/latest-thinking/brochure/xpress-optimizer-reference-manual`.

FlexSim (2020). URL: `https://www.flexsim.com/`.

Gill, Jon (2008). "Communicating forecast uncertainty for service providers". In: *WMO Bulletin* 57.4, pp. 237–243.

Gurobi Optimization, LLC (2020). *Gurobi Optimizer Reference Manual.* URL: `http://www.gurobi.com`.

Hevner, Alan R (2007). "A three cycle view of design science research". In: *Scandinavian journal of information systems* 19.2, p. 4.

Hillier, Frederick S. and Gerald J. Lieberman (2015). *Introduction to Operations Research.* Tenth. New York, NY, USA: McGraw-Hill.

IBM (2020). *IBM ILOG CPLEX 12.10.* URL: `https://www.ibm.com/products/ilog-cplex-optimization-studio`.

Irawan, Chandra Ade, Dylan Jones and Djamila Ouelhadj (2017). "Bi-objective optimisation model for installation scheduling in offshore wind farms". In: *Computers & Operations Research* 78, pp. 393–407.

Jablonsk, Josef et al. (2015). "Benchmarks for current linear and mixed integer optimization solvers". In: *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis* 63.6, pp. 1923–1928.

Jathe, Nicolas et al. (2019). "A Review on the Planning Problem for the Installation of Offshore Wind Farms". In: *IFAC-PapersOnLine* 52.13, pp. 1337–1342.

Kaldellis, JK and D Apostolou (2017). "Life cycle energy and carbon footprint of offshore wind energy. Comparison with onshore counterpart". In: *Renewable Energy* 108, pp. 72–84.

KNMI, (2020). URL: `https://www.knmi.nl/nederland-nu/weer/waarschuwingen-en-verwachtingen/weer-en-klimaatpluim`.

Lars, Grüne and P Jürgen (2011). *Nonlinear model predictive control theory and algorithms.*

Lütjen, Michael et al. (2019). "Evaluation of Loading Bay Restrictions for the Installation of Offshore Wind Farms Using a Combination of Mixed-Integer Linear Programming and Model Predictive Control". In: *Applied Sciences* 9.23, p. 5030.

Mittelmann, Hans D (2017). "Latest Benchmarks of Optimization Software". In: *INFORMS Annual Meeting. Houston, TX.*

– (2020). "Benchmarking Optimization Software-a (Hi) Story". In: *SN Operations Research Forum*. Vol. 1. 1. Springer, pp. 1–6.

Muhabie, Y Tekle et al. (2018). "A discrete-event simulation approach to evaluate the effect of stochastic parameters on offshore wind farms assembly strategies". In: *Ocean Engineering* 149, pp. 279–290.

OG Monitor (2020). URL: `https://www.ogmonitor.com/van-oord-saint-brieuc-wind-project/`.

OpenCLSim, (2020). URL: `https://openclsim.readthedocs.io/en/latest/`.

REN21 (2020). *Renewables 2020 Global Status Report.*

Rippel, Daniel et al. (2019). "Simulation and Optimization of Operations for Offshore Installations Planning using a Model Predictive Control Scheme". In: *2019 Winter Simulation Conference (WSC)*. IEEE, pp. 1719–1730.

Scher, Sebastian and Gabriele Messori (2018). "Predicting weather forecast uncertainty with machine learning". In: *Quarterly Journal of the Royal Meteorological Society* 144.717, pp. 2830–2841.

Senouci, Ahmed B and Saleh A Mubarak (2016). "Multiobjective optimization model for scheduling of construction projects under extreme weather". In: *Journal of Civil Engineering and Management* 22.3, pp. 373–381.

Simpy, (2020). URL: `https://simpy.readthedocs.io/en/latest/index.html`.

Thomsen, Kurt (2014). *Offshore wind: a comprehensive guide to successful offshore wind farm installation.* Academic Press.

Van Oord, (2020b). URL: `https://www.vanoord.com/offshore-wind`.

Van Oord, (2020c). URL: `https://www.vanoord.com/news/2020-ailes-marines-selects-van-oord-saint-brieuc-offshore-wind-farm`.

Van Oord, (2020a). URL: `https://www.vanoord.com/news/2018-jackets-installation-campaigns-east-anglia-one-wind-farm`.

Van Oord, (2020d). URL: `https://www.vanoord.com/news/2016-van-oord-acquires-bilfinger-offshore-wind-activities`.

Vis, Iris FA and Evrim Ursavas (2016). "Assessment approaches to logistics for offshore wind energy installation". In: *Sustainable energy technologies and assessments* 14, pp. 80–91.

Appendices

A. Remaining locations for the optimisations

Location ID	Region	Sacr. casing	Tool change	Jacked	Temp. casing	Seabed
B08	South	Yes	No	Yes	Short	Sand
B09	South	No	No	Yes	Short	Sand
B11	South	No	No	Yes	Long	Sand
B12	South	Yes	No	Yes	Long	Sand
B15	South	Yes	No	No	Long	Sand
B19	South	No	No	Yes	Long	Rock
B21	South	No	No	Yes	Short	Rock
B22	South	No	No	Yes	Long	Sand
B23	South	Yes	No	Yes	Long	Sand
B24	South	No	No	Yes	Long	Sand
B25	North	No	No	Yes	Long	Rock
B28	North	No	No	Yes	Short	Rock
B32	South	No	No	Yes	Short	Sand
B33	South	No	No	Yes	Short	Sand
B34	South	No	No	Yes	Long	Sand
B35	South	Yes	No	Yes	Long	Sand
B36	South	Yes	No	Yes	Long	Sand
B37	South	Yes	No	Yes	Long	Sand
B38	South	No	No	Yes	Short	Sand
B40	North	No	Yes	Yes	Short	Rock
B43	North	No	No	Yes	Long	Sand
B47	South	No	No	Yes	Long	Sand
B48	South	No	No	Yes	Short	Sand
B49	South	Yes	No	Yes	Long	Sand
B53	North	No	No	Yes	Short	Rock
B54	North	No	Yes	Yes	Short	Rock
B55	North	Yes	No	Yes	Long	Sand
B56	North	Yes	No	No	Long	Sand
B60	North	No	No	Yes	Short	Rock
B61	North	No	No	Yes	Short	Rock
B62	North	Yes	No	Yes	Long	Sand

B. Result of optimisation with average weather forecast

Location ID	Start	End	Duration [h]	Stand-by until start [h]
B54	01-10-2021 00:00	06-10-2021 20:00	140	0
Idle	06-10-2021 20:00	01-03-2022 00:00	3484	0
B60	01-03-2022 00:00	03-03-2022 12:00	60	0
B40	04-03-2022 08:00	11-03-2022 03:00	163	20
B09	25-03-2022 18:00	31-03-2022 03:00	129	351
B32	01-04-2022 12:00	08-04-2022 09:00	165	33
B48	10-04-2022 20:00	14-04-2022 05:00	81	59
B53	14-04-2022 05:00	17-04-2022 06:00	73	0
B33	17-04-2022 06:00	20-04-2022 12:00	78	0
B21	21-04-2022 23:00	25-04-2022 09:00	82	35
B38	25-04-2022 13:00	28-04-2022 04:00	63	4
B28	28-04-2022 13:00	02-05-2022 22:00	105	9
B61	03-05-2022 02:00	08-05-2022 03:00	121	4
B25	08-05-2022 06:00	12-05-2022 11:00	101	3
B34	12-05-2022 11:00	15-05-2022 13:00	74	0
B15	15-05-2022 13:00	20-05-2022 09:00	116	0
B08	20-05-2022 10:00	24-05-2022 15:00	101	1
B56	24-05-2022 19:00	29-05-2022 03:00	104	4
B36	29-05-2022 10:00	02-06-2022 11:00	97	7
B55	02-06-2022 16:00	08-06-2022 21:00	149	5
B37	09-06-2022 21:00	16-06-2022 04:00	151	24
B62	16-06-2022 05:00	21-06-2022 14:00	129	1
B49	21-06-2022 18:00	27-06-2022 06:00	132	4
B35	27-06-2022 10:00	01-07-2022 04:00	90	4
B23	01-07-2022 04:00	05-07-2022 14:00	106	0
B12	05-07-2022 18:00	09-07-2022 23:00	101	4
B43	10-07-2022 02:00	13-07-2022 21:00	91	3
B24	13-07-2022 21:00	16-07-2022 09:00	60	0
B11	16-07-2022 09:00	20-07-2022 14:00	101	0
B19	20-07-2022 18:00	25-07-2022 05:00	107	4
B47	25-07-2022 09:00	28-07-2022 09:00	72	4
B22	28-07-2022 12:00	31-07-2022 11:00	71	3

Total hours operational	**3213**
Total hours stand-by	**586**
Total hours idle	**3484**
Total costs	**Confidential**

C. Result of optimisation with poor weather forecast

Location ID	Start	End	Duration [h]	Stand-by until start [h]
Idle	01-10-2021 00:00	01-03-2022 00:00	3624	0
B60	01-03-2022 00:00	03-03-2022 12:00	60	0
B40	04-03-2022 08:00	11-03-2022 03:00	163	20
B09	25-03-2022 18:00	31-03-2022 03:00	129	351
B32	01-04-2022 12:00	08-04-2022 09:00	165	33
B48	10-04-2022 20:00	14-04-2022 05:00	81	59
B53	14-04-2022 05:00	17-04-2022 06:00	73	0
B33	17-04-2022 06:00	20-04-2022 12:00	78	0
B21	21-04-2022 23:00	25-04-2022 09:00	82	35
B38	25-04-2022 13:00	28-04-2022 04:00	63	4
B28	28-04-2022 13:00	02-05-2022 22:00	105	9
B61	03-05-2022 02:00	08-05-2022 03:00	121	4
B54	08-05-2022 06:00	13-05-2022 01:00	115	3
B19	13-05-2022 01:00	16-05-2022 14:00	85	0
B25	16-05-2022 17:00	20-05-2022 18:00	97	3
B34	20-05-2022 23:00	24-05-2022 10:00	83	5
B22	24-05-2022 12:00	27-05-2022 12:00	72	2
B11	27-05-2022 15:00	31-05-2022 09:00	90	3
B47	31-05-2022 20:00	05-06-2022 02:00	102	11
B55	05-06-2022 05:00	13-06-2022 19:00	206	3
B15	14-06-2022 11:00	19-06-2022 17:00	126	16
B62	19-06-2022 23:00	24-06-2022 22:00	119	6
B36	25-06-2022 15:00	29-06-2022 15:00	96	17
B37	29-06-2022 20:00	04-07-2022 01:00	101	5
B12	04-07-2022 05:00	08-07-2022 09:00	100	4
B08	08-07-2022 13:00	12-07-2022 08:00	91	4
B56	12-07-2022 09:00	16-07-2022 10:00	97	1
B49	16-07-2022 15:00	22-07-2022 03:00	132	5
B23	22-07-2022 07:00	26-07-2022 20:00	109	4
B35	26-07-2022 22:00	30-07-2022 16:00	90	2
B24	30-07-2022 16:00	02-08-2022 07:00	63	0
B43	02-08-2022 11:00	06-08-2022 15:00	100	4

Total hours operational	**3194**
Total hours stand-by	**613**
Total hours idle	**3624**
Total costs	**Confidential**