IMPROVING THE MODELLING OF MARINE OPERATIONS IN THE INSTALLATION OF OFFSHORE WIND FARMS

Dissertation in partial fulfilment of the requirements for the degree of
MASTER OF SCIENCE WITH A MAJOR IN ENERGY TECHNOLOGY
WITH FOCUS ON WIND POWER

UPPSALA UNIVERSITY

Uppsala University
Department of Earth Sciences, Campus Gotland

Manuel Alvarez

October 11, 2016
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Approved by:
Supervisor: Heracles Polatidis

Examiner: Jens N. Sørensen

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Abstract

Offshore wind energy is a fast growing industry mainly due to the great wind resources that marine environments possess and for shortage of onshore sites. Often, offshore sites have very high wind, waves and current resources making the installation phase a challenging operation with many barriers to overcome. Optimising the installation process to reduce costs, while maintaining safe operations, is an essential task for the offshore wind sector.

The main objective of this Thesis is to develop a tool that coordinates marine operations during the installation of offshore wind farms, and calculate delays associated with these operations. Initially, a literature review has been conducted that encompassed topics like components of offshore wind farms, vessels and equipment involved in the installation process, installation techniques and logistics, the importance of modelling the installation process and the description of the modelling tool ECN Install. The existing tool was extended to allow the introduction of interdependent activities. A method to introduce these interdependencies in the existing tool is created. The method has been applied in a case study of an ongoing installation of an offshore wind farm, comparing the results with and without interdependencies, and drawing relevant conclusions.

Results show that the accuracy of the tool is improved, making a better prediction of the duration and starting/ending time of a number of offshore operations, improving the calculation of weather downtimes and bringing the modelling closer to reality.
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Acronyms

AC  Alternating Current
DP  Dynamic Positioning
EWEA  European Wind Energy Association
HVAC  High Voltage Alternate Current
HVDC  High Voltage Direct Current
LCoE  Levelized Cost of Electricity
MW  Mega Watt
O&G  Oil and Gas
O&M  Operation and Maintenance
OWF  Offshore Wind Farm
ROV  Remotely Operated Vehicle
TP  Transition Piece
WT  Wind Turbine
XLPE  Cross-Linked Polyethylene
Chapter 1

Introduction

1.1 Background

The global demand for renewable energy sources continues to increase and governments aim to increase the share of renewables in their national energy mix. This is forcing the industry to bring innovative solutions to supply the increasing demand on green electricity. One of these solutions is the development of wind energy power plants into the sea. With the first commercial offshore wind farm installed in 1991 in Vindeby (Denmark) [1] the industry has experienced a dramatic growth with more than 3 GW connected to the grid only in 2015, reaching a total installed capacity of 11GW only in Europe (EWEA)[2].

On the one hand, offshore electricity generation provides many advantages, such as more electricity generated per megawatt installed, smaller visual impact, and less noise and flickering effects. On the other hand, such projects also involve numerous challenges. One of the most difficult ones is the installation phase [3], as the delicate operations performed by installation vessels are hampered by the harsh meteorological and oceanographic conditions.

1.2 Thesis description

This Thesis work is about improving the modelling of the offshore wind farm installation operations. First, a literature review was done that deals with
the following fields: offshore wind farm components, vessels and equipment required, logistics and techniques used for the installation and modelling tools, more specifically the modelling tool developed at ECN (ECN Install).

This tool is able to calculate delays and cost associated to the installation process, and provides an accurate Gantt chart of the planning and costs breakdown. The methodology developed in this Thesis concerns the enhancement of this tool by improving the logical algorithm on which the tool is based. A lack of an option to link activities or simulate interdependent activities has been identified. This option to set interdependencies is crucial to perform parallel offshore activities or activities where coordination between vessels is involved, as delays (mostly weather downtimes) are numerous and it is unpredictable when an activity will be able to start.

Subsequently, an application of the improved algorithm is unfolded that includes the modelling of the Jacket foundation installation for Wikinger wind farm, using weather data recorded from the offshore measurement platform FINO 2. A comparative study is done between the previous and the improved model. Results shows that the accuracy of the model is improved by creating a more realistic project planning including delays, with its respective Gantt chart and excel sheet showing plan's starting/ending times.

1.3 Justification

It has been pointed out many times that one of the bigger challenges for offshore wind cost reduction is the optimization of the installation process. The costs of vessels and harbor leases are high, and the delays and risks numerous. One way to improve the installation process is by creating a good logistic planning, taking into consideration possible delays. There are different tools used by developers to model the installation process. One of these tools is developed at ECN (Energy Research Centre of the Netherlands). Improving this tool will help not only developers to create a better plan, but also contractors and financial institutions will benefit.
1.4 Research approach & methodology

To reach the goal of this Thesis work different steps have been taken:

1. Understanding logistics and techniques used for the installation of offshore wind farms.
2. Learning and understanding how the modelling tool ECN Install works.
3. Finding the gaps where there is room for improvement.
4. Creating MATLAB algorithms to improve the tool.
5. Validation of the tool by comparison with previous versions.
6. Showing the added value by application to a case study.

A summary of the research approach can be seen in Fig. 1.1

![Figure 1.1: Summary of the research approach](image)

1.5 Outline of the Thesis report

The Thesis continues as follows: In the next Chapter 2 the literature review describing the elements involved in the installation process of an offshore wind farm is presented. Chapter 3 describes the methodology used for the improvement of ECN Install. In Chapter 4 a case-study is presented to show the applicability and the outputs of the improved modelling tool. Additionally, the results from the previous version of the tool are shown. Chapter 5 includes a discussion of the findings and a comparative analysis with the results from the previous version of the tool, showing the improvements made. Chapter 6 summaries and concludes this Thesis work, and includes further recommendations for future research.
Chapter 2

Installation of offshore wind farms - State of the art

2.1 Introduction

In this Chapter 2, the components of a standard offshore wind farm will be presented and described, as well as the vessels and equipment needed for the installation. Then, some of the most representative installation techniques and logistic concepts used to install offshore wind farms will be analysed. More specifically, the Sections 2.2, 2.3 and 2.5 refer to the main components of an offshore wind farm: foundations, wind turbines and electrical systems respectively. Then, Section 2.6 describes the vessels and tools used to install the components. Section 2.7 describes the installation techniques and logistic concepts used to install the wind farms. Finally, Section 2.8 describes the importance of modelling the installation of any OWF (Offshore Wind Farm) as to reduce risks and costs during the process. An installation modelling tool developed at ECN (Energy Research Centre of the Netherlands): ECN Install V2.0 will then be explained and analysed.

To help the reader understand the whole installation process, definitions of the elements, vessels and equipment involved in the installation of any OWF are presented in the following.
2.2 Substructures

2.2.1 Introduction

One of the main components of an OWF are the supporting substructures for the gigantic wind turbines used. The substructures can be either bottom-fixed or floating. Even though the floating ones are still in testing phase, their future is very promising for deep-waters wind power plants. Each substructure within a wind farm is tailor-made for the specific conditions of its location. Factors such as sea-bed composition, size of the wind turbine and water depth determine the characteristic of the foundation that should be used.

2.2.2 Bottom-fixed substructures

2.2.2.1 Monopiles

Monopiles are the most commonly used foundations for shallow waters in the North, Baltic and Irish sea, where most of the wind farms have been installed. Until 2015, there were 2653 monopiles installed, making up for about 80% of the total installed foundations for wind turbines [2]. This popularity comes from the expertise that the offshore industry has from Oil Gas, where those structures are used, and from the relatively low weight compared with other types of foundations [4].

A monopile consists of a steel made cylinder that is driven about 40% to 50% of its length into the sea bed [5]. It can be seen as a prolongation of the turbine tower, but reinforced to resist the waves and currents it is exposed to during the whole life cycle. It normally has a diameter of 4 to 6 meters. On the top of it and between the monopile and the wind turbine, the transition piece is placed.

The transition piece is a cylindrical part of steel used to link the monopile with the wind turbine, and acts as a landing base to provide the workers a much easier access to the wind turbine [6]. The transition piece (TP) is placed on the top of the monopile and then a strong cement called grout'is applied to connect it to the monopile. Its function is also to guarantee the verticality of the wind turbine, as the monopile may have some degrees of
inclination after the piling operation [7]. With the increase of the monopile's size, it has been demonstrated that grouting is not effective anymore due to the chemical composition of the cement. Thus, the new trend is using bolted connection to link both TP and WT (Wind Turbine). Examples of monopiles and other types of bottom-fixed substructures can be seen in Fig. 2.1.

2.2.2.2 Gravity-based substructure (GBS)

Gravity-base foundations consist of a concrete tubular substructure with a flat base in which a ballast (rocks or sand) is placed to anchor the foundation into the seabed. Although they are not as popular as monopiles, gravity foundations have a huge potential for the offshore industry due to their relatively low cost compared with monopiles. Nevertheless, it is the second most used type of foundations. Gravity foundations are the most efficient solution for shallow waters and rigid sea beds, where the drilling work needed for piles is difficult [8].

2.2.2.3 Jacket foundation

The use of this type of foundation is increasing as new wind farms are installed in deeper waters. It consists of a steel lattice tower with a basic truss structure to provide stability and strength. Therefore, higher foundations can be built using less steel than monopiles. As such, material costs are reduced and the global stiffness is conserved. As a drawback, welding needs to
be carefully done to allow the structure to resist loads from waves and currents in its expected lifetime [9]. Jacket foundations are fixed to the seabed by three or four pin-piles which are a smaller version of monopiles.

2.2.2.4 Tripod foundation

Less popular than the previous ones, tripods consist of a central steel shaft connected to three cylindrical steel tubes which are driven into the sea bed. They are more expensive than normal monopiles, but their structure is suitable for deeper waters. As there are three connection points with the sea bed instead of one, the overall stability is improved [10].

2.2.3 Floating substructures

2.2.3.1 Introduction

The idea of installing turbines on buoys evolved because building bottom-fixed substructures for waters deeper than 50 meters is not cost efficient due to material costs and installation difficulty [11]. The advantages of using this type of substructure are as numerous as the complexity of the design. On the one hand, a floating substructure should handle the effect of the combined wind-wave-currents loads and keep the turbine straight. On the other hand, the installation process is much simpler, having the possibility to be installed onshore and then to be dragged as a whole to the deployment point. This decreases the LCoE (Levelized Cost of Electricity) drastically. Musial [12] states that the architecture of the floating substructure is highly influenced by the mooring system used. The most common are catenary mooring, taut-leg mooring, and vertical tension legs. In the following, the two most advanced concepts in the market will be described. In Fig. 2.2 examples of floating substructures can be seen.

2.2.3.2 Spar buoy floating substructure

Spar buoys have been used for a long time in the O&G (Oil and Gas) industry and are the simplest form of floating structures. It consists of a cylindrical tank with a ballast underneath, achieving hydrodynamic stability by simply maintaining the center-of-mass as static as possible [12]. One example of success and performance, is the model Hywind from Statoil, installed in Norway in 2009. Achieving a capacity factor of up to 54% [13], Statoil recently
announced a mid scale wind farm (25 MW) off the coast of Scotland.

2.2.3.3 Semi submersible platforms

Semi submersible platforms consist of three or four slender columns that connect to each other through braces [14]. The three main architectural parameters affecting the performance of such structures are: the wet area of a single column, the height of the buoyancy center and the distance between two columns. One of the main advantages is that the structure design produces the “wave-cancellation effect”. This effect improves significantly the dynamic response of the structure to wave loads, as it minimizes the effect and movements that waves cause in the whole structure [15]. On the one hand, the design complexity is higher than other type of floating substructures, but on the other hand, the advantages in installing, mooring associated costs, hydrodynamic behaviors and surge response make these substructures the most advantageous among the others [16];[17].
2.3 Wind Turbines

Offshore wind turbines are functionally the same as their relatives onshore, but with some added purpose-built structural reinforcements to handle harsh oceanic conditions. Another difference is the size, as the onshore logistics (size of the roads, bridges, etc.) are not a threshold anymore. Massive wind turbines can be manufactured near harbor and then transported to site. The latest wind turbine model that has been installed has a 6 MW generator, while onshore the largest capacity per single generator is about 3.5 MW, which is almost half the capacity.

As can be seen in Fig. 2.3, wind turbines consist of different spare parts. Some of those parts are assembled previously on harbor, and some are assembled on site. It is this pre-assembly process determining the logistic operations and procedures to install the OWF. Such operations are described later on in this paper.

Figure 2.3: Spare parts of wind turbine Source: Emre Uraz, 2011
2.4 Electrical Infrastructure

2.4.1 Introduction

The overall performance of a wind farm is also determined by the electric interconnection between the wind turbines and/or the substation (collector system) and the wind turbines/substation with the onshore connection point (transmission system). The industry has long-lasting experience in installing subsea cables, and this knowledge is applied to install the electrical system in the OWF.

2.4.2 Collector system

The interconnection turbine-turbine, and turbine-collector point/substation is made with XLPE submarine cables called array cables. These cables transport the AC(Alternating Current) current generated by the wind turbines. On early-stage wind farms, a simple and straightforward radial connection was built. Nowadays, with the increment in size and capacity, a failure in a cable can create high production losses. Therefore, back-up designs are being implemented [18]. Fig.2.4 shows some examples and the most common typologies are briefly described in the following:

- **Radial design:** The simplest one, turbines are interconnected to a single series circuit.

- **Ring design:** More reliable than the previous one, as there are cable loops between turbines that creating back-up circuit. Therefore, if one cable fails the other one is active and able to transport energy.

- **Star design:** Turbines are interconnected with several feeders, allowing the use of smaller cables. As a drawback, the switchgear used is much more complex [19].
2.4.3 Offshore substation

With the increment in size and distance to shore, the presence of electric substations is becoming necessary. They are expensive and laborious to transport and install, but the benefits of using them justifies their implementation. They are responsible for collecting, transforming, and, in some cases, converting the power produced in the wind turbine generators. They consist of a cubic-shaped building which contains all the electric devices necessary to treat the power produced. In addition to that, they can contain accommodation facilities for O&M activities [3].

2.4.4 Transmission system

The transmission system is basically the export cable connecting the OWF with the onshore substation. Depending on the distance, the technology used is HVAC or HVDC. However, due to less cable losses in bigger distances, HVDC technology is becoming more popular in the upcoming OWF. The installation technique is exactly the same for both cases, with cables being laid and buried into the sea bed. Both will be explained later in this paper.

2.5 Vessels

2.5.1 Introduction

Vessels are considered to be the most important elements for a smooth execution of the installation phase. At the early stage of the technology, the vessels used came from the O&G industry. However, contractors and shipyards quickly responded to the requirements, and purpose vessels were being
During the installation phase, around fifty-two different vessels are involved in the different tasks that need to be performed, and thirty vessels at a time can be found on site [21]. Installation vessels are extremely expensive to rent, having a big portion in the installation cost breakdown. Therefore, a more efficient use of them preventing weather downtimes will be the key to a successful installation process.

The most relevant installation vessels and their characteristics are described in the following sections.

2.5.2 Jack-up Vessels/Barges

They are responsible for the installation of wind turbines, foundations and transition pieces. They consist of a self-elevating floating hull with (4 to 6) legs. Their legs can be placed on the sea bed and raise the hull over the sea level, providing a solid and stable base for installation operations, which include heavy liftings of components [22]. According to Consult (2013)[20], the vessels used for offshore installation can be divided in three different categories, depending on the generation when they were built.

1. **Small Jack-up Barges:** They were built for O&G. They are not self-propelled and for instance they should be towed to site by other service vessels. Deck space, storage and accommodation capacity are relatively small.

2. **Large Jack-up Barges:** Essentially the same as their predecessors but with a substantial increment in deck space, storage and accommodation capacity.

3. **Jack-up Vessels:** They are ship-shaped and self-propelled. Purposely build to serve the offshore wind industry, they are capable to transport and install many components such as monopiles, jackets, transition pieces and turbines up to 5 or 6 MW. They are the most commonly used by the industry nowadays, and the availability and working conditions are continuously improving. In addition, they are
2.5. VESSELS

equipped with a DP system (Dynamic positioning). An example of this type of vessel can be seen in Fig. 2.5(a)

DP is a system that helps the vessel to automatically maintain its position during an operation by means of thruster force. This system is of extreme importance to perform the installation operations accurately. DP system contains subsystems of power supply, thruster and DP control. As weather conditions on the open sea can be really harsh, it is not rare that a failure occurs in the DP system, and in response to that, redundant systems are installed in the vessels. In consequence, the DP-Series notation has been created, depending on how many dynamic positioning systems a vessel has, it can be DPS0, DPS1, DPS2 or DPS3. Besides improving the performance of the vessel, some coastal states impose minimum DP Equipment Class requirements for activities carried out within their jurisdiction [23].

2.5.3 Heavy Lift Vessels

O&G industry already has an extended experience with this type of vessels and in handling heavy-lifts. Normally, these vessels are used to perform activities that others vessels can not because of their limitations. Leasing prices are significantly higher than those of jack-up vessels and therefore they are used for very specific tasks. Some examples are the installation of substations (which are heavier than 1000 tones normally), the installation of jacket foundations, or even installing full preassembled wind turbines (see Beatrice Wind Farm Demonstration Project, Scotland) [20]. An example of this vessel can be seen in Fig. 2.5(b)

2.5.4 Cable Laying Vessels

Their function is the installation of array and export cables. Their main features are available desk space, maneuverability, and cable carrying capacity. The cable is transported spooled in the central carrousel. The capacity of the carrousel is a key characteristic for export cables, as joints are a non-desirable condition because they increase the probability of failure [20] [24]. An example of this vessel can be seen in Fig. 2.5(c)
Figure 2.5: From top to bottom. (a) Jack-up vessel Aeolus (b) Heavy lift vessel, Rambiz (c) Cable laying vessel Nexus Sources: London Array, 2016 Van Oord, 2016
2.5.5 Support Vessels

They are present in every part of the installation phase and their function is to assist the main vessel's needs. Therefore, the level of involvement is determined by the features of the main installation vessels. \[5\]. The most important are briefly described here \[20\]:

- **Diving support Vessels** provide diving services as scour surveys, underwater inspections and maintenance, J&I tube installation etc.

- **Construction support vessels** are responsible to transport components to site.

- **Service Crew Boat/Vessel** are responsible to provide the crew a comfortable and safe transport to the work place. It is very important that the crew arrives in good physical conditions to be as efficient as possible during the work offshore.

- **Tugboats** are responsible to pull any kind of barge or platform that does not have a self-propelling system or needs help for anchoring operations.

- **Safety Vessels** perform emergency response duties such rescue personal, fire-extinguish or medical services in case of an accident.

- **Multi-Purpose Project Vessels** provided with a crane and a large open deck are normally used for anchor handling and light transport duties.

- **Accommodation Vessels** are providing comfortable accommodation to the crew when they work in long shifts. For the furthest wind farms, the transportation time is really long. Thus this provides a solution also when fast action has to be taken.

- **Multi-Purpose Vessels** are designed to perform any kind of operation.
2.6 Additional equipment

2.6.1 Introduction

Extra equipment is needed to perform most of the installation operations. This equipment has an extra weight, decreasing the cargo capacity of the vessel. In addition, their reliability and performance affects the development of the installation phase, as it is not rare that a failure occurs. Fig. 2.6 shows some examples of such equipment.

2.6.2 Cranes

Cranes are one of the main and most important components of jack-up vessels. Each vessel has onboard a variety of cranes to perform lifts and installation tasks. The main parameters that define the crane capacity are [25]:

- Boom length.
- Radius.
- Safe working load.

In most of the cases, vessels have one main crane responsible of lifting heavier components, but also a number of smaller or secondary cranes, responsible to perform some other necessary lifts on board of the vessel. Like the vessels, cranes are also evolving to fulfill the demands of the industry. Newly built cranes have a lifting capacity of more than 1200 tons. Subsequently, crane's parameters affect the installation strategy as well, as they determine the number of pre-assembled components that the crane is able to lift.

2.6.3 Hydro-Hammer

Most of the foundations require this tool to be installed. Hydraulic hammers introduce the piles into the seabed by striking them. This action is called piling. Hydro-hammers are purposely-designed for different scenarios, and a variety of them can be found on the market. Some of the cases are:

- Vertical pile driving.
2.6. ADDITIONAL EQUIPMENT

- Racket pile driving.
- XXL pile diameter.
- Under water piling [26].

2.6.4 Grout Mixer Spreader

The super strong cementitious materials used to connect the foundations with the transition pieces need to be mixed and prepared in special devices. Those can produce about 12 m$^3$ of material per hour but depending on the strength needed for the material this number varies [7].

2.6.5 ROV/Underwater plough

During the cable laying operations, either a ROV (Remotely Operated Vehicle) or an underwater plough are used to simultaneously lay and bury the cable. The advantage of ROVs over ploughs is that they can be monitored and controlled from the vessel [27].
2.7 Installation Strategies and Procedures

2.7.1 Introduction

In this section, the most common installation techniques and logistic concepts will be described and explained. Although the offshore industry is growing and evolving quickly, there is still no standardized method of installation. Each developer has different working strategies, depending on a variety of different factors e.g. type of foundations, wind turbine size, vessel's availability and characteristics, onshore facilities (marshalling harbor, storage area),

Figure 2.6: (a) Crane (b) Grout mixer (c) ROV (d) Hydro-hammer Sources: GeoSea, 2016 IHC, 2015 Gemini, 2016 Core, 2016
sea-bed conditions or distance to shore, different country's regulations, etc. [28]. Analyzing the procedures used so far, a trend can be observed and similarities are found. Therefore, these similarities can be used as a starting point to classify them.

In each installation process, five different operation modules can be found. Their activities involved, materials and resources used vary from one to another. Those activities are listed in the following:

- Foundation installation.
- Array cable installation.
- Export cable installation
- Substation installation.
- Wind turbine installation.

The logical sequence of activities is provided by the components installed. Therefore, wind turbines can be installed only after the monopiles are introduced into the sea bed. Nevertheless, some of the activities can be carried out in parallel as their execution does not influence others.

It is important to differentiate between logistic concepts and installation techniques in the installation process. A summary of the logistics for foundations and wind turbines installation can be seen at Fig. 2.7, a detailed explanation of the same is held in Sections 2.7.3.1 and 2.7.4.1.
For this review, a variety of the most relevant OWF projects have been identified and their logistic operations and installation techniques studied. To create this list, different parameters have been taken into consideration: Year of commissioning, distance to shore (km), type of foundation and wind turbine model. The list can be seen in the following Table:

Table 2.1: List of studied offshore wind farms

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>Year</th>
<th>Distance to shore (km)</th>
<th>Foundation type</th>
<th>Number of wind turbines &amp; model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amrumbank West</td>
<td>2015</td>
<td>45</td>
<td>Monopile</td>
<td>80x Siemens SWT-3.6-120</td>
</tr>
<tr>
<td>Anholt</td>
<td>2012</td>
<td>15</td>
<td>Monopile</td>
<td>111x Siemens SWT-3.6-120</td>
</tr>
<tr>
<td>Gemini</td>
<td>2016</td>
<td>85</td>
<td>Monopile</td>
<td>80x Siemens SWT-3.6-120</td>
</tr>
<tr>
<td>Gode Wind 1&amp;2</td>
<td>2016</td>
<td>40</td>
<td>Monopile</td>
<td>97x Siemens SWT-6.0-154</td>
</tr>
<tr>
<td>Greater Gabbard</td>
<td>2012</td>
<td>36</td>
<td>Monopile</td>
<td>140x Siemens SWT-3.6-107</td>
</tr>
<tr>
<td>Gwynt y Mor</td>
<td>2015</td>
<td>18</td>
<td>Monopile</td>
<td>160x Siemens SWT-3.6-107</td>
</tr>
<tr>
<td>London Array</td>
<td>2012</td>
<td>20</td>
<td>Monopile</td>
<td>175x Siemens SWT-3.6-120</td>
</tr>
<tr>
<td>Ormonde</td>
<td>2013</td>
<td>9.5</td>
<td>Jacket</td>
<td>30x REPower 5MW</td>
</tr>
<tr>
<td>Thornton Bank Ph 2&amp;3</td>
<td>2013</td>
<td>26</td>
<td>Jacket</td>
<td>80x Senvion 5MW, 48x Senvion 6.15MW</td>
</tr>
<tr>
<td>West of Duddon Sands</td>
<td>2013</td>
<td>15</td>
<td>Monopile</td>
<td>108x Siemens SWT-3.6-120</td>
</tr>
</tbody>
</table>
2.7.2 Foundation installation

2.7.2.1 Logistic concepts

In Section 2.2 various types of foundations have been described. In this section, only monopiles and jackets will be studied, as they are the most demanded. The three main logistic concepts (shown in Fig. 2.7) used for the installations of foundations are the following:

1. **Concept 1, Floating monopile:** This is the most efficient and inexpensive way of transporting monopiles. It consists in sealing the monopiles airtight with a hydraulic plug in both sides. Therefore, only the presence of a tug boat is required and the transportation costs are significantly reduced. The only drawback is that only one monopile per tug boat can be transported [29]. See Fig. 2.8 (a).

2. **Concept 2, Feeder barge:** An Installation vessel stays on site, and a floating barge towed by a tug boat transports the foundation components from the operation base/manufacturer's marshalling area to the installation vessel, this action is called *feeding*. This is a good and inexpensive solution if vessels do not have enough deck space to transport the foundations. This is a good option when foundations can be manufactured locally, therefore sailing distances reduce and consequently, risk involved in the transportation of such heavy components are diminished [28]. See Fig. 2.8 (b).

3. **Concept 3, Installation vessel:** A purpose-built vessel does the entire job, going back and forth from site to storage area at the operation base. The vessel loads and transports the components to site and then installs them. This is the simplest logistic concept, as only one vessel is required and therefore, coordination delays and other risks associated with floating barges are avoided [28]. See Fig. 2.8 (c).
2.7. INSTALLATION STRATEGIES AND PROCEDURES

2.7.2.2 Monopile installation

Monopiles are installed using three of the logistic concepts previously mentioned. When the monopile is on site, an upending operation is performed, meaning positioning the monopile in its vertical axis. The state of the art of monopile positioning is using an upending bucket and a pile gripper. The combination on these tools allows the vessel to hold the monopile in its position accurately, with a deviation angle of 2 degrees or less [30].

About 30%-50% of the monopile’s total length is driven inside the seabed. Then, depending on the sea bed stiffness, three installation techniques can be identified:
1. **Impact pile driving:** The monopile is introduced into the sea bed by striking it from the top with a hydro-hammer. Depending on the sea bed conditions and the size of the monopile, the driving time will vary. Some countries are imposing restrictions around this technique, as the noise emissions are harmful for the marine life. Generally, noise mitigations systems such as bubble curtains or iron casts are placed around the monopile, reducing the noise to the minimum allowed by each country’s regulation [31].

2. **Vibrating pile driving:** The monopile is introduced by vibrating it rapidly through the seabed. Some researches proved this technique to be both faster and quieter than conventional impact pile driving [32]. It is suitable for less rigid areas like sandy seabed.

3. **Drilling pile driving:** When the seabed is rocky, conventional techniques are not suitable to drive monopiles, in these cases, drilling into the rock is the only solution for installation [9] [33].

After the monopile is firmly introduced into the sea-bed, the TP is lifted, placed on top and then linked to the monopile. As previously mentioned, this connection can be done either by grouting it with a special cement, or by bolts.

Due to marine currents, an undesirable effect of erosion is produced on the seabed surrounding the monopile and therefore the stability of the whole structure can be compromised. To avoid this, a **scour protection** is settled around the monopile, placing rocks on the sea bed. This action can be done before or after the monopile is driven.

### 2.7.2.3 Jacket installation

As vessel’s deck space is not enough to allocate such structures. Transporting them is only possible with feeder barges. Normally, they are produced locally, thus storage facilities at the operation base are not needed. Feeder barges can travel back and forth from the manufacturer’s yard to site [34].

There are two procedures of installing jackets, depending on the time piles are driven into the sea-bed:
2.7. INSTALLATION STRATEGIES AND PROCEDURES

1. **Pre-piling:** Pin-piles are driven into the seabed before the jacket is placed. This operation should be really accurate to place each pin-pile in the exact position. Due to vessels wind-waves sensibility, an improvement in the accuracy is obtained by placing a frame on the seabed. Pin-piles are driven into each of the frame's corner, achieving a deviation of maximum 2 centimetres [35]. Then, the jacket is lifted, placed on the top of the piles and grouted to secure the joints.

2. **Post-piling:** There are sleeves in each corner of the jacket to drive the pin-piles through. Firstly, the substructure is placed on the seabed, then the pin-piles are driven carefully to avoid any possible damage [36].

2.7.3 Wind Turbine installation

2.7.3.1 Logistic concepts

As previously mentioned in Sections 2.2 and 2.5, installation techniques and procedures are determined by how many parts are previously assembled. The feeder barge logistic concept is not used by the industry to install turbines due to the risk associated to transporting WT components. Normally, floating barges are not self-elevated, and thus the movements induced by wind, waves and currents can create complications on the lifting operations. Therefore, a self-elevating vessel is needed to perform such operations [28]. The two logistic concepts used are:

1. **Concept 1, Load-in at operation base:** There is a storage area available at harbor. Often, there are cranes and tools to assemble some components, which will reduce the number of offshore lifts. As these operations are the most restrictive, weather downtime is substantially reduced. An example can be seen in Fig. 2.9 (a).

2. **Concept 2, Load-in at manufacturer's nearest harbor:** An Installation vessel loads the components at the manufacturer's nearest harbor, then carries them straight to site. Only the tower is assembled previously, allowing the vessel to carry more turbines at a time and thus, reducing the number of transits. This logistic concept is becoming more popular with new purpose-built vessels with higher transport capacity and transit speed. Some of the advantages of this concept are reducing the risk inherent in barge transportation, and saving money.
in harbor facilities lease (usually very expensive). An example can be seen in Fig. 2.9 (b)

Figure 2.9: Logistic concept 1(with bunny-ear configuration) (b) Logistic concept 2
Sources: GeoSea, 2016; Belwind, 2016

2.7.3.2 Pre-assembly at operation base: Pre-assembly strategies

As mentioned in Section 2.2 there are different spare parts that conform a wind turbine (tower in two pieces, three blades, hub and nacelle). The installation technique can be classified depending on the number of pre-assembled parts and the combination of them. At the same time, this technique is determined by the available vessels, the turbine size, and the crane's lifting capacity. According to Uraz (2011)[25], there are three main combinations of pre-assembled components for the subsequent transportation to site:

1. **All components separately:** only two sections of the tower can be assembled previously. Nacelle and blades are carried separately in a stacker in the same vessel.

2. **Bunny-Ear configuration:** two of the blades are assembled to the rotor and the rest of the parts carried in the same vessel. The tower can be either in one or two pieces.

3. **Star-rotor configuration:** the three blades are pre-assembled to the hub. Nacelle and tower are carried in the same vessel and usually the tower is pre-assembled as well.
Fig. 2.10 shows how the offshore lifts are reduced as spare parts are assembled previously.

![Image of installation method and number of offshore lifts](image-url)

**Figure 2.10: Installation method and number of offshore lifts involved**

Source: Mark J. Kaiser

In conclusion, there are different advantages and drawbacks in each of the mentioned installation strategies. On the one hand, onshore lifts and assembly are less dependent on weather conditions, thus delays are reduced. On the other hand, the desk space consumed by assembled parts is larger than separate. Therefore, more pre-assembled parts mean less number of turbines that the vessel is able to transport in one single trip. Additionally, bigger cranes are needed as the joint components are heavier than spare ones.
2.7.4 Cable installation

2.7.4.1 Subsea cable installation techniques

According to [37];[28], there are five main techniques to install subsea cables. Those techniques and the required execution time depend on different factors such as weather windows, cable size and weight (that will depend on the capacity and the distance between turbines and from site to shore), soil conditions (it will affect in how deep the cable can be buried), or the vessel's DP system. The most common techniques used are listed in the following:

1. **Simultaneous lay and bury using plow**: This is the most popular technique used by the industry, especially for export cables. The plow is pulled by the cable lying vessel. A water jet is used to create a trench of around two meters deep, by fluidizing the seabed with pressure water. Then, the cable is buried and the natural solidification of the soil will cover it.

2. **Simultaneous lay and bury using tracked ROV**: Same as the previous one but using a Remote Operational Vehicle instead of a plow. This technique is commonly used for array cables, as the amount of cable that the ROV's spool can carry is limited.

3. **Pre-excavate**: Excavating a trench using a backhoe dredger, and laying the cable in the trench to subsequently fill it up with the dredger.

4. **Lay and trench**: Laying the whole cable first with the cable-laying vessel, and then trench it using a ROV.

5. **Pull and trench**: Used only for array cables, this technique pulls cables among turbines using a winch and then buries them with a ROV.

2.7.4.2 Array cable

The connection of the cables with the wind turbines is done through a conduct welded to the foundations, called J-Tube. This process of feeding the cable is done with a winch, pulling the cable from the wind turbine side, and a ROV from the sea bed.
2.7. INSTALLATION STRATEGIES AND PROCEDURES

2.7.4.3 Export cable

There are two main procedures to install export cables differentiated by how the cable is brought to the connection point onshore:

1. **Directional horizontal drilling:** A drilling device is placed onshore and drills towards the ocean, then a plastic conduct is placed through the drill and the cable is pulled to shore by a winch from the cable laying vessel. A ROV is used to introduce the cable in the borehole.

2. **Beaching:** The action of a cable laying vessel or barge brought into the shore at high tide. When the tide is low, the vessel is aground into the beach and the cable pulled to shore with rollers and a winch. Then, when the tide is high again, the vessel/barge is refloated and ready to continue the cable laying activities.

2.7.5 Floating wind turbine installation

2.7.5.1 Introduction

The first full-scale floating wind turbine prototype was the Hywind, installed in 2009 in Norway. Since then, few other prototypes have been deployed. In this section only the deployment process will be described and discussed, as the installation of the wind turbine is either done onshore or following one of the already described techniques. Regarding the electric infrastructure, the only difference is that the cable is partially or totally floating instead of buried into the seabed, depending on the water depth.

So far, only few prototypes have been deployed, and thus the experience with this type of substructures is limited.

2.7.5.2 Spar buoy

The only functional full-scale wind turbine with spar buoy is the Hywind. The developer and contractor (StatOil) states that the steps done to deploy such a turbine were the following [38]:

- Construction of the substructure.
- Towing of substructure to suitable upending and assembly point.
2.7. INSTALLATION STRATEGIES AND PROCEDURES

- Upending of the substructure.
- Ballasting the substructure with rocks and water.
- Attaching tower and turbine with blades.
- Towing the upended structure to deployment site.
- Connecting the upended structure to pre-laid mooring and electrical cables.

Although the installation of this type of substructure is very straightforward, the developer identified two key challenges that will have to be faced to reach the commercial phase of this technology:

1. **Water depth:** The submerged part of the spar buy is considerably bigger than the semi-submersible platforms. Therefore, the actions of upending them and installing wind turbines require enough water depth at the commissioning site and along the towing route. There are three different key scenarios that would have to be studied. First, when the waters at port are shallow. Second, when waters at port are deep enough but there is a shallow water passage on the towing route. Third, and the most favorable one, when the whole towing route from port to site is deep enough.

2. **Waves and swells:** The assembly of Hywind required low wind speed and wave height, which is a threshold for the installation, as this is the case only during a short period of time each year [38].

In DNV's technical report [39] are proposed different innovative procedures for the correct deployment of spar-type floating substructures, depending on the water depth along the towing route. One of the techniques is to transport the wind turbine assembled to the buoy but with certain inclination. This can be achieved by decreasing the length of the buoyancy wire by a winch, which is sufficient to overcome the shallow passages that can be found on the route. Another one is using a jack-up vessel to transport the turbine to the shallow passage. Then, it jacks-up in the shallow waters and installs the turbine on the buoy. Once installed, the turbine is towed to deployment site.
2.7. INSTALLATION STRATEGIES AND PROCEDURES

2.7.5.3 Semisubmersible platform

The installation of this type of substructures is very straightforward. Fig. 2.10 shows some activities performed during the installation of this type substructures. The submerged parts are not penetrating deep into the water. The whole structure can be installed either onshore at harbor facilities, or near harbor using a heavy lift vessel. After being assembled, a tug boat brings it to site and then a mooring system of anchors and chains attaches the platform to the sea bed. The industry already has a lot of experience in deep sea mooring from O&G platforms. The advantages of this technology are many, one is the versatility of seabed conditions where it can be moored and thus, an exhaustive geological survey is not needed. Additionally, the increase in material cost with depth is minimum. [40]; [41]

There are already three prototypes running and with a good commercial perspective, all three of them have been installed following the previous techniques. They are listed in the following:

1. **WindFloat**: Off the coast of Portugal in the Atlantic Ocean. 2MW wind turbine placed in one side of the floater. Commissioned on harbor [41].

2. **Fukushima-FORWARD 1**: 2MW downwind turbine. It is placed on the central column of a compact semisubmersible foundation. It uses eight catenary mooring lines. Commissioned on harbor [40].

3. **Fukushima-FORWARD 2**: 7MW wind turbine with oil pressure drive-type floating. One of the innovations here is that the pontoons are connected directly to columns without the supporting braces. Commissioned near harbor by a heavy lift vessel [11].
2.8 Offshore Wind Farm Installation Modeling

2.8.1 Introduction

In previous sections, all the components and techniques used for the installation of OWF have been described. From this description, it can be understood that it is a complex process with many elements involved. Additionally, weather conditions at offshore sites are harsh and unpredictable, creating numerous delays within the project. Therefore, creating a model of the installation process can be extremely beneficial throughout the whole installation phase for a variety of stakeholders and decision makers.

The main purpose of the modelling is to calculate weather downtimes and other different delays and risks associated, helping project managers to create
a more accurate project plan. Additionally, more realistic cost and resources needed for the installation can be derived from this model. There are only few models in the market that are able to do so. The one used for this Thesis work is the one developed at ECN (Energy research Center of the Netherlands): ECN Install V 2.0.

2.8.2 Meteorological conditions and weather downtimes

As mentioned in Section 2.8.1, weather condition is one of the most influential factors in the installation process. Frequent high wind speeds and waves are present during the installation of the components, being a hindrance for the correct performance of the offshore operations. Weather restrictions vary for different types of operations, vessels and equipment used. For example, a sailing operation has less restrictions than an offshore lift. Additionally, within the same operation different restrictions are found, i.e. towers and nacelles have a maximum wind speed tolerance of 10 m/s and blades 7 m/s [42]. The main restrictive parameters for offshore operations are listed in the following:

- Wind speed
- Wave height
- Current speed

Other factors, such as fog, rain, ice, water depth or seabed conditions may affect the workability and the correct development of the installation as well. The interval of time with suitable weather conditions for installation operations is called “weather window”. Different operations require different windows lengths and restrictions to be executed in the highest safety conditions. Thereby, the ability to accurately predict when the weather windows will take place is crucial for a successful installation process.

2.8.3 ECN Install: Model description

A brief explanation of how the tool works is given here to allow the reader to be familiar with the processes involved in the modeling.
The model is divided in different steps that represent installation activities with different equipment or restrictions introduced as input. The site's historical weather data is used to create accessibility vectors that indicate the existence of weather windows. Weather windows are the intervals of time when the weather conditions do not hinder the activity to be performed. The length of the weather window is defined by the user and depends on how much time the activity needs to be performed. The meteorological parameters taken into consideration to calculate the accessibility vectors are wind speed ($W_S$) and significant wave height ($H_S$). Within the same activity, there are different restrictions for vessels, equipment, and the nature of the activity (Loading, Sailing or Installing). The accessibility vectors take into consideration the aggregate of the different weather restrictions within the same step. This aggregate can be seen in the following expression (2.1).

Where $V$, $E$ and $S$ represent Vessel, Equipment and Step respectively:

$$\{W_S, H_S\} = \{\min(V_{WS}, E_{WS}, S_{WS}), \min(V_{HS}, E_{HS}, S_{HS})\}$$  \hspace{1cm} (2.1)

Applying the previous formula to each step, the tool finds a weather window that respects all the individual restrictions. For each step, only one vessel and equipment should be used. The user introduces the desired starting time of the step and its duration. These two parameters are used to define the weather windows. The first one determines the starting point for which accessibility is considered, and the second one determines its duration. As it was aforementioned, risks, delays and uncertainties in offshore operations are numerous. For this reason, the tool allows the user to introduce the step weather duration, that can be bigger than the step duration to take into consideration any delays due to unexpected situations.

For each year of weather data that is introduced, the tool performs one simulation. If the whole installation process lasts for more than one year, it takes the following years to analyze the accessibility. If the number of climate data years is exceeded, the data is repeated from the first year chosen [5].
2.8.4 ECN Install: Tool description

ECN Install is a MATLAB based model that uses a number of relevant inputs for the installation process. As output, it calculates different parameters like timing, delays and costs. It consists of a number of modules that are described in the following sections.

2.8.4.1 Inputs and planning

In this module, the user can introduce the inputs that are relevant for the project planning. This planning consists of a number of sequences that are subdivided in steps, representing the activities to be performed. Besides general inputs, the user also defines the proposed installation plan. Some of the examples for inputs are wind turbines, climate data, operation base, components, vessels, permit constraints, etc. Additionally, relevant inputs regarding vessels and equipment should be introduced. Those inputs are weather restrictions (wind and waves), cost parameters and duration of those activities.

Once the inputs are introduced, the steps of the installation should be introduced under the label “planning”. The type of those steps can be loading, travelling and installation depending on the nature of the activity to be performed. The equipment and vessel used for each of the steps is introduced by the user. Fig. 2.12 and 2.13 show screenshots of the Planning and Inputs module respectively.

<table>
<thead>
<tr>
<th>Sequence Name</th>
<th>Type</th>
<th>Iterations</th>
<th>Line Start</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scour Protection</td>
<td>Sequence 15</td>
<td>01-06-2015</td>
<td>29 days</td>
<td></td>
</tr>
<tr>
<td>Foundations (Ship A)</td>
<td>Sequence 30</td>
<td>30-06-2015</td>
<td>74 days</td>
<td></td>
</tr>
<tr>
<td>Infield Cables</td>
<td>Sequence 1</td>
<td>01-07-2015</td>
<td>105 days</td>
<td></td>
</tr>
<tr>
<td>Export Cables</td>
<td>Sequence 1</td>
<td>01-03-2015</td>
<td>166 days</td>
<td></td>
</tr>
<tr>
<td>Foundations (Ship B)</td>
<td>Sequence 20</td>
<td>25-07-2015</td>
<td>50 days</td>
<td></td>
</tr>
<tr>
<td>Substations</td>
<td>Sequence 1</td>
<td>01-08-2015</td>
<td>11 days</td>
<td></td>
</tr>
<tr>
<td>Turbines (Ship A)</td>
<td>Sequence 25</td>
<td>01-02-2016</td>
<td>106 days</td>
<td></td>
</tr>
<tr>
<td>Turbines (Ship B)</td>
<td>Sequence 25</td>
<td>15-02-2016</td>
<td>106 days</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.12: Screenshot of the Planning module module Source: ECN Install User Manual
2.8.4.2 Pre-Processor

This module allows the user to assess his inputs for simulation before the weather data is processed for each activity. The user should introduce also the equipment needed i.e. vessels, hydro-hammer, etc. and the costs associated to them. The main functionality is to show the weather data, mean values per year/month and workability windows. Additionally, Gantt charts and CAPEX breakdown graphs can be created without taking delays into consideration.

2.8.4.3 Simulator

This module simulates the project based on the historical weather data introduced and selected by the user. It calculates if an activity can be performed, based on the operational conditions of the elements involved in the activity and the weather data selected. If the activity cannot be performed in the time introduced by the user, it finds the next suitable weather window and outputs the difference in time as a delay, including the associated cost.
Fig. 2.14, an example of the potential delays during the installation can be seen. The main function of the simulator is to calculate the amount of delays that an offshore operation potentially has. These delays are classified in the following:

- **Weather delay**: When an activity cannot be executed due to bad weather conditions.

- **Shift delay**: When an activity cannot be executed due to the shift of the workers.

- **Harbor delay**: It is an inherent delay that all harbors have due to harbor lock.

- **Resources delay**: When an activity cannot be performed due to lack or resources.

- **Permit delay**: When an activity cannot be performed due to lack or legal permits.

Figure 2.14: Screen-shot of the calculated delays module Source: ECN Install User Manual
2.8.4.4 Post-Processor

This module gives a summary of the selected outputs. An overview of the results can be exported to MS Excel. Additionally, Gantt charts with potential delays can be created in MS Project [27]. An example of this can be seen in Fig. 2.15

![Gantt chart](image)

Figure 2.15: Screen-shot of Variable Cost overview and Project Gantt chart with delays module Sources: ECN Install User Manual; Katsouris, 2015

In this Chapter 2, the components, installation techniques and installation modeling of offshore wind farms have been described. The next Chapter 3 unfolds the methodology used to improve the modelling tool ECN Install and the algorithm implemented.
Chapter 3

METHODOLOGY AND DATA

3.1 Introduction

The current version of the ECN Install tool has a fixed starting date for each sequence introduced by the user. However, in real installation operations the execution of some of the activities will directly depend on other activities. Weather downtimes are numerous and before simulating the activities with the corresponding weather data it is hard to give an estimation of the starting/ending time of any activity. Therefore, in order to improve the accuracy of the tool, a new algorithm backed up by a new method (Section 3.3) will be implemented in the tool. This new functionality allows the user to introduce interdependencies between activities. The changes made, upgrade the tool from Version 2.0 (V2.0) to Version 2.1 (V2.1).

In Fig. 3.1 the methodology used for this Thesis work can be seen. The orange arrows represent the flow of the original version, and the green arrows represent the flow of the upgraded version.
Section 3.2 gives a number of definitions necessary to comprehend the changes implemented in the tool. Section 3.3 defines the mathematical background developed to support the logic of the algorithm implemented in the tool. Section 3.4 presents the application of the method to the particular case of ECN Install. Finally, Section 3.5 shows the implementation of the logic using MATLAB, reinforcing it with an illustrative flowchart.

### 3.2 Definitions

#### 3.2.1 Gantt chart

The term Gantt chart is applied to any bar diagram used to illustrate the schedule of a project. The bars represent the dates when a specific action starts and finishes, as well as the duration. The elements of a Gantt chart establish the work structure of the project and how these activities are related to each other.
3.2.2 Interdependent activities within a Gantt chart

Interdependent activities in a Gantt chart have linked execution, so the starting or ending times of each activity linked in this way affects another. Therefore, four different interdependencies between two activities can be defined: (1) start-start, (2) start-finish, (3) finish-finish, (4) finish-start. For this Thesis work, only start-start and finish-start interdependency will be considered. All types of interdependencies are described in the following:

Considering two different activities A and B.

1. **Start-Start**: activity B can start when A has started.
2. **Start-Finish**: activity B can finish when activity A has started.
3. **Finish-Finish**: activity B can finish when A has finished.
4. **Finish-Start**: activity B can start when activity A has finished.

3.2.3 Compatibility of a Gantt chart with interdependent activities

This term refers to the logical relationship between a number of interdependent activities within the same Gantt chart. As an example for the reader to visualize an incompatible system, if there are two activities A and B. The user sets A to start when B finishes, but also B to start when A finishes. This relationship is incompatible or illogical because it creates an infinite loop in which none of the activities is able to start. The mathematical foundation to support this idea is presented in the next Section 3.3.

3.3 Algebraic method to determine the compatibility of a Gantt chart with interdependent activities

3.3.1 Activities

Let \( J = \{1, 2, ..., n\} \) be a set of activities. For the activity \( i \in J \), let \( t_{1,i} \) and \( t_{2,i} \) be the starting time and ending time of the activity \( i \) respectively. Each
of the activities has a duration $d_i > 0$. From the previous statements, the following can be deduced: $t_{2,i} = t_{1,i} + d_i$ and therefore $t_{2,i} > t_{1,i}$.

### 3.3.2 Single dependency between activities

It can be assumed that there are two kinds of relations between activities:

- Activity $i$ and $j$ start simultaneously, or equivalently $t_{1,i} = t_{1,j}$ and is represented by:

![Diagram of simultaneous start](image)

- Activity $i$ starts, when activity $j$ ends, or equivalently $t_{1,i} = t_{2,j}$ and is represented by:

![Diagram of start on end](image)

Therefore, associated to every set of relations among the activities, there is a system of equations of the type:

\[
\begin{align*}
    t_{1,i_1} &= t_{1,j_1} \cdots t_{1,i_N} = t_{1,j_N} \\
    t_{1,i_{N+1}} &= t_{2,j_{N+1}} \cdots t_{1,i_M} = t_{2,j_M} \\
    t_{1,i} &< t_{2,i}, \quad i = 1, \ldots, n
\end{align*}
\] (3.1)

For clarification to the reader, the previous equations can be defined as:

**Line 1:** Starting time $t_1$ of any activity $i_1$ is equal to Starting time $t_1$ of
any activity $j_N$.

**Line 2:** Starting time $t_1$ of any activity $i_{N+1}$ is equal to Ending time $t_2$ of any activity $j_M$.

**Line 3:** Starting time $t_1$ of any activity $i$ is smaller than ending time $t_2$ of the activity $i$.

From the statement in Eq. (3.1), it can be deduced the following:

$$\text{if } t_{1,i} = t_{2,j} \rightarrow t_{1,j} \neq t_{2,i} \quad (3.2)$$

When the starting time of the activity $i$ is equal to the ending time of the activity $j$, then the starting time of the activity $j$ cannot be equal to the ending time of the activity $i$.

Therefore, one can draw the Gantt chart if and only if the set of relations is compatible if and only if system (3.1), is compatible, i.e. it has a solution or the system (3.1) is satisfied. Equivalently, one cannot draw the Gantt chart if and only if the set of relations is non-compatible if and only if system (3.1) is non-compatible, i.e. it has not any solution or the system (3.1) is not satisfied.

### 3.3.3 Multiple dependency of one activity

It is possible to have more than one interdependency per activity. In that situation, three different cases or relationships can be found.
3.3. ALGEBRAIC METHOD TO DETERMINE THE COMPATIBILITY OF A GANTT CHART WITH INTERDEPENDENT ACTIVITIES

Case 1: More than two activities start simultaneously:

\[ t_{1,i} = t_{1,j} = t_{1,k} = t_{1,n} \quad (3.3) \]

In this case there would be \(2^n\) combinations giving the same result, with \(n\) representing the number of activities.

Case 2: One activity starts, when more than one activity end:

\[ t_{1,i} = t_{2,k} \text{ and } t_{1,i} = t_{2,j} \text{ with } t_{2,k} \neq t_{2,j} \quad (3.4) \]
3.3. ALGEBRAIC METHOD TO DETERMINE THE COMPATIBILITY OF A GANTT
CHART WITH INTERDEPENDENT ACTIVITIES

To solve this:

\[
\begin{cases}
\text{if } t_{2,k} > t_{2,j} \rightarrow t_{1,i} = t_{2,k} \\
\text{if } t_{2,k} < t_{2,j} \rightarrow t_{1,i} = t_{2,j}
\end{cases}
\]  
(3.5)

**Note:** Any activity \(i\) starts when other activities \(k\) and \(j\) end and their ending times are not equal (3.4). Therefore, there is a double interdependency of the type finish-finish-start. To solve this system, the expression (3.5) states that the starting time of \(i\) will be the biggest ending time among the other interdependent activities. Hence, all the requirements for the activity \(i\) to start are met.

**Case 3:** One activity starts, when another starts, and when another finishes:

\[ t_{1,i} = t_{1,j} \text{ and } t_{1,i} = t_{2,k} \text{ with } t_{1,j} \neq t_{2,k} \]  
(3.6)

To solve this:

\[
\begin{cases}
\text{if } t_{1,j} > t_{2,k} \rightarrow t_{1,i} = t_{1,j} \\
\text{if } t_{1,j} < t_{2,k} \rightarrow t_{1,i} = t_{2,k}
\end{cases}
\]  
(3.7)
Note: Any activity $i$ starts when other activities $j$ starts and $k$ finishes (3.6). Therefore, there is a double interdependency of the type start-finish-start. To solve this system, the expression (3.7) states that the starting time of $i$ will be the biggest starting or ending time among the other interdependent activities. Hence, all the requirements for the activity $i$ to start are met.

### 3.4 Application of the method in ECN Install

The activities to be performed in ECN Install are divided in sequences, which are subdivided in steps. Each step has different working restrictions and thus accessibility vector (Eq. (2.1)) depending on vessel, equipment and nature of the step. In Fig. 3.2, a generic sequence and its corresponding steps can be seen.

![Figure 3.2: Generic sequence and its steps](image)

To install a monopile, a number of different steps are performed. From the nature of the activities, it can be understood that each step already has an inherent interdependency with the previous step of the same sequence. Therefore, Step 2 can only start when Step 1 is finished. Thus, there is an interdependency of the type finish-start between Step 1 and Step 2 and so on.

The tool is configured to allow the user to introduce the desired starting time of the sequence. The starting time of the rest of the $n$ steps ($t_{1,n}$) within the sequence will be given by the following equation:

$$t_{1,n} = t_{2,(n-1)} = t_{1,(n-1)} + Duration_{(n-1)} + Delays_{(n-1)}$$

(3.8)
3.4. APPLICATION OF THE METHOD IN ECN INSTALL

Eq. (3.8) states that the starting time \( t_{1,n} \) of any step \( n \) within a sequence, is equal to the ending time \( t_{2,(n-1)} \) of the previous step \( (n - 1) \) of the sequence. The ending time \( t_{2,(n-1)} \) of the previous step of the sequence, is given by the starting time of that step \( t_{1,(n-1)} \) plus the duration of that step \( (\text{Duration}_{(n-1)}) \) plus the sum of all the delays the step has \( (\text{Delays}_{(n-1)}) \).

The uncertainties due to weather and other risks during marine operations, particularly when scheduling linked activities or operations where vessels have to be coordinated. Sometimes, delays due to weather downtimes can last for days or weeks.

As seen in Section 2.5.1, there are numerous vessels involved in the installation of an OWF. Many of these vessels work independently, but many others are performing activities together. Therefore, the performance of an activity from one vessel directly depends upon the activities of other vessel(s). Is in this collaborative work, where the implementation of the interdependencies make sense.

In Fig. 3.3 a general example of sequences shows when interdependencies are necessary. In this example, an array cable will be installed. As seen in Section 2.4.2, these cables are connecting wind turbines. The previous required operations to install the cable are the installation of two substructures. Therefore, two operations are required to install this cable. As previously seen, it is hard to estimate the starting/ending time of an activity without performing a proper simulation with weather data. Thus, implementing an interdependency of the type finish-start between the sequences “Install Monopile 2” and “Install Array cable” will set the starting time of “Install Array cable” as the ending time of “Install Monopile 2”.


Figure 3.3: Example of activities that require interdependency

The implementation of an algorithm that allows the project manager to determine the starting time of an activity depending on the starting/ending time of another different activity, is crucial to improve the model’s accuracy, planning optimization, utilization of resources and decreasing costs. The delays of any activity given by an interdependency with another different activity will be shown as a gap between two steps or an increment in the starting time of a sequence. This gap or increment is considered to be a planning delay.

In Fig. 3.4, the improvement in the estimation of the starting/ending time of any activity can be seen. Before the simulation, Sequence 2 would start when Sequence 1 finishes (15:00). Due to weather delays, the tool found out that Sequence 1 is likely to finish two hours later. Therefore, as Sequence 2 has an interdependency finish-start with Sequence 1, it is likely to start at 17:00, two hours later. This two-hour difference is the planning delay of Sequence 2 and the rest of the delays of that sequence are calculated starting from that point.
3.5 Implementing the method in ECN Install: MATLAB algorithm

Adapting the method to the specific case of ECN Install required changes in all the different modules that compose the tool.

Firstly, the Inputs & Planning module has been modified to allow the user to introduce the desired interdependencies and their type. This information is stored within the rest of the specifications of the step/sequence (Limitations, duration of the activity, required weather duration, resources used, etc.) and sent to the Pre-processor module.

Secondly, the Pre-processor module creates a structure that stores all the interdependencies defined in the previous module. An algorithm validates this structure based on the algebraic method defined in Section 3.3. If the
algorithm detects a non compatible system of interdependencies, the system displays an error and points out where the non-logical link is. When the validation is finished, the pre-processor module changes the starting times of the interdependent activities following the indications of the structure and creates an initial project Gantt chart. This Gantt chart illustrates the times the activities are supposed to start and finish without taking into consideration potential delays. The structure of the planning is sent to the Simulator.

Thirdly, a filter algorithm has been implemented in the Simulator to ensure the optimum performance of the tool. In the previous version, the Simulator would simulate linearly all the steps starting from step 1 of Sequence 1 and ending in the last step of last sequence. This way of operating makes it impossible to implement any interdependencies or execution of parallel sequences. The complete flowchart of the new simulator module can be found in APPENDIX A.

The preference of evaluation in the simulator module is listed in the following:

1. First step of the sequence, no interdependency.

2. First step of the sequence, interdependency, interdependent step simulated.

3. $n$ step within the sequence, no interdependency, previous step $(n-1)$ simulated.

4. $n$ step within the sequence, interdependency, both previous and interdependent step simulated.

Finally, when all steps have been simulated, the post processor draws the project Gantt chart and creates an excel sheet with project planning, costs and resources breakdown. The new Gantt chart includes the realistic starting and ending times of the activities, and the amount of delays of each sequence/step.

Fig. 3.5 shows the working flow of the upgraded version, the simulator workflow has been added in APPENDIX A. However, in the picture below is represented as an empty oval.
Figure 3.5: Flowchart of the working flow of ECN Install V2.1
This Chapter 3 has described the methodology used to improve the modelling tool ECN Install. Next, Chapter 4 will describe the application of the upgraded tool to the case study of a German offshore wind farm and the results are presented.
Chapter 4

APPLICATION OF THE METHODOLOGY AND RESULTS

4.1 Introduction

For the evaluation of the interdependency module and the overall improvement of the ECN Install tool, a case study is modeled. This case study represents the installation of five jacket foundations for Wikinger offshore wind farm, in the German Baltic Sea. A comparison between the previous and the new model's output is performed to evaluate the improvements done.

The following sections include a detailed description of the case study and the data used to recreate the conditions of the installation. Additionally, the interdependencies introduced and the logic of those interdependencies are presented and described. Finally, the output results for this case study are presented.
4.2 Case study: Wikinger offshore wind farm

4.2.1 Description

Wikinger offshore wind farm is a challenging project developed by Scottish Power. This 350 MW (70 turbines) project covers an area of approximately 34 km$^2$ in the German Baltic sea. The site is located approximately 75 km off the German coast, near the island of Rügen (Fig. 4.1). Due to the deep water (37-43m), Jacket foundations have been chosen for the project. Foundations are manufactured in Spain and Denmark and sent to operation base in Sassnitz. Dutch offshore company Boskalis is responsible to install the foundations [43]. By the time this Thesis was written, the pin-piles were already placed into the seabed, and the installation of the jackets just started [44].

![Figure 4.1: Wikinger Location Adapted from Scottish Power](image-url)
4.2.2 Climate data and site workability

As mentioned in Section 2.8.4.1, simulations are performed using historical weather data. The data used for this work has been recorded by the research platform FINO 2. This platform is installed in the Baltic Sea, located 33 km north of Rügen island with coordinates 55 00’ 24,94” N / 13 09’ 15,08” E. [45].

This weather data consists of three years (2010, 2011, 2012) wind speed and significant wave height measurements with resolution (measurement frequency) of one hour. A representation of the monthly average wind speed and wave height of the data used can be seen in Fig. 4.2

![Monthly average wind speed and wave height data at FINO2. Years 2010, 2011 and 2012](image)

Figure 4.2: Monthly average wind speed and wave height data at FINO2. Years 2010, 2011 and 2012

Additionally, ECN Install calculates the workability (amount of time that vessels are able to work) and weather windows for a given threshold. In this case study thresholds are set as 9 m/s for wind speed and 1 m. for significant wave height. As it can be seen in Fig. 4.3 spring and summer months have about twice the workability time than autumn and winter when the oceanic conditions are harsher.
4.2.3 Operation base

Mukran harbor is used to store and load the jacket foundations. This harbor is located in the coastal area of Sassnitz, in the Federal State of Mecklenburg-Vorpommern, Germany. The distance between harbor and site is about 75
km. Fig. 4.4 is a satellite image of the harbor, with a representation of the jackets waiting to be loaded and the vessels used in the construction (in blue). The delay due to harbor lock is set as 1 hr. Weather conditions at harbor would be slightly different than wind farm site. However, the same climatology has been introduced due to lack of reliable harbor weather data.

Figure 4.4: Mukran satellite picture with vessels and jacket representation. Adapted from Marine Traffic (Traffic, 2016)

4.2.4 Vessels

As mentioned in Section 2.5, several vessels are involved in the installation process of an OWF. However, For this verification study, only three of the vessels described in Section 2.5 have been used:

- Giant 7 semi-submersible barge (Fig.4.5(c)) is responsible for transporting the jackets from harbor to site. It has a length of 137 m, breadth of 36 m and uses six anchors [46].
4.2. CASE STUDY: WIKINGER OFFSHORE WIND FARM

• **President Hubert tug boat** (Fig.4.5(b)) has the function of tugging Giant 7. It can reach a maximum speed of 16 kn. However, for this model an average speed of 6 knot is considered.

• **Taklift 4 heavy lift vessel** (Fig.4.5(a)) is used for loading and installing the jackets. It has a maximum lifting capacity of 2200 tonnes [47]. It requires a tug boat for anchor and positioning using four anchors, however the tug boat is not considered in this case study.

• **ABIS Duisburg** is used to transport the grout spreader for grouting the jacket to its pin-piles. It is a general cargo vessel equipped with DP2.

![Figure 4.5: (a) Taklift 4 (b) President Hubert (c) Giant 7 Source: MarineTraffic.com](image-url)
4.2.5 Planning steps and interdependencies

This case study uses a variant of the *feeder barge* concept described in the literature (Section 2.7.2.1). As there is no crane at harbor with enough lifting capacity to load the jackets, Taklift 4 performs that activity. Therefore, Taklift 4 and Giant 7 go back and forth from harbor to site loading, transporting and installing the jackets. This model consist of three sequences with each sequence comprising a number of steps, as shown in Fig. 4.6 and summarized in Appendix B. Each of the sequences are performed by one main vessel, and the interdependencies are introduced in the activities where more than one vessel is involved and hence, vessel coordination is needed.

The sequences and interdependencies are described in the following:

1. **Transport Jacket:** This consists of four steps representing each of the activities to be performed. Firstly, when the jacket is loaded, Giant 7 transports it to Wikinger site (3 hours). When Giant 7 arrives at site, it has to be positioned and anchored near the jacket location, an average time of 45 minutes per anchor is taken for this operation (total of 4.5 hours). When the jacket is placed, it sails back to harbor. Lastly, once the barge arrives at harbor it has to be positioned to be loaded again (1 hour). Starting date is 01-07-2016 and this sequence is iterated 5 times in order to transport 5 jackets.

2. **Install Jacket:** This consists of six steps. Firstly, considering that Giant 7 is already at harbor and positioned, it loads the jacket in the barge (3 hours). Secondly, it sails to site with Giant 7 (3 hours). Once in site, Taklift 4 has to be positioned and anchored. It requires the assistance of a tug boat however is not considered here. The average time for each anchor is considered to be 45 minutes. Once both vessel and barge are anchored and positioned, it proceeds to install the jacket, which refers to lift the jacket and insert it into the pin-piles (3 hours). Lastly, once the vessel arrives at harbor it has to be positioned to load again. This sequence is iterated 5 times in order to install 5 jackets. The starting date is coming from an interdependency.

3. **Grout Jacket:** It consists of 5 steps. Once the jacket is placed, ABIS Duisburg proceeds to grout each of the pin-piles separately (1.2 hour
per pile). When all the grouting is finished, it sails to next location. The starting date is coming from an interdependency.

- **Interdependencies and working flow:** The interdependencies between steps within the three sequences can be seen in Fig. 4.6. The logical execution of the steps in this particular case study reinforce the inherent necessity for interdependencies. Thereby, the activities start by loading the jacket into the barge in the activity “Load Jacket at Harbor”. Subsequently, both vessel and barge will sail to site and perform anchor and positioning operations. When both vessel and barge are fixed (red arrow), then the activity “Install Jacket” can be performed. Additionally, both vessel and barge can sail either to next location or back to harbor only when the step “Install Jacket” is finished (purple arrow). ABIS Duisburg can proceed with the grouting only when “Install Jacket” is finish (orange arrow). Therefore, interdependencies of the type finish-start are established.
4.2. CASE STUDY: WIKINGER OFFSHORE WIND FARM

Figure 4.6: Case study sequences and interdependencies
4.3 Assumptions

The ECN Install tool is setup to recreate as realistically as possible the real marine operations for Wikinger installation. However, due to lack of information some assumptions have to be made. Despite this, the added value of the tool is shown comparing the same case scenario's output between the old and new version of the tool. Therefore, this lack of information will not affect the results and conclusions. The modeling assumptions are summarized in the following:

- The same climate data (FINO2) is used for both site and harbor operations. However, it is known that weather conditions at harbor are milder than offshore. Therefore, in order to avoid excessive delays, lower weather restrictions are applied for harbor operations, i.e. the step “Load Jacket at harbor”.

- Distances between deployment locations are considered to be the same. However, in real life they differ.

- Traveling time is considered to be cruising speed of the vessel and tug boat. However, for heavy loads (such as jackets) the speed can be lower.

- Costs are omitted for this case study due to lack of reliable information. Nevertheless, this information is not relevant to show the improvements made to the tool.

4.4 Results

As it was mentioned before, there are several outputs given by the tool: costs, resource usage and project planning. For this Thesis only the project planning is considered as it is the most relevant to show the improvement of the model.

Fig. 4.7 is a summary of the results that ECN Install gives as an output. This Excel sheet contains a detailed description of the project steps, i.e. step start, step finish, amount of delays etc. Both of the tables are the same, but the one above shows the results without interdependencies and the one below the results with interdependencies. The full table can
be found in Appendices C and D. However, it is interesting to see the fact that the project duration and delays increase significantly. Comparing both cases, the duration of the overall project increases by 3 days, 3 hours and 36 minutes. Additionally, total delays increase in 1.46 days, from 6.95 to 8.41. Extrapolating this increment to the installation of the 70 Jackets, the project duration increases in 42 days, 2 hours and 40 minutes. Additionally, the delays increases in 20.44 days. Considering that jack-up vessel’s leasing costs are around 200,000 Euro/day, it is a substantial increment.

<table>
<thead>
<tr>
<th>Summary of delays &amp; costs</th>
<th>Key simulation results (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed wind farm capacity</td>
<td>350.0 MW</td>
</tr>
<tr>
<td>Number of wind turbines in farm</td>
<td>70</td>
</tr>
<tr>
<td>Simulation</td>
<td></td>
</tr>
<tr>
<td>Simulation period</td>
<td>3 yr</td>
</tr>
</tbody>
</table>

**Figure 4.7:** Excel Simulation results Top: ECN Install V2.0 Bottom: ECN Install V2.1

ECN Install creates a detailed Gantt chart of the project planning including the calculated delays in the simulator (described in section 2.8.4.3).

Fig. 4.8 shows the difference between the Gantt charts with and without interdependencies. In order to simplify it for the reader, only one section of the Gantt chart is shown. This section corresponds to the transport, installation and grouting of one jacket. The complete Gantt chart can be found in Appendix E.
Figure 4.8: Gantt chart for the installation of one jacket. Above: without interdependencies; Below: with interdependencies
4.4. RESULTS

It can be seen how in the bottom Gantt chart (with interdependencies), some of the activities perform for one vessel are starting when other activities carried out by the other vessel has finished. Therefore, the bottom chart represents a coordinated activity performed by two vessels while in the top chart coordination is inexistent.

In this Chapter 4 the application of the upgraded tool to a real case in Germany has been presented. The next Chapter 5 discuss the results and the improvement comparing it with the results from the previous version.
Chapter 5

DISCUSSION AND ANALYSIS

Different simulations of the case study are performed to accomplish a comparative analysis of the outputs and determine the added value to the tool. On the one hand, the first simulation is performed without setting any type of interdependency between the activities. On the other hand, the second simulation contains the interdependencies declared in Section 4.2.5.

The Gantt chart in Fig. 4.8 (Above), shows the project planning without interdependencies. An option to introduce the starting hour of a sequence is missing in the previous version of the tool. Hence, by default any sequence starts at 00:00 hours. This is the first drawback of the old tool in simulating operations depending upon each other, as some of the activities have to be completed in order to perform others. i.e. “Sail to Wikinger site (Giant7)” is only possible after the jacket is loaded (“Load Jacket at harbor (Taklift 4)”).

Moreover, delay calculation is over estimated. As an example of this inconsistency, weather delay in step “Sail to Wikinger site (Giant7)” starts from July 1st 00:00, while it should start from July 1st 13:00. Therefore, thirteen extra hours are added to the total weather delay, cumulating a total of 26 hours delay.

Regarding coordination between vessels, in Fig. 4.8 (Above) it can be seen
that ABIS Duisburg starts the grouting activities before the Jacket is placed into its pin-piles. More particularly, “Grout Pin-pile 1” starts at July 2\textsuperscript{nd} 18:00 and “Install Jacket (Taklift 4)” ends at July 2\textsuperscript{nd} 21:00. Therefore, this is again a planning inconsistency.

Fig. 4.8 (Below) shows the improved project Gantt chart. The order in the step execution and additional comments are described in the following:

- Firstly, Taklift 4 loads a jacket at harbor. This activity is scheduled to start at at July 1\textsuperscript{st} 00:00 however, due to harsh weather conditions it has a weather delay of ten hours. Therefore, starting time is delayed till July 1\textsuperscript{st} 10:00.

- Secondly, only when jacket is loaded both Taklift 4 and Giant7 are able to start sailing to Wikinger site. This interdependency is reflected in the arrow connecting the steps “Load Jacket at harbor (Taklift 4)” and “Sail to Wikinger site (Giant7)”. These operations have also weather delays due to poor weather conditions. However, the weather delay for the step “Sail to Wikinger site (Giant7)” starts counting from the ending time of “Load Jacket at harbor (Taklift 4)”. Therefore, this delay is only 13 hours (against 26 hours of the previous version).

- Thirdly, once Taklift 4 and Giant7 arrive at site, the anchoring and positioning operations start. Giant7 uses six anchors while Taklift 4 uses only four, hence Taklift 4 anchors faster than Giant7. Only when both vessel and feeder barge are anchored in their position, the installation operation is able to start. Thus, Taklift 4 should wait until Giant 7 is positioned, this is reflected in the gap between the activities “Anchor and Position 4 anchors (Taklift 4)” and “Install Jacket (Taklift 4)”. In addition, the arrow connecting the steps “Anchor and Position 6 anchors (Giant7)” and “Install Jacket (Taklift 4)” denotes that the starting time of install jacket comes from the ending time of Giant 7 positioning.

- Lastly, once the installation operation is finished both vessel and barge are able to sail back to harbor to load another jacket. In addition, the grouting operations performed by ABIS Duisburg are able to start. These two interdependencies are reflected in the arrows connecting “Install Jacket (Taklift 4)” and “Sail back to harbor (Giant7)” and “Grout Pin-pile 1” respectively.
In conclusion, the case study described above shows how the upgraded version of the tool creates a more integrated approach of the project planning, taking into consideration how different factors are interconnected and hence affect each other. Additionally, the changes made may affect not only the planning but also project budgeting.
Chapter 6

CONCLUSIONS

For this Thesis work, the modelling of marine operations for the installation of offshore wind farms using the tool ECN Install is improved. An intensive literature study was conducted to obtain a deep insight in the most common installation techniques and procedures, as well as all the elements involved in an OWF installation. A study of the current tool developed at ECN have been done to be able to identify the weak points where the tool can be improved and apply the necessary changes in the existing code. The option to simulate parallel activities that affect each other was missing. Therefore, simulating coordinated operations between vessels was not possible. A methodology has been developed to introduce the improvements needed, reinforcing them with a mathematical foundation.

The new upgraded version allows the tool to simulate the execution of linked activities in parallel, bringing the model and the outputs closer to reality and thus diminishing uncertainties and risks associated. The interdependency functionality consists of different algorithms implemented each of the tool's modules. As a general description, the whole algorithm reads the interdependencies, validates their compatibility, and simulates in each installation step taking into consideration these dependencies. A regression test was run using test cases in both the old tool and the new tool without interdependencies turned on, to ensure that no errors had been introduced. The results are identical, meaning the algorithm implemented didn’t decrease the performance of the tool.
A case study is modelled to show the added value in comparison with the previous tool. This case study is the installation of five jacket foundations for Wikinger OFW. Interdependencies are added in the operations that require vessels coordination.

Results show that the estimation of the project duration and the accuracy in scheduling the activities including potential delays are significantly improved. Additionally, the tool is now able to simulate vessels coordinated operations which is a key point for a proper development of the installation phase.

Suggestions for future work

During the study of the tool’s functionality, a number of actions for improvement have been identified

- Additional changes should be implemented in the user interface to allow the introduction of the interdependencies. In this version the interdependencies are hard-coded.
- An option to see the actual park layout and hence the turbine location, taking into consideration distance differences should be implemented.
- It would be useful to conduct a comparative analysis with real cases to quantify the accuracy of the tool in weather downtime prediction.
Appendices
Appendix A

Simulator module flowchart
Appendix B

Summary of the project sequences, steps and duration

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Step</th>
<th>Duration (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport Jacket (Giant 7)</td>
<td>Sail to Wikinger Site</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Anchor and Position 6 anchors</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>Sail back to Harbor</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Positioning at Harbor</td>
<td>1</td>
</tr>
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Excel results: Jackets for Wikinger without interdependencies
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Appendix D

Excel results: Jackets for Wikinger with interdependencies
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Appendix E

Comparison between gantt charts without interdependencies (Above) and with interdependencies (Below)
Bibliography


