Improving Decision-Making to Reduce Downtime Caused by Equipment Breakdown during Offshore Wind Installation Projects

Thesis report

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MSc Transport, Infrastructure and Logistics

Improving Decision-Making to Reduce Downtime Caused by Equipment Breakdown during Offshore Wind Installation Projects

by

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to obtain the degree of Master of Science in Transport, Infrastructure and Logistics
at the Delft University of Technology,
to be defended publicly on Thursday December 21, 2023.

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Report number:	2023.TIL.8882	
Project duration:	November 14, 2022 – December 21, 2023	
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TU Delft

ENGINEERING SOLUTIONS

Preface

This thesis is written as part of my master's program Transport, Infrastructure and Logistics (TIL) at Delft University of Technology. I performed this research project at Heerema Engineering Solutions (HES). The objective of my research is to show how downtime due to equipment breakdown can be reduced in offshore wind installation projects by prioritizing preventive maintenance on the critical path.

Before starting my thesis, I expected that I would apply the things that I learned during my studies. However, I learned many new things as well. My own background in TIL is completely different than offshore studies. The different backgrounds were an added value to the project, but sometimes it was also challenging to keep in mind that what seems natural to me, might not be so easy to understand for someone else, and the other way around. I learned how to deal with sensitive data, which made reporting about my findings quite challenging, also for my supervisors to verify my results. I learned new ways to analyse data, not only statistically, but also using plotly for making figures. I learned how to work with Metis, and I even managed to develop my own model, which worked together with Metis in the way that I envisioned. Lastly, I learned that entering a new industry requires flexibility and an open mind.

This research would not have been possible without my committee. I would like to thank my chair prof. dr. Rudy Negenborn for his helpful comments during my thesis. Many thanks to my supervisors from the TU Delft dr. ir. Xiaoli Jiang and dr. Jaap Vleugel for their help and guidance during my thesis, I learned a lot from our discussions. Many thanks to my supervisors from HES ir. Christof Westland and ir. Karin Leijs as well. Thank you for giving me insight in the offshore wind industry, teaching me about data-analysis and helping me with understanding Metis.

Special thanks to Joris van Drunen from Heerema Marine Contractors (HMC) for helping me with handling sensitive data and all the checks of my report and presentations. I would like to thank HES for giving me the opportunity to do my thesis project at their company. I would also like to thank everyone from HES and HMC who helped me during my thesis by giving input during interviews, meetings and presentations. It was a pleasure working at HES; I felt part of the team and I really appreciated the lunches together.

Lastly, I want to thank my family for their endless support. Sûnder jimme hie ik it nea oprêdden; tige tank!

Machteld Rouwé
Delft, december 2023

Summary

Define

Equipment breakdown can disrupt the installation schedule and might delay the delivery of the offshore wind installation project. Weather conditions are mentioned in literature as the main cause of downtime in an offshore wind installation project. Furthermore, various simulation methods are mentioned in the literature to mitigate downtime due to weather conditions, such as Discrete-Event Simulation (DES), Mixed Integer Linear Programming (MILP), robust optimization and stochastic modelling. Equipment breakdown is also mentioned in literature as a cause for downtime in offshore wind installation projects, but no methods are proposed to reduce downtime due to equipment breakdown in offshore wind installation. The magnitude and root-causes of downtime due to equipment breakdown are identified as a knowledge gap in the literature. The scope of this research is installation equipment that is used on board of the installation vessel, for example, the hammer. In this research, the following research question is answered:

'How can downtime due to equipment breakdown be reduced during the installation process of an offshore wind project?'

The objective of this research is to give insight into how decision-making regarding preventive maintenance and equipment breakdown affects the installation schedule of an offshore wind installation project. Quantifying the effects of decisions enhances informed decision-making, which can reduce downtime due to equipment breakdown in offshore wind installation projects.

In other industries downtime due to equipment breakdown is reduced by process improvement methods, maintenance strategies and Artificial Intelligence (AI). In this research, the Define - Measure - Analyse - Design- Verify (DMADV) method for process improvement is applied to examine equipment breakdown in offshore wind installation projects. First, the problem is defined and a theoretical framework is composed. Next, the magnitude of downtime due to equipment breakdown is measured using observed failure data. Then, root-causes of equipment breakdown and downtime due to equipment breakdown in offshore wind installation are identified. After that, designs are proposed to reduce downtime due to equipment breakdown. Lastly, the designs are verified in a model to quantify the effects of implementing the designs on key performance indicators (KPI's).

Measure

A case-study is conducted to examine the magnitude of downtime due to equipment breakdown in one offshore wind installation project. The results of the case-study indicate that downtime due to equipment breakdown is the largest cause of downtime during the spring and summer seasons, which are the seasons with favourable weather conditions for installation operations. Pinpile installation is more sensitive to equipment breakdown than jacket installation, because pinpile installation requires more types of equipment. From the case-study it is also concluded that wear and tear of the equipment, design flaws and offshore conditions are frequent causes for equipment breakdown. Furthermore, repaired equipment remains vulnerable, which might cause recurrent breakdowns.

Analyse

Interviews are conducted with experts in the industry to identify root-causes for downtime due to equipment breakdown. Downtime on the critical path is caused by the repair and replacement of equipment. Wear and tear of the equipment and offshore conditions are identified as reasons for equipment breakdown, which is in line with the conclusion from the case-study. Another root-cause for breakdown is the limited time that is available for preventive maintenance of the equipment outside the critical path. This is especially a problem during spring and summer seasons, because then weather conditions are favourable for installation. During autumn and winter seasons, preventive maintenance can be carried out while waiting on weather windows. Additionally, it is mentioned that planned preventive maintenance is sometimes postponed when weather conditions are favourable for installation operations. Decision-making on site is another root-cause for downtime due to equipment breakdown. Decisions are made based on experiences in oil and gas projects, whereas offshore wind installation requires a different approach due to the repetitive cycles. Decision-making is also compromised by biased data collection and a conflict of interest between stakeholders.

An overview of the problem is presented in Figure 1 in a problem hierarchy analysis. This shows that equipment breakdown is caused by maintenance strategy, which can be traced back to the narrower problem of decision-making based on experiences under different circumstances. The effect of equipment breakdown is downtime on the critical path, which leads to increased costs when the project delivery is delayed.

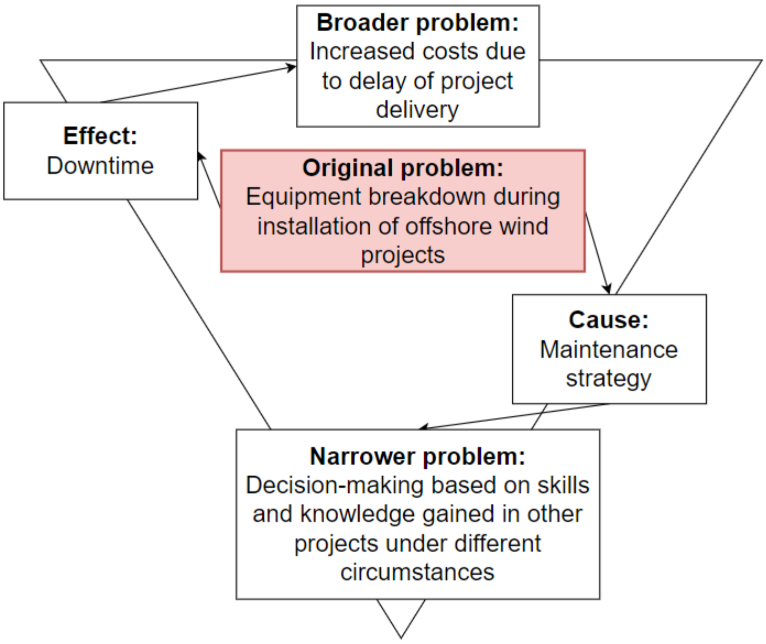

Figure 1: Problem hierarchy analysis

Design

Four designs are proposed to reduce downtime due to equipment breakdown by prioritizing preventive maintenance on the critical path over other operations. The scope of the designs is breakdown and preventive maintenance of the hammer, because the hammer caused the most downtime in the case-study. By evaluating the effect of the designs on selected KPI's, insight can be gained into the consequences of the decision-making. The designs are presented in Figure 2.

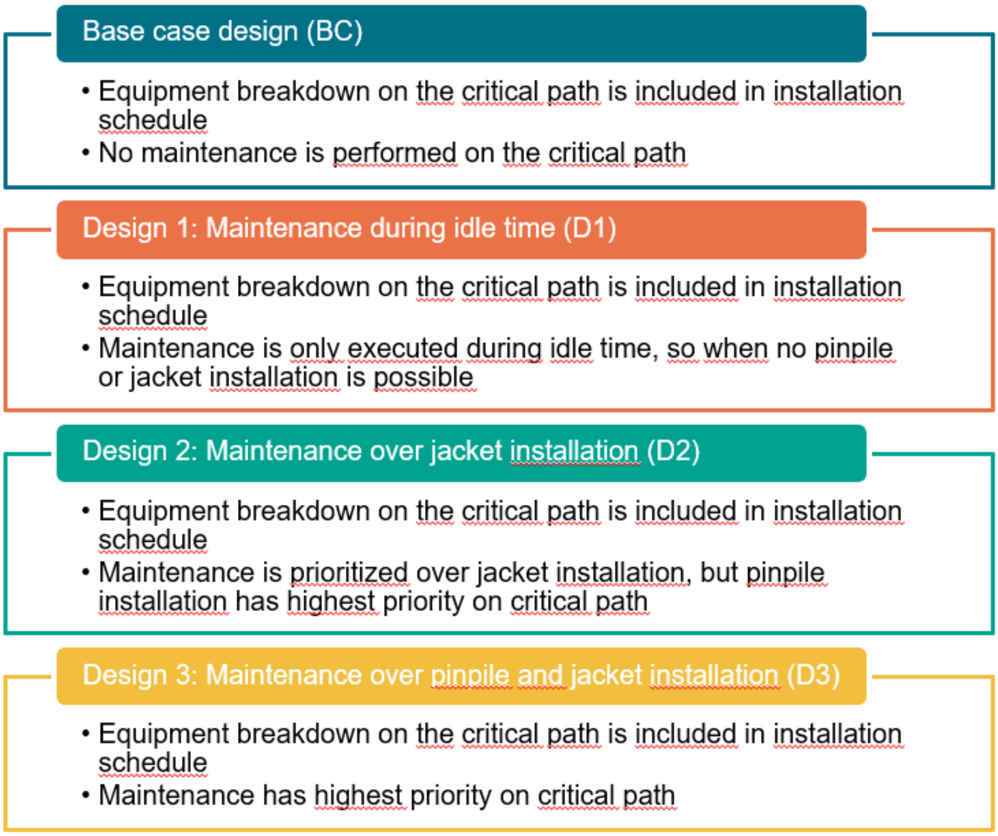

Figure 2: Description of designs.

The following KPI's are selected to evaluate the designs:

- Downtime due to breakdown (hours)
- Downtime due to preventive maintenance (hours)
- Idle time (hours)
- Waiting on weather time (hours)
- Critical breakdowns (#)
- Mean Time between Failures (MTBF)
- Mean Time to Repair (MTTR)
- Time spent by installation vessel on project (hours)
- Project duration (hours)

DES software Metis, developed by Heerema Engineering Solutions (HES), is used to simulate the designs. Metis is used to generate installation schedules for offshore wind installation projects. Metis determines which actions need to be performed by each of the vessels to complete the installation of the offshore wind project. By including high-quality historical weather in Metis, Monte-Carlo simulations can be performed that include waiting on weather time. To enable evaluation of equipment breakdown and preventive maintenance, an additional model is developed in this study. This model keeps track of the total drive time of the hammer during the simulation. This model determines for each cycle where the hammer is used if the hammer will break down. A probability of failure is calculated in the model based on a time-to-failure function, which is derived from observed failure data. If the probability exceeds a random number between 0 and 1, the hammer breaks down. When a maintenance condition is reached, preventive maintenance to the hammer can be performed on the critical path.

Verify

From the verification of the designs it is concluded that when preventive maintenance is prioritized on the critical path, equipment breakdown reduces. Furthermore, the downtime due to equipment breakdown is reduced. The MTBF also increases, which is an indicator of the reliability of the equipment. Nonetheless, prioritizing preventive maintenance on the critical path does not affect the total project duration, idle time and waiting on weather time.

Some assumptions had to be made in the model, because not all required data was available. Furthermore, it is likely that some of the applied distributions change as more data becomes available. Sensitivity analyses are conducted to assess the impact of different input parameters. The results of these experiments indicate that the downtime due to breakdown, downtime due to preventive maintenance, number of breakdowns and MTBF are sensitive to changing input parameters. This urges the need for high-quality input data.

Conclusion

In this research a new method is presented that combines the effect of weather conditions and equipment characteristics in a DES model used for examining offshore wind installation schedules. This research shows that downtime due to equipment breakdown can be reduced by improving decision-making. The consequences of decisions are illustrated by quantifying the effects of the decision on the KPI's by using the model. The condition of the hammer does improve by prioritizing preventive maintenance on the critical path, even though the total project duration is not affected. Modelling decision alternatives can help established stakeholders to convert their knowledge and skills from other offshore branches into a competitive advantage in the rapidly developing offshore wind market.

Discussion

The current model can be improved for future applications. In this research only the effect of preventive maintenance to the hammer is included in the model. Other types of equipment can be added in the future. The model needs to be adjusted to the characteristics of a specific project for future application. The model is a simplified representation of breakdown and preventive maintenance of the hammer, as only one hammer is modelled. In practice, often a spare hammer is available to replace the hammer in case of a breakdown. However, to include that in the model separate data on replacement and repair are required. Another difference between the model and practice is that preventive maintenance in the model is conducted after a certain drive time of the hammer. In practice, preventive maintenance is carried out after a set number of blows. Furthermore, the drive time distribution is derived from the pinpile installation distribution. Next to that, structured data collection is needed to ensure high-quality data and reliable outcomes of the model.

Recommendations

The model can be further improved by including more types of equipment. Furthermore, the use of spare equipment can be implemented in the model to resemble reality. Additionally, Metis could enable to add extra data for objects or activities. If that is implemented in Metis, characteristics like the number of blows of the hammer can also be considered to determine the preventive maintenance condition. Future research can be done on optimizing preventive maintenance intervals and developing and implementing a digital twin of the equipment in the model. In that way, the model can also examine the effect of adopting predictive maintenance strategies in offshore wind installation projects. It is recommended for the company to structure and automate data-collection. This enhances the quality of the results of the model. Lastly, the company can implement lean and Six Sigma tools to improve installation processes, but also to enhance efficiency in the workplace.

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Acronyms

AI Artificial Intelligence.

BBN Bayesian Belief Network.

CDF Cumulative Distribution Function.

CPM Critical Path Method.

CTQ Critical-to-Quality.

DBBC Double Big Bubble Curtain.

DES Discrete-Event Simulation.

DMADV Define - Measure - Analyse - Design- Verify.

DSS Decision Support Systems.

FDD Fault Detection and Diagnosis.

FLRT Filter Layer Removal Tool.

FMEA Failure Mode Effect Analysis.

FMECA Failure Mode Effect and Criticality Analysis.

HES Heerema Engineering Solutions.

HLV Heavy Lift Vessel.

HMC Heerema Marine Contractors.

HTV Heavy Transport Vessel.

ILT Internal Lifting Tool.

JLT Jacket Lifting Tool.

KPI's key performance indicators.

MILP Mixed Integer Linear Programming.

MPC Model Predictive Control.

MTBF Mean Time between Failures.

MTTR Mean Time to Repair.

OEE Overall Equipment Effectiveness.

OSS Offshore Sub-Station.

PM preventive maintenance.

RMSE Root Mean Square Error.

ROV Remotely Operated Vehicle.

RPN Risk Priority Number.

TPM Total Productive Maintenance.

Definitions

5S Seiri (sort), Seiton (Set-in-order), Seiso (Shine), Seiketsu (standardize), Shitsuke (Sustain): lean tool to improve quality, productivity and efficiency by structuring the workplace (Chandrayan et al., 2019).

bottleneck Point of congestion in the supply chain that slows or stops progress.

critical path The shortest path connecting all required activities to complete a project (Atin and Lubis, 2019).

delay Period of time by which the offshore wind installation project is late, compared to the original installation schedule.

downtime Time that is spent on the critical path of the offshore wind installation project, where installation operations can not be performed, for example due to equipment breakdown or maintenance.

equipment breakdown Sudden and accidental breakdown of the equipment, or a part of the equipment, that needs to be repaired or replaced.

failure mode The way in which the equipment might fail.

idle Spend time doing nothing, for example planned in logistic cycle.

installation equipment Equipment that is specifically designed and used for installation purposes.

kaizen lean tool for continuous improvement.

lean (manufacturing) ideology for production processes, where productivity is maximised together with minimizing waste (The Welding Institute, nd).

logistics The detailed organization and planning of a complex operation.

offshore wind energy Energy generated from the wind at sea.

offshore wind installation chain Part of the supply chain where the wind turbines are installed at sea.

performance How well the supply chain or equipment operates.

renewable energy Energy from a source that is not depleted when used, such as wind or solar power.

Six Sigma Methodology for continuous improvement of processes, focusing on preventing defects to reduce variation in production processes (The Lean Six Sigma Company, nd).

supply chain Network of stakeholders that are involved in producing, transporting and creating a product to deliver it to the customer.

waste anything that does not add value to production processes (The Welding Institute, nd).

I

Define

1 Introduction

Climate change requires innovations in energy supply to reduce greenhouse gas emissions. 196 parties agreed in the Paris Agreement to limit global warming to 2°C (UN, 2015). To meet the Paris Agreement, the share of renewable energy sources must increase in the coming years. Offshore wind energy can play a key role in the energy transition, due to technological developments and industrial growth (Díaz and Soares, 2020). The offshore wind capacity is likely to increase shortly, as can be seen in Figure 1.1. The European Commission also includes offshore wind in its energy and climate strategy. In 2021, the total installed capacity for offshore wind was 14,6 GW. The European Commission aims to increase the total installed capacity to at least 60 GW by 2030 and even up to 300 GW by 2050 (European Commission, nd). This stresses the need for robust offshore wind installation planning.

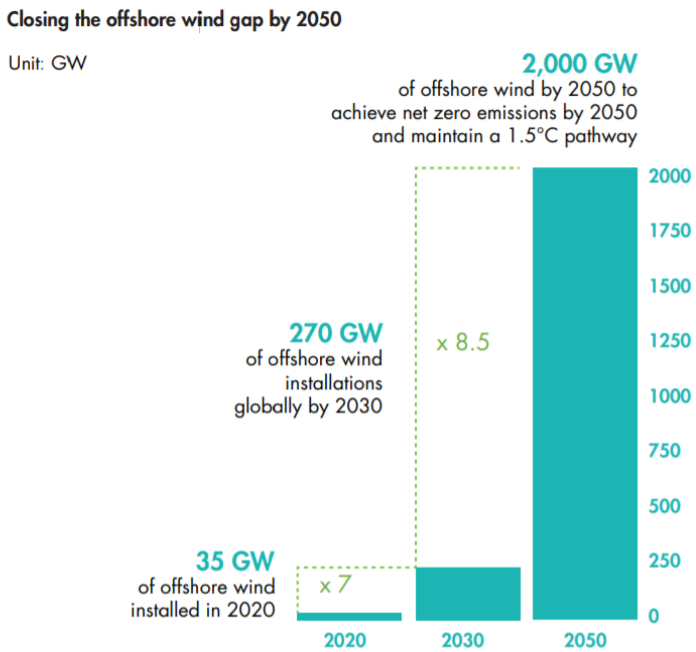


Figure 1.1: Offshore wind installation outlook.
Note. Reprinted from Global Wind Energy Council (2021).

Although offshore wind is supported by the EU and governments for environmental reasons, offshore wind energy needs to be competitive with other energy sources as well to increase their market potential. To be cost-competitive with other energy technologies, costs must be kept as low as possible. One of the ways to increase the financial feasibility of offshore wind is to improve installation logistics and decrease uncertainty during the installation phase. Risk factors, such as weather conditions, failures or supply chain disruptions, can cause downtime in the supply chain and therefore delay the installation of offshore wind projects (Leontaris et al., 2017). An overview of the cost allocation for an offshore wind project is included in Figure 1.2. About 10-20% of the costs for an offshore wind project consist of installation costs, although this can vary per project (BVG Associates, nd). Even though installation costs are only a relatively small part of total commissioning costs, total installation costs can rapidly increase if the project is delayed (Rippel et al., 2021). Delays during installation are costly, because specialised equipment and vessels have high day-rates and are only rented for a specific duration (Gintautas and Sørensen, 2017). Furthermore, when project deliveries are delayed, the energy supply is also delayed, which decreases the total profit for the wind farm owner (Jansen et al., 2020).

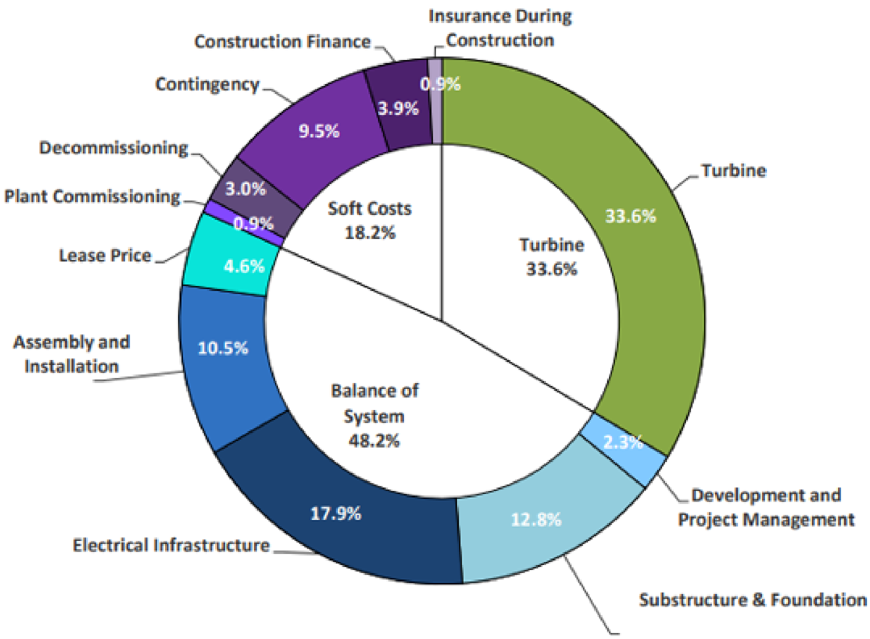


Figure 1.2: Overview of costs for an offshore wind project.
Note. Reprinted from Stehly and Duffy (2022).

This research fills a knowledge gap in the literature on reducing downtime due to equipment breakdown during the installation of offshore wind projects by improving decision-making. The method that is presented in this study combines the effect of weather conditions and equipment breakdown in a model, which has not been done before in other studies. By giving insight into the effects of decision-making, knowledge can be gained in the rapidly developing offshore wind installation industry. Furthermore, this research is a starting point for further expansion of simulation models for offshore wind installation planning with equipment characteristics. This research is also socially relevant: by decreasing the downtime during offshore wind installation, offshore wind energy costs can decrease. This can be beneficial for society, because offshore wind energy is needed to achieve climate goals and fulfil the need for power supply. Especially, because it is expected that due to the transition from fossil energy sources to renewable energy sources, the demand for electrical power will increase significantly shortly (Bogdanov et al., 2021). Furthermore, when offshore wind energy becomes more competitive with other energy sources, less financial support is required from governments. Governments can then choose to spend the financial support on other environmental or social purposes.

1.1. Research objective

The objective of this research is to better understand how equipment breakdown of installation equipment affects the logistics of offshore wind installation. This is done by composing a theoretical framework and performing data analysis on a specific offshore wind installation project. The causes of failure and supply chain disruptions are also identified. Additionally, it is aimed to design logistical solutions that help to reduce downtime due to equipment breakdown. By verifying the designs in a model, the effects of implementing the solutions are quantified.

1.2. Scope

The scope of this research is limited to the offshore part of the supply chain. Furthermore, the equipment under scrutiny in the case-study is narrowed down to equipment that is used for installation purposes, such as hammers and the template. Equipment needed for vessel operation, such as an engine, is beyond the scope of this research. The model only includes breakdown and maintenance of the hammer. Additionally, this research is focused on processes and operations, rather than the design of the equipment itself.

The supply chain for offshore wind installation is shown in Figure 1.3. The blue boxes at the top indicate the processes in the supply chain. The orange boxes indicate which stakeholder executes the corresponding process. The purple boxes represent the components. Blue arrows indicate transport over water and green arrows indicate road transport. The scope of this research is indicated by the red box.

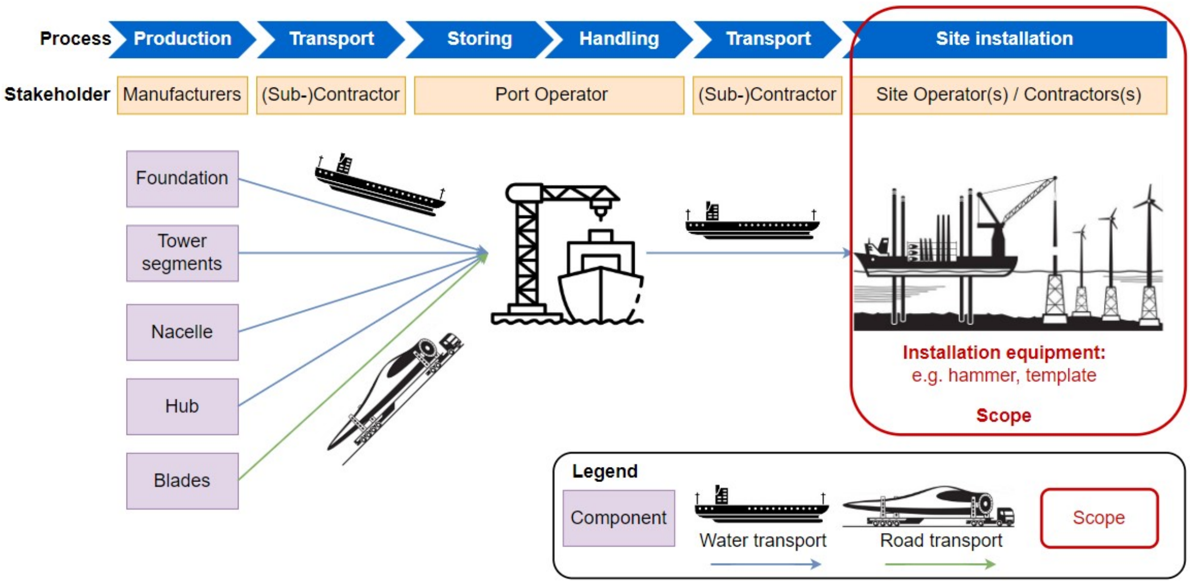


Figure 1.3: Supply chain for installing offshore wind projects.
Note. Adapted from Beinke et al. (2017) and Schweizer et al. (2014).

Turbine components are all manufactured by different manufacturers. The components are then transported by a contractor to the port. At the port, the components are stored until they are needed at the installation site. The components are transported from the port to the installation site by different contractors. The components for simultaneous offshore wind projects do not necessarily follow the same supply chain. Parts can be manufactured by different manufacturers and transport can be handled by multiple contractors. This means that the actual supply chain is more a network than a chain (Beinke et al., 2017).

1.3. Research questions

The main research question that is answered in this thesis is as follows:

How can downtime due to equipment breakdown be reduced during the installation process of an offshore wind project?

To answer the main research question, sub-questions are answered. These sub-questions are listed below.

1. What types of foundations, equipment and vessels are used and what are process steps in offshore wind installation?
2. What causes for downtime in offshore wind installation are discussed in literature and what solutions are currently proposed in literature to reduce downtime?
3. How is downtime due to equipment breakdown reduced in other industries?
4. How much downtime does equipment breakdown cause and when does equipment breakdown occur in one offshore wind installation project?
5. What are root causes for downtime due to equipment breakdown in offshore wind installation?
6. What requirements should be fulfilled in order to manage downtime due to equipment breakdown during wind installation projects?
7. What are relevant key performance indicators (KPI's) to assess equipment breakdown on the critical path of an offshore wind installation project?
8. What designs can be implemented to reduce downtime due to equipment breakdown and what is the effect of implementing the designs on the KPI's regarding equipment breakdown?

1.4. Heerema Engineering Solutions

This thesis is carried out at Heerema Engineering Solutions (HES). The company was founded in 2019 and is part of the Heerema group. The company aims to provide practical solutions for the offshore renewable industry. They combine theoretical knowledge with offshore experience to solve challenges for their clients. Examples of projects that the team executes are early-stage feasibility studies, equipment installation projects, software development projects, offshore support, and major detailed design projects (Heerema, nd).

HES also performs logistical analyses for their clients. To support these analyses, HES developed in-house Discrete-Event Simulation (DES) software Metis that can simulate various logistical problems for offshore wind installation projects. By simulating different scenarios and including historical weather data, the efficiency of the installation phase can be increased (Heerema Engineering Solutions, nd).

1.5. Structure thesis

Figure 1.4 shows an overview of the research questions and methods that are used to answer each sub-question.

Chapter	Research question	Method
1. Introduction		
2. Key elements	1. What types of foundations, equipment and vessels are used and what are process steps in offshore wind installation?	Literature research
3. Theoretical perspective	2. What causes for downtime in offshore wind installation are discussed in literature and what solutions are currently proposed in literature to reduce downtime?	Literature research
	3. How is downtime due to equipment breakdown reduced in similar industries according to literature?	Literature research
4. Case-study: Offshore wind installation project	4. How much downtime does equipment breakdown cause and when does equipment breakdown occur in one offshore wind installation project?	Data-analysis
5. Root-cause analysis	5. What are root causes for downtime due to equipment breakdown in offshore wind installation?	Interviews
6. Model	6. What requirements should be fulfilled to manage downtime due to equipment breakdown during offshore wind installation projects?	Requirements analysis
	7. What are relevant key performance indicators to assess equipment breakdown on the critical path of an offshore wind installation project?	Critical-to-Quality tree
7. Design: prioritizing maintenance	8. What designs can be implemented to reduce downtime due to equipment breakdown and what is the effect of implementing the designs on the key performance indicators regarding equipment breakdown?	Design / simulation
Conclusion, discussion and recommendations	**Main research question:** How can downtime due to equipment breakdown be reduced during the installation process of an offshore wind project?	

Figure 1.4: Research questions and methods

2

Key elements

In this chapter the first research question *'What types of foundations, equipment and vessels are used and what are process steps in offshore wind installation?'* is answered by using literature research. The components, vessels and equipment are key elements of offshore wind installation. By exploring the key elements of the system and describing the process steps, the context of this research is illustrated.

2.1. Foundations and components

Every supply chain for an offshore wind project is different. This does not only depends on the location and environment of the project, but also the type of turbine and the required parts. Offshore wind turbines consist of multiple components. An overview of the large components is given in Figure 2.1.

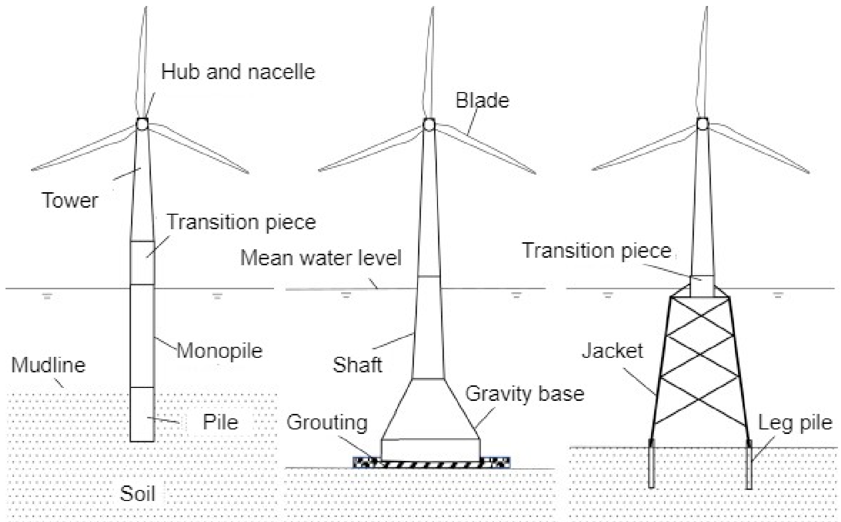


Figure 2.1: Illustration of parts of offshore wind turbines.
Note. Reprinted from Jiang (2021).

Offshore wind turbines can be divided into fixed-bottom turbines and floating wind turbines, as indicated in Figure 2.2. The choice which foundation is most suitable depends on seabed characteristics, water depth, applied loading, economic feasibility and logistics. Currently, the monopile is the most used foundation type, because of the ease of installation and for economic reasons. When fixed-bottom turbines are not suitable, for example, for water depths greater than 50 m, floating wind turbines can be used (O'Kelly and Arshad, 2016).

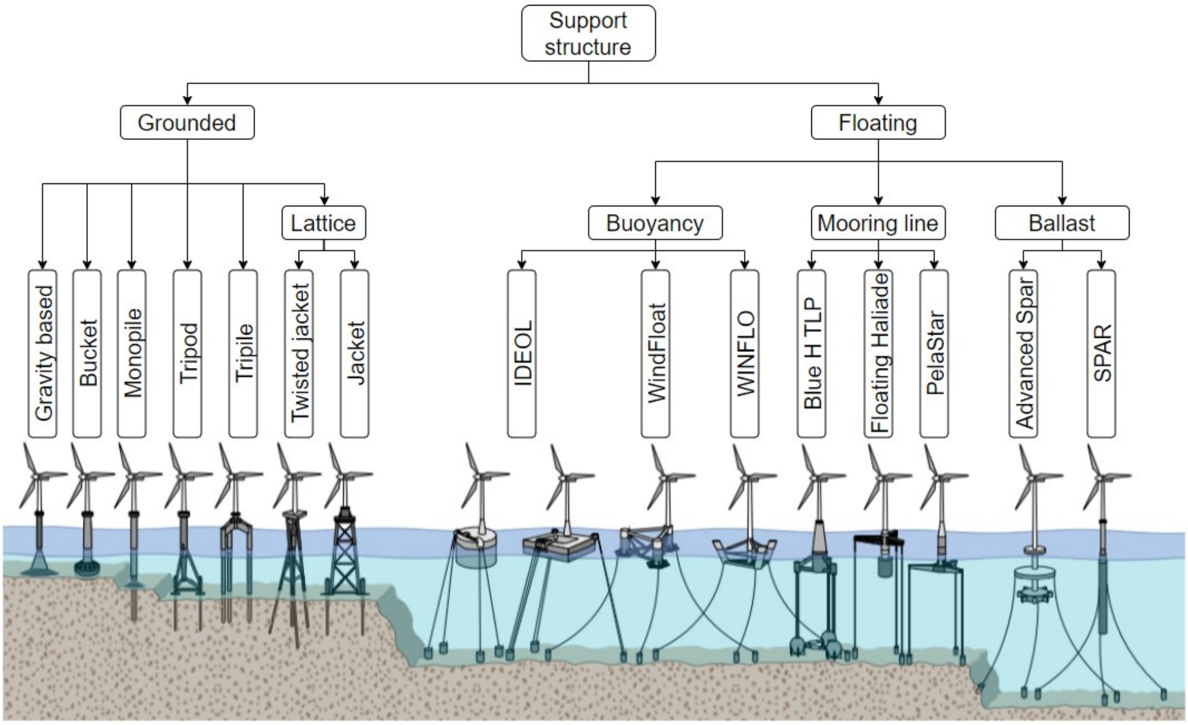


Figure 2.2: Different types of foundations for offshore wind turbines.
Note. Adapted from Rodrigues et al. (2016).

2.2. Equipment

During installation and transport different types of equipment are required. Specialized equipment is designed together with offshore wind technologies (Jiang, 2021). The required equipment is determined in the preparation phase and depends on the type of turbine and project-specific criteria (Thomsen, 2014). Therefore, for each project different equipment is used. An overview of most used equipment and their purpose is given in Table 2.1. Pictures of a hammer, template, Remotely Operated Vehicle (ROV) and Double Big Bubble Curtain (DBBC) are included in Figure 2.3 and Figure 2.4.

Some of the equipment, for example cranes, are always on board of the installation vessel. Other equipment, such as hammers and gripper devices, are placed on installation vessels if needed for the project. There is also equipment that is installed on a separate support vessel that is rented for a project, this applies to equipment like the DBBC and grouting equipment.

Table 2.1: Purposes of installation equipment.

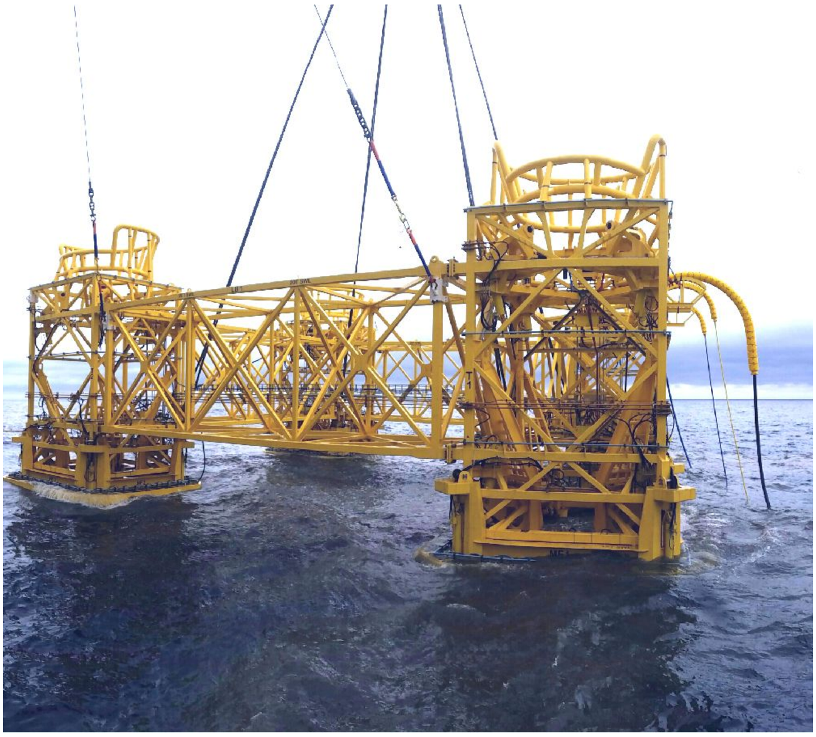
Installation equipment	Purpose
Cranes	Lifting
Double Big Bubble Curtain (DBBC)	Noise mitigation
Filter Layer Removal Tool (FLRT)	Cleaning template and remove filter layer
Gripper devices	Gripping piles
Grouting equipment	Casting turbine components
Hammer	Driving pile into seabed
Internal Lifting Tool (ILT)	Lifting
Jacket Lifting Tool (JLT)	Lifting jacket
Prepiling template	Locate pinpiles on seabed
Remotely Operated Vehicle (ROV)	Investigating deep sea operations
Self Propelled Modular Trailer (SPMT)	Insert ILTs into piles
Umbilical	Linking equipment
Winch	Adjust tension of cables

Table 2.2: Vessels used during offshore wind installation and day rates.
Note. Adapted from Ahn et al. (2017), Barlow et al. (2014), Heerema Marine Contractors (2023b) and Jiang (2021).

Vessel type	Purpose	Day rate (US$)
Construction support vessel	Is used for various dedicated operations, by employing equipment like DBBC, FLRT or grouting	unknown
Crane barge	Lifting of pre-assembled turbines or support structures	80.000-100.000[1]
Heavy Lift Vessel (HLV)	Carrying heavy modular components	30.000-50.000 [1] [2]
Heavy Transport Vessel (HTV)	Transports heavy components, such as jackets	
Jackup barge	Lifting of pre-assembled turbines or support structures, lifting capacity: 200-1300 tonnes	100.000-180.000 [1]
Purpose-built jackup vessel	Transport and installation of turbines, equipped with dynamic positioning systems, lifting capacity: 800-1500 tonnes	150.000-250.000[1]
Semi-submersible crane vessel	Lifting of heavy turbine assemblies, lifting capacity: 3000-20000 tonnes	280.000-500.000[1]
Tugboat	Towing of non-self propelled barges or floating foundations	1000-5000[1]

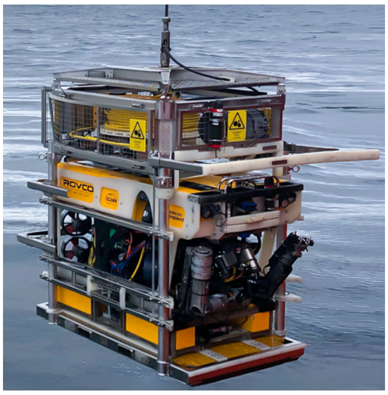
[1] Source: Jiang (2021), might not be representative for current market rates.
[2] Day rates for bigger HLV's are higher than indicated by Jiang (2021).

(a) Hammer.
Note. Reprinted from Buljan (2021).



(b) Template.
Note. Reprinted from OffshoreWIND.biz (2016).

Figure 2.3: Equipment used in offshore wind installation.



(a) ROV.
Note. Reprinted from Adis Ajdin (2021).

(b) Bubble curtain placed around installation vessel by support vessel.
Note. Reprinted from Vattenfall (2020).

Figure 2.4: Equipment used in offshore wind installation.

2.3. Vessels

During the installation of offshore wind projects, various vessels are required. An overview of vessel types is listed in Table 2.2. Figure 2.5 shows eight different vessels that are used for installation. For each project, vessels are selected based on requirements of the project, such as size and number of components. In addition to that, economic reasons, availability of vessels and applied wind turbine technologies are also considered (Jiang, 2021).

(a) Construction support vessel.
Note. Reprinted from Marine Traffic (2020).

(b) Crane barge

(c) HLV. *Note.* Reprinted from Heerema Marine Contractors (2023a).

(d) Jacket HTV.
Note. Reprinted from VSLJOIN (nd).

(e) Jackup barge.
Note. Reprinted from Jiang (2021).

(f) Purpose-built jackup vessel.
Note. Reprinted from Jiang (2021).

(g) Semi-submersible installation vessel.
Note. Reprinted from Jiang (2021).

(h) Tug.
Note. Reprinted from Jiang (2021).

Figure 2.5: Vessels used in offshore wind installation.

2.4. Process steps

In this section, the process steps of an offshore wind installation project are explained using literature. The installation process steps differ per foundation type. The installation steps for monopiles and jackets are explained hereafter.

Figure 2.6 shows some steps of the installation of a monopile. There are several supply options for monopile installation. The foundations can be supplied by barges or transported by the installation vessel itself. Furthermore, if two installation vessels are available the installation of foundations and transition pieces can be executed simultaneously, instead of sequential. First, the monopile is upended from the transportation barge or installation vessel. Then, a gripper device on board of the installation vessel is used for handling the monopile and to make sure that the monopile is placed at the correct position. Next, a hydraulic hammer is used to drive the monopile into the seabed. When the monopile reaches the predefined depth, the transition piece is placed on the monopile. After that, the transition piece and monopile are grouted together (Kaiser and Snyder, 2010).

The main process steps of jacket installation are depicted in Figure 2.7. The first step is to lift the template from deck and place it onto the seabed. This enables the positioning of the pinpiles, which are driven into the seabed using the hammer. Then, the template is removed from the seabed and placed back on deck. After that, the HLV is moved next to the HTV, to lift the jacket from the HTV and position it on the pinpiles. To secure the structure, the pinpiles and jacket are grouted (Jiang, 2021). The transition piece is already attached to the jacket, to decrease the number of lifting operations (Kaiser and Snyder, 2010).

The installation of the turbine onto the foundation can be done in different ways. Turbines are composed of a hub, nacelle, three blades and at least two tower segments. Pre-assembly of components reduces the number of required lift operations. However, the application of pre-assembled components affects installation time. Next to that, vessels with a higher lifting capacity are needed (Kaiser and Snyder, 2010).

An overview of all process steps for the installation of offshore wind turbines is presented in Figure 2.8. Every row in the overview represents the process steps of an installation stage, which is indicated in the white ellipses. The processes are categorized into: hammering (yellow), lifting (orange), mooring and positioning (blue), support (green) and other operations (grey).

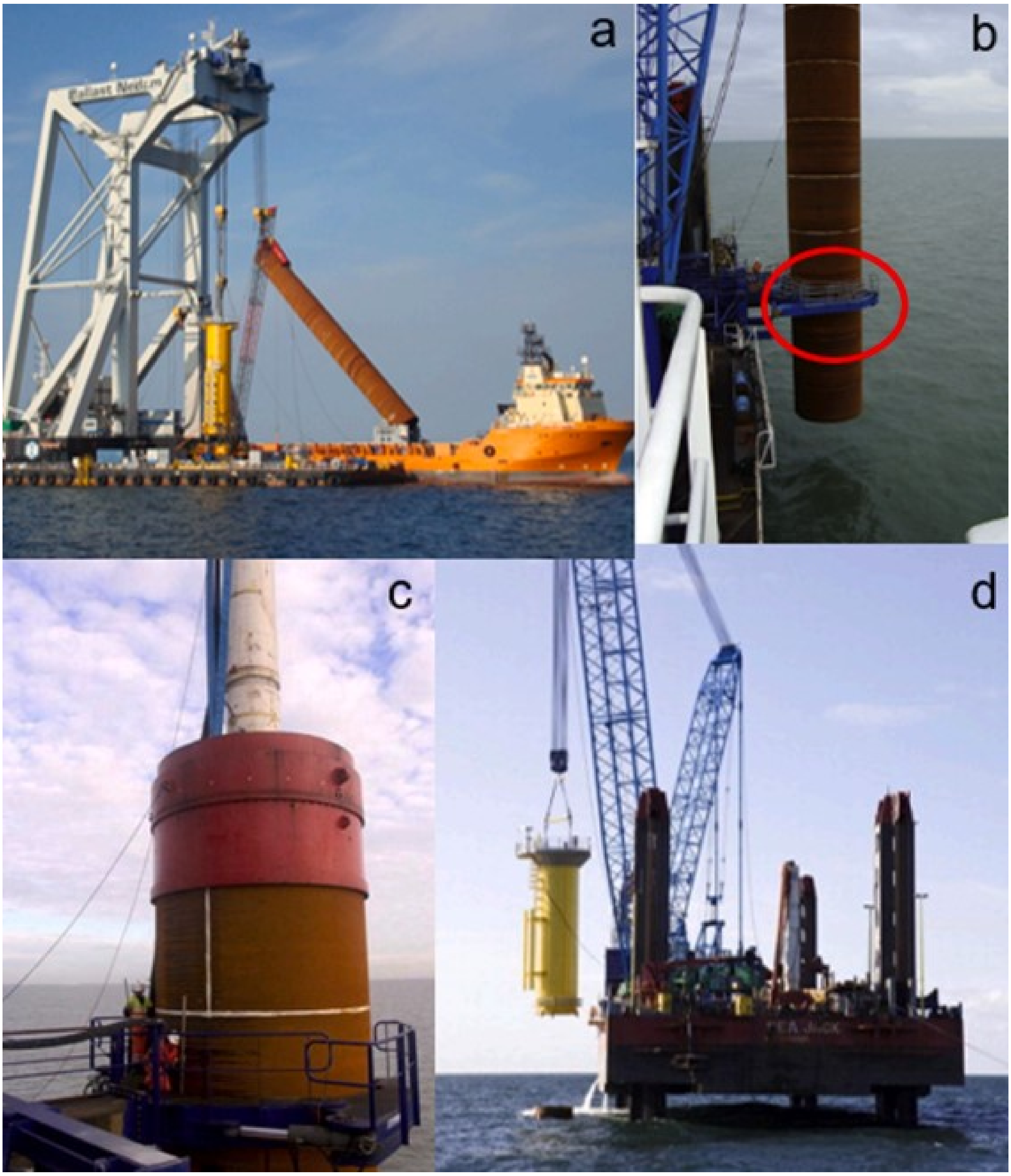


Figure 2.6: Monopile installation. a) Upending of the monopile from transportation barge. b) Gripper device (red circle) is used for positioning and handling of the monopile. c) Hydraulic hammer drives the monopile into the seabed. d) Grouting is used to cast the transition piece and monopile together.
Note. Reprinted from Jiang (2021).

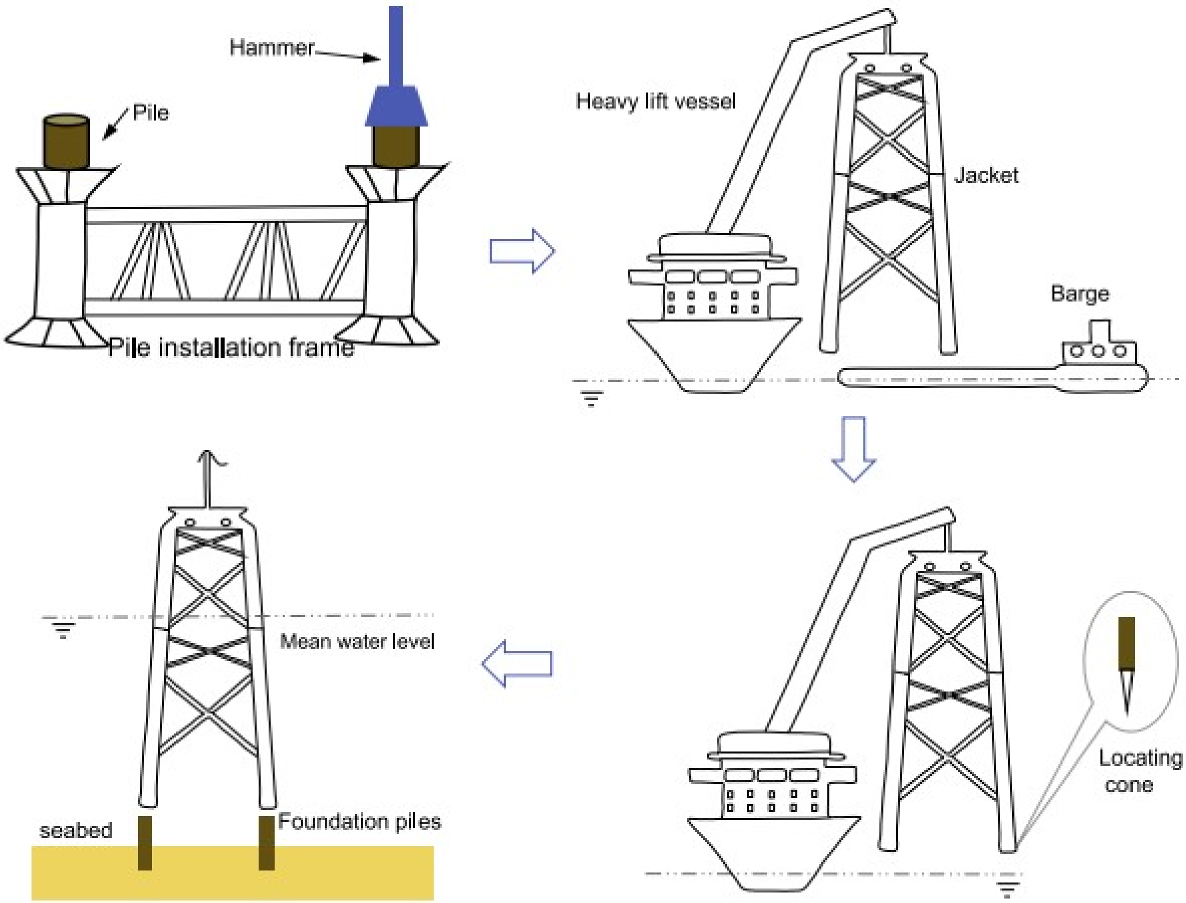


Figure 2.7: Illustration of key process steps in jacket installation.
Note. Reprinted from Jiang (2021).

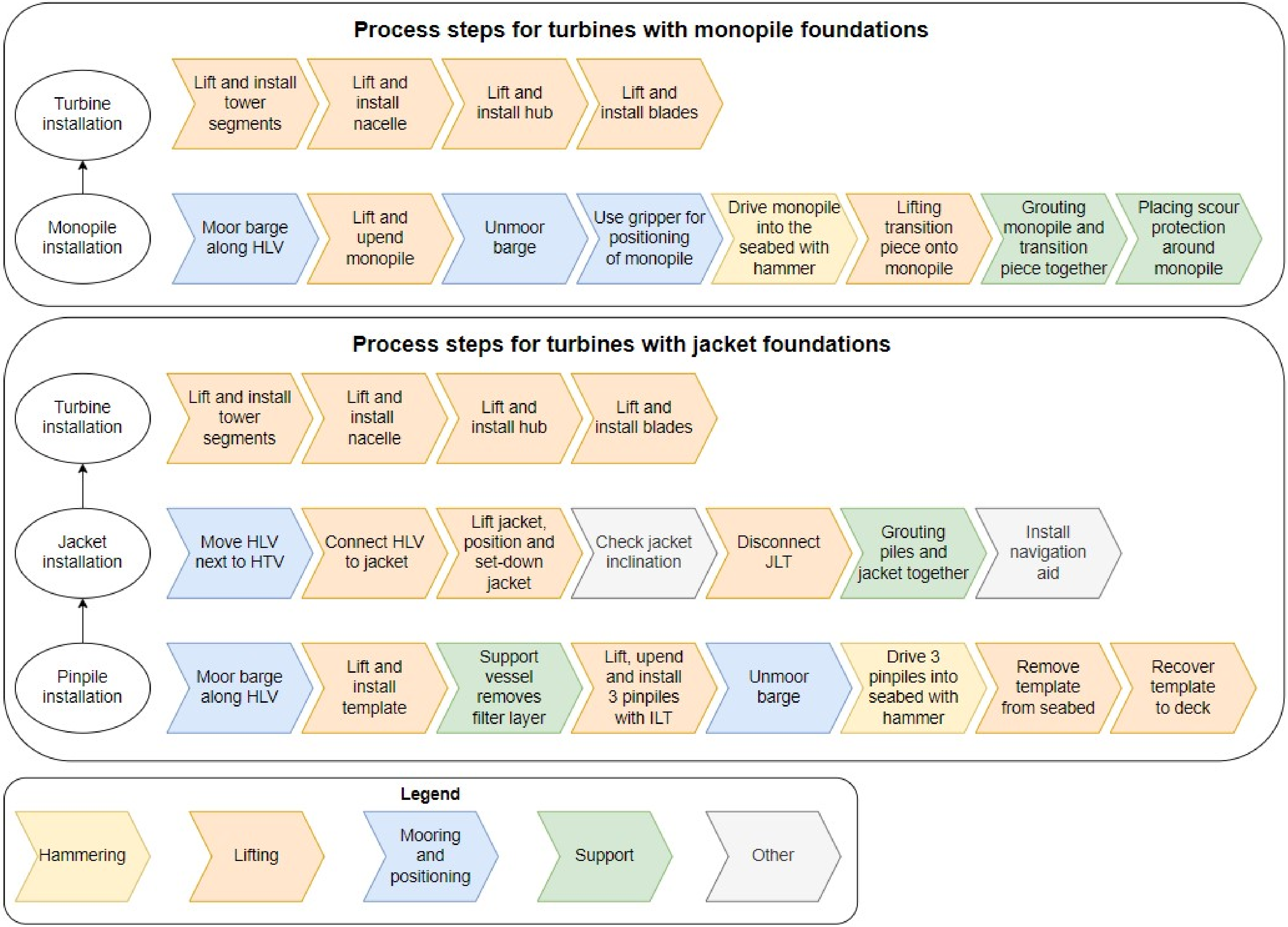


Figure 2.8: Process steps per installation stage for the installation of offshore wind turbines with monopiles and jacket foundations.

3
Theoretical perspective

The literature is examined to define the research problem. The literature review shows what is known in the literature about downtime in offshore wind installation and what knowledge gap in literature needs to be filled. First, the literature review on reducing downtime in offshore wind installation is presented. Second, the knowledge gap is deducted from the literature review. Last, a literature review on dealing with equipment breakdown in other industries is presented.

3.1. Literature review: Reducing downtime in offshore wind installation

To answer the research question, *'What causes for downtime in offshore wind installation are discussed in literature and what solutions are currently proposed in literature to reduce downtime?'*, the literature is studied. An overview of all reviewed researches regarding downtime in offshore wind installation is presented in Table 3.1. First, the causes of downtime in offshore wind are explained. Then, currently used solutions to reduce downtime in offshore wind installation are discussed, which are split up into modelling and process improvements.

Downtime and delay are two terms that are closely related, but the terms are no synonyms. Delay is defined as *"the situation in which you have to wait longer than expected for something to happen, or the time that you have to wait"* by Cambridge Dictionary (2023a). When applied to offshore wind, the following interpretation of delay will be used: *period of time by which the offshore wind installation project is late, or the time that is spend waiting to continue with installation processes*. The definition of downtime is: *"the time during which a machine, especially a computer, is not working or is not able to be used"* by Cambridge Dictionary (2023b). In this research downtime is interpreted as *time that is spent on the critical path of the offshore wind installation project, where installation operations can not be performed.*

3.1.1. Causes for downtime in offshore wind installation

Causes for downtime during offshore wind installation projects can be categorized into weather-related downtime, vessel and equipment-related downtime, supply chain or infrastructure related downtime and other causes for downtime. In the next sections these topics will be explained in more detail.

Table 3.1: Overview of studies addressing downtime in offshore wind installation.

Reference	**Causes**				**Solutions**							
					Modelling				*Supply chain improvement*			
	Unfavourable weather conditions	Vessel and equipment	Supply chain / infrastructure	Other	Discrete-Event Simulation	Mixed Integer Linear Programming	Robust optimization	Stochastic model	Coordination	Investments	Productivity	Resources (vessels, ports)
Aagaard et al. (2015)				x					x			
Altuzarra et al. (2022)	x	x					x					
Barlow et al. (2015)	x	x			x							
Barlow et al. (2018)	x				x		x					
Cairney (2015)	x			x					x		x	
Dinh and McKeogh (2019)		x	x						x	x		
Gintautas et al. (2016)	x	x						x				
Gintautas and Sørensen (2017)	x	x						x				
Halvorsen-Weare et al. (2021)	x	x	x		x[a]							
Hrouga and Bostel (2021)	x	x				x						
Lange et al. (2012)	x	x	x		x							
Leontaris et al. (2017)	x		x					x				
Leontaris et al. (2019)		x	x					x				
Lerche et al. (2022a)				x							x	
Lerche et al. (2022b)	x	x		x							x	x
Oelker et al. (2021)	x				x							
Parkison and Kempton (2022)			x							x		x
Paterson et al. (2020)	x							x[b]				
Poulsen and Lema (2017)			x							x		x
Rippel et al. (2019a)	x	x	x			x[c]						
Rippel et al. (2019b)	x						x[c]					
Rippel et al. (2021)	x	x					x					
Scholz-Reiter et al. (2010)	x					x						
Scholz-Reiter et al. (2011)	x	x				x						
Ursavas (2017)	x						x					
Vis and Ursavas (2016)	x				x						x	

[a] Agent-based simulation
[b] Auto-regressive
[c] Combined with MPC

Installation operations are limited by weather conditions like wind speed and wave limits, because the weather conditions affect response of equipment like crane wire tension, which increases the probability of operation failure (Gintautas et al., 2016; Gintautas and Sørensen, 2017). If weather limits are exceeded, installation can not be carried out and the downtime increases, which leads to additional costs (Oelker et al., 2021). Transport, handling, and installation operations can be affected by bad weather conditions and cause delays of several months (Scholz-Reiter et al., 2010; Hrouga and Bostel, 2021). Altuzarra et al. (2022) recommend to plan installation operations between April and August, because that period has the highest probability of suitable weather windows, hence lowest risk for downtime and increasing costs. Especially, the installation of foundations, like jackets, and turbines is sensitive to weather downtime compared to other installation processes, like cable laying (Barlow et al., 2015).

Vessel capacity has great impact on the costs and duration of the installation of an offshore wind project (Barlow et al., 2015). Research of Rippel et al. (2019a) shows that the fleet composition in combination with port infrastructure affects the project duration as well. According to Hrouga and Bostel (2021), most literature studies for vessel decisions relate to minimizing costs by determining optimal composition of the fleet and optimal deployment of vessels. Lack of specialized vessels and equipment is considered a major bottleneck in the offshore wind installation phase (Dinh and McKeogh, 2019). Offshore waiting time or downtime cause increasing total operational costs of vessels, even up to 30% of the charter rate (Rippel et al., 2021). The installation vessels are involved in decisions on both the tactical and operational levels. Decisions at the tactical level involve planning of vessel tasks. On the operational level, daily vessel routing and operations scheduling are decided on. When installation equipment on board of the vessel can not be used, this is also considered as vessel-related downtime by Lerche et al. (2022b).

Infrastructure is a bottleneck in the development of offshore wind as well. The logistical strategies and layout of the supply chain have impact on the project planning, duration and costs of a offshore wind installation project (Lange et al., 2012). Furthermore, continuous coordination is required between collaborating contractors on site (Aagaard et al., 2015). Leontaris et al. (2017) indicate that damage and transport problems can cause delays in the installation supply chain. Supply chain disruptions are also a risk factor in large installation projects (Leontaris et al., 2019). According to Poulsen and Lema (2017), the global offshore wind supply chain is not ready for the expected growth in the coming years, because there is not enough capacity in the supply chain to accommodate the rising demand for port capacity, vessels, skills, tools and personnel. Additionally, a shortage of marshaling port area is restricting growth in the US (Parkison and Kempton, 2022).

Lerche et al. (2022b) studied the frequency of causes of downtime in offshore wind installation projects. It was concluded that the most important causes for downtime are: previous tasks, weather conditions, vessel-related problems, location, information, equipment, parts, permit, planning, and components. Cairney (2015) points out that downtime is caused by over-confidence of stakeholders and a lack of quantitative risk assessments. This results in failures, mismatch between planned and actual installation activities, late design changes and lack of crane capacity, man-power and vessel availability. Next to that, contracts between stakeholders contain weaknesses, which leaves projects exposed to financial risks in case of unforeseen events.

COVID-19 was also a supply chain disruption. Lerche et al. (2022a) included the implications of the pandemic in their study on the application of Kanban and Takt planning to offshore wind installation. The study showed that 10% of the disruption hours in the first months of 2020 were caused by COVID-19. Although this was only 0,4% of the total installation time, it was considered a uncontrollable variation. Especially, the closing borders resulted in unavailable resources needed for installation.

3.1.2. Solutions to reduce downtime during installation: Modelling

Several models that are currently used to reduce downtime in offshore wind installation are mentioned in the literature: Discrete-Event Simulation (DES), Mixed Integer Linear Programming (MILP), robust optimisation models and stochastic models.

DES can be used to compare and evaluate different installation scenario's without financial risk (Barlow et al., 2015). The simulation models of Lange et al. (2012) showed that especially the final part of the installation chain is prone to risk of downtime and increasing costs, due to weather restrictions prohibiting transport and installation. Vis and Ursavas (2016) applied DES to compare different pre-assembly scenarios and concluded that number of components, distance to shore and the number of turbines on a vessel are important variables. Halvorsen-Weare et al. (2021) combined DES with agent-based simulation to optimise different scenario's for weather conditions and component transfers. Especially during the planning and biding stages of the offshore wind project, DES can be applied to support decision-making and scheduling (Barlow et al., 2018). Oelker et al. (2021) use DES to prove that only increasing the wave limits from 1 m up to 1.6 m, results in a cost reduction of 17.9% for the installation costs and decreases the total installation time by 32 days and still allows for a safe and reliable installation of rotor blades.

MILP is used to determine an optimal installation planning for vessels and vessel loadings, considering weather forecasts (Scholz-Reiter et al., 2010, 2011). Hrouga and Bostel (2021) propose to use MILP to evaluate logistical strategies and decisions to minimise the total costs for installation, transport and storage for the global supply chain. Rippel et al. (2019a) combined MILP with Model Predictive Control (MPC) to schedule installation activities of vessels, because it allows for increased prediction horizons with short response times.

Robust optimisation can be used to calculate vessel renting periods on short term. However, it depends on accurate weather forecast data (Ursavas, 2017). Additionally, although modelling logistics of offshore wind installation allows for global optimisation of the duration of the project, the use of historical data, for example, weather data, also increases the uncertainty of the model, because the base line for decision making is the same for every run of the model (Rippel et al., 2021). There are several ways to counter this weather data dependency discussed in the literature. Barlow et al. (2018) combined DES with robust optimisation, because it incorporates the ability to optimize schedules of the optimisation model, whilst accounting for weather conditions due to the DES model. The combination of robust optimisation with MPC also enables mid to long term scheduling of offshore wind installation processes (Rippel et al., 2019b).

Gintautas et al. (2016) presented a statistical approach to predict operation failure due to bad weather conditions. By using this stochastic model, the uncertainty of operation failure is directly related to the uncertainty of weather forecasting, at least for the short term (Gintautas and Sørensen, 2017). Stochastic models can also be applied to study the impact of supply chain disturbances on the total cost (Leontaris et al., 2017). This application of stochastic models allows for optimal decision-making for installation schedules, buffer stock of components, fleet composition and selection of installation ports (Leontaris et al., 2019). Paterson et al. (2020) used a Markov-switching auto-regressive model to provide stochastic weather conditions (wind speed and wave height time series) that can be applied to assess marine operations such as offshore wind installation processes.

3.1.3. Solutions to reduce downtime during installation: Supply chain improvement

Another way to reduce downtime in offshore wind installation is supply chain improvement. In the literature, multiple way to improve installation processes are discussed: coordination, investments, productivity and resources.

The categories investments and resources are strongly related, as expanding capacity and resources mostly require investments. It is important to improve capacity and resources, because differences in preconditions, such as vessels, equipment and ports, also determine delaying factors and therefore affect productivity (Lerche et al., 2022b). Dinh and McKeogh (2019) state that the offshore wind supply chain needs a strong demand-side pull to enhance specialisation, integration, competition and cooperation. Poulsen and Lema (2017) recommend that European countries should invest in technological development to reduce supply chain bottlenecks and to invest in key infrastructure, equipment, assets and skills. Additionally, Europe and China could collaborate regarding research and business models. To meet US offshore wind targets, the supply chain capacity needs to be expanded by investing in infrastructure, port locations and installation vessels according to Parkison and Kempton (2022).

Increasing productivity can help to reduce downtime in the offshore wind installation supply chain. It is important to be realistic about weather conditions and other risk factors when preparing an offshore wind installation process (Cairney, 2015). Productivity in offshore wind installation processes can be improved by applying Takt planning, Kanban, and plan-do-check-act, according to Lerche et al. (2022a).

Informal continuous coordination between subcontractors can also help to improve project planning. According to Aagaard et al. (2015), positive drivers for such informal relations are trust, previous successful collaborations, risk and associated costs, prospects for future collaboration, low level of customer satisfaction and limited number of employees. At the other hand, high task uncertainty, tight economic constraints and high economic impact are identified as negative drivers for informal coordination. Cairney (2015) recommends to arrange a good information-flow between all contractors and emphasises the importance of clear liquidated damage clauses.

3.2. Knowledge gap

From the literature review can be concluded that weather conditions are a typical cause for downtime in offshore wind installation. There are various types of models, such as DES, MILP, robust optimization and stochastic models, that are currently used to predict suitable weather windows and incorporate weather conditions in installation schedules, as presented by Altuzarra et al. (2022), Barlow et al. (2015, 2018), Gintautas et al. (2016), Gintautas and Sørensen (2017), Halvorsen-Weare et al. (2021), Lange et al. (2012), Paterson et al. (2020), Rippel et al. (2019b, 2021), Scholz-Reiter et al. (2010, 2011) and Ursavas (2017). Some of the models also evaluate planning of vessels and operations. However, these models are not complete yet and still contain uncertainty due to the use of historical data (Rippel et al., 2021).

The literature also addresses that bottlenecks in the offshore wind supply chain cause downtime. Investments in infrastructure, ports and installation vessels are required to accommodate the growing offshore wind industry, according to Parkison and Kempton (2022) and Poulsen and Lema (2017). To improve collaboration between the different stakeholders on-site, a good information flow and coordination are essential (Aagaard et al., 2015; Cairney, 2015). Lerche et al. (2022a) points out that process improvement tools like Takt and Kanban are barely used, while it can increase productivity.

Unavailable or failing installation equipment is also mentioned to cause downtime by Dinh and McKeogh (2019), Gintautas et al. (2016), Gintautas and Sørensen (2017), Lange et al. (2012) and Lerche et al. (2022b). Most of the unavailability of equipment is explained by unsuitable weather conditions. However, none of the reviewed articles explained the equipment breakdown. So, it is known that equipment breakdown causes downtime during the installation of offshore wind projects, but the magnitude and causes of the problem are unclear because there is no literature available that specifically studied this problem. Additionally, possible approaches to reduce equipment breakdown induced downtime are unknown as well. Therefore, this research focuses on reducing downtime due to equipment breakdown during the installation of offshore wind projects.

3.3. Literature review: Dealing with equipment breakdown in other industries

Supply chains in other fields might face the same challenges with equipment breakdown, or have even solved them already. The literature about how equipment breakdown is handled in other industries is reviewed to determine which methods can be used to reduce downtime due to equipment breakdown in offshore wind installation. This answers the research question: *'How is downtime due to equipment breakdown reduced in similar industries according to literature?'*.

An overview of the studies that discuss methods to reduce equipment breakdown in other industries is presented in Table 3.2. The methods can be divided into methods to reduce downtime, methods to improve maintenance strategies and methods to automate detection and decision-making regarding failures and maintenance. The methods are explained in the next sections.

3.3.1. Process improvement in supply chains

The Define - Measure - Analyse - Design- Verify (DMADV) method is a lean (manufacturing) Six Sigma methodology that is implemented in supply chains to improve quality and customer satisfaction (Kolte and Dabade, 2017). A DMADV project includes five steps: define, measure, analyse, design and verify. During the first step, the problem is defined by setting the scope and objective of the project. Then, in the measure step, the processes of the system are determined and data is collected. Next, the data and system are analysed using lean methods to identify root causes for the problem and to pinpoint potential points of improvement. Requirements for the design are also collected during the analyse phase. During the design step, a design with improvements to the system is composed. Last, in the verification stage, the final design is tested and compared to the requirements and collected data (Alnounou et al., 2022).

Table 3.2: Overview of articles addressing reducing risk of downtime due to equipment breakdown in other supply chains.

Reference	**Industry**	**Methods**								
		Process improvement		**Maintenance**			**Automation**			
		DMADV	FMEA	OEE	PM	TPM	AI	BBN	DSS	FDD
Abdul Rahman et al. (2020)	Food industry			x		x			x	
Ahmed et al. (2021)	Asset-intensive industries						x			x
Alnounou et al. (2022)	Food industry	x		x		x				
Chin et al. (2020)	Chemical industry				x					
Heda (2019)	Mechanical equipment				x		x			x
Kolte and Dabade (2017)	Manufacturing industries	x	x	x	x	x				
Liu et al. (2019)	Mechanical equipment				x		x			x
Meca Vital and Camello Lima (2020)	Manufacturing industries			x		x				
Mwanza and Mbohwa (2015)	Chemical industry			x		x				
Nayal et al. (2022)	Agriculture						x			
Oger et al. (2022)	Supply chains								x	
Paul et al. (2020)	Pharmaceutical industry							x		
Purushothaman and Ahmad (2022)	Manufacturing industries	x	x							
Rozak et al. (2020)	Automotive industry		x	x						
Soltanali et al. (2021)	Food industry			x	x	x				

An Failure Mode Effect Analysis (FMEA) is frequently used during an DMADV project to identify critical processes (Kolte and Dabade, 2017). However, the tool can also be applied separately to reduce risks of failure in a supply chain. In a FMEA, a Risk Priority Number (RPN) is calculated based on collected failure modes, effects, causes and the ease of failure detection. The failures with the highest RPN will then be prioritized to counter (Rozak et al., 2020).

A combination of methods is often implemented during DMADV projects to analyse the data or problem. For example, Purushothaman and Ahmad (2022) combined DMADV with the theory of inventive problem solving, quality function deployment and design failure mode effects analysis, which is a variation of FMEA, to build an automated inspection system for the manufacturing processes of adhesive tape.

3.3.2. Solutions to improve maintenance of equipment

Total Productive Maintenance (TPM) is a lean concept that targets improving productivity of equipment by reducing losses. These losses are categorized into six categories: time lost by equipment breakdown, losses due to adjustments and set-up time, idle time due to process disruptions, speed loss due to difference in actual speed and design speed, quality losses due to defects and learning curve (Abdul Rahman et al., 2020; Alnounou et al., 2022). The TPM methodology is based on eight pillars, which can be seen in Figure 3.1. The eight pillars are described below:

1. **Autonomous Maintenance:** *"the mission of integrating operators into basic maintenance activities and providing the polyvalence of operators in their activities"* (Meca Vital and Camello Lima, 2020)
2. **Planned Maintenance:** mitigates equipment breakdown probability by resolving the inspection frequency based on the failure rate of the equipment and revising and replacing components (Braglia et al., 2019)
3. **Focused Maintenance or Continuous Improvement (kaizen):** *"aims to reduce losses in the workplace that affect productivity and efficiency"* (Setiawan and Hernadewita, 2021)
4. **Quality Maintenance:** application of failure detection in the equipment to reduce breakdown and increase customer satisfaction (Adesta et al., 2018; Setiawan and Hernadewita, 2021)
5. **Training and Education:** improve knowledge and skills of operators on operation and maintenance of the equipment (Al-Refaie et al., 2022)
6. **Office TPM:** extending the principles of lean and continuous improvement through the whole company, including administrative tasks (Adesta et al., 2018)
7. **Safety, Health and Environment:** providing a safe and healthy working environment, aiming for zero safety accidents (Setiawan and Hernadewita, 2021)
8. **Early Equipment Management:** incorporating lessons learned from previous projects in design of new equipment (Adesta et al., 2018)

The first four pillars concentrate on improving equipment efficiency through maintenance. The other pillars support maximising effectiveness by addressing other area's for improvement (Meca Vital and Camello Lima, 2020). Before TPM can successfully be implemented, a 5S foundation is required. 5S is a lean concept that helps to keep an organized and effective workplace by going through five steps: sort, set in order, shine, standardize and sustain. Furthermore, maintenance planning is a vital part of process improvement and can be used as a competitive advantage (Mwanza and Mbohwa, 2015). According to Soltanali et al. (2021),

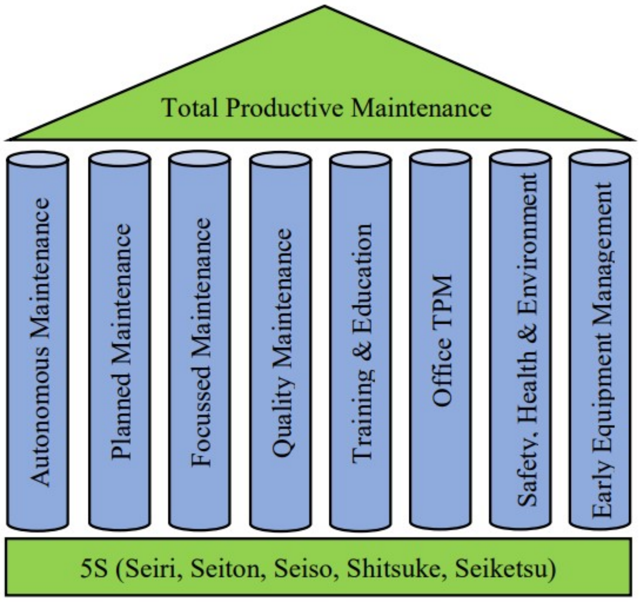


Figure 3.1: The eight pillars of Total Productive Maintenance.
Note. Reprinted from Setiawan and Hernadewita (2021).

various studies proved that the application of TPM was effective in food industries to increase equipment productivity.

The metric that is used in TPM to measure the performance of the equipment is Overall Equipment Effectiveness (OEE). The OEE is defined as the product of the equipment availability, the performance rate and the quality rate (Abdul Rahman et al., 2020). An advantage of the use of OEE is that it converts multiple key performance indicators (KPI's)'s into one numerical value. However, Soltanali et al. (2021) indicates that if performance metrics like speed variation or downtime are not automatically measured, this causes uncertainty in the OEE calculation. Other metrics that are used to evaluate equipment breakdown are the Mean Time between Failures (MTBF) and the Mean Time to Repair (MTTR) (Kolte and Dabade, 2017).

Maintenance strategies can be divided into two categories: corrective maintenance and proactive maintenance. The different strategies are depicted in Figure 3.2. Chin et al. (2020) explain the different maintenance strategies. When applying corrective maintenance, the maintenance is carried out after the equipment breaks down. These unexpected failures are undesirable, because they result often in high costs and frequent downtime. When applying proactive maintenance, the maintenance is carried out before problems arise. Proactive maintenance can be divided into sensor-based maintenance and time-based maintenance. In sensor-based maintenance, sensors are used to monitor the equipment and determine the risk of failure. For preventive maintenance (PM) a time-based probability of failure is used to describe the reliability of the equipment. In opportunistic maintenance, idle time is used as an opportunity for maintenance, because operations are not performed and equipment can be inspected without spending extra time. This can be very beneficial from a cost-perspective. Research of Kolte and Dabade (2017) shows that the implementation of PM in the manufacturing line of automobile engines reduces equipment failure, increases and improves availability of the equipment and therefore improves the performance of the production line as a whole. Optimal scheduling of maintenance requires an accurate prediction of the remaining life of the equipment (Heda, 2019; Liu et al., 2019).

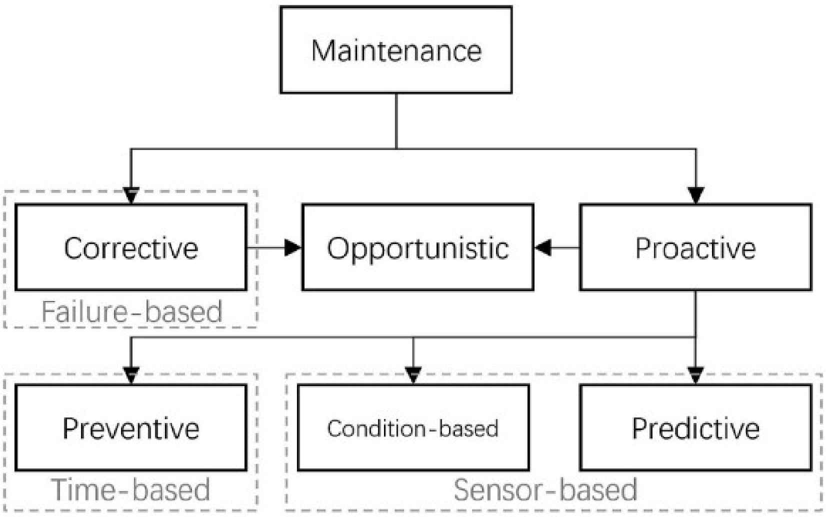


Figure 3.2: Overview of maintenance strategies.
Note. Reprinted from Ren et al. (2021).

3.3.3. Automation of failure detection and maintenance decision-making

Artificial Intelligence (AI) is applied in several ways to reduce equipment breakdown and increase reliability of the equipment. One of the ways AI is applied, is in Fault Detection and Diagnosis (FDD). FDD is implemented in several industries to increase the reliability of equipment. FDD decreases costs for maintenance and increases availability of the equipment (Ahmed et al., 2021). The method is used to detect failure of the equipment when they arise, or when it is likely a fault will emerge. By predicting failure, maintenance can be carried out before the fault causes problems (Heda, 2019). Another way AI is used to predict failure of the equipment, is to develop a digital twin of the equipment. A virtual double of the equipment is simulated real time, to examine the operation of the equipment in detail. Results of Liu et al. (2019) shows that the application of a digital twin to predict failure of an aero-engine bearing is more accurate than the traditional prediction method, where the vibration frequency is used as warning signal. In agricultural supply chains, AI is used together with other technologies, such as robotics, big data, blockchain technology and internet-of-things to reduce risk of supply chain disturbance by improving information sharing in automated system-of-systems (Nayal et al., 2022).

A Bayesian Belief Network (BBN) model is applied by Paul et al. (2020) to assess transportation disruption risk in supply chains. Machine breakdown is included as technological disruption of the supply chain. The BBN model uses expert judgment to fill in gaps in the available data to generate probabilities for supply chain disruption.

Decision Support Systems (DSS) are used to support decision making with regards to supply chain capacity planning under uncertainty on a strategic level (as opposed to the operational and tactical levels for decision-making) by Oger et al. (2022). Equipment capacity and performance is a essential part of supply chain capacity planning. Supply chain data is gathered and assessed in the DSS model and what-if scenario's. The best supply chain capacity plan can then be determined based on the results of the simulation in the dashboard. DSS can also be applied to measure and to keep track of objectives for production performance during improvement processes (Ahmed et al., 2021).

3.4. Conclusion

The literature is assessed to discover what is known in the literature about downtime in offshore wind installation. First, the causes and solutions for downtime in offshore wind are presented in a literature review. From this literature review it can be concluded that reducing downtime due to equipment breakdown in offshore wind installation is a knowledge gap in the current literature. The causes and magnitude of downtime due to equipment breakdown are unknown in the current literature. Furthermore, there is no method applied in offshore wind installation to reduce downtime due to equipment breakdown. To determine methods that can be used to fill this knowledge gap, a second literature review is conducted to evaluate what methods are used in other industries to reduce downtime caused by equipment breakdown. DMADV is applied in this study to examine the research problem and to design solutions to reduce downtime due to equipment breakdown in offshore wins installation projects.

II

Measure

4

Case study: data-analysis of a completed offshore wind installation project

A case-study is performed to measure the current situation for downtime caused by equipment breakdown. The results of the case-study are used to quantify the magnitude of the problem. First, the analysed data-set is described. Then, the occurrence and duration of downtime due to equipment breakdown are examined using data-analysis. A completed installation project is used as an example in the data-analysis.

4.1. Description data-set

The magnitude and occurrence of downtime due to equipment breakdown in an offshore wind installation project is assessed in a case-study. In the case-study, pinpiles need to be installed, before a jacket can be installed. There are more than 400 data-points used for downtime. These are all the recorded windows of downtime on the critical path during the project, including downtime on the critical path due to waiting on support vessels. Downtime on the critical path means that installation processes are put on hold or postponed until all conditions are met for the operations to continue. The critical path is the planned time horizon where installation is executed. Repairs to equipment are not critical, when they can be performed at the same time as active installation operations, for example when that specific piece of equipment is not required for the active operation. The installation of the Offshore Sub-Station (OSS) is excluded from this data-analysis.

The project is divided into 17 periods, which are indicated on the x-axis. All values in this data-analysis are normalised, based on the minimum and maximum value per data-type. The values are scaled in a range between 0 and 1. This means that the highest duration gets the value 1 and the lowest duration gets the value 0, all other values are calculated according to this range. Hence, a downtime duration of 0.1 means that that breakdown took 10% of the longest case of downtime. The normalised durations of the breakdowns are indicated on the y-axis.

4.2. Downtime caused by equipment breakdown

The fourth research question *'How much downtime does equipment breakdown cause and when does equipment breakdown occur in one offshore wind installation project?'* is answered in this section by using data-analysis. The amount of equipment breakdown duration will be compared between jacket installation and pinpile installation, per affected operation and per equipment type.

4.2.1. Total project duration

To examine what the total share of breakdown is on the project duration, the uptime and downtime during the project are included in Figure 4.1. The figure also shows what categories the downtime consists of. Waiting on weather is the largest share of downtime during the project. However, this is already expected during the planning of the project, for example weather conditions during the winter season. Breakdown and maintenance on the critical path are unexpected downtime, and can be considered as lost uptime.

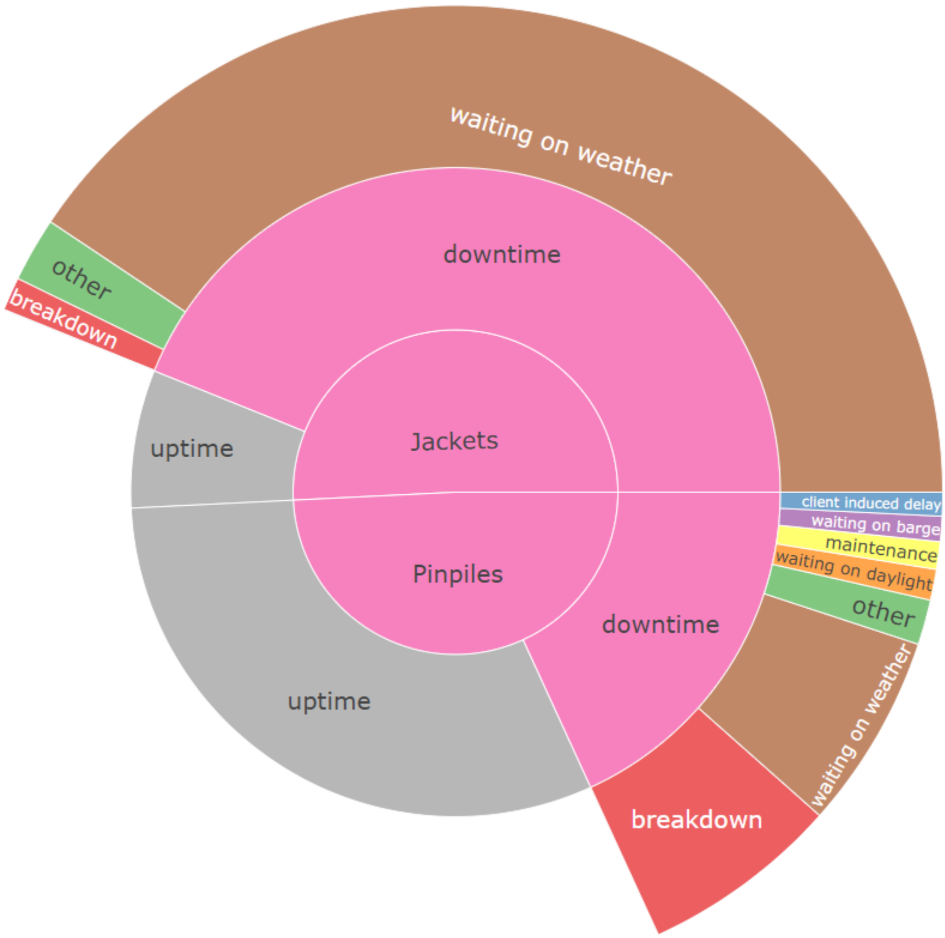


Figure 4.1: Division of total time spent during the installation project.

4.2.2. Downtime

Given the differences in downtime during pinpile installation and jacket installation, it is useful to look into the different types of downtime more closely to identify causes for downtime.

During the spring and summer, weather conditions are favourable for installation activities. Hence, most installation is planned and executed during the spring and summer. Therefore, these periods are studied in detail for pinpile installation, see Figure 4.2. The ratio between the sizes of the pie charts show the ratio between the time spent on pinpile installation in both seasons. The larger pie chart for summer means that more time is spent on pinpile installation in the summer, compared to the spring, mainly because during spring more time is spent on jacket installation or jacket downtime. Figure 4.3 shows the share of downtime due to breakdown during pinpile installation in spring and summer seasons. In Appendix B, the overviews for all seasons for pinpile installation and jacket installation are included.

Breakdown on the critical path is in both spring and summer about the same portion of the total time as well, which is lost installation time and unexpected downtime. During the summer, there is also maintenance performed on the critical path, which is also lost installation time. This means that installation had to be put on hold, in order to perform essential maintenance, such as exchanging a crane wire. Crew-transfers, waiting on support vessels and other unforeseen events are registered as other types of downtime. Downtime due to modifications of the project are categorized as client induced downtime. Some operations, like pile driving, have to comply to sunset targets. When these targets are not met, this downtime is included as waiting on daylight. Waiting on barge is a logistical downtime, because the barge with components did not arrive in time for installation.

Figure 4.2: Split for causes of downtime for pinpile installation during spring and summer.
Note. Removed due to sensitive data.

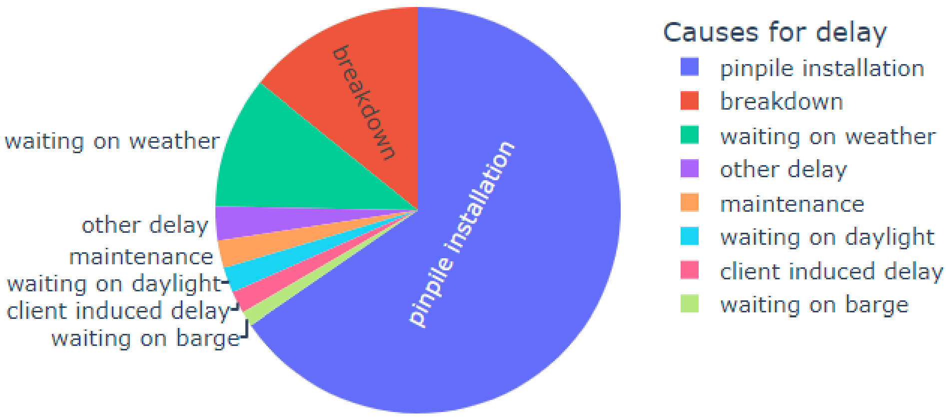


Figure 4.3: Share of breakdown during pinpile installation in spring and summer seasons.

4.2.3. Equipment and operations

The durations of equipment breakdown are also examined per equipment type to determine which types of equipment are most sensitive to critical breakdown, see Figure 4.4.

The histogram shows the summed normalised durations of the downtime per equipment type. It is also indicated by the different colours what the downtime is per operation for each type of equipment. The values are normalised based on the durations of the cases of breakdown and then accumulated. This means that the value of 1 represents the longest duration of one case of equipment breakdown, in this histogram that is one case of breakdown at one of the mooring assist tugs. All bars represent the total breakdown duration for that type of equipment.

The bars can consist of multiple cases of breakdown, therefore also values higher than 1 may occur.

Breakdown of the hammer, mooring assist tug, hammer umbilicals and FLRT result in the highest total downtime. The most affected operations by equipment breakdown are pile driving and pile stabbing (see also Appendix B). Breakdown to the main crane of the installation vessel also caused downtime to the entire operation. Jacket installation is less affected by breakdown, because jacket installation requires less equipment than other operations. This also explains why pinpile installation is more sensitive to downtime due to equipment breakdown than jacket installation.

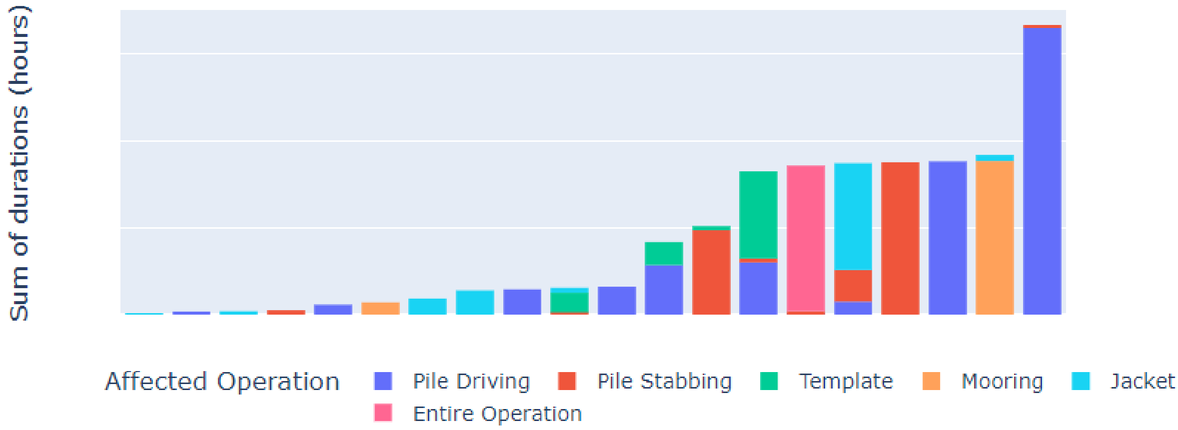


Figure 4.4: Histogram of breakdown per equipment type.
Note. Axes removed due to sensitive data.

4.3. Occurrence of equipment breakdown

Patterns of breakdown were analysed by looking into breakdown during the project. The hammer and FLRT are both studied in detail to see when equipment tends to cause critical breakdown, because they have both a distinct breakdown pattern.

4.3.1. Project overview

An overview of breakdown durations is given in Figure 4.5 to examine when equipment breakdown occurs. The topfigure (A) shows boxplots of the duration of equipment breakdown during the project, for both jacket installation and pinpile installation. The values are normalised, so a breakdown duration of 0.02 means 2% of the longest downtime duration. The middle figure (B) shows a histogram of the number of breakdowns per period for both pinpile and jacket installation. The values on the y-axes show the number of breakdowns in one period, as a percentage of the total number of breakdowns for either pinpile installation or jacket installation. The bottom figure (C) indicates the number of completed installation cycles per period for pinpile installation, as well as for jacket installation, as a the percentage of the total number of installation cycles per type.

From Figure 4.5 can be concluded that pinpile installation suffers more from equipment breakdown than jacket installation, which corresponds to the analysis in Figure 4.1. Jacket installation encounters breakdown mostly in the last periods of the project, while pinpile installation faces breakdown during every period that pinpile installation is executed. Most breakdowns during pinpile installation have short durations, except for some outliers. These outliers are breakdowns of the hammer, template, FLRT and issues at one of the support vessels.

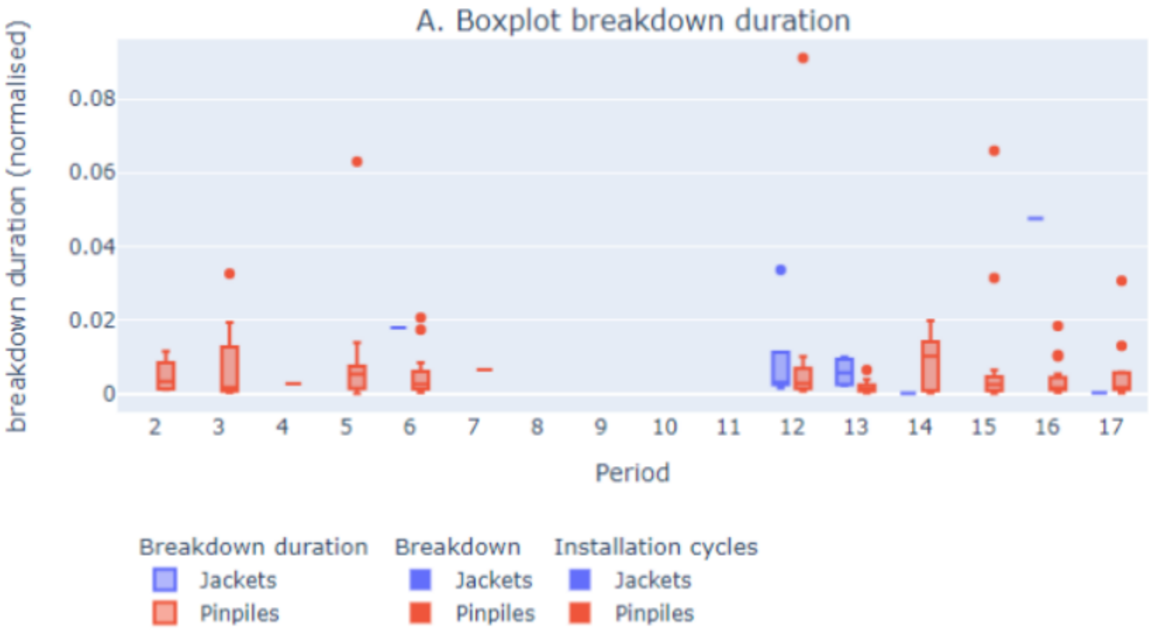


Figure 4.5: Overview of breakdown duration and number of cycles during the project for both jacket and pinpile installation.
Note. B and C removed due to sensitive data.

4.3.2. Hammer

An overview of breakdown and usage of the hammer is included in Figure 4.6. The top figure shows a boxplot of breakdown of the two hammers, as one spare hammer was on board. The values are normalised based on the maximum duration for downtime. A value of 0.2 means a duration of 20% of the longest case of downtime. The bottom figure shows the division of number of breakdowns over the studied periods in red. A percentage of 10 means that 10% of the total number of breakdowns of the hammer occurred in that period. The percentage of installation cycles where the hammer is used are also included in the bottom figure in green. A value of 10 % means that 10% of the installation cycles using a hammer were completed in that period.

At the start of the project, the hammer had start-up issues due to design flaws. Some of the breakdowns were fixed by switching to the other hammer. However, at the end of the project the downtime due to breakdown of the hammer took a long time compared to the other cases of hammer breakdown, even if it was solved by replacing the hammers. The hammers were revised during the installation break halfway the project. Nevertheless, both hammers faced several cases of breakdown in the second half of the project. Since some breakdowns concern the same component, equipment might remain vulnerable after a repair on the critical path.

Figure 4.6: Overview of breakdown duration, percentage of breakdowns and percentage of cycles of the hammer per period.
Note. Removed due to sensitive data.

4.3.3. FLRT

The FLRT is also studied in detail. An overview of breakdown and operations of the FLRT during the project is included in Figure 4.7. The top figure shows a boxplot of the breakdown durations. The durations are normalised based on the maximum value for downtime. A value of 0.1 means that the downtime is 10% of the longest case of breakdown, which is not necessarily a case of breakdown. The bottom figure shows the division of completed installation cycles during the project as a percentage of the total number of cycles in green. A value of 5 means that in that period 5% of the total number of installation cycles using the FLRT was used were completed. The red bars in the bottom figure represent the percentages of number of breakdown during the project. a value of 10 means for example, that 10% of the total number of FLRT breakdowns occured in that period.

It can be concluded that the FLRT only faces critical breakdown near the end of the project, although the equipment was used during the entire project (see Figure 4.7 bottom figure). Furthermore, the number of breakdowns on the critical path increases over the measured periods. This could mean that the equipment was degraded by wear and tear during the project, which was not diminished by preventive maintenance. Moreover, the first breakdown was caused by an incident, which could also mean that equipment remains vulnerable to breakdown after incidents and repairs.

Figure 4.7: Breakdown duration, percentage of breakdowns and percentage of cycles of the FLRT per period.
Note. Removed due to sensitive data.

4.4. Conclusion

The installation data-set of one offshore wind installation project was analysed in this case-study. From the data-analysis is concluded that waiting on weather is the largest share of downtime, followed by equipment breakdown. Weather conditions are already included in the installation planning, especially during autumn and winter. However, equipment breakdown is lost uptime and causes downtime during the spring and summer, when most installation cycles are completed. During spring and summer seasons, equipment breakdown is the largest cause of downtime during pinpile installation. Pinpile installation is more sensitive to equipment breakdown than jacket installation, because pinpile installation requires more equipment. The three pieces of equipment that caused the most downtime are the hammer, FLRT and the template.

In section 4.3 the breakdown during the project was analysed. There is not a specific moment during the project where breakdown occurred, because equipment broke down during every period that installation was performed. However, from the data-analysis some specific causes for critical breakdown were deducted:

- Wear and tear of equipment
- Design flaws caused start-up problems
- Repaired equipment remains vulnerable
- Offshore conditions (current, rocks, corrosion due to seawater)

III

Analyse

5 Root-cause analysis

In the case-study causes for equipment breakdown on the critical path were identified. However, these causes only explain the breakdown, but not the downtime. Therefore, a root-cause analysis is performed to identify underlying reasons for downtime due to equipment breakdown. This will answer the research question, *'What are root causes for downtime due to equipment breakdown in offshore wind installation?'*.

5.1. Expert opinions

Interviews with experts are conducted to get more insight in the underlying causes for downtime and equipment breakdown. See Appendix C for details of the interviews. During the interviews, several causes were mentioned for equipment breakdown in offshore wind installation. The answers from these interviews are used to compose a problem-hierarchy analysis and an Ishikawa diagram.

The equipment that is used for offshore wind installation is specifically designed for this purpose. The equipment is very expensive, which adds to high day rates for the vessels that are used in offshore wind installation. Next to that, some of the equipment is too expensive to buy another piece of equipment as spare equipment to replace failing equipment. The space on deck of installation ships is limited. Some equipment, for example a template, is too big to store a second one on board.

Equipment is often rented, so the user is not always the owner of the equipment, which complicates the repair. The mechanics on board are skilled, but do not always have the skills and knowledge to repair the rented equipment. Additionally, there is a lack of specialized mechanics in general.

The logistic schedules for offshore wind installation are tight. There are multiple contractors that are one site, who all have their own planning. Additionally, the day rates for the ships are high, because there are highly specialized and scarce. Modelling the logistics is used to reduce installation duration and costs, but this comes with uncertainty and risks, like weather conditions and failure. The installation site has a long distance to shore, so all required spare parts and tools for repair need to be on board. A Failure Mode Effect and Criticality Analysis (FMECA) is conducted to anticipate possible failure effects of the equipment and to determine which spare parts and tools are required on board.

Offshore wind installation is a relatively new industry, with stakeholders transferring from other industries. Limited preventive maintenance is performed on equipment for offshore wind installation, because this was not required in the oil and gas industry, due to unique processes. However, offshore wind installation uses equipment in repetitive cycles, so the equipment is used more frequently. Equipment wears out during usage, this makes equipment in offshore wind more prone to equipment breakdown than in the oil and gas industry. Seawater affects the equipment by corrosion. Usage and breakdown data is recorded, but limited due to new stakeholders and rapid development of equipment and project size. Equipment is also used under heavier conditions that what it was designed for, for example longer usage under offshore conditions, which makes the equipment more vulnerable to breakdown.

If equipment fails, corrective maintenance like repair or replacement of the equipment is needed. In both cases, the installation process is put on hold, resulting in disruption of the supply chain and downtime. This also comes with extra costs, as the ships are payed per day. When the installation is delayed, the weather conditions might be different than what was anticipated for. Especially at the end of the installation season this can cause extra downtime as the weather conditions approach the allowed limits for daylight, wave height and wind speed.

5.2. Problem-hierarchy analysis

An overview of the aforementioned causes and effects of equipment breakdown during installation of offshore wind projects is presented in Figure 5.1. Causes are indicated by blue boxes, effects are indicated by purple boxes. A clear distinction can be made between the logistical side and maintenance side of the problem, indicated by the orange dashed line.

At the left side of the diagram in Figure 5.1, equipment breakdown is induced by maintenance issues. For example, when scheduled preventive maintenance is postponed, because the weather conditions are good for installation. Then, installation is preferred over preventive maintenance. Moreover, limited data is available on equipment breakdown, because the offshore wind sector is under continuous development. Especially the repetitiveness of the operations requires a different mindset regarding preventive maintenance. The design process of equipment is difficult, because equipment can only be tested on scale. This gives a accurate impression of what the conditions in reality might be, but not everything can be tested for. Additionally, equipment is sometimes used longer than designed for. When equipment breaks down during installation, corrective maintenance is required on the critical path. This results in disruption of the logistics chain, delay of the installation and higher costs. As a consequence of the downtime, weather conditions might change, which can lead to more waiting on weather.

Although equipment breakdown itself is not a logistical problem, it can have a severe logistical impact, in the form of downtime and higher costs. At the right hand side of the diagram, the causes of these logistical implications of equipment breakdown are shown. The equipment is highly specialized, and therefore expensive. This adds to the high day rates of the installation vessels as well. Furthermore, equipment is big, which limits the space for spare equipment. Moreover, some of the equipment is too expensive to bring a spare equipment to replace damaged equipment. The logistics planning of an offshore wind project is tight, because it depends on favorable weather conditions. Next to that, vessels and equipment have high day rates. The planning is also complicated by the different (sub)-contractors that are involved, who have their own schedules as well.

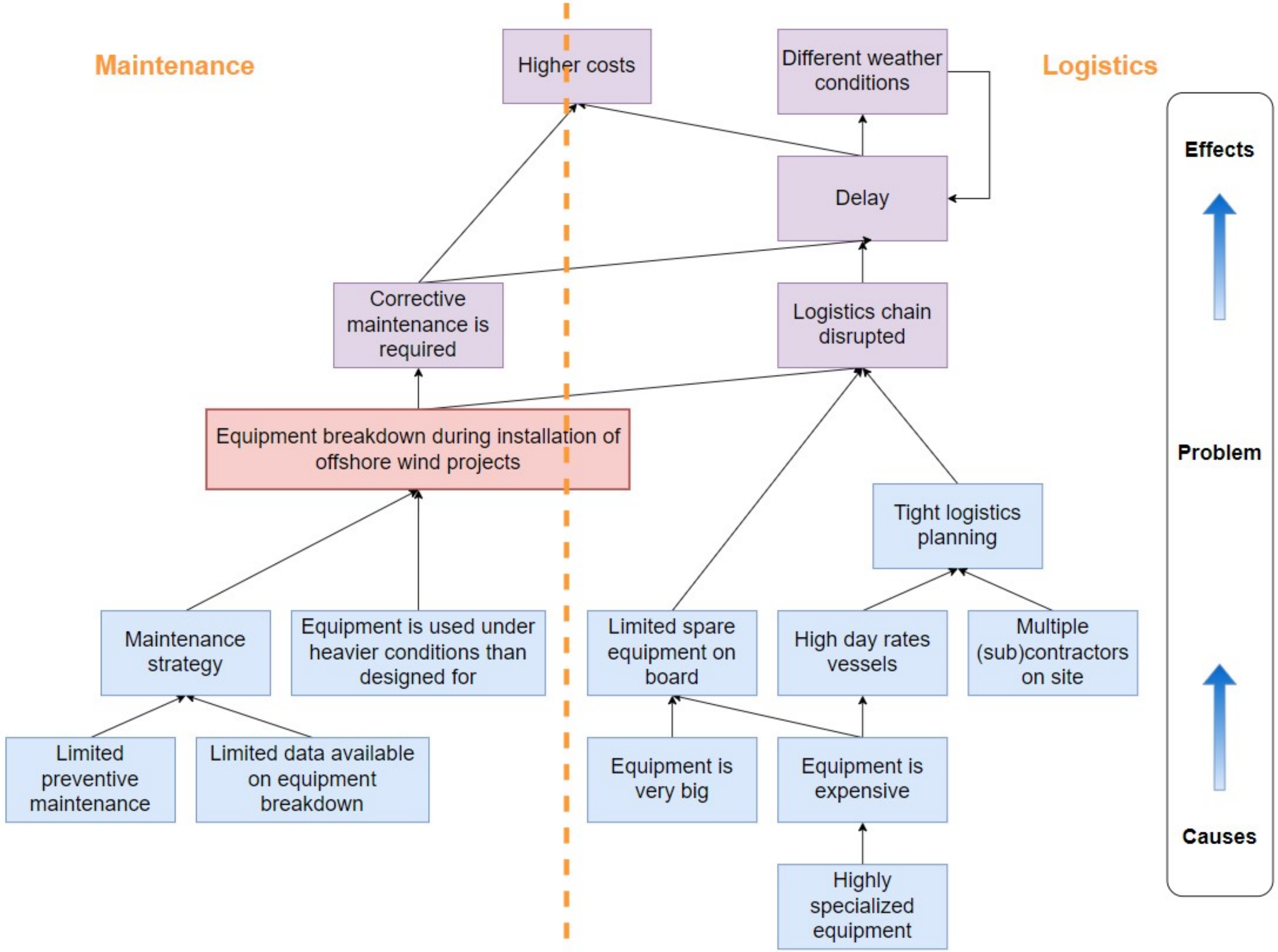


Figure 5.1: Overview of causes and effects of equipment breakdown during offshore wind installation projects.

The causes and effects of equipment breakdown in offshore wind installation projects are used to compose a problem hierarchy analysis. The problem hierarchy analysis is presented in Figure 5.2. A problem hierarchy analysis is used to find underlying causes and incentives to solve the original problem (Wang et al., 2021). It shows the cause and effect of the original problem and links the original problem to a broader problem and a narrower problem.

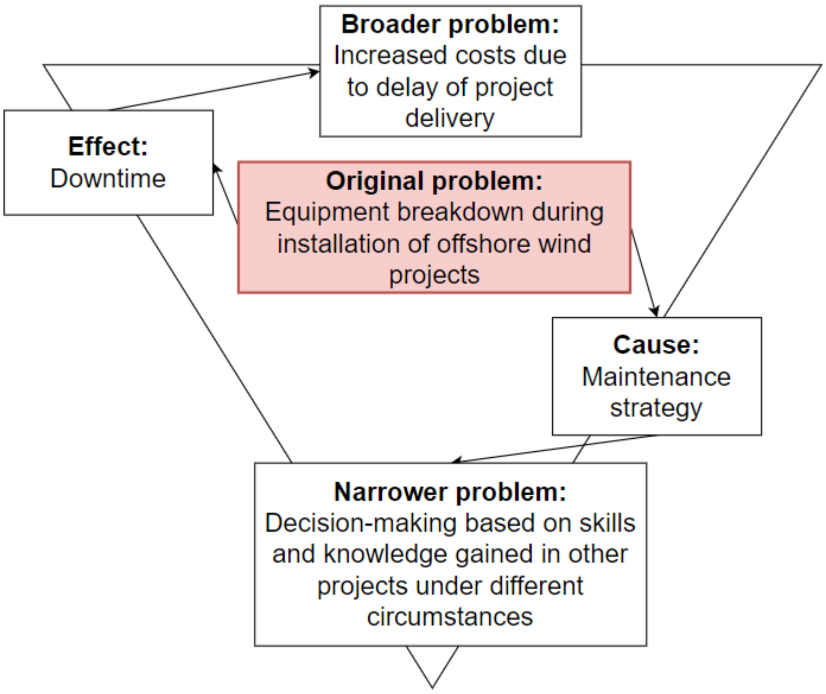


Figure 5.2: Problem hierarchy analysis.

5.3. Ishikawa diagram

The Ishikawa diagram is included in Figure 5.3. An Ishikawa diagram is a qualitative method that is used to identify underlying causes for a problem (Rodgers and Oppenheim, 2019). It gives an overview of all underlying causes and sub-causes for downtime due to equipment breakdown. The causes are divided into different categories: methods, machinery, manpower, measurements, materials and environment.

Favourable weather conditions are prioritized over preventive maintenance offshore. This means that scheduled preventive maintenance might be postponed to continue installation. However, there is limited time for preventive maintenance outside of the critical path. In case of equipment breakdown, the corrective maintenance needs to be performed on the critical path, which causes downtime. Furthermore, even though logistic simulations provide an installation schedule which accounts for favourable weather conditions, these simulations still contain uncertainty and risk.

There are also underlying factors with respect to the machinery that make that critical breakdown causes downtime. When preventive maintenance is postponed, the equipment is longer used than designed for. Additionally, the testing environment for equipment can never fully mimic the offshore environment. Some of the equipment is rented, which makes that the owner of the equipment is also responsible for the availability of the equipment. However, the interests of the owner of the equipment might not be he same as the installation contractor.

The equipment is often modified for a project, because each project requires specific tailoring of the equipment to the components and vessels. This complicates repair and maintenance. Repairing equipment on the critical path always causes downtime, because it takes time. Even replacing the failing equipment by a spare equipment takes time. Moreover, not all equipment can be replaced by a spare, because there is limited space on deck to store a spare equipment and bringing spare equipment is expensive.

Man power needs to be considered as well when explaining the downtime on the critical path due to equipment breakdown. In general, it is difficult to find specialized mechanics. The staff on board of the vessels is skilled, but more focused on the vessel than the equipment. Unexpected breakdowns require the mechanics to be flexible, next to their regular workload. The different contractors all have their own objectives, which is a potential conflict of interest. Next to that, mutual contracts include very strict agreements on liability in case of delay of the project. Another manpower related factor in the downtime due to equipment breakdown is that offshore wind is a new industry. Stakeholders from other industries enter an emerging market. Established knowledge and skills may be outdated or have to be applied in a different manner. This requires flexibility and learning capacity to keep up with technological developments.

Measurements are a key factor in explaining downtime due to critical breakdown. Currently, data is collected for commercial purposes. This means that the available data might be biased. Furthermore, data-sheets are filled in manually, which is vulnerable to errors and personal judgement. Survey equipment and sensors are also sensitive to critical failure. Regarding measurements, it needs to be considered that seasonality might explain differences in cycle times and downtime. To reduce downtime due to critical breakdown and to learn from previous projects it is important to define which data needs to be collected during the project to improve processes in future projects.

Material also plays an important role in downtime on the critical path due to equipment breakdown. Equipment wears out during usage, due to heavy loads, repetitive cycles and offshore conditions. It is essential to bring spare parts on board to save time in case of breakdown. Currently, it is determined before the project starts which spare parts are critical and are needed on board to reduce downtime. This also holds for the tools that are required for repairs.

Lastly, environmental factors cause downtime as a result of equipment breakdown. The installation site has a long distance to shore, so all people, spare parts and tools required for repair have to be on board, because sending them over takes time. Furthermore, weather conditions like daylight, current, waves and wind limit operations. Hence, downtime on the critical path, such as equipment breakdown, may result in extra downtime when weather limits are exceeded. Equipment corrodes due to the exposure to seawater for a longer period. Rocks can cause downtime due to critical breakdown by jamming pipes.

Not all causes can be influenced, like environmental causes. Causes in the other categories can be adjusted, however categories like machinery and materials are more rigid to change than man power, methods and measurements.

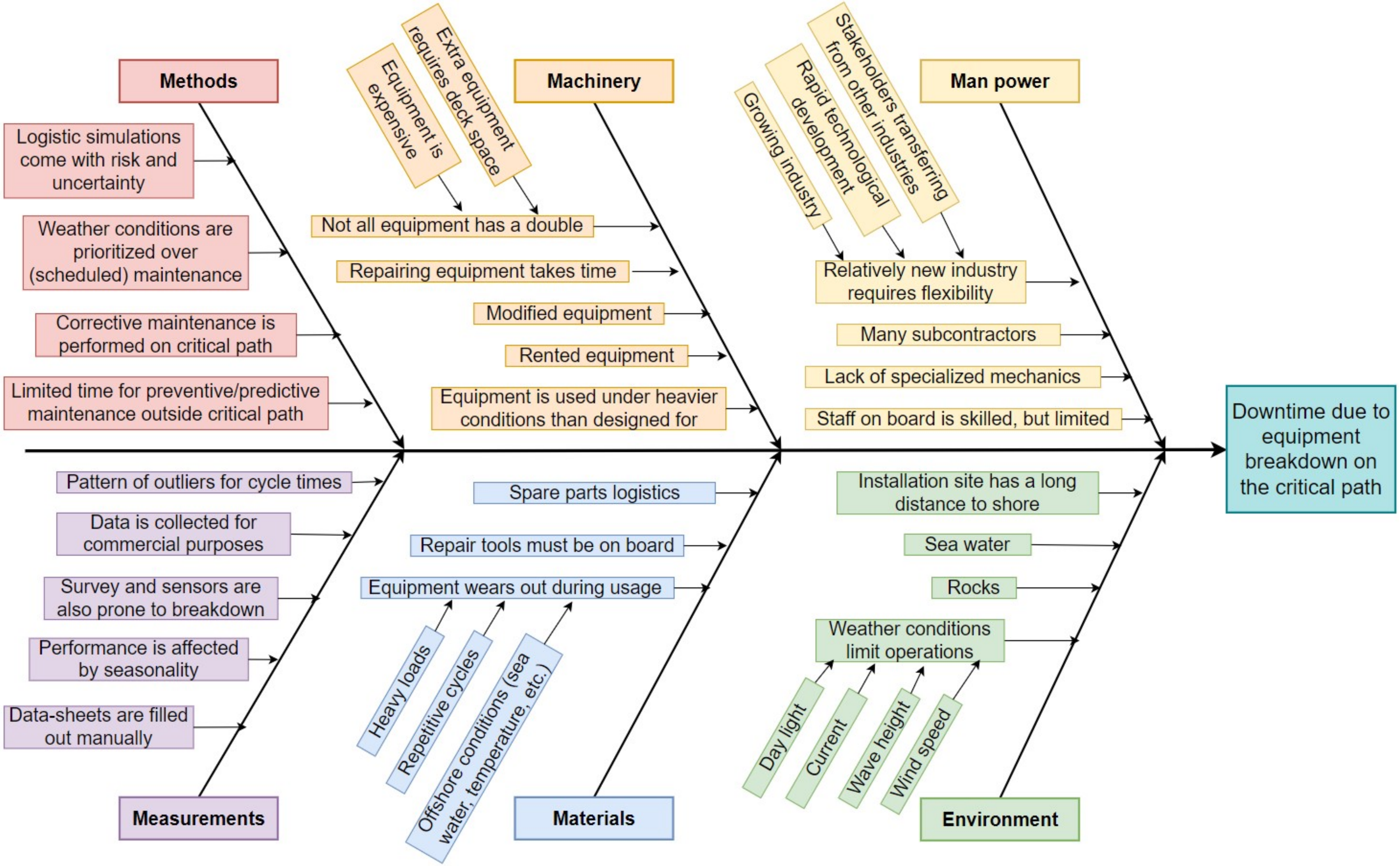


Figure 5.3: Ishikawa diagram.

5.4. Conclusion

Downtime on the critical path due to equipment breakdown is complex to reduce due to the many different factors that play a role. Root-causes for downtime induced by critical breakdown are identified based on expert opinions, a problem hierarchy analysis and an Ishikawa diagram.

Root-causes for critical breakdown are:

- equipment wears out during usage
- prioritizing operations over preventive maintenance due to favourable weather conditions
- limited time for preventive maintenance outside critical path
- offshore conditions (seawater, rocks)

Root-causes for the downtime on the critical path are:

- repairing equipment takes time, including replacement by spare(parts)
- established skills and knowledge in other industry are applied in offshore wind installation, but are not applicable due to different circumstances
- conflict of interest with different stakeholders
- biased data-collection

The underlying problem of equipment breakdown in offshore wind installation projects is the decision-making based on experiences under different circumstances. This makes that the effect of decisions can be different than intended or foreseen. The incentive to reduce downtime caused by equipment breakdown is that when the project delivery is delayed, the costs for installation of the offshore wind project increase, due to the high dayrates of the used vessels.

IV

Design & Verify

6
Model

In this chapter the model is explained. First, the requirements of the model are described. Then, relevant key performance indicators (KPI's) for reducing downtime due to equipment breakdown are evaluated. Next, the use of Discrete-Event Simulation (DES) for offshore wind purposes is discussed. Furthermore, the model is described. Last, the model is validated.

6.1. Requirements

The research question *'What requirements should be fulfilled to manage downtime due to equipment breakdown during offshore wind installation?'* is answered is this section. The design should comply to these requirements to meet the objective of this research.

The requirements are divided into constraints and objectives. Constraints are obligatory requirements, this means that the design must comply to these requirements. Furthermore, constraints are binary: the design either satisfies the constraint or not (Bahill, 2009). Objectives are preferences for the model. It is aimed to comply as much as possible to objectives, often scores or rankings are applicable. The constraints and objectives are also divided into functional and non-functional. The things the system has to do are functional requirements. Attributes of the system are the non-functional requirements (Van Binsbergen, 2020).

The requirements of the design are presented in Figure 6.1. Weather conditions are a functional constraint, because installation can not be performed if operational limits are exceeded. It is chosen to only examine installation during spring and summer seasons, because equipment breakdown is mainly an issue during those seasons (see chapter 4). During winter and autumn, there is more downtime due to unfavourable weather conditions, so preventive maintenance can be performed during waiting on weather windows. Therefore, 40 turbine installations will be modelled. This is the number of installations that were installed in the case-study in one consecutive spring-summer season. Only preventive maintenance on the critical path is modelled, because the model is based on the failures of the hammer on the critical path in the case-study in chapter 4. It is assumed that activities during waiting on weather windows are equal to the case-study, so there is no more room for extra activities in those windows. Another functional constraints is the availability of components on the yard. It is assumed that pinpiles and jackets are always available on the yard, because the supply chain of the components to the yard is not within the scope of this research.

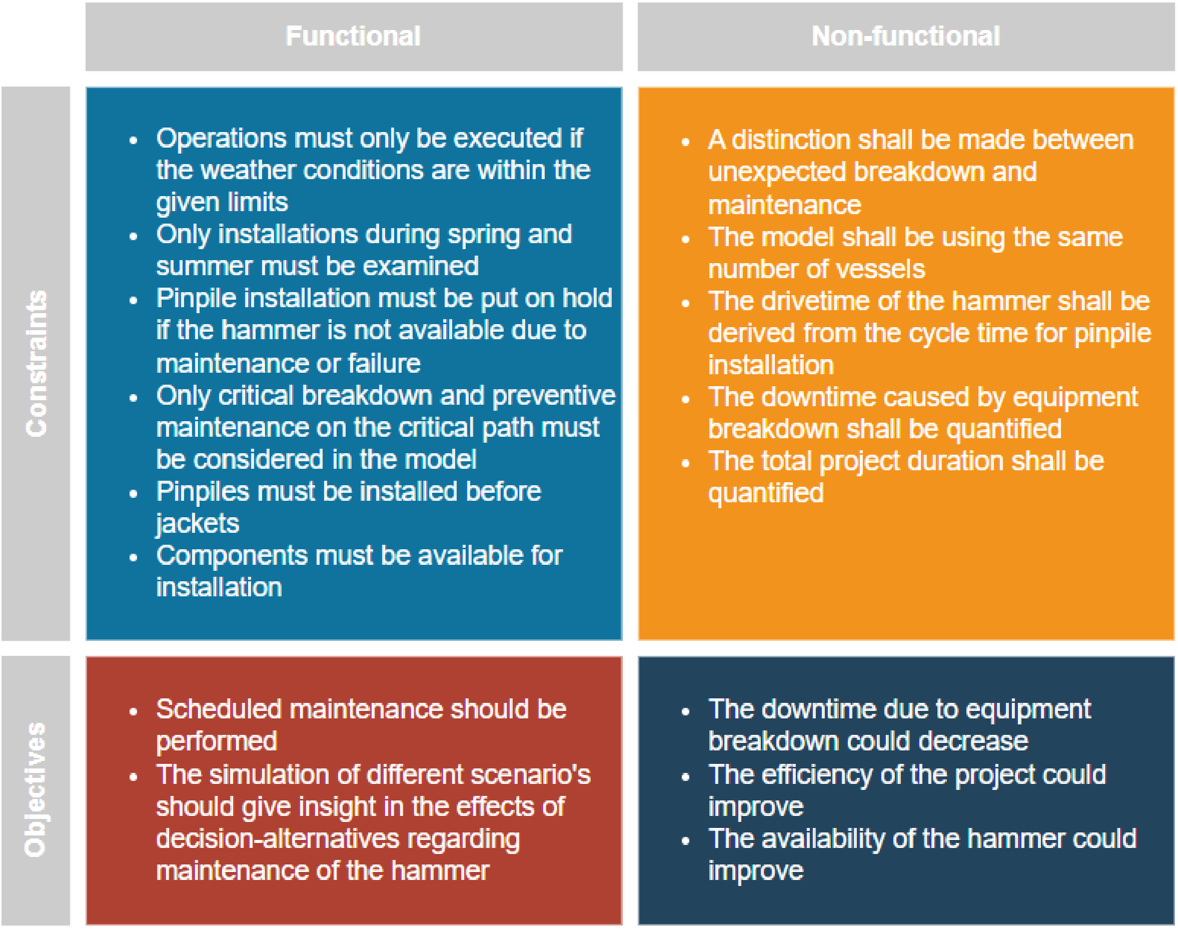


Figure 6.1: Requirements

Non-functional constraints are mandatory attributes of the model. To determine if the downtime due to equipment breakdown reduces, it is required that preventive maintenance and unexpected breakdown are recorded as different activities. Furthermore, it is assumed that the whole project is carried out with the same number of vessels (barges, HTV's and installation vessel) throughout the simulation. The drive time of the hammer in the model shall be derived from the cycle time for pinpile installation. Pile driving is one of the activities that are part of the total pinpile installation cycle. It is assumed that pile driving has the same share in each cycle of the pinpile installation cycle. Therefore, the drive time of the hammer follows the same distribution as the distribution of the pinpile installation cycle.

Performing scheduled preventive maintenance when planned is a functional objective of the model. The objectives of the model should match the objectives of this research. Therefore, the simulation of different scenario's should give insight in the effects of different maintenance strategies for the hammer. Furthermore, the downtime due to equipment breakdown could decrease, the efficiency of the project could improve and the availability of the hammer could improve.

6.2. Key Performance Indicators

In this section, the sub-question *'What are relevant key performance indicators to assess equipment breakdown on the critical path of an offshore wind installation project?'* is answered. The KPI's are determined by analysing quality drivers for offshore wind logistics in general, which are not necessarily the same as the objective of this research. Interviews are used to determine the KPI's. Details about the interviews can be found in Appendix C.

CTQ factors are used to convert objectives into measurable criteria that comply to the quality requirements for the design (He et al., 2010). The CTQ tree is depicted in Figure 6.2.

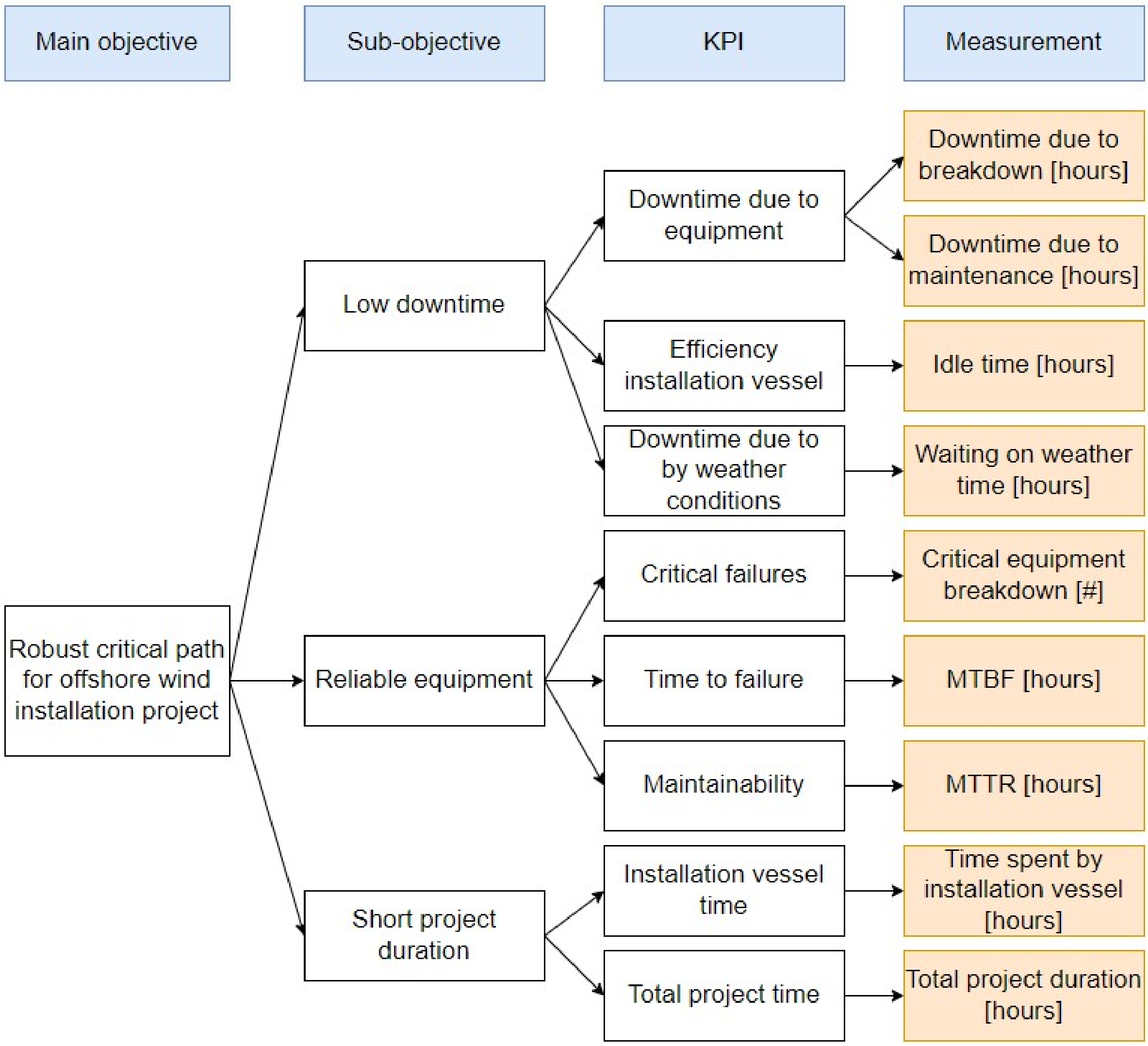


Figure 6.2: Critical to quality tree.

The main objective is defined as 'robust critical path for offshore wind installation project'. Low downtime, reliable equipment and short project duration are required to accomplish this objective. The KPI's and measurements for these sub-objectives are explained hereafter. The KPI's are selected based on the conclusions from the case-study (see chapter 4), interviews (see Appendix C) and root-cause analysis (see chapter 5).

From the interviews, it is concluded that the critical path is leading in offshore wind installation projects. Therefore, a robust critical path for offshore wind installation projects is selected as main objective. The Critical Path Method (CPM) is a method that is used to minimize the time required to complete projects that require different activities to be performed within a certain order, where the critical path is defined as the shortest path connecting all required activities (Atin and Lubis, 2019). CPM focuses on value-adding activities and throughput, rather than optimizing the flow (Lerche et al., 2022a). The critical path of offshore wind installation includes mostly installation activities; preventive maintenance is scheduled and performed outside of the critical path as much as possible. However, when breakdown occurs, it can not be avoided to repair the equipment, which causes downtime.

Low downtime is a sub-objective of a robust critical path. By reducing the downtime, the project can be executed with the least delay. Delay is the time that is spend more than planned for on the critical path (Atin and Lubis, 2019). The KPI's for reducing downtime are categorized into: downtime due to equipment, efficiency of the installation vessel and downtime due to waiting on weather. Downtime due to equipment is divided into downtime due to equipment breakdown and downtime due to preventive maintenance on the critical path. Efficiency of the installation vessel is measured as idle time, which is defined as time during the project when processes on the installation vessel are put on hold (Ottesen, 2019). In offshore wind, this is for example when installation is stalled, because the no new components are available to install. Waiting on weather is measured as a separate category, because the weather conditions can not be influenced. During waiting on weather windows all activities take place that are not critical, yet necessary.

Reliability of the equipment is another sub-objective in a robust critical path for offshore wind installation projects, because downtime due to equipment breakdown should be reduced. Reliable equipment is measured as the number of critical breakdowns, the time to failure and maintainability of the equipment. The time to failure is measured by Mean Time between Failures (MTBF), this is the time the equipment functions without failure and is calculated by dividing the total operating time by the number of failures. So, the MTBF is related to the number of failures. If breakdown occurs, it is important that the equipment can be easily repaired or replaced. This reduces the downtime due to equipment breakdown. The maintainability of the equipment is measured by Mean Time to Repair (MTTR), this expresses the time that is required to repair the equipment after critical breakdown and is calculated by the total downtime due to equipment breakdown divided by the number of breakdowns. Hence, the MTTR is related to the number of breakdowns and to the downtime due to equipment breakdown. Even though the MTBF and the MTTR are related to other KPI's, they give insight in the reliability of the equipment itself.

Another sub-objective of a robust critical path for offshore wind installation projects is a short project duration, mainly for economical reasons. KPI's for a short project duration are time spent by the installation vessel and the total project duration. Since there are more vessels involved in the offshore wind installation project than the installation vessel, the total project duration is not necessarily equal to the time spent on the project by the installation vessel. It is important to consider both KPI's, because only the equipment on board of the installation vessel is within the scope of this research. However, measures on board of the installation vessel can still affect the performance of the whole installation project and other vessels involved in the project.

6.3. Discrete-event simulation for offshore wind installation

The in-house discrete-event simulation software Metis of HES is used to build the model. In this section, it is explained why Discrete-Event Simulation (DES) is a suitable method to simulate offshore wind logistics, how it will be applied in this research and what the added scientific value is of this model compared to previous applications.

DES is a widely used simulation method that is applied in offshore wind to reduce downtime due to bottlenecks in logistics scheduling of offshore wind installation projects. The method can be used to simulate repetitive and sequential activities, in particular when these activities depend on external constraints (Vis and Ursavas, 2016). DES is suitable for the simulation of offshore wind logistics, because it enables the simulation of repetitive installation cycles for each turbine. Moreover, the dependence on weather limits for operations is possible to simulate by using DES (Oelker et al., 2021).

In DES, a system is modelled as a collection of objects performing a series of sequential activities in discrete time (Tako and Robinson, 2018). In this model, vessels transport and install the components of an offshore wind turbine at a windpark on a dedicated location, while testing operational limits against historical weather data. The model is simulated multiple times, which is called Monte-Carlo simulation. By applying Monte-Carlo simulation, the weather conditions are varied for each run of the simulation. Each run of the simulation simulates the weather conditions in one year in the historical data-set. Furthermore, the start dates of the project are varied in each run around a specific date. After a large number of runs of the model, the average results converge to a final, statistical relevant value that can be used for comparison of the designs. The variability between different runs shows the uncertainty of the results (Muhabie et al., 2018). In the validation of the model, later in this chapter, a Monte-Carlo experiment is conducted to show how many runs are required for the total breakdown duration to converge to a final value.

In chapter 3 it is described how DES is already applied to reduce downtime in offshore wind installation. In this research, DES is used to simulate the logistics schedule of an offshore wind installation project, not only to reduce downtime due to exceedance of weather limits, but also to examine how downtime caused by breakdown on the critical path can be reduced. Similar to previous scientific studies where DES was applied, this model simulates the supply chain from the marshalling yard to the installation site offshore and includes the constraint of weather conditions to operations. Additional to previous DES models applied on offshore wind installation projects, this model allows to incorporate equipment breakdown and preventive maintenance of the equipment in the installation schedule, which was not considered in other DES models in literature.

6.4. Model description

In this section the model is described. Metis does not yet have a functionality to model equipment breakdown, therefore an additional module is added to Metis: 'breakdown model for the hammer'. First, an overview of the model is given where the interaction between the two models is shown. Next, the model in Metis is described. Then, the model for breakdown of the hammer is explained.

6.4.1. Model overview

An overview of Metis and the breakdown model for the hammer and their interaction is given in Figure 6.3.

Input is listed in the yellow blocks. The parameters and variables applied in the simulation are listed in Appendix D. Objects are modelled in Metis, these are listed in the orange block. Furthermore, Metis uses weather data and operational limits, this is shown in the green block. Both Metis and the breakdown model have output variables, these are listed in the grey blocks. The models interact via the exchange of variables. The total drive time for the hammer and the drive time for the coming cycle are send from the Metis model to the breakdown model. The breakdown model then calculates whether or not the hammer will fail. After that, the total drive time is updated and send back to Metis.

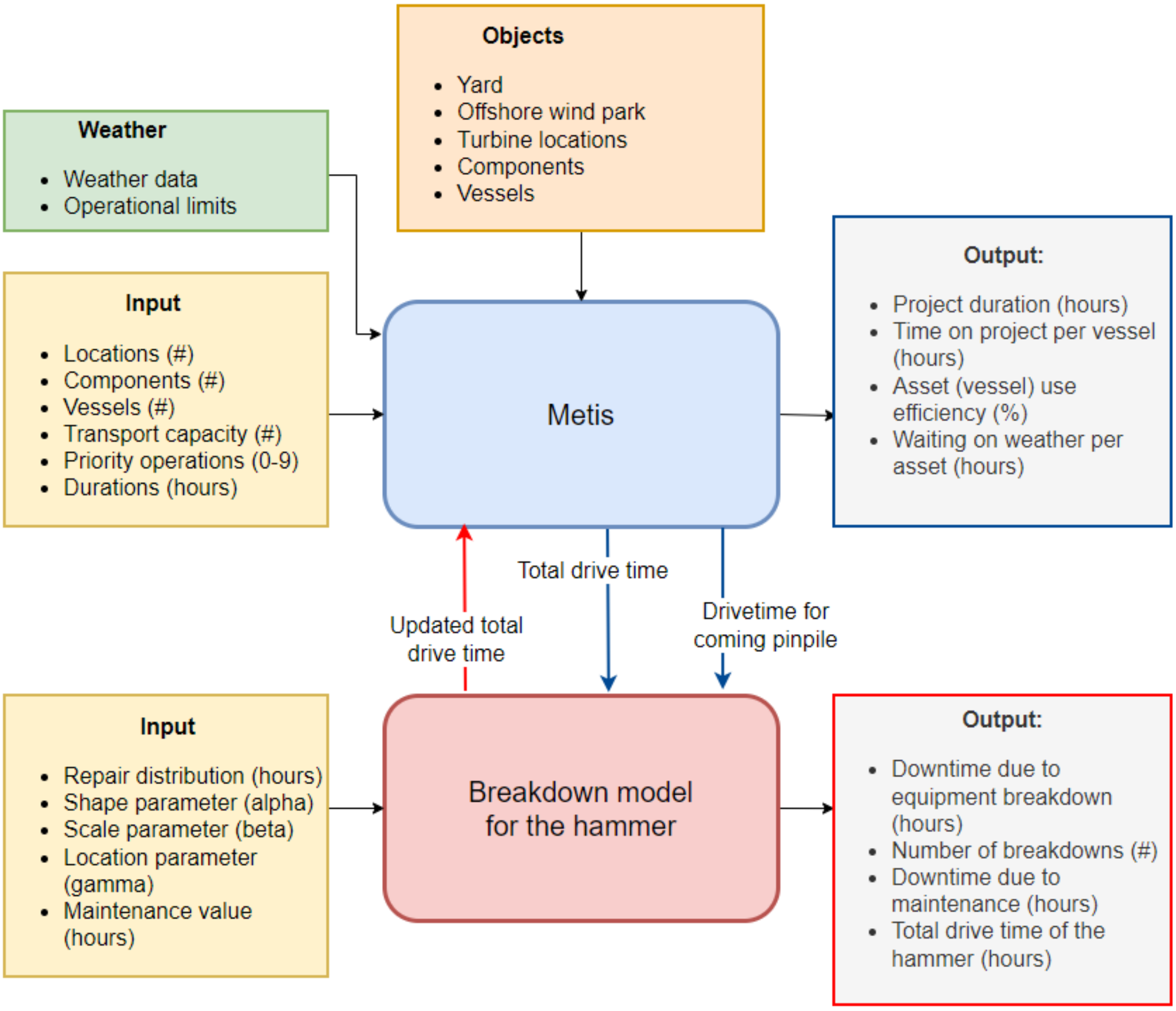


Figure 6.3: Overview of relation between Metis and hammer breakdown model.

6.4.2. Metis description

In the following sections, Metis is described by explaining the objects that are defined in the model, the input of the model, the activities that are performed, how priority is assigned to activities, how weather conditions are included in the model and the output of the model.

Objects

The yard, park, turbine locations, components and vessels are defined as objects in Metis. In this case the components that are installed are pinpiles and jackets. Barges transport pinpiles from the yard to the wind park. Jackets are transported by a Heavy Transport Vessel (HTV) from the yard to the park. A Heavy Lift Vessel (HLV) is used as installation vessel at the wind park.

Input

The input of the Metis model determines the number of locations for turbines that have to be installed, the number of components that have to be installed, the number of vessels per type that are used in the simulation and the transport capacity of the vessels. The values of the input parameters are included in Appendix D.

Activity sequences

The installation of offshore wind projects is divided into sequences of activities. Each sequence can consist of multiple activities that are executed consecutively, for example the installation sequences where the installation vessel first checks for availability of components and suitable weather conditions and then installs the component. Activity sequences are assigned to objects in Metis if needed, so objects can execute a specific task in the installation chain. The durations of the activities are given as input as well. Durations can be given as a integer or as an distribution, for example a normal distribution or a gamma distribution. The activity sequences for each object are listed below:

- Yard activities:
  - Load component on transport vessel
  - Release transport vessel from yard
- Barge and HTV activities:
  - Sail to park
  - Transfer components
  - Release component
  - Sail back to yard
- Installation vessel activities:
  - Install pinpiles (3 pinpiles are required per spot)
  - Install jacket
  - Sail to transfer spot

Priority

Each of the activity sequences are assigned a priority in Metis, where 0 is the highest priority and 9 is the lowest priority. The priority of the sequence determines in which order sequences can be executed in the simulation. This enables to give preference to one sequence over another sequence if the object has the possibility to execute different sequences. By assigning priorities, it is made sure that the model consistently carries out the sequences according to the preference of the modeller.

Constraints

Constraints can be set for activity sequences. Constraints are added to the activities to make sure that the operation can be performed. For example that three pinpiles need to be installed on a spot before the jackets can be installed. After the simulation starts the sequence with the highest priority, the constraints are checked. If the constraints are met, the activities in the sequence are executed. If the constraints are not met, another sequence might be started.

Weather conditions
Metis allows to include a weather database to simulate local weather conditions during the installation project. The weather data is historical timetrace data derived from satellite data and reanalysed by different weather models. It is important to use high quality weather data, because this enhances reliable outcomes of the simulation. The weather database is used to compare to the operational limits that are set for the vessels. In the model, operational limits are included for transferring components by the HTV and for installation of pinpiles and jackets by the installation vessel.

Output
Metis provides Gantt chart of the installation schedule as output, where each activity and waiting on weather window for all vessels is indicated in time. From the installation schedule, various output parameters can be derived, such as the total project duration, the time each vessel spent on the project, the efficiency of the vessel during the project, the idle time per asset and the number of days each vessel had to wait for weather conditions below the operational limits.

In Figure 6.4 the activity sequences in the model are depicted in a flowchart: the pinpile installation sequence, the preventive maintenance sequence and the jacket installation sequence. The decisions and processes belonging to each sequence are shown vertically under the sequences. The diamond shapes represent decisions, the rectangles indicate processes and the purple shapes show where downtime could occur. First, it is determined which activity sequence has the highest priority on the critical path. This sequence is carried out first. Then, the decisions and processes are executed for the sequence. If there are no components to install or no turbine location ready for either pinpile installation or jacket installation or the preventive maintenance threshold is not reached, it can be determined which sequence has the next highest priority. The sequences will be repeated until all pinpiles and jackets are installed.

6.4.3. Breakdown model for the hammer

In the following sections, the additions to the Metis model are explained first. Then, an overview of the breakdown model is given. Next, the calculation of the time to failure function is explained. Last, it is described how it is determined whether or not the hammer will break down and how the repairtime is determined.

Additional activities to Metis
For the breakdown model for the hammer, additions to the Metis model are made together with an additional model to determine whether the hammer will break down. The following features are added to the installation vessel in Metis (indicated in red in Figure 6.4:

- breakdown of the hammer (included in the pinpile installation sequence)
- preventive maintenance to the hammer (separate sequence added to Metis)

Overview breakdown model
The feature 'breakdown of the hammer' uses the breakdown model to determine if the hammer will break down and how long repair takes. If the hammer does not break down, the activity has a duration of 0 hours. An overview of the model structure is shown in Figure 6.5. The blue block represents the Metis model. Metis provides the variables *total drive time* and *single drive*, which are attributes of the installation vessel. The *total drive time* represents the accumulated drive time of the hammer until now. The *single drive* is the drive time of the hammer for the coming pinpile installation sequence. The drive time of the hammer is distributed according

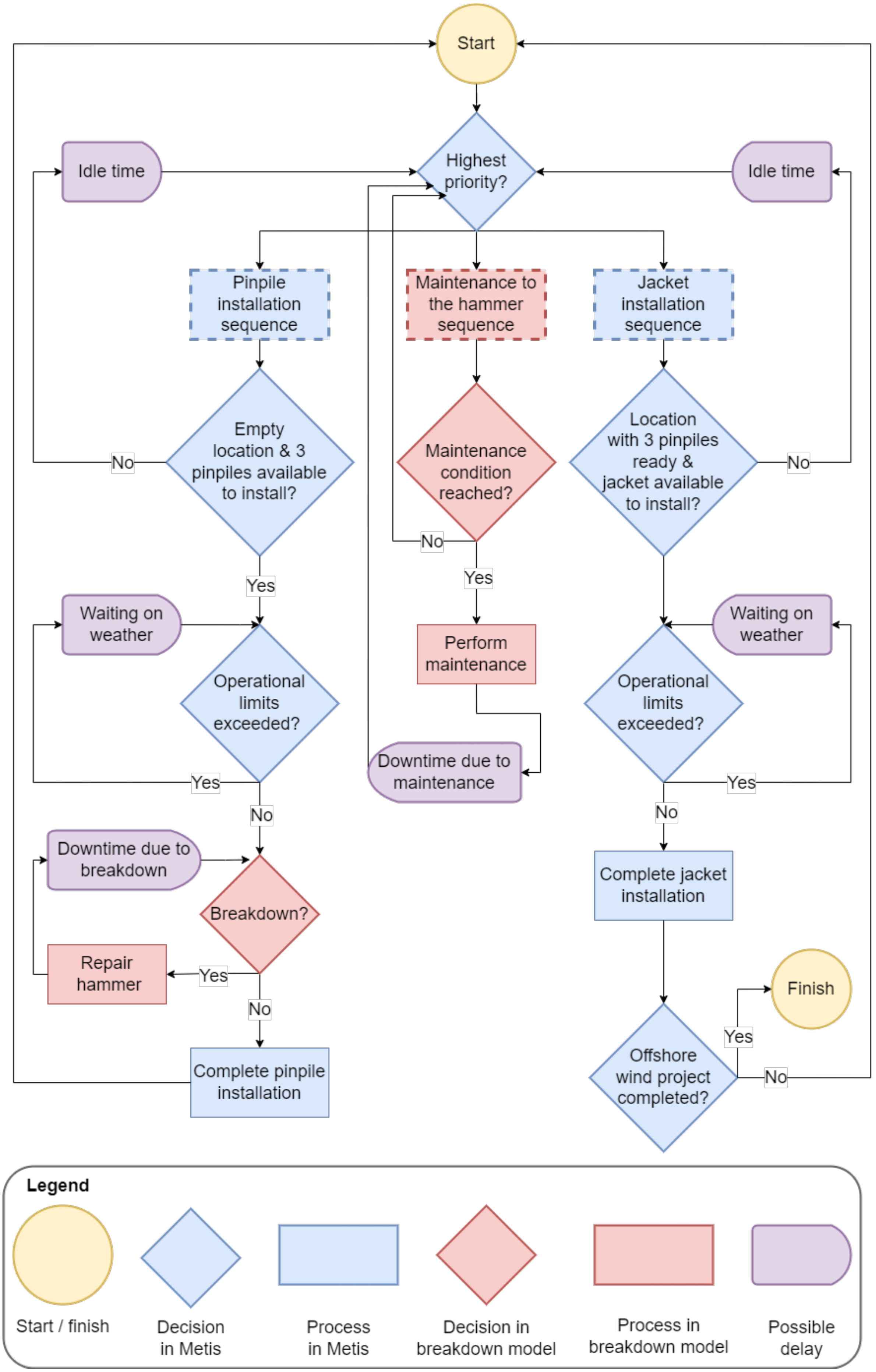


Figure 6.4: Flowchart of activities in model.

to the distribution of the cycle time for pinpile installation and therefore not the same for every cycle. In the green block, the probability of failure is calculated using the time to failure function. In the red block, it is determined if the hammer will breakdown. If the hammer breaks down, the repairtime is also generated. After the breakdown model is finished, the *total drive time* is updated and the *breakdown duration* is provided. The green and the red block are explained in detail in the next sections.

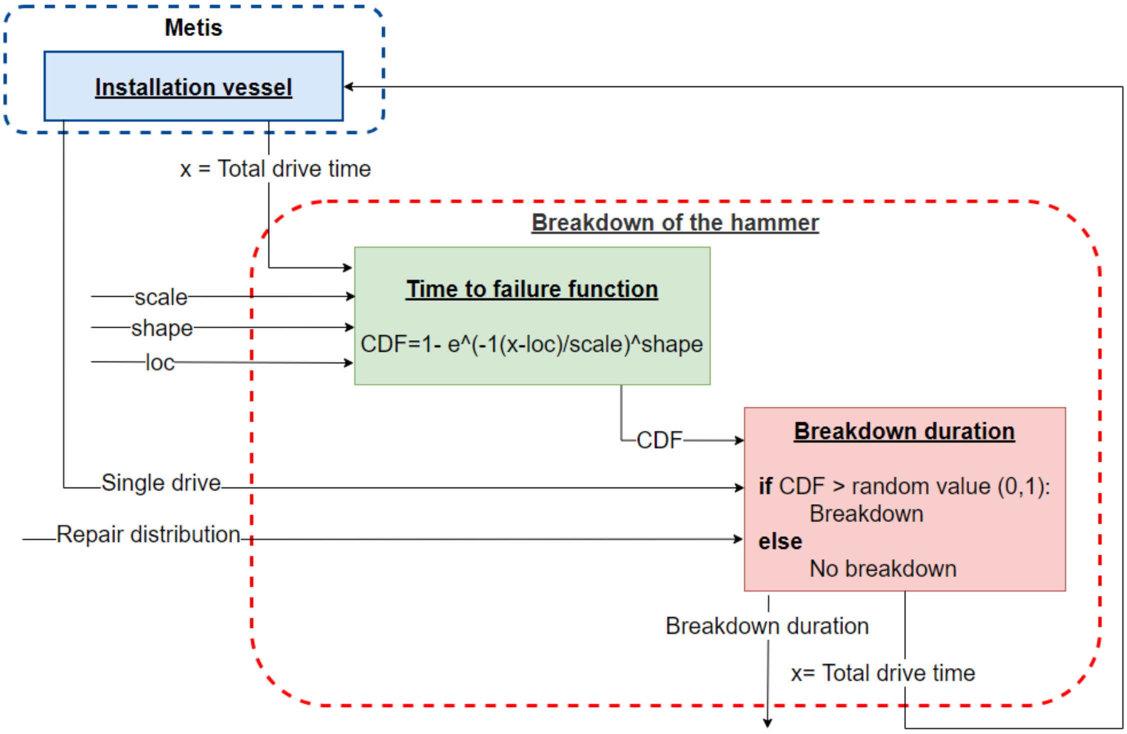


Figure 6.5: Overview of the breakdown model for the hammer.

Time to failure function

In the green block in the breakdown model, a Cumulative Distribution Function (CDF) is used to calculate the time to failure function of the hammer. Weibull and log-normal distributions are methods that are implemented to generate failure behaviour based on observed failure data (Xie et al., 2019; Zhang et al., 2022). The Weibull 3-parameter function proved to be the best fit for this distribution in the observed failure data of the hammer. The function of the CDF of the 3-parameter Weibull function is included in Equation 6.1. The calculation of the parameters of the 3-parameter Weibull distribution based on observed failure of the hammer can be found in Appendix D.

$$CDF(x) = 1 - e^{-(\frac{x-\gamma}{\alpha})^{\beta}} \tag{6.1}$$

Where:

- α : scale parameter
- β : shape parameter
- γ : location parameter
- x = total drive time hammer (hours)

Breakdown duration

The failure probability of the hammer after a certain drive time is calculated by the function in Equation 6.1. After that, a random value between 0 and 1 is drawn. The failure probability is then compared to the random value. If the failure probability is higher than the random value, the hammer will break down during the coming installation cycle. The duration of the repair of the hammer is determined by the repair distribution. Furthermore, the variable *total drive time* is set to 0, because the CDF is based on the time between failures. If the failure probability is below the random value, the hammer does not fail. The *total drive time* is then updated by adding *single drive* to the value.

Preventive maintenance to the hammer

To improve the service life of the hammer, preventive maintenance can be performed to the hammer. This activity is added to the Metis model as a separate sequence. This enables to assign a dedicated distribution for the duration of the preventive maintenance sequence. It is chosen to apply preventive maintenance rather than condition-based or predictive maintenance, because it is time-based maintenance (see Figure 3.2). Time-based maintenance works well with DES, since DES models track the duration of the activities in the model. Metis already generates the distribution for the cycle time for pinpile installation. Otherwise, sensor-data, such as the number of blows, should be included in the model as well and assigned to each installation cycle. The number of blows can also be calculated in a model, but then soil data per location is required. Preventive maintenance is performed when the threshold value for preventive maintenance is exceeded. The threshold value is included in Equation 6.2. The MTBF used to determine the threshold value is calculated based on observed failure data using Equation 6.3. The preventive maintenance threshold value is therefore static and is not affected by the failures during the simulation. After preventive maintenance, the variable *total drive time* of the installation vessel is set to 0. This is the same variable that is used to determine if the hammer will break down in the coming installation cycle. Furthermore, the preventive maintenance activity sequence is assigned a priority.

$$\text{preventive maintenance threshold value} = 0.8 * MTBF \tag{6.2}$$

$$MTBF = \frac{\text{total drive time hammer}}{\text{number of failures}} \tag{6.3}$$

6.5. Assumptions in the model

The model is a simplified representation of installation operations, equipment breakdown and preventive maintenance of the hammer. The following assumptions are made in the model for simplification:

- Only breakdown and preventive maintenance to the hammer are considered in the model. No other equipment is included in the model, but it can be implemented in the future.
- A project size of 40 turbines is assumed in the model, to ensure that the project can be completed in one consecutive spring and summer season under favourable weather conditions. Favourable weather conditions are essential in the model, to resemble a situation with limited time for preventive maintenance outside the critical path.
- The number of support vessels remains the same during the entire simulation.
- The hammer is only repaired, but not replaced. So no spare hammer is considered in the model.

- The drivetime of the hammer is derived from the distribution of the cycle time of pinpile installation.
- Pinpile installation is put on hold if the hammer is not available due to preventive maintenance or breakdown. No other activities are possible during repairing breakdown or preventive maintenance in the model, because Metis does not yet allow alternative paths. Therefore, only critical breakdown and preventive maintenance on the critical path are included in the model. In practise, preventive maintenance and repair might be possible simultaneous to other processes.
- Breakdown of the hammer is is not further specified, whilst in practice different failure modes are possible. The distribution of breakdown duration is based on all data-points for breakdown of the hammer in the observed data-set.
- Time-based maintenance is applied in the model, because this works well in a DES model. In practise, preventive maintenance is scheduled after a specific number of blows of the hammer. To implement this in the model, soil data or sensor-data would be required.
- The installation vessel can not switch to another activity sequence in the model if the weather conditions are not suitable for installation. In reality, it is possible to switch to jacket installation instead of pinpile installation for example.

6.6. Validation model

To validate if the model shows the appropriate behaviour, the distributions that are used in the model are compared to the data from the case-study. This can be found in Appendix D. Furthermore, it is determined how many runs of the simulation are required to generate stable, statistically relevant results.

In a Monte-Carlo experiment, a large number of runs of a model is simulated to get an accurate result (Chiacchio et al., 2020). In this Monte-Carlo experiment, the breakdown model is simulated multiple times to determine the number of runs that is required for accurate results of the model. First, the total breakdown duration per run is accumulated. Next, the moving average of the total downtime is calculated for each additional run. From Figure 6.6 it is determined that the average total downtime converges to 39 hours when more than 1800 runs are executed.

In the simulation, 10 start-dates around 1 April are simulated for every year in the weather database. Furthermore, these runs are repeated 4 times to reach 1848 runs in total, which should be enough to reach a stable result according to the Monte-Carlo experiment.

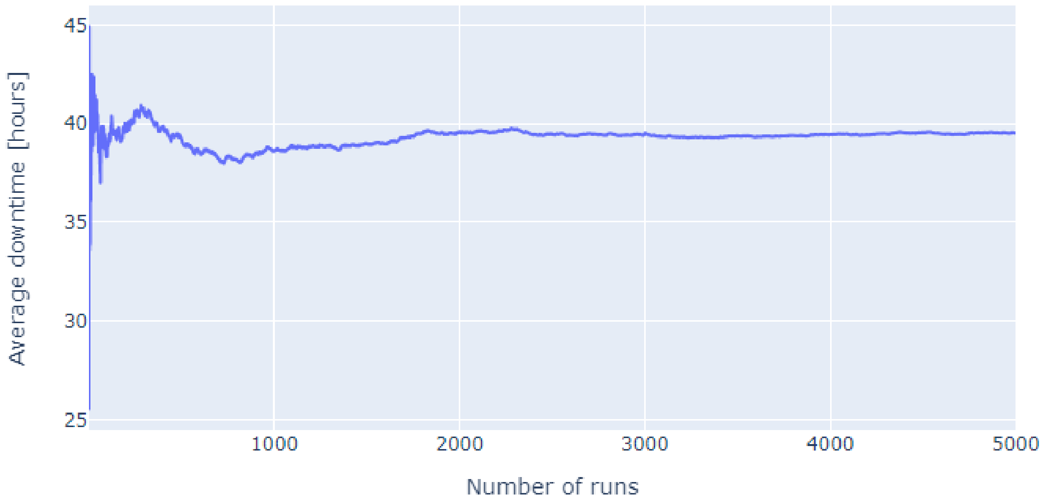


Figure 6.6: Monte-Carlo simulation of multiple runs of the breakdown model.

6.7. Conclusion

Before the model is set up, requirements of the model are identified, to reduce downtime due to equipment breakdown (see Figure 6.1). The requirements are divided into constraints and objectives, which define what the design should do and what the model should have. Furthermore, KPI's have been selected that are used to measure the performance of the model in chapter 7. The KPI's can be found in Figure 6.2 and are listed below:

- Downtime due to preventive maintenance (hours)
- Downtime due to breakdown (hours)
- Idle time (hours)
- Waiting on weather time (hours)
- Critical breakdown (#)
- MTBF (hours)
- MTTR (hours)
- Time spent by the installation vessel (hours)
- Total project duration (hours)

The in-house discrete-event simulation software Metis of HES is used to simulate large numbers of installation schedules to determine the risk of exceedance of planned installation schedules. DES is already used in previous scientific studies to simulate offshore wind installation schedules, but those studies focused mainly on improving installation schedules by considering weather conditions. In previous studies, equipment breakdown was not modelled using DES. Moreover, equipment breakdown is not yet included in Metis. To be able to simulate equipment breakdown, an additional model is added to Metis: 'breakdown model for the hammer'. This model calculates the probability of failure based on observed time to failure data (chapter 4). Additionally, the model determines how long the repair time is after equipment breakdown. The additional model also allows to include preventive maintenance to the hammer on the critical path.

In chapter 7, the designs to reduce downtime due to equipment breakdown during offshore wind installation projects are proposed. The model described in this chapter is used to examine the performance of the designs.

7

Case-study: designs to reduce downtime due to breakdown of the hammer

In this chapter the model will be applied to evaluate designs in a case-study. This answers the research question *'What designs can be implemented to reduce downtime due to equipment breakdown and what is the effect of implementing the designs on the key performance indicators (KPI's) regarding equipment breakdown?'*. First, the designs to reduce downtime due to equipment breakdown in offshore wind installation are explained. Second, the results of the simulations of the designs are described. Third, a sensitivity analysis is conducted to get a better understanding of how the parameters affect the outcomes of the model.

7.1. Prioritizing preventive maintenance while considering weather conditions

In this section the designs to reduce downtime due to equipment breakdown in offshore wind installation are presented. The designs are based on the conclusions from the root-cause analysis in chapter 5, the interviews (see Appendix C) and the literature study in chapter 3.

Several causes for equipment breakdown on the critical path in offshore wind installation are taken into account for the designs. From the root-cause analysis in chapter 5, it is concluded that critical breakdown in offshore wind installation is caused by wear and tear of the equipment, which is aggravated by offshore conditions. Preventive maintenance can reduce wear and tear of equipment, but preventive maintenance planning for equipment in offshore wind installation can be more challenging than in for example a production factory, because weather conditions also need to be taken into account in the installation schedule. Scheduled preventive maintenance to the equipment is sometimes postponed on site when the weather conditions are favourable for installation. If preventive maintenance is postponed, or not carried out, this can accelerate the wear and tear of the equipment. These decisions are based on experiences in another industry and therefore different circumstances than offshore wind, where equipment is used more frequently. Therefore, decision-making during the project is one of the root-causes for downtime due to equipment breakdown in offshore wind installation.

Agreements between stakeholders also induces perverse incentives for stakeholders to make decisions that not benefit the reliability of the equipment. Hence, the organisation of activities on the critical path, decision-making based on experience in a different industry and interests of different stakeholders make offshore wind installation vulnerable to downtime due to critical equipment breakdown.

The literature review in chapter 3 showed that Total Productive Maintenance (TPM) is a potential method to reduce downtime due to equipment breakdown, because it is successfully applied in other industries to reduce downtime due to equipment breakdown. However, no studies were found that applied TPM in offshore wind installation. TPM can be applied to reduce downtime due to equipment breakdown and increase availability of the equipment by improving the maintenance strategies, as the method provides multiple approaches to reduce downtime due to equipment breakdown, amongst others by scheduling preventive maintenance (Kolte and Dabade, 2017).

In this research, it is proposed to reduce downtime due to equipment breakdown in offshore wind installation by including preventive maintenance to the hammer in the installation schedule. Four designs with each different priorities on the critical path are simulated using the model described in chapter 6. By comparing the results of the simulations of the four designs, it is demonstrated what the effect of preventive maintenance is on the KPI's selected in chapter 6. Demonstrating the effects of including preventive maintenance on the critical path, while considering weather conditions, should enhance informed decision-making and therefore reduce downtime due to equipment breakdown.

The four designs are explained hereafter:

- **Base-case (BC):** The installation project without preventive maintenance is simulated in the base-case. This scenario does include equipment breakdown based on the cumulative failure probability. Hence, if the hammer has reached the maximum value for failure, the hammer will break down and needs to be repaired. The time to repair is also calculated in this scenario. This scenario is used as a base-case to show how often equipment breaks down and how much downtime is induced by equipment breakdown if no preventive maintenance is performed.

- **Design 1: Perform preventive maintenance during idle time (D1):** Preventive maintenance to the hammer is added to the model in this scenario. However, pinpile installation and jacket installation are still prioritized over preventive maintenance activities. This means that installation is continued and not interrupted by preventive maintenance activities. Nonetheless, if the maximum service-life of the hammer is reached, the hammer will break down and requires a repair. The difference with the base-case is that if installation is not possible, preventive maintenance is performed during the idle time, for example if there are no pinpiles to install supplied by the barges. This design examines the potential of using idle time to improve the equipment service-life.

- **Design 2: Prioritize preventive maintenance on the critical path over jacket installation (D2):** In this scenario, preventive maintenance is prioritized over jacket installation. So, if the preventive maintenance threshold of the hammer is reached, jacket installation is postponed and preventive maintenance is carried out. However, pinpile installation still has the highest priority. Hence, pinpile installation will be scheduled even if the preventive maintenance threshold value is reached. This design examines the effect of rescheduling jacket installation for the benefit of improving equipment service-life.

- **Design 3: Prioritize preventive maintenance on the critical path over all other installation activities (D3):** In this scenario, preventive maintenance is prioritized over installation activities. That means that whenever the hammer reaches the preventive maintenance threshold, it is carried out. Also when installation activities can take place, so there are pinpiles available for installation and weather conditions are suitable for installation. This design examines the effects of prioritizing preventive maintenance on the critical path.

The scientific value of testing these designs is that preventive maintenance planning on the critical path is combined with weather conditions and operational limits to improve decision-making. Abdul Rahman et al. (2020) presented a Decision Support System DSS based on Overall Equipment Effectiveness (OEE) data aiming to improving decision-making and to increase the production efficiency in the food industry. However, weather conditions were not included in that study, because the weather does not affect the production line in the food industry. The literature review in chapter 3 showed that there are simulation models to improve offshore wind installation planning available, which include weather conditions in the installation schedule. However, those models do not take equipment breakdown into account in the model, whilst it is known to cause downtime in offshore wind installation.

7.2. Verification of the designs

The designs are simulated using the model described in chapter 6. Then, the results are derived from the generated installation schedules. After that, the results are compared to examine the impact of the proposed designs on the key performance indicators (KPI's), which are identified in chapter 6. This answers the research question *'What is the effect of implementing the designs on the KPI's regarding equipment breakdown?'*.

As described in chapter 6, a project size of 40 turbines is assumed to ensure that the whole offshore wind project can be installed during good weather seasons. The start-date of the project is therefore also limited to a range of 11 days. Monte-Carlo simulation is applied to vary over different start-dates and different weather conditions. Furthermore, only the effects of breakdown and preventive maintenance of the hammer are examined, no other equipment is considered. Therefore, the results can not be compared to the results of the case-study in chapter 4.

The effect of implementing the designs on the downtime due to equipment breakdown is presented in a boxplot and violin plot in Figure 7.1. The results show that the downtime due to equipment breakdown decreases as preventive maintenance is prioritized. There is almost no difference in downtime due to equipment breakdown between the base case design and design 1. On average, downtime due to breakdown is lowest when preventive maintenance is prioritized over both pinpile installation and jacket installation. Furthermore, it can be seen in the figure that the upper whiskers of design 2 and design 3 decrease as compared to the upper whiskers of design 1. The lower whiskers of all designs have a similar value. The decrease in upper whiskers for design 2 and 3 indicate that the third quartile of breakdown duration for all runs of the model also decreases, whereas the first quartile remains the same.

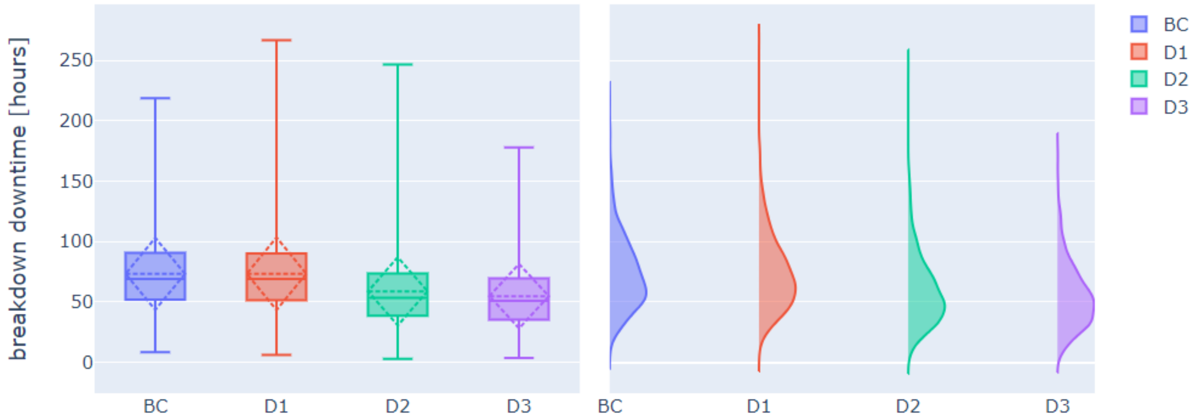


Figure 7.1: Boxplot and violin plot downtime due to breakdown.

The base case is not included in the results for downtime due to preventive maintenance, because there is no preventive maintenance carried out in the base case. The boxplot and violin plot in Figure 7.2 shows that there is almost no preventive maintenance carried out during the idle time in design 1. This can mean that the preventive maintenance threshold was not reached during idle time. Another explanation might be that there is very little idle time available where preventive maintenance can be performed. When preventive maintenance is prioritized over jacket installation, the downtime due to preventive maintenance increases. The downtime due to preventive maintenance increases even more when it is prioritized over pinpile installation as well.

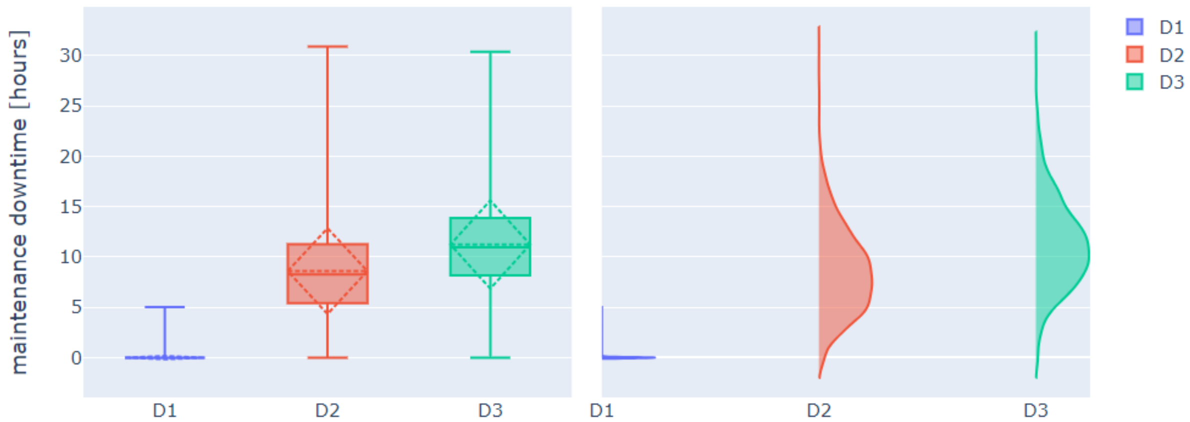


Figure 7.2: Boxplot and violin plot of downtime due to preventive maintenance.

The downtime due to equipment breakdown and preventive maintenance are also accumulated, this results are given in Figure 7.3. The downtime decreases as preventive maintenance is prioritized on the critical path, even if that means that additional time is spent on preventive maintenance. Furthermore, the length of the whiskers decrease for D2 and D3 compared to D1, which means that the variance of the results also decreases.

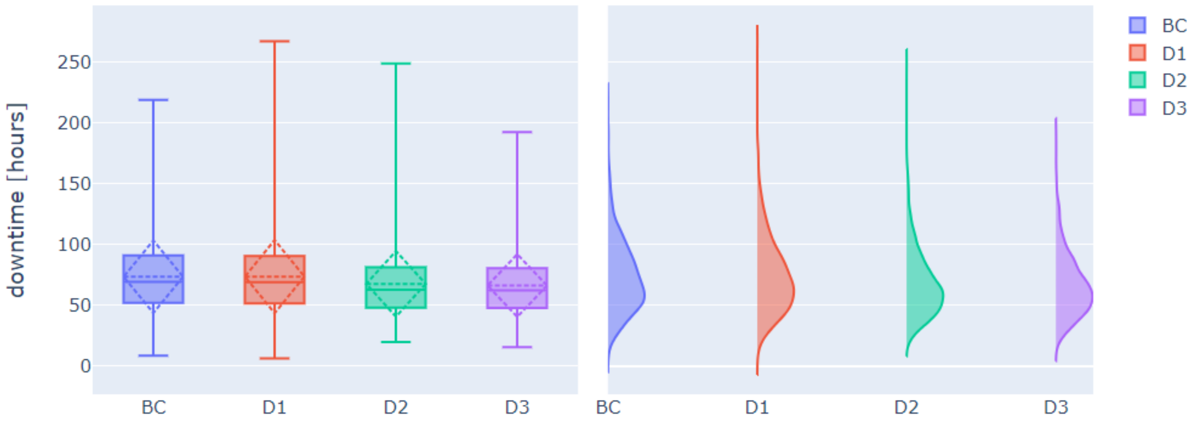


Figure 7.3: Boxplot and violin plot of downtime due to breakdown and preventive maintenance.

Figure 7.4 shows a boxplot of the waiting on weather time for the installation vessel for each of the designs. It can be concluded that there is almost no difference in waiting on weather time for the designs. Furthermore, the length of the whiskers is also similar, so the variance is almost equal as well.

Figure 7.4: Boxplot waiting on weather time.
Note. Removed due to sensitive data.

The idle time in the installation schedule of the installation is examined to determine if prioritizing preventive maintenance on the critical path affects the efficiency of the installation schedule. The efficiency of the the installation schedule is measured as the share of idle time as part of the total time on the project. In this case, the idle time does not include waiting on weather time, downtime due to preventive maintenance and downtime due to breakdown, because they are measured separately. Figure 7.5 presents the shares of installation activities, downtime due to breakdown, downtime due to preventive maintenance, waiting on weather time and idle time as part of the total time spent by the installation vessel in pie charts per design. It can be seen in the figure that idle time is about the same share for all designs, although the base case and design 1 have a bit smaller share of idle time. Looking at the share of installation activities, design 2 and 3 have higher shares than the base case and design 1.

Figure 7.5: Pie charts of the total time spent by the installation vessel per category.
Note. Removed due to sensitive data.

The boxplot and violin plot in Figure 7.6 shows the results for the number of breakdowns of the hammer per design. The number of breakdowns decrease when preventive maintenance to the hammer is prioritized on the critical path. The decrease is greater for design 3 than for the design 2. However, the variance of the number of breakdowns increases for D2 and D3, compared to the base case design and D1.

The Mean Time between Failures (MTBF) is calculated using Equation 7.1. The results for the MTBF of the hammer are given in Figure 7.7. The boxplot shows that there is almost no difference in MTBF between the base case and design 1. When preventive maintenance is prioritized over jacket installation, the MTBF increases. The MTBF increases even more,

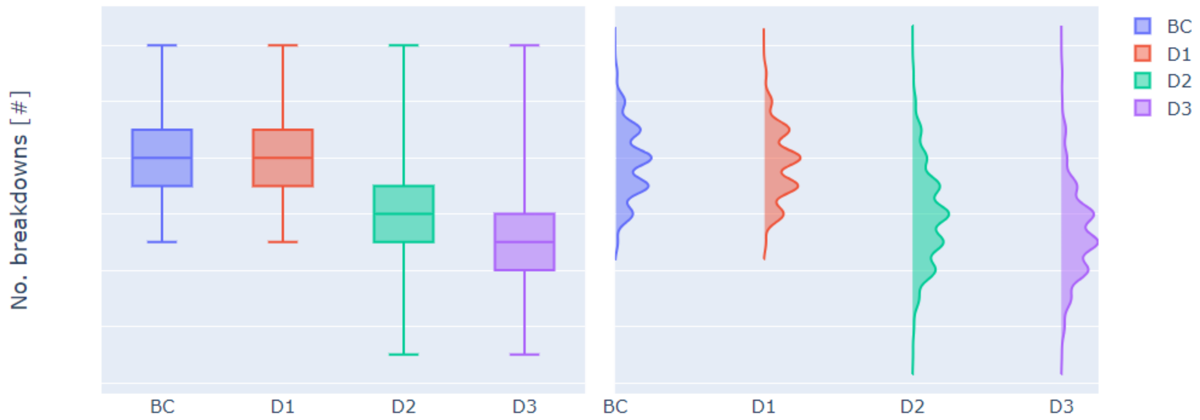


Figure 7.6: Boxplot and violin plot of number of breakdowns.
Note. Axis removed due to sensitive data.

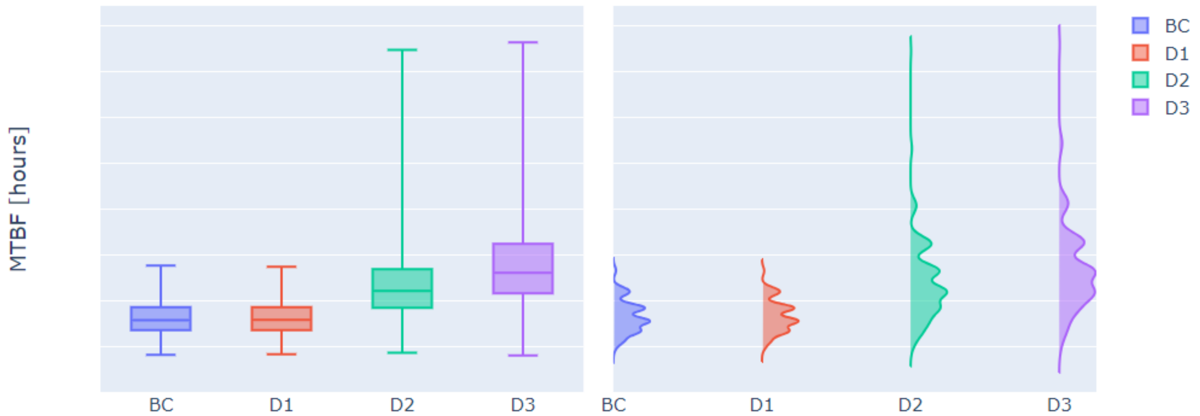


Figure 7.7: Boxplot and violin plot of Mean Time between Failures (MTBF) hammer.
Note. Axis removed due to sensitive data.

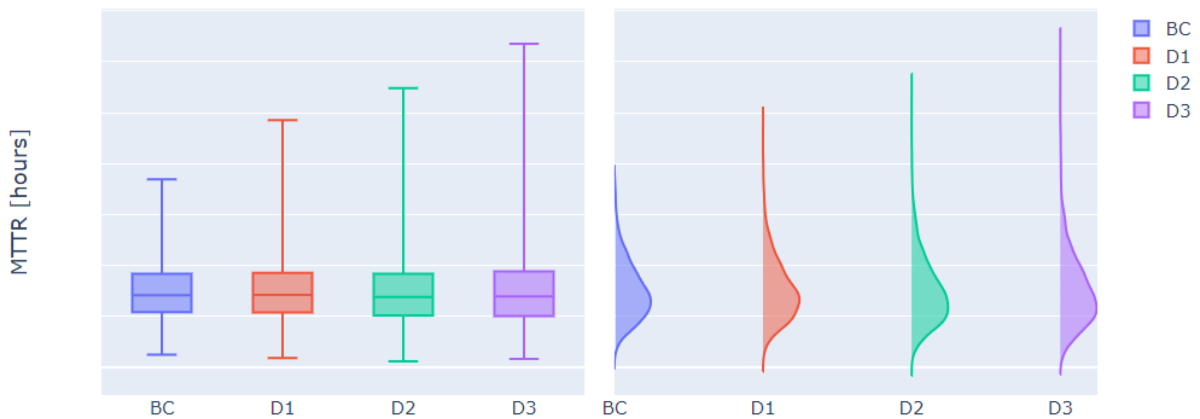


Figure 7.8: Boxplot and violin plot of Mean Time to Repair (MTTR) hammer.
Note. Axis removed due to sensitive data.

when preventive maintenance to the hammer is also prioritized over pinpile installation. Nevertheless, the lower whiskers of design 2 and 3 are comparable to the lower whiskers of the base case and design 1. This means that the median of the first quartile is comparable for all designs. An increasing MTBF means that the hammer breaks down after a higher drivetime, so the condition of the hammer improves.

$$MTBF = \frac{\text{total drive time hammer}}{\text{number of failures}} \tag{7.1}$$

Equation 7.2 is used to calculate the Mean Time to Repair (MTTR). Figure 7.8 shows that the MTTR is comparable for all designs. However, the upper whiskers in the boxplot increase as preventive maintenance is prioritized on the critical path, which means that the variance of the MTTR increases.

$$MTTR = \frac{\text{total downtime due to breakdown}}{\text{number of failures}} \tag{7.2}$$

An overview of the effect of implementing the design on the KPI's is presented in Table 7.1, Table 7.2, Table 7.3 and Table 7.4. The tables show the average value for each of the KPI's after simulating the model for each design. The percentiles, which indicate the probability of exceedance, for each KPI can be found in Appendix E. Prioritizing preventive maintenance on the critical path affects the downtime due to breakdown of the hammer, downtime due to preventive maintenance, MTBF and the number of breakdowns of the hammer. The idle time, waiting on weather time, MTTR, the time spent on the project by the installation vessel and the total project duration are slightly affected. It should be noted that the time on project by the installation vessel (Heavy Lift Vessel (HLV)) does decrease as preventive maintenance to the hammer is prioritized, but the difference is only 8 hours on a project, which means that the end date of the project remains the same day.

Table 7.1: Mean values of downtime due to equipment and preventive maintenance KPI's for implementing each of the designs and percentual change compared to the base case.

KPI's downtime	*unit*	BC	D1	D2	D3	D1	D2	D3
downtime breakdown	*hours*	73.3	73.4	58.8	54.8	0.1	-19.7	-25.2
downtime maintenance	*hours*	-	0.01	8.59	11.23	-	-	-
sum	*hours*	73.3	73.38	67.39	66.02	0.2	-8.0	-9.9

Table 7.2: Mean values of other downtime KPI's for implementing each of the designs and percentual change compared to the base case.
Note. Values removed due to sensitive data.

KPI's other downtime	*unit*	BC	D1	D2	D3	D1	D2	D3
idle time	*hours*					0.2	0.6	0.1
waiting on weather time	*hours*					0.1	-0.1	0.2

Table 7.3: Mean values of equipment KPI's for implementing each of the designs and percentual change compared to the base case.

KPI's equipment	*unit*	BC	D1	D2	D3	D1	D2	D3
critical breakdown	#	10	10	8	7	0.0	-20.0	-30.0
MTBF	*hours*	26.60	26.70	33.78	36.55	0.4	27.0	37.4
MTTR	*hours*	7.48	7.53	7.38	7.49	0.7	-1.3	0.1

Table 7.4: Mean values of project duration KPI's for implementing each of the designs and percentual change compared to the base case.
Note. Values removed due to sensitive data.

KPI's project duration	*unit*	BC	D1	D2	D3	D1	D2	D3
time on project	*hours*					0.0	-0.3	-0.3
total project duration	*hours*					0.0	-0.3	-0.3

The percentual differences per KPI's are also included in Figure 7.9. The orange circle represents the base case design and the 0% line. The other lines indicate the range of improvement of the design compared to the base case design. The downtime due to breakdown decreases up to 25% compared to the base case design. Even when additional preventive maintenance is performed, the downtime decreases by 10%. The total number of critical breakdowns of the hammer decreases by 30% if preventive maintenance is prioritized. The MTBF increases up to 37% by prioritizing preventive maintenance, which means that it takes longer for the hammer to break down. Differences for the MTTR, time on project and project duration are similar to the base case design.

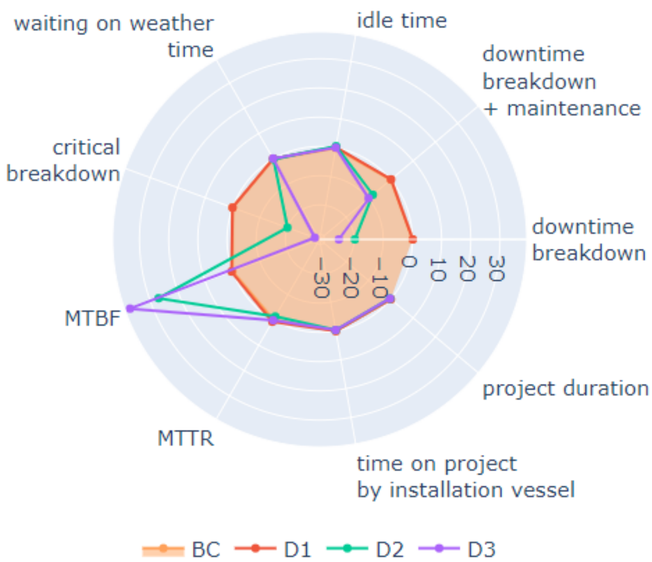


Figure 7.9: Radarplot of percent difference of designs compared to the base case.

7.3. Correlation between KPI's

It is also examined if the KPI's are related. The correlation coefficients of all KPI's are presented in Figure 7.10 in a heatmap. Furthermore, a correlation matrix is included in Appendix E. The downtime due to equipment breakdown and combined downtime due to preventive maintenance and equipment breakdown are strongly positively related, because downtime due to breakdown is part of the combined KPI. The MTBF and the number of breakdown are strongly negatively related, which can be explained because the number of failures are used to calculate the MTBF, see Equation 7.1. This also holds for the correlation between the MTTR and the downtime due to breakdown, see Equation 7.2. The total project duration and the time spent by the installation vessel are strongly correlated, as the installation vessel is required during almost the entire project. Furthermore, the waiting on weather time is strongly related to the project duration.

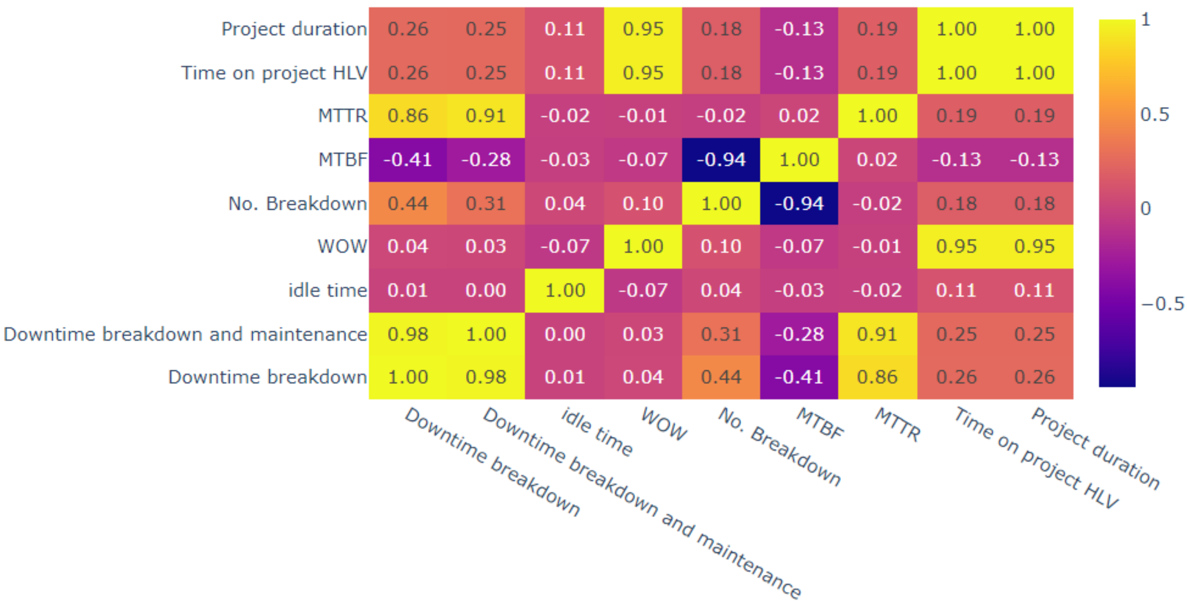


Figure 7.10: Heatmap of correlation coefficients of KPI's.

7.4. Sensitivity analysis

A sensitivity analysis is carried out to examine how the input parameters affect the results of the simulations. Furthermore, the data to determine some of the parameters is limited, so assumptions had to be made. The sensitivity analysis shows how the model behaves, if those input parameters change, for example if more data becomes available.

Several experiments are set up, in which input parameters are varied to compare the results to the results in the previous section. It is chosen to perform the sensitivity analysis with the D3 design, because this design includes preventive maintenance on the critical path and reduces downtime due the equipment breakdown best. The results of the experiments are then compared to the base case design. The following parameters are examined in the next section consecutively: preventive maintenance threshold value, time-to-failure-function, number of turbines to be installed, preventive maintenance duration distribution and repairtime after breakdown distribution.

7.4.1. Experiment 1: Preventive maintenance threshold value

The preventive maintenance threshold value determines at what moment the hammer requires preventive maintenance. This is calculated as 80% of the MTBF retrieved from the completed installation project. The 80% threshold is assumed in the model and not based on actual data. To see how the threshold value affects the KPI's, a sensitivity experiment is performed for 70% and 90% of the MTBF. The results of this experiment are included in Table 7.5. The values in hours represent the actual results of the simulations. The values in percentages show the difference with the 80% threshold simulation used in the model and are presented in Figure 7.11.

Table 7.5: Results for sensitivity analysis for preventive maintenance threshold (80% is applied in original designs). *Note.* Values removed due to sensitive data.

			70%	80%	90%	70%	80%	90%
	unit	*BC*	*D3*	*D3*	*D3*	*%*	*%*	*%*
KPI's downtime								
downtime breakdown	*hours*	73.3	50.0	54.8	60.0	-31.8	-25.2	-18.2
downtime maintenance	*hours*	-	15.06	11.23	7.75	-	-	-
sum		73.3	65.02	66.02	67.71	-11.3	-9.9	-7.6
KPI's other downtime								
idle time	*hours*					-0.3	0.1	0.1
waiting on weather time	*hours*					0.2	0.2	0.1
KPI's equipment								
critical breakdown	#	10	7	7	8	-28.6	-28.6	-18.4
MTBF	*hours*	26.60	40.49	36.55	33.04	52.2	37.4	24.2
MTTR	*hours*	7.48	7.48	7.49	7.43	0.1	0.1	-0.6
KPI's project duration								
time on project	*hours*					-0.4	-0.3	-0.2
total project duration	*hours*					-0.4	-0.3	-0.2

The results in Table 7.5 show that the downtime due to breakdown increases as a higher threshold is applied in design 3, but the downtime is still lower than in the base case. Additionally, the downtime due to preventive maintenance decreases as a higher threshold value is applied in design 3. The number of breakdowns also increases as a higher threshold value is used in design 3, but there are less breakdown than in the base case. Therefore, the MTBF also decreases for the 90% threshold, because the number of breakdowns is used to calculate the MTBF (see Equation 7.1). Idle time, waiting on weather time, MTTR, time on project by the installation vessel and the total project duration are almost insensitive to changing the preventive maintenance threshold in design 3. It can be concluded that a higher threshold value will result in more breakdown of the hammer and also a higher downtime. Furthermore less preventive maintenance is carried out. This experiment also shows that it is relevant to optimize the threshold value, in order to reduce as much downtime due to breakdown for the least possible amount of additional downtime due to preventive maintenance.

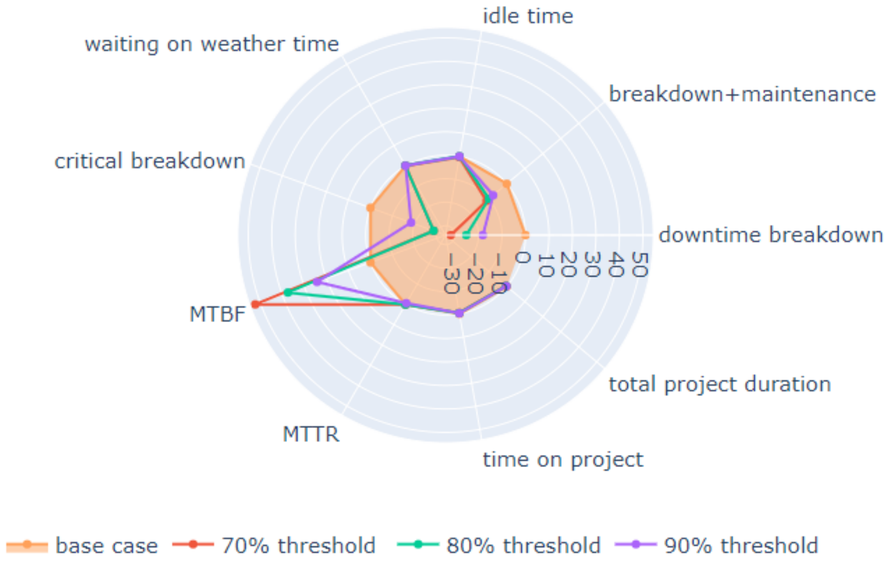


Figure 7.11: Radarplot of percent difference with base case design for sensitivity experiment with maintenance threshold value.

7.4.2. Experiment 2: Time-to-failure function

The time-to-failure function that is used to calculate the failure probability of the hammer in the model might not give a generalizable result, because it is based on a limited data-set. Therefore, a sensitivity analysis of the time-to-failure function is carried out. In the experiment, 90% and 110% of the failure probability are simulated to see what the effect of a different time-to-failure function is on the KPI's. The results for the sensitivity experiment for the time-to-failure function are presented in Table 7.6. The changes in percents compared to the base case are also presented in Figure 7.12.

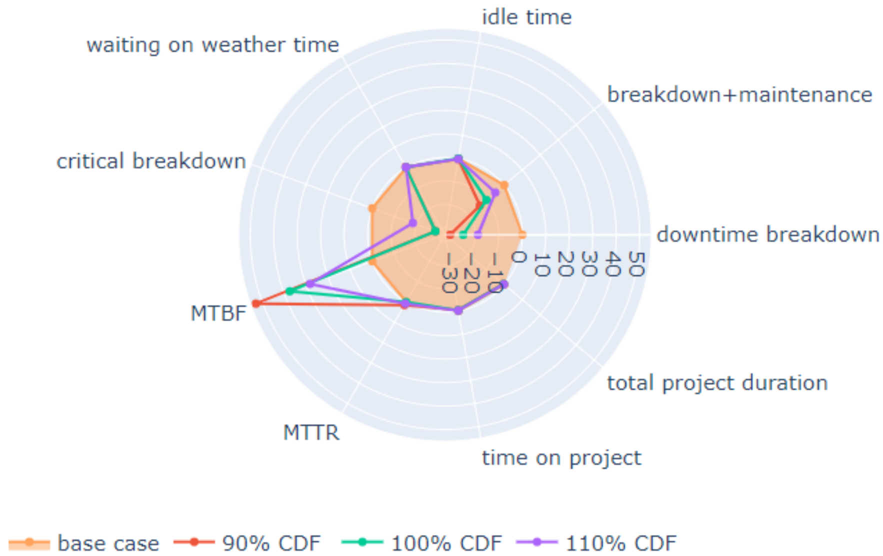


Figure 7.12: Radarplot of percent difference with base case design for sensitivity experiment with time-to-failure function.

The results in Table 7.6 indicate that when the probability of failure increases in design 3, the downtime due to breakdown of the hammer increases, possible because the number of

Table 7.6: Results for the sensitivity analysis for the time-to-failure function.
Note. Values removed due to sensitive data.

Time-to-failure function			90%	100%	110%	90%	100%	110%
	unit	*BC*	*D3*	*D3*	*D3*	*%BC*	*%BC*	*%BC*
KPI's downtime equipment								
downtime breakdown	*hours*	73.3	50.7	54.8	59.4	-30.8	-25.2	-18.9
downtime maintenance	*hours*	-	12.60	11.23	10.23	-	-	-
sum		73.3	63.32	66.02	69.62	-13.6	-9.9	-5.0
KPI's other downtime								
idle time	*hours*					-0.2	0.1	-0.2
waiting on weather time	*hours*					0.5	0.2	0.3
KPI's equipment								
critical breakdown	#	10	7	7	8	-28.6	-28.6	-18.4
MTBF	*hours*	26.60	40.63	36.55	34.10	52.8	37.4	28.2
MTTR	*hours*	7.48	7.60	7.49	7.54	1.6	0.1	0.9
KPI's project duration								
time on project	*hours*					-0.4	-0.3	-0.2
total project duration	*hours*					-0.4	-0.3	-0.2

breakdowns increase as well. This also explains the decrease of the MTBF for a higher time-to-failure function. The downtime due to preventive maintenance increases when the failure probability is decreased by 10%. The MTTR increases when the time-to-failure function is changed in either direction, although the differences are small compared to the base case. The results for idle time, waiting on weather time, time on project for the installation vessel and total project duration differ slightly compared to the base case, when the time-to-failure parameter is changed. The difference between the base case design and results for the sensitivity experiment with the time-to-failure function is presented in Figure 7.12.

7.4.3. Experiment 3: Preventive maintenance duration distribution

There is no data available on preventive maintenance duration in previous projects. The distribution that is used in the model is based on the distribution for equipment breakdown, excluding the first en last two observations. Another preventive maintenance duration can change the outcome of the designs, therefore a sensitivity analysis for the location parameter of the preventive maintenance distribution is conducted. By changing the location parameter of the distribution, the shape of the distribution remains the same and the distribution gets shifted along the y-axis.

The results in Table 7.7 shows that especially the downtime due to preventive maintenance is affected when the location parameter of the distribution is varied. The results can not be compared to the base case, because there is no preventive maintenance performed on the critical path in the base case. The downtime due to equipment breakdown is also affected by the preventive maintenance distribution. The other KPI's are insensitive to changes of the location parameter of the preventive maintenance duration distribution in the D3 design, which can also be seen in Figure 7.13.

Table 7.7: Results for the sensitivity analysis for the location parameter of the preventive maintenance duration distribution.
Note. Values removed due to sensitive data.

maintenance duration		-	50%	100%	150%	50%	100%	150%
	unit	*BC*	*D3*	*D3*	*D3*	*%BC*	*%BC*	*%BC*
KPI's downtime equipment								
downtime breakdown	*hours*	73.3	55.9	54.8	53.7	-23.7	-25.2	-26.6
downtime maintenance	*hours*	-	8.47	11.23	13.98	-	-	-
sum		73.3	64.38	66.02	67.72	-12.1	-9.9	-7.6
KPI's other downtime								
idle time	*hours*					-0.3	0.1	0.2
waiting on weather time	*hours*					0.1	0.2	0.4
KPI's equipment								
critical breakdown	#	10	7	7	7	-28.6	-28.6	-28.6
MTBF	*hours*	26.60	36.66	36.55	36.93	37.8	37.4	38.8
MTTR	*hours*	7.48	7.62	7.49	7.43	1.9	0.1	-0.7
KPI's project duration								
time on project	*hours*					-0.5	-0.3	-0.2
total project duration	*hours*					-0.4	-0.3	-0.2

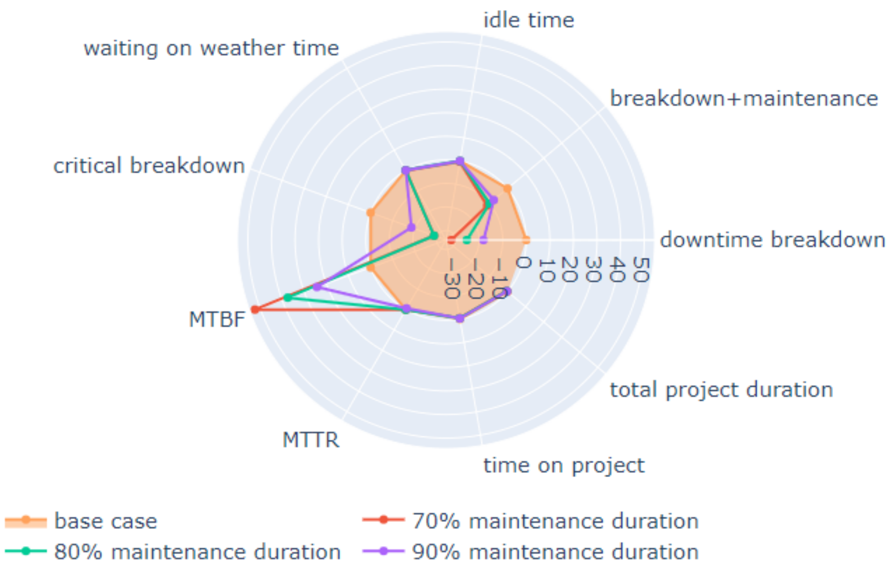


Figure 7.13: Radarplot of percent difference with base case design for sensitivity experiment with location parameter of maintenance duration distribution.

7.4.4. Experiment 4: Breakdown duration distribution

The breakdown duration is based on a limited number of data-points from the case-study. Therefore, a sensitivity analysis for the shape parameter of the breakdown duration distribution is carried out.

Table 7.8: Results for the sensitivity analysis of the shape parameter of breakdown duration.
Note. Values removed due to sensitive data.

breakdown duration			50%	100%	150%	50%	100%	150%
	unit	*BC*	*D3*	*D3*	*D3*	*%BC*	*%BC*	*%BC*
KPI's downtime								
downtime breakdown	*hours*	73.3	28.4	54.8	79.1	-61.3	-25.2	8.0
downtime maintenance	*hours*	-	11.13	11.23	11.38	-	-	-
sum		73.3	39.53	66.02	90.49	-46.1	-9.9	23.5
KPI's other downtime								
idle time	*hours*					-0.6	-1.6	1.2
waiting on weather time	*hours*					0.6	0.2	0.0
KPI's equipment								
critical breakdown	#	10	7	7	7	-28.6	-28.6	-28.6
MTBF	*hours*	26.60	36.27	36.55	37.68	36.4	37.4	41.7
MTTR	*hours*	7.48	3.83	7.49	11.11	-48.7	0.1	48.6
KPI's project duration								
time on project	*hours*					-1.6	-0.3	0.8
total project duration	*hours*					-1.6	-0.3	0.8

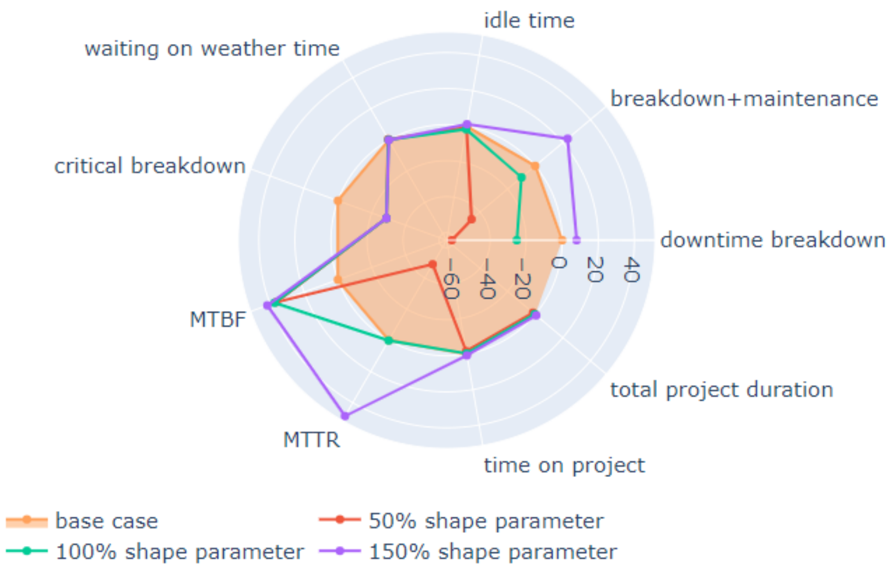


Figure 7.14: Radarplot of percent difference with base case design for sensitivity experiment with shape parameter of breakdown duration distribution.

The results in Table 7.8 and Figure 7.14 show that especially the downtime due to breakdown and the MTTR are sensitive to changing the shape of the breakdown duration distribution. Both KPI's decrease as the shape parameter of the breakdown duration distribution is decreased by 50%. The MTTR is calculated using the downtime due to breakdown, see Equation 7.2, therefore the MTTR changes when the downtime due to breakdown increases, but the number of breakdowns is equal. The other KPI's are also affected when the breakdown distribution changes, although these differences are rather small. It should be noted that a different distribution for breakdown duration does affect the time on the project of the installation vessel and the total project duration, even though the difference compared to the base case is small.

7.5. Conclusion

Four designs are simulated using the model described in chapter 6. By evaluating the effects of the designs on the KPI's, it is aimed to give insight in different decision-alternatives of prioritizing preventive maintenance to the hammer on the critical path.

The results indicate that prioritizing preventive maintenance on the critical path can reduce downtime due to equipment breakdown by 25% compared to the base case design, where no maintenance is performed. However, it should be taken into account that additional time will be spent on preventive maintenance on the critical path. Nonetheless, the downtime due to equipment breakdown and preventive maintenance together is still 10% lower than when no preventive maintenance is carried out. The total number of breakdowns can be reduced by 30% by prioritizing preventive maintenance on the critical path and therefore the MTBF can increase up to 37% compared to the base case design. Other KPI's are not affected when preventive maintenance is prioritized on the critical path. Although downtime is reduced, the project will still finish on the same day because the difference is small. However, if more types of equipment are added to the model this effect can increase.

The amount and quality of the available data is limited, as data is collected manually and some assumptions had to be made in the model because not all data was available. The results of the sensitivity analysis shows that changing the input of the model also affects downtime due to breakdown and preventive maintenance, number of breakdowns and MTBF. Additionally, the MTTR is affected when the breakdown duration distribution is changed. This means that the effect of prioritizing preventive maintenance can change if input parameters are changed. Therefore, high-quality input data is needed.

V

Conclusion, discussion and recommendations

8 Conclusion

This research is carried out to answer the research question *'How can downtime due to equipment breakdown be reduced during the installation process of an offshore wind project?'*.

A new method is proposed in this research that helps to get insight in the effect of decision-making on the critical path of offshore wind installation projects. In previous studies only the effect of weather conditions is included in Discrete-Event Simulation (DES) models to improve installation schedules. The implementation of failure and preventive maintenance characteristics in a DES model is new. The probability of failure of the hammer is determined using a time-to-failure-function based on observed failure data. In this study only the hammer is included in the model, to see what the effect of decision-making is on the downtime and condition of the hammer.

An important finding of this research is that decision-making on the critical path is currently based on experiences under different circumstances, but offshore wind installation requires a different approach due to the repetitive cycles. The offshore industry distinguishes itself from other industries by the dependence on good weather conditions. The weather conditions determine if installation operations are possible. Next to that, the favourable weather conditions limit the time for preventive maintenance outside the critical path. It is mentioned that planned preventive maintenance is postponed if weather conditions are favourable for installation. The model presented in this study is used to examine what the effect of prioritizing preventive maintenance is on key performance indicators (KPI's) of the offshore wind installation project.

Four designs are evaluated in this research to reduce downtime due to critical breakdown of the hammer in an offshore wind installation project:

1. base case design: no maintenance is carried out on the critical path;
2. Design 1 (D1): preventive maintenance is performed when no installation operations are performed and the preventive maintenance condition is reached;
3. Design 2 (D2): if no pinpile installation is possible and when the preventive maintenance condition is reached, preventive maintenance is prioritized over jacket installation operations;
4. Design 3 (D3): preventive maintenance is performed if the preventive maintenance condition is met, and preventive maintenance is prioritized on the critical path over pinpile and jacket installation activities.

The results indicate that the downtime due to breakdown of the hammer can be reduced by 25% by prioritizing preventive maintenance of the hammer on the critical path over the installation sequences for pinpiles and jackets, compared to the base case where no maintenance is carried out on the critical path. When preventive maintenance is only prioritized over jacket installation, the downtime due to critical breakdown of the hammer can be reduced by 20% compared to the base case. Although, performing preventive maintenance requires additional downtime on the critical path, the total downtime is reduced by 10% in D3 en 8% in D2. Performing preventive maintenance during idle time does not reduce downtime due to breakdown of the hammer. Although downtime due to breakdown is reduced, the time spent on the project by the installation vessel and the total project duration only decreases by 0.3% compared to the base case and the project still ends on the same day. Prioritizing preventive maintenance on the critical path affects other key performance indicators (KPI's) of an offshore wind installation project as well. The number of critical breakdowns of the hammer decrease by 20% in D2 and even up to 30% in D3. This results in an increased Mean Time between Failures (MTBF) of 27% in D2 and 37% in D3. Moreover, the results show that idle time and waiting on weather time are similar for all designs.

The implementation of the model can improve DES models that are used to assess installation schedules prior to project execution, because it adds an extra dimension to the installation schedule. Furthermore, the model shows that it can be beneficial to examine different KPI's. Installation schedules can get more accurate when downtime due to equipment breakdown and preventive maintenance is considered in the installation schedule. The value of the model can be increased if more types of equipment are included in the model and high-quality data is used as input.

Implementing a model that simulates the effects of the decision-making during offshore wind installation projects benefits science, the company and society. The added scientific value of the model is the combination of a DES model for offshore wind installation planning that includes equipment breakdown, preventive maintenance and weather conditions. Implementation of the model also benefits the company, as decision-makers are able to oversee the consequences of their decisions on multiple KPI's. This tool can be used as a competitive advantage. Furthermore, this research demonstrates the importance of structured data collection during the project. The model becomes more accurate and useful for decision-makers if high-quality data is used. Last, society can benefit from improved installation schedules for offshore wind installation, as the operational time of the project increases when the project is delivered on time. Furthermore, improved installation schedules for offshore wind installation projects add to the market position of offshore wind energy in the energy transition and therefore also might benefit the environment.

9 Discussion

Reflecting on the model, designs and literature used in this study gives insight into the value and future application of the results of this study.

It is concluded from this study that modelling decision-making can reduce downtime due to equipment breakdown, but the model that is used in this study can be improved. In this research, the amount and quality of data was limited and several assumptions had to be made in the model. Therefore, the model only indicates what the effect of modelling breakdown of the hammer is for a specific set of input parameters and the results can not be generalized for the entire industry. When the model is applied to different offshore wind installation projects, the model needs to be adapted to the characteristics of that particular project.

The amount of data that was available for the model is limited, as only one completed project was studied. Additionally, the available data is not very reliable, as it was manually registered during the project. Each individual that collects the data, has a different perspective on how the data should be registered. Different data sets on equipment regarding the same project showed discrepancies between the number and type of breakdowns, also the durations and dates did not match. Furthermore, there is no data available on maintenance duration, only the actions are logged. Therefore, the maintenance distribution in the model is estimated based on the distribution of the repair time. In chapter 6, it is emphasized that high-quality weather data is needed for reliable outcomes of Metis. The same reasoning can be applied to the quality of the breakdown and maintenance data: the model requires high-quality breakdown and maintenance data to ensure valid results to support decision-making. In general, to make a high-quality installation schedule, it is necessary to know how long each activity takes to complete.

Another limitation is that the model is a simplified representation of breakdown and maintenance of the hammer. In the model, only breakdown and maintenance on the critical path are included, whilst in reality these activities are performed simultaneously to other operations if possible. Maintenance to the hammer is in reality often performed during jacket installation or waiting on weather time, because then the hammer is not used. Furthermore, in the project two different hammers are used that can be switched in case of breakdown. This is simplified in the model because switch time and repair time are not separately logged. The time to failure function is also based on the data from both hammers, instead of each hammer separately for simplification of the model. In future models, it should be possible to model multiple pieces of equipment that can be replaced in case of breakdown, but the data is required on the time that is needed to switch the equipment and repair time to make an informed trade-off between repairing the breakdown or to replace the piece of equipment.

Preventive maintenance is performed in the model, because time-based maintenance works well with a time-based model such as Discrete-Event Simulation (DES). In practice, maintenance is carried out after a specified number of blows of the hammer, which is categorized as condition-based maintenance. However, to be able to integrate the number of blows by the hammer in the model, additional data on the soil per turbine location is required. The drive time of the hammer is more easy to include in the model, as all durations of activities are based on a distribution. To improve the model, a specific distribution for the drive time of the hammer can be included. In the current model, the drive time of the hammer is derived from the distribution for pinpile installation.

10

Recommendations

This research is a first step towards reducing downtime due to critical breakdown on the critical path in offshore wind installation projects. The research shows how the decision-making on the critical path can be improved. However, next steps can be taken in science and by the industry and company to reduce downtime due to equipment breakdown further.

Improvements to the model

The model can be further improved to resemble reality, as the current model contains assumptions for simplification. In this research, only breakdown and preventive maintenance of the hammer are included in the model. In future applications of the model, all types of equipment can be included in the model. Furthermore, this model does not consider replacing equipment by a spare piece of equipment, as happens in practice for some equipment. To include this in the model, data should be available at the time that is required to replace the failed equipment with a spare. The model can then also be used to examine if replacing the equipment takes less time than repairing the failed equipment.

Currently, the maintenance interval in the model is time-based: preventive maintenance is performed after a certain drive time of the hammer, because the drive time can be derived from the pinpile installation activity in the installation schedule. In practice, the number of blows of the hammer is used to determine when the hammer needs preventive maintenance. If it is preferred to implement this condition in the model, Metis should enable to include additional data to activities.

Future research

Future research can be done on optimizing the maintenance intervals during the offshore wind installation project. Preventive maintenance comes with extra downtime on the critical path to reduce downtime due to equipment breakdown, as shown in the results of this study. When maintenance intervals are optimized, an optimum can be reached for minimizing the downtime due to preventive maintenance and at the same time minimizing the downtime due to equipment breakdown.

A time-to-failure function is used in the current model to determine whether or not the hammer will break down. Therefore, the quality of the outcomes of the model depends on the quality of the failure data that is used as input. Moreover, all types of breakdowns of the hammer are treated equally in the model. Further research can be done to implement predictive maintenance in the model and in practice to get a better insight into what type of failure can be expected at what moment in the installation schedule. More specifically, it can be studied how a digital twin of the equipment can help to predict failure and improve maintenance strategies. This allows to examine the effect of the loads on the hammer, weather conditions and soil conditions on the failure behaviour of the hammer. Additionally, when failures can be predicted accurately, it can be studied how spare parts logistics can be integrated into the model and installation schedule.

Offshore wind installation equipment is sometimes rented. This affects the interests of the involved stakeholders, for example how each stakeholder values the key performance indicators (KPI's). Further research can be done to examine the effect of insourcing and outsourcing equipment on equipment availability, downtime and decision-making.

Recommendations for the company

The available data did not always filled the requirements of this research. Therefore, data collection within the company can be improved. The quality of the data can be improved by standardizing and automating data collection. This reduces human error, caused by multiple people filling in the same sheets for example. Furthermore, to make a trade-off if preventive maintenance can reduce equipment breakdown downtime, the duration of maintenance activities needs to be logged specifically.

Lastly, it is recommended to implement lean and Six Sigma tools in the company. This can help to improve the repetitive cycles of offshore wind installation, which is different from operations in the oil and gas industry. The designs presented in chapter 7 only address the planned maintenance pillar of the Total Productive Maintenance (TPM) framework. The other aspects of the TPM framework can be applied as well to improve maintenance strategies in offshore wind installation projects, such as the autonomous maintenance, quality maintenance and early equipment management pillars. It is also recommended to apply the 5S concept, which is the foundation of the TPM framework. Moreover, lean and Six Sigma tools can be applied to enhance efficiency in the workplace.

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VI

Appendices

A

Scientific paper

Improving Decision-Making to Reduce Downtime Caused by Equipment Breakdown during Offshore Wind Installation Projects

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Abstract

Offshore wind energy can play a key role in the energy transition. Reducing installation costs for offshore wind installation projects helps to be cost-competitive with other renewable energy technologies. Installation costs can increase when the installation project planning is delayed. Literature shows that offshore wind installation projects are delayed by weather conditions exceeding operational limits and downtime caused by vessels and equipment. However, the magnitude and causes of downtime due to equipment breakdown are unclear. Additionally, no method is found in the literature to reduce downtime due to equipment breakdown in offshore wind installation. Data-analysis of observed failure data shows that equipment breakdown causes downtime during pinpile installation during the spring and summer seasons. Root-cause analysis indicates that scheduled preventive maintenance is often postponed on the critical path when weather conditions are favourable for installation. These decisions are made based on knowledge of oil and gas projects, but that knowledge is not applicable anymore. In this study a new method is proposed, which includes equipment characteristics and preventive maintenance on the critical path of an installation schedule, using Discrete-Event Simulation (DES). In the DES model, four designs are simulated to gain insight into the effect of decision-making on the critical path on key performance indicators (KPI's). The designs are based on the planned maintenance pillar of the Total Productive Maintenance (TPM) framework. Implementing equipment breakdown and preventive maintenance in the installation schedule gives insight into the effects of decision-making before project execution. The results of this study indicate that the downtime due to breakdown and preventive maintenance of the hammer can be reduced by 10% if preventive maintenance is prioritized on the critical path.

Keywords: Offshore wind installation, equipment breakdown, downtime, discrete-event simulation, decision-making, logistics

1. Introduction

Climate change requires innovations in energy supply to reduce greenhouse gas emissions. 196 parties agreed in the Paris Agreement to limit global warming to 2°C (UN, 2015). To meet the Paris Agreement, the share of renewable energy sources must increase in the coming years. Offshore wind energy can play a key role in the energy transition, due to technological developments and industrial growth (Díaz and Soares, 2020). The offshore wind capacity is likely to increase shortly, as can be seen in Figure 1. In 2021, the total installed capacity for offshore wind was 14,6 GW in Europe. The European Commission aims to increase the total installed capacity to at least 60 GW by 2030 and even up to 300 GW by 2050 (European Commission, nd).

Although offshore wind is supported by the EU and governments for environmental reasons, offshore wind energy needs to be competitive with other energy sources and to increase its market potential. To be cost-competitive with other energy technologies, costs must be kept as low as possible. One of the ways to increase the financial feasibility of offshore wind is to improve installation logistics and decrease uncertainty during the installation phase. Risk factors, such as weather conditions, failures or supply chain disruptions, can cause downtime in the

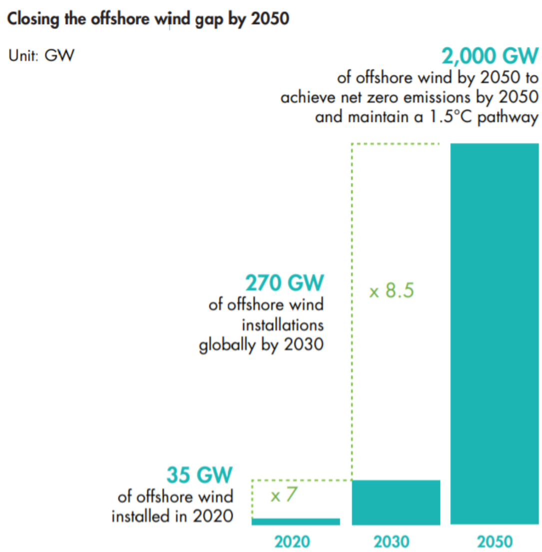

Figure 1: Offshore wind installation outlook.
Note. Reprinted from Global Wind Energy Council (2021).

supply chain and therefore postpone the installation of offshore wind projects (Leontaris et al., 2017). An overview of the cost allocation for an offshore wind project is included in Figure 2.

About 10-20% of the costs for an offshore wind project consist of installation costs, although this can vary per project (BVG Associates, nd). Although installation costs are only a relatively small part of total commissioning costs, total installation costs can rapidly increase if the project is delayed (Rippel et al., 2021). Downtime during installation is costly because specialised equipment and vessels have high day-rates and are only rented for a specific duration (Gintautas and Sørensen, 2017). Furthermore, when project deliveries are delayed, the energy supply is also delayed, which decreases the total profit for the wind farm owner (Jansen et al., 2020).

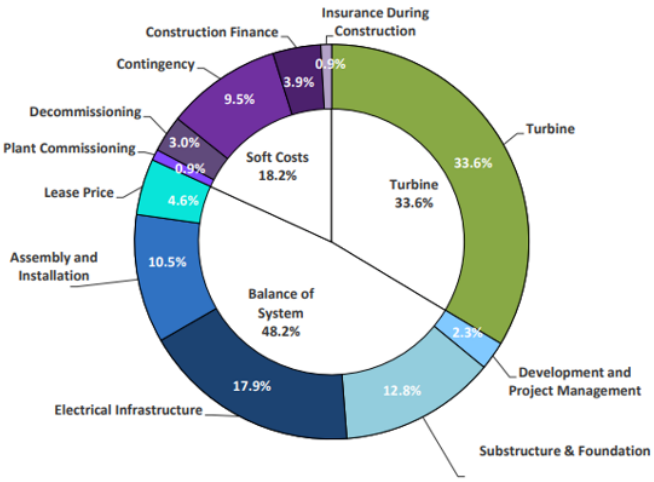

Figure 2: Overview of costs for an offshore wind project.
Note. Reprinted from Stehly and Duffy (2022).

2. Literature review on reducing downtime in offshore wind installation

The current state-of-the-art on reducing downtime in offshore wind installation is included in Table 1.

Downtime and delay are two closely related terms, but the terms are not synonyms. Delay is defined by Cambridge Dictionary (2023a) as *"the situation in which you have to wait longer than expected for something to happen, or the time that you have to wait"*. When applied to offshore wind, the following interpretation of delay will be used: *time by which the offshore wind installation project is late, or the time that is spent waiting to continue with installation processes*.

Downtime is defined by Cambridge Dictionary (2023b): *"the time during which a machine, especially a computer, is not working or is not able to be used"*. In this research downtime is interpreted as *time that is spent on the critical path of the offshore wind installation project, where installation operations can not be performed, for example, due to equipment breakdown or maintenance.*

2.1. Causes for downtime in offshore wind installation

Installation operations are limited by weather conditions like wind speed and wave limits or vessel motions because the weather conditions affect the response of equipment like crane wire tension, which increases the probability of operation failure (Gintautas et al., 2016; Gintautas and Sørensen, 2017). If weather limits are exceeded, installation can not be carried out and the downtime increases, which leads to additional costs (Oelker et al., 2021). Transport, handling, and installation operations can be affected by bad weather conditions and cause delays of several months (Scholz-Reiter et al., 2010; Hrouga and Bostel, 2021). Altuzarra et al. (2022) recommend planning installation operations between April and August, because that period has the highest probability of suitable weather windows and, hence, the lowest risk of downtime and increased costs. In particular, the installation of foundations, such as jackets and turbines, is sensitive to weather downtime compared to other installation processes, such as cable laying (Barlow et al., 2015).

The capacity of the vessel has a great impact on the costs and duration of installation of an offshore wind project (Barlow et al., 2015). Research from Rippel et al. (2019a) shows that the composition of the fleet in combination with the port infrastructure also affects the duration of the project. According to Hrouga and Bostel (2021), most literature studies for vessel decisions relate to minimizing costs by determining the optimal composition of the fleet and optimal deployment of vessels. The lack of specialised vessels and equipment is considered a major bottleneck in the offshore wind installation phase (Dinh and McKeogh, 2019). Offshore waiting time or downtime increases total operational costs of vessels, even up to 30% of the charter rate (Rippel et al., 2021). Installation vessels are involved in decisions at both the tactical and operational levels. Decisions at the tactical level involve the planning of vessel tasks. On the operational level, daily vessel routing and operations schedules are decided on. When installation equipment on board of the vessel can not be used, this is also considered vessel-related downtime by Lerche et al. (2022b).

Infrastructure is also a bottleneck in the development of offshore wind. Logistics strategies and supply chain layout have an impact on project planning, duration and costs of an offshore wind installation project (Lange et al., 2012). Furthermore, continuous coordination is required between the contractors that collaborate on-site (Aagaard et al., 2015). Leontaris et al. (2017) indicate that damage and transport problems can cause delays in the installation supply chain. Supply chain disruptions are also a risk factor in large installation projects (Leontaris et al., 2019). According to Poulsen and Lema (2017), the global offshore wind supply chain is not ready for the expected growth in the coming years, because there is not enough capacity in the supply chain to accommodate the rising demand for port capacity, vessels, skills, tools and personnel. Additionally, a shortage of marshalling port area is restricting growth in the US (Parkison and Kempton, 2022).

Lerche et al. (2022b) studied the frequency of causes of downtime in offshore wind installation projects. It was concluded that the most important causes of downtime are previous tasks, weather conditions, vessel-related problems, location, information, equipment, parts, permit, planning, and components. Cairney (2015) points out that the delay is caused by over-confidence of stakeholders and a lack of quantitative

Table 1: Overview of studies addressing downtime in offshore wind installation.

Reference	**Causes**				**Solutions**							
					Modelling				*Supply chain improvement*			
	Unfavourable weather conditions	Vessel and equipment	Supply chain / infrastructure	Other	Discrete-Event Simulation	Mixed Integer Linear Programming	Robust optimization	Stochastic model	Coordination	Investments	Productivity	Resources (vessels, ports)
Aagaard et al. (2015)				x					x			
Altuzarra et al. (2022)	x	x					x					
Barlow et al. (2015)	x	x			x							
Barlow et al. (2018)	x				x		x					
Cairney (2015)	x			x					x		x	
Dinh and McKeogh (2019)		x	x						x	x		
Gintautas et al. (2016)	x	x						x				
Gintautas and Sørensen (2017)	x	x						x				
Halvorsen-Weare et al. (2021)	x	x	x		x[a]							
Hrouga and Bostel (2021)	x	x				x						
Lange et al. (2012)	x	x	x		x							
Leontaris et al. (2017)	x		x					x				
Leontaris et al. (2019)		x	x					x				
Lerche et al. (2022a)				x							x	
Lerche et al. (2022b)	x	x		x							x	x
Oelker et al. (2021)	x				x							
Parkison and Kempton (2022)			x							x		x
Paterson et al. (2020)	x							x[b]				
Poulsen and Lema (2017)			x							x		x
Rippel et al. (2019a)	x	x	x			x[c]						
Rippel et al. (2019b)	x						x[c]					
Rippel et al. (2021)	x	x					x					
Scholz-Reiter et al. (2010)	x					x						
Scholz-Reiter et al. (2011)	x	x				x						
Ursavas (2017)	x						x					
Vis and Ursavas (2016)	x				x						x	

[a] Agent-based simulation
[b] Auto-regressive
[c] Combined with MPC

risk assessments. This results in failures, mismatches between planned and actual installation activities, late design changes and lack of crane capacity, manpower and vessel availability. Next to that, contracts between stakeholders contain weaknesses, which leaves projects exposed to financial risks in case of unforeseen events.

2.2. Methods to reduce downtime in offshore wind installation

Discrete-Event Simulation (DES) can be used to compare and evaluate different installation scenarios without financial risk (Barlow et al., 2015). The simulation models of Lange et al. (2012) showed that especially the final part of the installation chain is prone to the risk of downtime and increasing costs, due to weather restrictions prohibiting transport and installation. Vis and Ursavas (2016) applied DES to compare different preassembly scenarios and concluded that the number of components, the distance to shore and the number of turbines on a vessel are important variables in offshore wind logistics. Halvorsen-Weare et al. (2021) combined DES with agent-based simulation to optimise different scenarios for weather conditions and component transfers. Especially during the planning and bidding stages of the offshore wind project, DES can be applied to support decision-making and scheduling (Barlow et al., 2018). Oelker et al. (2021) use DES to show that only increasing the wave limits from 1 m to 1.6 m results in a cost reduction of 17.9% for the installation costs and decreases the total installation time by 32 days and still allows a safe and reliable installation of the rotor blades.

Mixed Integer Linear Programming (MILP) is used to determine the optimal installation planning for vessels and vessel loads, considering weather forecasts (Scholz-Reiter et al., 2010, 2011). Hrouga and Bostel (2021) propose to use MILP to evaluate logistical strategies and decisions to minimise the total costs for installation, transport and storage for the global supply chain. Rippel et al. (2019a) combined MILP with Model Predictive Control (MPC) to schedule vessel installation activities, because it allows for longer prediction horizons with short response times.

Robust optimisation can be used to calculate vessel renting periods on short term. However, it depends on accurate weather forecast data (Ursavas, 2017). Furthermore, although modelling offshore wind installation logistics allows global optimisation of the duration of the project, the use of historical data, for example, weather data, also increases the uncertainty of the model, because the baseline for decision-making is the same for every run of the model (Rippel et al., 2021). There are several ways to counter this weather data dependency discussed in the literature. Barlow et al. (2018) combined DES with robust optimisation, because it incorporates the ability to optimize schedules of the optimisation model, whilst accounting for weather conditions due to the DES model. The combination of robust optimisation with MPC also enables mid to long-term scheduling of offshore wind installation processes (Rippel et al., 2019b).

Gintautas et al. (2016) presented a statistical approach to predict operation failure due to bad weather conditions. By using this stochastic model, the uncertainty of operation failure is directly related to the uncertainty of weather forecasting, at least for the short term (Gintautas and Sørensen, 2017). Stochastic models can also be applied to study the impact of supply chain disturbances on total cost (Leontaris et al., 2017). This application of stochastic models allows for optimal decision-making for installation schedules, buffer stock of components, fleet composition and selection of installation ports (Leontaris et al., 2019). Paterson et al. (2020) used a Markov-switching auto-regressive model to provide stochastic weather conditions (wind speed and wave height time series) that can be applied to assess marine operations such as offshore wind installation processes.

The categories of investments and resources are strongly related since expanding capacity and resources mostly require investments. It is important to improve capacity and resources, because differences in preconditions, such as vessels, equipment, and ports, also determine delaying factors and therefore affect productivity (Lerche et al., 2022b). Dinh and McKeogh (2019) state that the offshore wind supply chain needs a strong demand-side pull to enhance specialisation, integration, competition, and cooperation. Poulsen and Lema (2017) recommend that European countries should invest in technological development to reduce supply chain bottlenecks and to invest in key infrastructure, equipment, assets and skills. Additionally, Europe and China could collaborate on research and business models. To meet US offshore wind targets, supply chain capacity must be expanded by investing in infrastructure, port locations, and installation vessels according to Parkison and Kempton (2022).

Increasing productivity can help reduce downtime in the offshore wind installation supply chain. It is important to be realistic about weather conditions and other risk factors when planning an offshore wind installation process (Cairney, 2015). Productivity in offshore wind installation processes can be improved by applying Takt planning, Kanban, and plan-do-check-act, according to Lerche et al. (2022a).

Informal continuous coordination between subcontractors can also help to improve project planning. According to Aagaard et al. (2015), the positive drivers for such informal relations are trust, previous successful collaborations, risk and associated costs, future collaboration prospects, low level of customer satisfaction, and a limited number of employees. On the other hand, high task uncertainty, tight economic constraints and high economic impact are identified as negative drivers for informal coordination. Cairney (2015) recommends arranging a good information flow between all contractors and emphasises the importance of clear liquidated damage clauses.

2.3. Knowledge gap and problem statement

The effect of downtime caused by equipment breakdown on offshore wind installation planning remains unclear. It is known that equipment breakdown causes downtime in offshore wind installation, but the magnitude and causes of the problem are unclear in the literature. Furthermore, no method is known to reduce downtime due to equipment breakdown in offshore wind installation.

In this research, the following main research question is answered:

How can downtime due to equipment breakdown be reduced during the installation process of an offshore wind project?

It is aimed in this research to propose a new method to reduce downtime due to equipment breakdown in offshore wind installation by improving decision-making. The method that is presented in this study combines the effect of weather conditions and equipment breakdown in a simulation model, which has not been done before in other studies. The objective of this research is to better understand how the breakdown of the installation equipment affects the logistics of offshore wind installation. By quantifying the effects of decision-making, new knowledge can be gained in the rapidly developing offshore wind installation market. Furthermore, this research is a starting point for further expansion of simulation models with equipment characteristics for offshore wind installation planning.

It is chosen to limit the scope to the installation schedule of the installation vessel. Furthermore, the equipment under scrutiny in the case-study will be narrowed down to equipment that is used for installation purposes, such as hammers and the template. Equipment needed for vessel operation, such as engines, is beyond the scope of this research. The model only includes the failure and preventive maintenance of the hammer. Additionally, the scope of this research is focused on processes and operations, rather than the design of the equipment itself.

3. Methods

3.1. Define-Measure-Analyse-Design-Verify

The Define - Measure - Analyse - Design- Verify (DMADV) method is used to analyse the research problem as a whole. The methods applied in this study are presented in Figure 3. DMADV is a lean Six Sigma methodology that is implemented in supply chains to improve quality and customer satisfaction (Kolte and Dabade, 2017). A DMADV project goes through five steps: define, measure, analyse, design and verify. During the first step, the problem is defined by setting the scope and objective of the project. Then, in the measuring step, the processes of the system are determined and data is collected. Data and the system are then analysed using lean methods to identify the root causes of the problem and to pinpoint potential improvements. Requirements for the design are also collected during the analysis phase. During the design step, a design with improvements to the system is composed. Last, in the verification stage, the final design is tested and compared to the requirements and collected data (Alnounou et al., 2022).

3.2. Root-cause analysis

Root-cause analysis is used as a qualitative method to identify root-causes in a case-study, for example by using a fishbone or Ishikawa diagram (Rodgers and Oppenheim, 2019).

3.3. Discrete-event simulation

The in-house discrete-event simulation software Metis of HES is used to build the model. In DES, a system is modelled as a collection of objects performing a series of sequential activities in discrete time (Tako and Robinson, 2018). DES is a widely used simulation method that is applied in offshore wind to reduce downtime due to bottlenecks in the logistics scheduling of offshore wind installation projects. The method can be used to simulate repetitive and sequential activities, in particular when these activities depend on external constraints (Vis and Ursavas, 2016). DES is suitable for the simulation of offshore wind logistics, because it enables the simulation of repetitive installation cycles for each turbine. Furthermore, the dependence on weather limits of operations can be simulated using DES (Oelker et al., 2021).

In this model, vessels transport and install the components of an offshore wind turbine at a windpark on a dedicated location, while testing operational limits against historical weather data. The model is simulated multiple times, which is called Monte-Carlo simulation. By applying Monte-Carlo simulation, the weather conditions are varied for each run of the simulation. Each run of the simulation simulates the weather conditions in one year in the historical data-set. Furthermore, the start dates of the project are varied in each run around a specific date. After a large number of runs of the model, the average results converge to a final, statistically relevant value that can be used for comparison of the designs. The variability between different runs shows the uncertainty of the results (Muhabie et al., 2018).

3.4. Total Productive Maintenance

Total Productive Maintenance (TPM) is a lean concept that aims to improve equipment productivity by reducing losses. These losses are categorised into six categories: time lost due to equipment breakdown, losses due to adjustments and setup time, idle time due to process disruptions, speed loss due to differences in actual speed and design speed, quality losses due to defects and learning curve (Abdul Rahman et al., 2020; Alnounou et al., 2022). The TPM methodology is based on eight pillars, which can be seen in Figure 4. The first four pillars concentrate on improving equipment efficiency through maintenance. The other pillars support maximising effectiveness by addressing other areas for improvement (Meca Vital and Camello Lima, 2020). Before TPM can successfully be implemented, a 5S foundation is required. 5S is a lean concept that helps to keep an organised and effective workplace by going through five steps: sort, set in order, shine, standardise, and sustain. Furthermore, maintenance planning is a vital part of process improvement and can be used as a competitive advantage (Mwanza and Mbohwa, 2015). According to Soltanali et al. (2021), various studies proved that the application of TPM was effective in the food industry to increase equipment productivity.

Maintenance strategies can be divided into two categories: corrective maintenance and proactive maintenance. The different strategies are depicted in Figure 5. Chin et al. (2020) explain

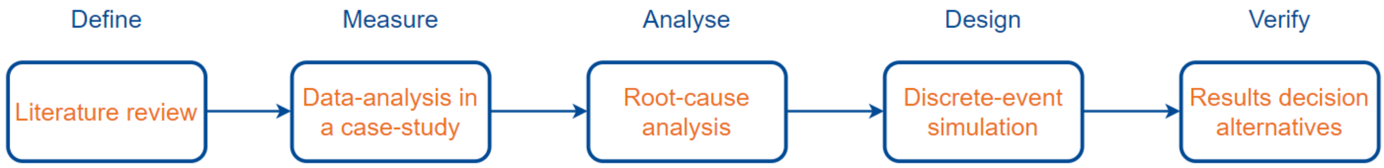

Figure 3: Application of all steps of the DMADV method in this research.

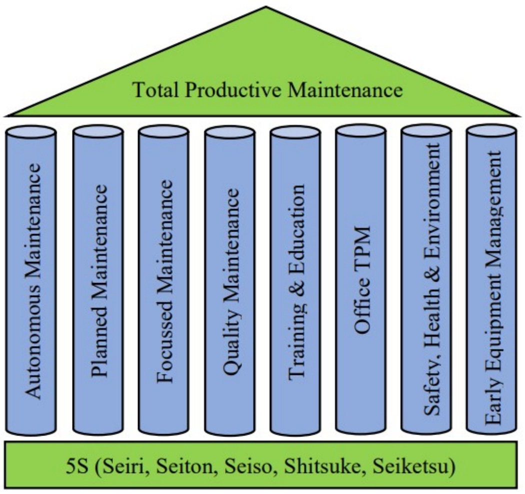

Figure 4: The eight pillars of Total Productive Maintenance.
Note. Reprinted from Setiawan and Hernadewita (2021).

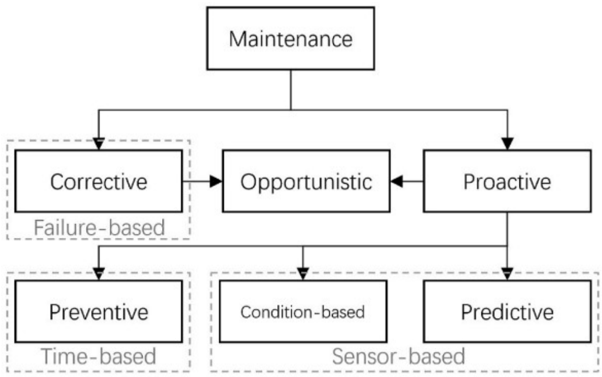

Figure 5: Overview of maintenance strategies.
Note. Reprinted from Ren et al. (2021).

the different maintenance strategies. When corrective maintenance is applied, the maintenance is performed after the equipment breaks down. These unexpected failures are undesirable, because they often result in high costs and frequent downtime. When proactive maintenance is applied, maintenance is carried out before problems arise. Proactive maintenance can be divided into sensor-based maintenance and time-based maintenance. In sensor-based maintenance, sensors are used to monitor equipment and determine the risk of failure. For preventive maintenance (PM) a time-based probability of failure is used to describe the reliability of the equipment. In opportunistic maintenance, idle time is used as an opportunity for maintenance, because operations are not performed and equipment can be inspected without spending extra time. This can be very beneficial from a cost perspective. Research of Kolte and Dabade (2017) shows that the implementation of PM in the manufacturing line of automobile engines reduces equipment failure, increases and improves the availability of the equipment and therefore improves the performance of the production line as a whole. Optimal maintenance scheduling requires an accurate prediction of the remaining life of the equipment (Heda, 2019; Liu et al., 2019).

3.5. Data-collection

The magnitude of downtime due to equipment breakdown in an offshore wind installation project is assessed in a case-study. In the case-study, pinpiles need to be installed, before a jacket can be installed. There are more than 400 data points examined for downtime. These are all the recorded windows of downtime on the critical path during the project, including downtime on the critical path due to waiting on support vessels. Downtime on the critical path means that installation processes are put on hold or postponed until all conditions are met for the operations to continue. The critical path is the planned time horizon where installation is executed. Repairs to equipment are not critical when they can be performed at the same time as active installation operations, for example when that specific piece of equipment is not required for the active operation.

Furthermore, interviews with experts are conducted to collect data for the root-cause analysis. Additionally, the data from the interviews are used to design decision alternatives, which are simulated using the model.

3.6. Model description

Metis does not yet have a functionality to model equipment breakdown, therefore an additional module is added to Metis: 'breakdown model for the hammer'. An overview of Metis and the breakdown model for the hammer and their interaction is given in Figure 6. Metis and the breakdown model interact via the total drive time of the hammer. The total drive time gets updated for each pinpile installation cycle. The total drive time of the hammer is used in the breakdown model to determine the probability of failure of the hammer in that cycle using Equation 1. This is also presented in Figure 7. The parameters of the time to failure function are based on the observed failure data in the case-study. If the probability is greater than a random value between 0 and 1, the hammer breaks down and the model generates a breakdown duration, which is included in the installation schedule. If the hammer does not break down, the pinpile can be installed. The Mean Time between Failures (MTBF) from the case-study is used to determine when maintenance to the

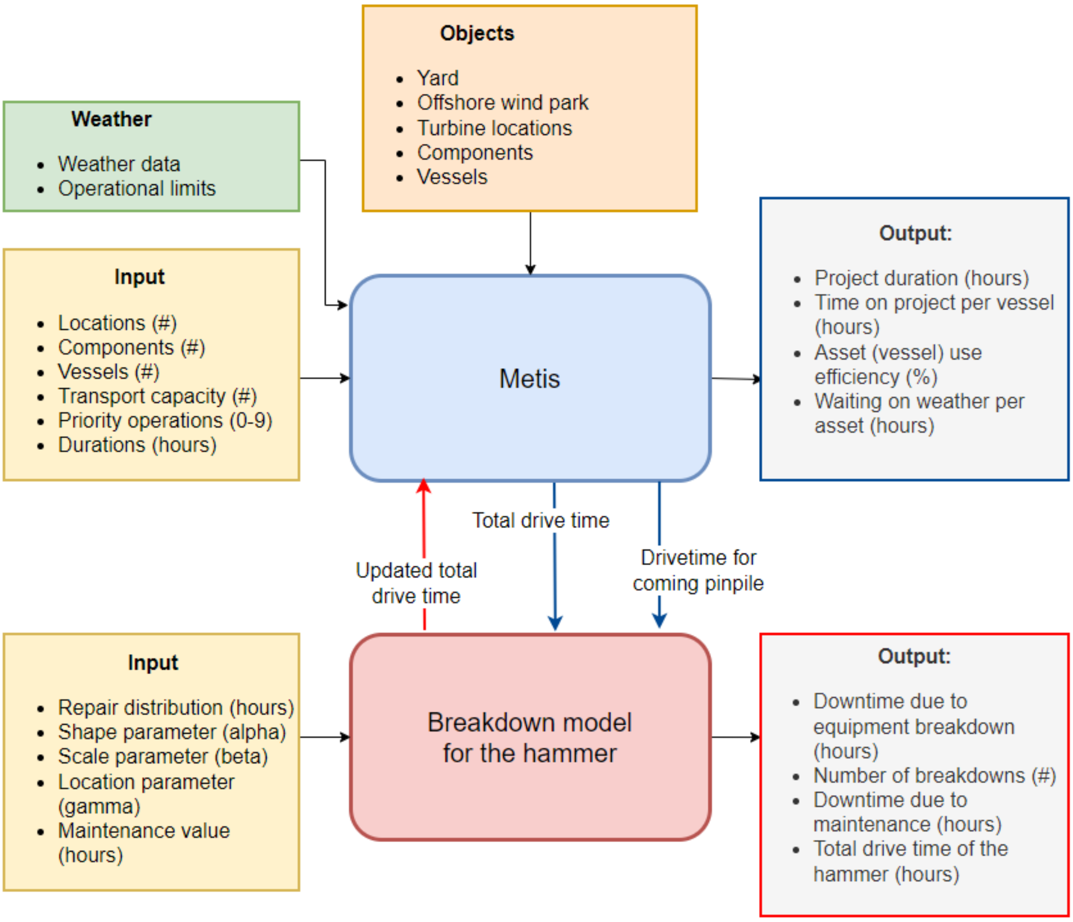

Figure 6: Overview of the relation between Metis and hammer breakdown model.

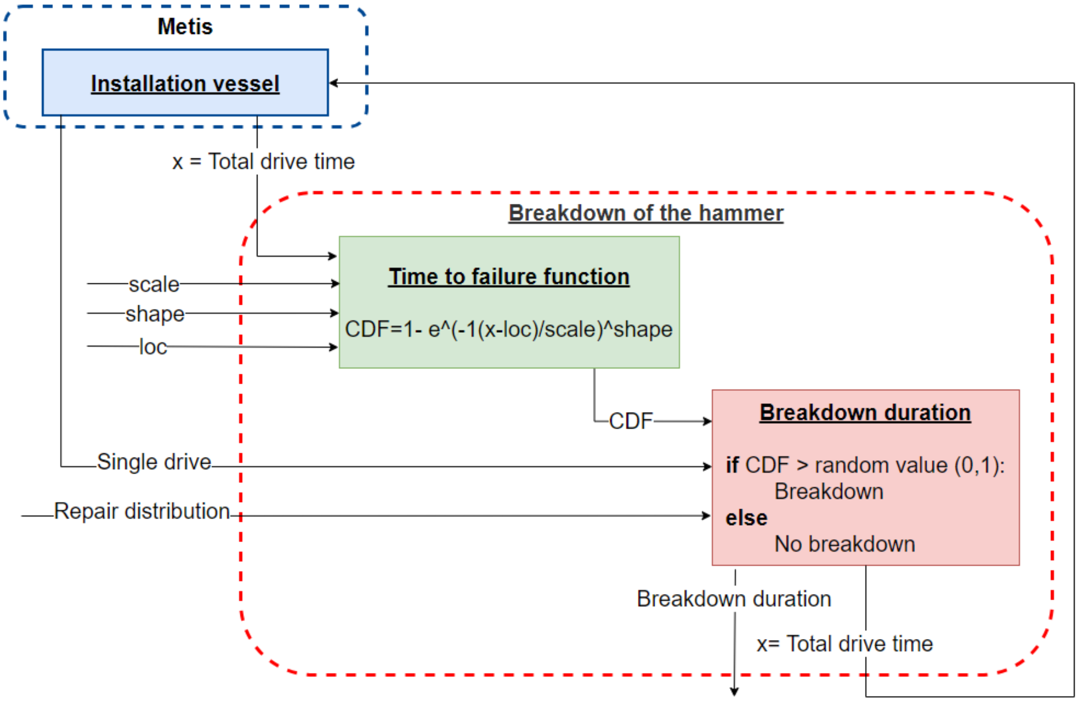

Figure 7: Overview of the breakdown model for the hammer.

hammer is required. Maintenance to the hammer is performed on the critical path if a maintenance condition is reached, see Equation 2.

$$CDF(x) = 1 - e^{-(\frac{x-\gamma}{\alpha})^{\beta}} \tag{1}$$

Where:

- α : scale parameter
- β : shape parameter
- γ : location parameter
- x = total drive time hammer (hours)

$$\text{Total drive time hammer} > 0.8 * MTBF \tag{2}$$

In the model, vessels transport and install the components of an offshore wind turbine at a windpark on a dedicated location, while testing operational limits against historical weather data. The model is simulated multiple times, which is called Monte-Carlo simulation. By applying Monte-Carlo simulation, the weather conditions are varied for each run of the simulation. Each run of the simulation simulates the weather conditions in one year in the historical data-set. Furthermore, the start dates of the project are varied by 10 days around a specific date in each run. After a large number of runs of the model, the average results converge to a final, statistically relevant value that can be used for comparison of the designs. The variability between different runs shows the uncertainty of the results (Muhabie et al., 2018).

All activities are modelled as activity sequences in Metis, for example, the pinpile installation sequence. In this sequence, the entire installation of pinpiles at one location is carried out, together with checks for the availability of location, components and suitable weather conditions. After completion of a sequence, the model can start another sequence. Each of the activity sequences is assigned a priority in Metis, where 0 is the highest priority and 9 is the lowest priority. The priority of the sequence determines in which order sequences can be executed in the simulation. This enables to give preference to one sequence over another sequence if the model can execute different sequences. By assigning priorities, it is made sure that the model consistently carries out the sequences according to the preference of the modeller.

The model is a simplified representation of installation operations, equipment breakdown and preventive maintenance of the hammer. The following assumptions are made in the model for simplification:

- Only breakdown and preventive maintenance of the hammer are considered in the model. No other equipment is included in the model, but it can be implemented in the future.
- A project size of 40 turbines is assumed in the model, to ensure that the project can be completed in one consecutive spring and summer season under favourable weather conditions. Favourable weather conditions are essential in the model, to resemble a situation with limited time for preventive maintenance outside the critical path.
- The number of support vessels remains the same during the entire simulation.
- The hammer is only repaired, but not replaced. So no spare hammer is considered in the model.
- The drivetime of the hammer is derived from the distribution of the cycle time of pinpile installation.
- Pinpile installation is put on hold if the hammer is not available due to preventive maintenance or breakdown. No other activities are possible during repairing breakdown or preventive maintenance in the model, because Metis does not yet allow alternative paths. Therefore, only critical breakdown and preventive maintenance on the critical path are included in the model. In practice, preventive maintenance and repair might be possible simultaneously with other processes.
- Breakdown of the hammer is not further specified, whilst in practice different failure modes are possible. The distribution of breakdown duration is based on all data-points for breakdown of the hammer in the observed data-set.
- Time-based maintenance is applied in the model, because this works well in a DES model. In practice, preventive maintenance is scheduled after a specific number of blows of the hammer. To implement this in the model, soil data or sensor-data would be required.
- The installation vessel can not switch to another activity sequence in the model if the weather conditions are not suitable for installation. In reality, it is possible to switch to jacket installation instead of pinpile installation for example.

4. Results

4.1. Case-study: a completed offshore wind installation project

Only breakdown on the critical path is measured in the case-study, this is referred to as critical breakdown. The results of the case-study indicate that critical equipment breakdown occurs mostly during the spring and summer seasons. Furthermore, pinpile installation is more sensitive to critical breakdown, because pinpile installation requires more types of equipment than jacket installation. Figure 8 shows the division of activities on the critical path during spring and summer. During spring and summer, downtime due to breakdown is the largest cause of downtime during pinpile installation. The equipment that causes the most downtime due to breakdown is the hammer. Therefore, the designs and model only examine decisions regarding the hammer.

4.2. Root-cause analysis

The Ishikawa diagram in Figure 9 shows the root-causes of downtime due to equipment breakdown on the critical path. The causes are divided into different categories: methods, machinery, manpower, measurements, materials and environment.

Favourable weather conditions are prioritized over preventive maintenance offshore. This means that scheduled preventive maintenance might be postponed to continue installation. However, there is limited time for preventive maintenance outside of the critical path. In case of equipment breakdown, corrective maintenance needs to be performed on the critical path,

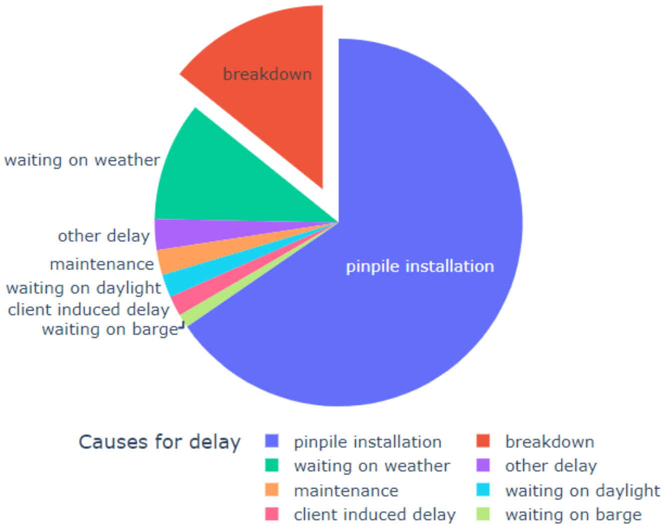

Figure 8: Overview of pinpile installation during spring and summer.
N.B.: this chart presents downtime due to breakdown of all equipment.

which causes downtime. Furthermore, even though logistic simulations provide an installation schedule which accounts for favourable weather conditions, these simulations still contain uncertainty and risk.

There are also underlying factors concerning the machinery that make that critical breakdown causes downtime. When maintenance is postponed, the equipment is longer used than designed for. Additionally, the testing environment for equipment can never fully mimic the offshore environment. Some of the equipment is rented, which means that the owner of the equipment is also responsible for the availability of the equipment. However, the interests of the owner of the equipment might not be the same as the installation contractor. The equipment is often modified for a project, because each project requires specific tailoring of the equipment to the components and vessels. This complicates repair and maintenance. Repairing equipment on the critical path always causes downtime, because it takes time. Even replacing the failing equipment with a piece of spare equipment takes time. Moreover, not all equipment can be replaced by a spare, because there is limited space on deck to store spare equipment and bringing spare equipment is expensive.

Manpower needs to be considered as well when explaining the downtime on the critical path due to equipment breakdown. In general, it is difficult to find specialized mechanics. The staff on board the vessels is skilled, but more focused on the vessel than the equipment. Unexpected breakdowns require the mechanics to be flexible, next to their regular workload. The different contractors all have their objectives, which is a potential conflict of interest. Next to that, mutual contracts include very strict agreements on liability in case of delay of the project. Another manpower-related factor in the downtime due to equipment breakdown is that offshore wind is a new industry. Stakeholders from other industries enter an emerging market. Established knowledge and skills may be outdated or have to be applied differently. This requires flexibility and learning capacity to keep up with technological developments.

Measurements are a key factor in explaining downtime due to critical breakdown. Currently, data is collected for commercial purposes. This means that the available data might be biased. Furthermore, data-sheets are filled in manually, which is vulnerable to errors and personal judgment. Survey equipment and sensors are also sensitive to critical failure. Regarding measurements, it needs to be considered that seasonality might explain differences in cycle times and downtime. To reduce downtime due to critical breakdown and to learn from previous projects it is important to define which data needs to be collected during the project to improve processes in future projects.

Material also plays an important role in downtime on the critical path due to equipment breakdown. Equipment wears out during usage, due to heavy loads, repetitive cycles and offshore conditions. It is essential to bring spare parts on board to save time in case of breakdown. Currently, it is determined before the project starts which spare parts are critical and are needed on board to reduce downtime. This also holds for the tools that are required for repairs.

Lastly, environmental factors cause downtime as a result of equipment breakdown. The installation site has a long distance to shore, so all people, spare parts and tools required for repair have to be on board, because sending them over takes time. Furthermore, weather conditions like daylight, current, waves and wind limit operations. Hence, downtime on the critical path, such as equipment breakdown, may result in extra downtime when weather limits are exceeded. Equipment corrodes due to exposure to seawater for a longer period. Rocks can cause downtime due to critical breakdown by jamming pipes.

The following root-causes are considered for composing the designs:

- equipment wears out during usage
- prioritizing operations over maintenance due to favourable weather conditions
- limited time for preventive maintenance outside the critical path
- repairing equipment takes time, including replacement by spare(parts)
- established skills and knowledge from oil and gas projects are applied in offshore wind installation, but circumstances are different for offshore wind installation projects

4.3. Designs

Designs are composed to improve decision-making on the critical path and gain insight into the effect of decision-making regarding preventive maintenance of the hammer. Prioritizing preventive maintenance is part of the TPM framework (see Figure 4. By quantifying the effects of decisions on KPI's, new knowledge can be gained in a rapidly developing market. The decision alternatives are represented by designs, see Figure 10. The base-case design represents the situation where no preventive maintenance is carried out on the critical path. The D1 design examines when preventive maintenance can be carried out during idle time, although it should be noted that this is comparable to the situation from the case-study. In the D2 design, the

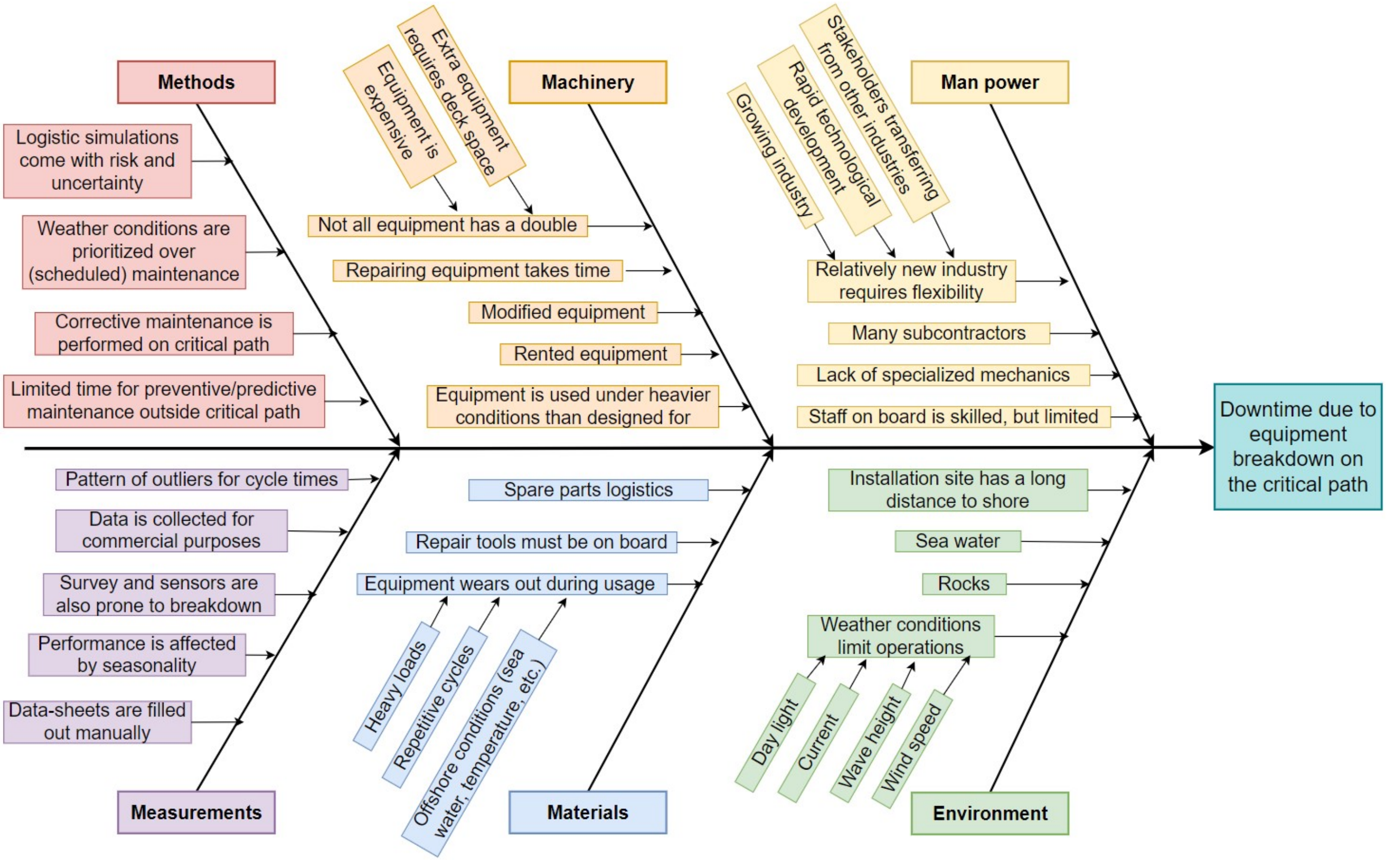

Figure 9: Ishikawa diagram for downtime due to equipment breakdown in offshore wind installation.

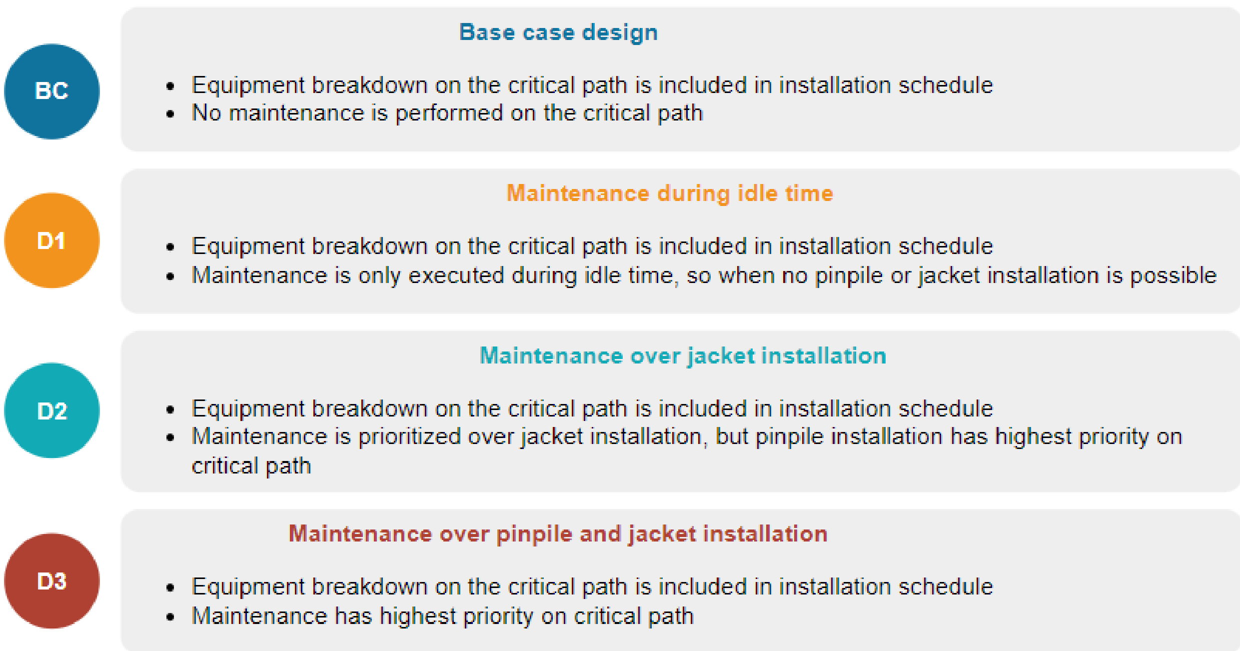

Figure 10: Description of designs.

preventive maintenance sequence is prioritized over the jacket installation sequence. This means that when the maintenance condition is reached, preventive maintenance to the hammer is performed over jacket installation, but pinpile installation still has the highest preference on the critical path. The D3 design represents the decision to prioritize preventive maintenance to the hammer over both pinpile and jacket installation if the maintenance condition is reached. If the maintenance condition is not reached, pinpile and jacket installation can be carried out.

4.4. Verification of the designs

The designs are verified using the model to see what the effects of the decisions are on selected KPI's. The results for the KPI's for downtime due to breakdown and preventive maintenance are included in Table 2. In the model, downtime due to equipment breakdown decreases as preventive maintenance is prioritized on the critical path. On the other hand, the downtime due to preventive maintenance on the critical path increases as preventive maintenance is prioritized on the critical path. The sum of downtime due to critical breakdown and preventive maintenance decreases as well when preventive maintenance is prioritized on the critical path. Moreover, there is almost no difference between the results of the base case designs and D1 for downtime due to breakdown and preventive maintenance.

Table 2: Mean values of downtime breakdown and preventive maintenance.

KPI	*unit*	BC	D1	D2	D3
downtime breakdown	*hours*	73.3	73.4	58.8	54.8
downtime maintenance	*hours*	-	0.0	8.6	11.2
sum	*hours*	73.3	73.4	67.4	66.0

The Mean Time between Failures (MTBF) is calculated using Equation 3. Equation 4 shows how the MTTR is calculated. The number of breakdowns, MTBF and MTTR are indicators of the reliability of the hammer. The results for the KPI's are presented in Table 3. By prioritizing preventive maintenance on the critical path, the number of critical breakdowns decreases. Furthermore, the MTBF increases, which is an improvement. The MTTR remains the same for all designs. Furthermore, there is also almost no difference between the base case design and D1, as well as for the KPI's related to downtime due to breakdown and preventive maintenance.

$$MTBF = \frac{\text{total drive time hammer}}{\text{number of failures}} \tag{3}$$

$$MTTR = \frac{\text{total downtime due to breakdown}}{\text{number of failures}} \tag{4}$$

The results for all KPI's are presented in Figure 11, measured as percent difference to the base case design. By prioritizing preventive maintenance on the critical path some of the KPI's improve; the downtime due to breakdown and preventive maintenance decreases by 10%; the number of critical breakdowns decreases by 30% and the MTBF increases by 37%. Furthermore, the MTTR, idle time, waiting on weather time, time spent

Table 3: Mean values of KPI's equipment

KPI	*unit*	BC	D1	D2	D3
critical breakdown	#	10	10	8	7
MTBF	*hours*	26.6	26.7	33.8	36.6
MTTR	*hours*	7.5	7.5	7.4	7.5

by the installation vessel on the project and the project duration are similar for all designs. From the results of this research can be concluded that the downtime due to equipment breakdown can be reduced and the condition of the equipment can be improved if preventive maintenance is performed on the critical path as scheduled, without affecting the idle time, waiting on weather time, time spent by the installation vessel and total project duration.

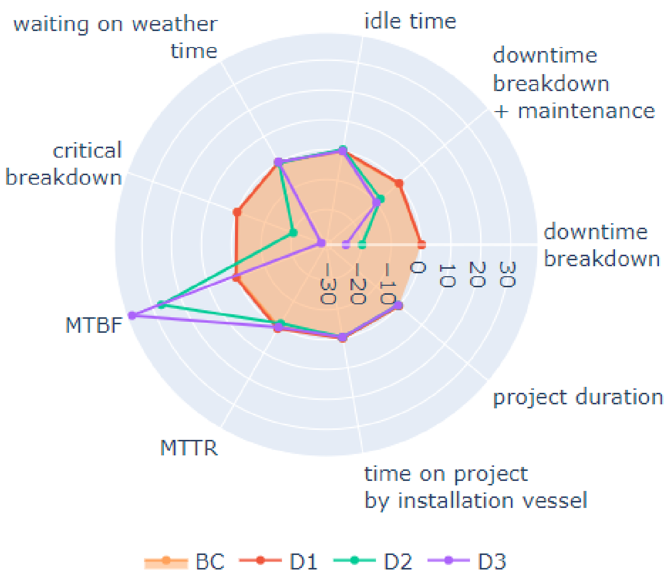

Figure 11: Radar chart with percentual difference between designs and base case design.

5. Conclusion and discussion

In this study, a new method is proposed to get insight in the effects of decision-making regarding preventive maintenance to reduce downtime due to equipment breakdown. The results show that the downtime due to breakdown and preventive maintenance can be reduced by 10% if preventive maintenance is prioritized on the critical path. Considering that the model used in this research only includes the hammer and a project size of 40 turbines is assumed, the impact of implementing this method can be even larger when all equipment is included in the model and project sizes increase.

DES is already applied in practice and in science to improve offshore wind installation schedules. However, this new method not only examines the effect of weather conditions on the installation schedule but also enables the evaluation of decision alternatives for preventive maintenance planning. By including preventive maintenance and breakdown characteristics of the equipment in a DES model, the effect of decision-making on the critical path of an offshore wind installation project can be evaluated preceding project execution. In this way, new knowledge can be gained, which is a competitive advantage in a developing industry. Moreover, implementing the model can raise awareness amongst decision-makers about the consequences of their decisions. Reducing downtime due to equipment breakdown benefits society as well, because the operational time of offshore wind parks can increase, which adds to the market position of offshore wind energy in the energy transition.

The results of this research are not generalizable, because the input parameters of the model need to be adapted to the requirements of a specific project. Furthermore, the model only includes the hammer, but no other types of equipment. If more equipment is included in the model, the results can also change, depending on the characteristics of that equipment. The model is a simplified representation of how the equipment breakdown and preventive maintenance affect the installation schedule of an offshore wind installation project, because several assumptions had to be made. Additionally, the amount and quality of the available data can be improved for future applications of the model.

Future work can be done on implementing all types of equipment in the model. It can also be considered to develop a digital twin of equipment and implement that in the model to enhance predictive maintenance. Additionally, future research can be done to optimize preventive maintenance intervals to further reduce downtime due to breakdown and preventive maintenance in offshore wind installation projects.

Acknowledgements

This research is carried out at Heerema Engineering Solutions (HES), which is part of the Heerema group. Special thanks to everyone at Heerema Marine Contractors (HMC) and HES, who provided input for this research during interviews, presentations and meetings.

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B
Data-analysis

Removed due to sensitive data.

C

Interviews

Interviews with expert's are used to gather information about the types of equipment breakdown that occur offshore and how it is solved. The interviews are semi-structured, this means that most of the questions are prepared in advance, but during the interview additional questions can be asked if needed, depending on the responses of the interviewed expert (Zhang and Wildemuth, 2009). The questions are sended beforehand to the interviewees. The list of questions is included in Table C.1. A short summary of the interviews is included as well.

Table C.1: Structured interview questions.

Installation chain

1. What are (company) objectives with regards to offshore wind installation?
2. Which quality criteria are set for the installation chain?
3. What are critical processes in offshore wind installation?
4. What are bottlenecks in the installation chain (offshore part)?

Equipment

5. What effect does equipment breakdown have in the installation chain?
6. Which quality criteria are set for equipment?
7. Where does equipment breakdown happen in the installation chain?
8. What causes equipment breakdown?
9. What impact does equipment breakdown have on the logistics?
10. How is equipment breakdown currently solved?
11. What might be possible solutions to reduce delay due to equipment breakdown?

Interview 1: Sr. Project Engineer

1. What are (company) objectives with regards to offshore wind installation?
Continuation of the company. Financial goals. Logistic goals are financial goals in this industry. Sustainability is also a goal, but a secondary goal.

2. Which quality criteria are set for the installation chain?

The installation chain must be robust and reliable. High uptime, no critical failure of equipment during a cycle.

3. What are critical processes in offshore wind installation?
Logistics (supply of components) is more important than installation. Installation ships adjust to the schedule of supply. In the past, installation ships had priority due to their high dayrates.

4. What are bottlenecks in the installation chain (offshore part)?
Supply of components, weather conditions, equipment breakdown, replacing equipment, maintenance.

5. What effect does equipment breakdown have in the installation chain?
Equipment is critical in the cycle, therefore often an backup equipment is onboard to replace the equipment in cases of breakdown. For equipment that is too big or too expensive to bring a backup, critical spare parts are on board for repairs.

6. Which quality criteria are set for equipment?
Safety is always important. Simple equipment, easy to maintain.

7. Where does equipment breakdown happen in the installation chain?
On board of the installation vessel.

8. What causes equipment breakdown?
Lack of maintenance, because there is no time reserved for maintenance. Not taking enough ownership of the equipment, sharing it with subcontractors. Design, equipment design is not always robust enough. Damage, in cases of heavy weather conditions the equipment can be damaged.

9. What impact does equipment breakdown have on the logistics?
The impact of equipment breakdown can be reduced by acknowledging the fact that equipment can face breakdown. In the preparing phase, maintenance protocols can be compiled and spare parts can be aligned with those protocols.

10. How is equipment breakdown currently solved?
On the spot, troubleshooting and solving.

11. What might be possible solutions to reduce delay due to equipment breakdown?
Planned maintenance always takes less time than repairing breakdown. Executing maintenance in idles and adapting maintenance schedules to logistics schedules. Taking equipment breakdown in mind when making the installation schedule. Plan some extra time at the start of the project to solve unexpected events.

Interview 2: Sr. Project Engineer

1. What are (company) objectives with regards to offshore wind installation?
Continuation of the company, making money. Sustainability is a secondary goal in that sense. Since the dimensions and weight of turbines increase, this market becomes interesting to our company.

2. Which quality criteria are set for the installation chain?
High quality standards, such as installation-tolerances, inclination-tolerances, no damage, counting the strokes of the hammer, fatigue life.

3. What are critical processes in offshore wind installation?
Supply chain path is critical, FMECA's, preventive maintenance, spare parts, backup equipment

4. What are bottlenecks in the installation chain (offshore part)?
Mechanical breakdown, sometimes logistics. Mechanical breakdown is hard to predict. Weather conditions cannot be controlled. Financial consequences of delay are huge, subcontractors also need to be payed.

6. Which quality criteria are set for equipment?
FMECA, preventive maintenance, spare parts, qualification-steps.

7. Where does equipment breakdown happen in the installation chain?
If you use it, hard to predict the exact moment. Independent of weather conditions.

10. How is equipment breakdown currently solved?
It depends. With hired equipment, there is also personnel of the supplier on board who can help to solve it. Additionally, there are spare parts on board for repairs.

11. What might be possible solutions to reduce delay due to equipment breakdown?
FMECA's are important. Discuss with the supplier what functionalities are required for the equipment and what spare parts are needed on board. Preparing the crew in the simulation center. Planned maintenance.

Interview 3: Project Engineer

1. What are (company) objectives with regards to offshore wind installation?
Within the market: short cycle times, low costs, optimize operations, re-use of equipment, leading position in the market, looking for innovation.

2. Which quality criteria are set for the installation chain?
Conducting audits previously to projects in order to check for quality, certification, reference projects, financial position and state of the facilities of the subcontractors. In practice, there is limited time to conduct the audits, little time to look ahead. Then traditional partners are favoured, because of previous experiences. However, other partners might also be a good choice, but are discarded because they did not collaborated before.

3. What are critical processes in offshore wind installation?
Pre-installation checks, post-installation checks, maintenance.

4. What are bottlenecks in the installation chain (offshore part)?
The right personnel, fabrication capacity, supply specific components (e.g. PLC's (programmable logic controllers)), uncertainty in delivery times.

5. What effect does equipment breakdown have in the installation chain?
Depends on the expectations at the start of the project. If you expect little breakdown, it is quickly a disappointment. If you are forced to dwell, it is always a loss.

6. Which quality criteria are set for equipment?
There are lots of standards for steel, welding and coating etc. For hydraulics: sub-components are certified, but this is more complicated. The standards for the individual components are checked, but it is hard to check if the assembly of components will suffice. The standards are not always specific enough for one-off equipment.

7. Where does equipment breakdown happen in the installation chain?
If equipment gets more complex, more problems will arise.

8. What causes equipment breakdown?
Equipment is not used for the purposes it is designed. Design is not completely aligned with practice. Practice appears different or more difficult than anticipated. The scale on which the equipment is tested is different than the scale on which the equipment is used.

9. What impact does equipment breakdown have on the logistics?
The logistics are based on feeder solutions. If something happens, a traffic jam for barges happens. A couple of hours delay will trouble the schedule, but a few days will.

10. How is equipment breakdown currently solved?
It takes time to find the specific cause for the failure, this results in temporary fixes. The repair engineer on board does not always know how the equipment works and how it can be fixed, because the equipment is very complex. Spare parts are used to replace failing parts.

11. What might be possible solutions to reduce delay due to equipment breakdown?
Bringing spare parts and backup equipment on board. However, backup equipment becomes too expensive. Making the logistics system more robust, e.g. using 3 barges instead of 2 barges. Modelling the transport and installation cycle, this enables comparing different scenario's. Taking the risk of equipment breakdown together for all equipment, then the risk gets more equally divided over the different cycles.

Interview 4: Lead Project Engineer

1. What are (company) objectives with regards to offshore wind installation?
The highest goal is continuation of the company.

2. Which quality criteria are set for the installation chain?
Cycle times are logged for later analysis.

3. What are critical processes in offshore wind installation?
Everything that fails is critical, as it postpones the installation process. Lots of breakdown of bolting equipment. The gangway is also critical. Powersupply is critical as well. Every equipment has its own place in the installation chain.

4. What are bottlenecks in the installation chain (offshore part)?
Equipment has a specific role and could be a bottleneck if it fails. Assembly of bolts is a bottleneck, supply is also a big bottleneck. The installation depends on the logistics of the supply.

6. Which quality criteria are set for equipment?
Equipment needs to be suitable for an offshore environment: temperature, sea water. FMECA's are used to mitigate risks.

8. What causes equipment breakdown?
This varies, e.g. equipment that is not suitable for offshore conditions.

9. What impact does equipment breakdown have on the logistics?
It delays the whole installation ship, this has direct effect on logistics. It also affects next projects that use the same equipment or ship.

10. How is equipment breakdown currently solved?
On the spot.

11. What might be possible solutions to reduce delay due to equipment breakdown?
Preventive maintenance, identify spares.

Interview 5: Equipment Manager Non-Floating Equipment

1. What are (company) objectives with regards to offshore wind installation?
Enabling the energy transition. Revenue is also nice. Being involved in the development of equipment.

2. Which quality criteria are set for the installation chain?
Cycle times. The installation chain is created if the installation planning is finished. Audits.

3. What are critical processes in offshore wind installation?
Supply of components by marshaling yards. Load outs with barges. Barge next to installation ship. Installation. Weather conditions determine big part of the schedule, this is the biggest cause for delay.

4. What are bottlenecks in the installation chain (offshore part)?
The supply chain is most affected by operations: supply, tugboats, barges, logistics, ports, support equipment. Weather conditions are a limiting factor. Supply chain to the marshaling yard.

5. What effect does equipment breakdown have in the installation chain?
Equipment breakdown is only an issue for the installation part of the supply chain.

6. Which quality criteria are set for equipment?
Reliability of the equipment, redundancy.

7. Where does equipment breakdown happen in the installation chain?
Tooling and handling equipment.

8. What causes equipment breakdown?
Wrong choice of equipment, not suitable for the task. Human error. New equipment.

9. What impact does equipment breakdown have on the logistics?
Delay in installation only affects following processes.

10. How is equipment breakdown currently solved?
Repair of the equipment. If possible, replacing the equipment by the backup equipment. Then, the equipment can be fixed simultaneous to the installation cycle. We are now starting to learn about preventive maintenance.

11. What might be possible solutions to reduce delay due to equipment breakdown?
Design of the equipment, preparation of the equipment, redundancy, maintenance and inspections.

Interview 6: Superintendent

1. What are (company) objectives with regards to offshore wind installation?
Efficient offshore wind installation, make profit, safety.

2. Which quality criteria are set for the installation chain?
Reliable equipment, easy to work with.

3. What are critical processes in offshore wind installation?
Foundation: place template on the sea bottom, place pinpiles in the template, remove template. Barge next to installation ship, place jacket on pinpiles, fill with grout.

4. What are bottlenecks in the installation chain (offshore part)?
Lifting tools are reliable, are well maintained and always on the ship. Hammers are placed on the ship only if needed for a project, are stored in between. Problems are more frequent when dealing with different parties.

5. What effect does equipment breakdown have in the installation chain?
It puts the entire process on hold. Replacing equipment also takes time.

6. Which quality criteria are set for equipment?
Determined by the equipment department.

7. Where does equipment breakdown happen in the installation chain?
Everywhere.

8. What causes equipment breakdown?
Lack of maintenance. Depends on the state of rented ships, they are less well maintained. Maintenance is also sometimes piled up for bad weather conditions, so then it is postponed. Lack of knowledge, rented equipment comes with an operator, but an operator does not always knows how equipment can be repaired. Environment, equipment is exposed to seawater, risk of rusting. Additionally, equipment is sometimes longer needed than anticipated.

9. What impact does equipment breakdown have on the logistics?
Logistics stops, waiting until the equipment is fixed.

10. How is equipment breakdown currently solved?
Equipment is repaired by on board mechanics. If the equipment is rented, they will repair it. Combination of on board mechanics and equipment supplier. Sometimes the equipment is inspected by someone on shore (online).

11. What might be possible solutions to reduce delay due to equipment breakdown?
Bring enough spare parts on board. Bring backup equipment on board. Perform maintenance before the ship sails out to the installation site. There is not much that can be changed in the order of the processes.

D

Validation model

Removed due to sensitive data.

E

Additional verification of designs

Removed due to sensitive data.