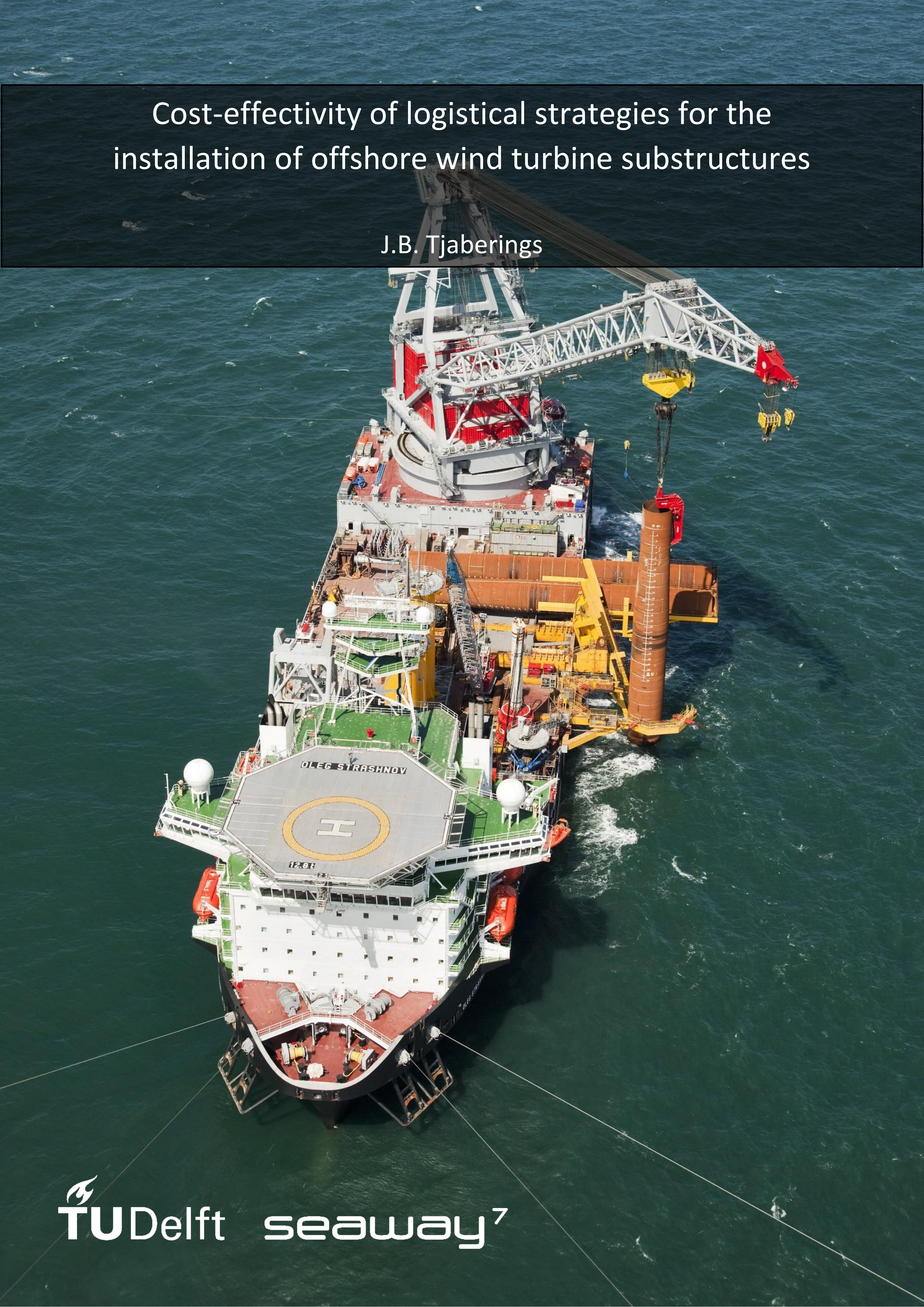
Cost-effectivity of logistical strategies for the installation of offshore wind turbine substructures

J.B. Tjaberings



TU Delft seaway7

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Cost-effectivity of logistical strategies for the installation of offshore wind turbine substructures

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MASTER OF SCIENCE

in **Management of Technology**
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by

J.B. Tjaberings
Student number: 4362845

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Graduation committee

Chairperson:	Dr. R.M. Verburg	ETI
First Supervisor:	Dr. S. Fazi	Transport & Logistics
Second Supervisor:	Dr. R.M. Verburg	ETI
Third Supervisor:	Dr. A. Jarquin Laguna	3mE
External Supervisor:	Ir. E. Steinebach	Seaway7
External Supervisor:	A. Mitterfellner	Seaway7

Preface

This thesis has been written as a partial fulfilment to obtain the Master's degree in Management of Technology (MoT) at Delft University of Technology (TU Delft). It is one of the two theses that were written in parallel as part of a Double Master's Degree programme. This research project has shown that the combination of the curricula of MoT and Offshore and Dredging Engineering (ODE) is very relevant for the fast-developing industry of offshore wind, which is increasingly oriented towards logistics. Seaway7 shares this vision of the increasing importance of offshore logistics in this industry, and I am grateful that they offered me the opportunity to carry out this research under their supervision. Despite the fact that the COVID-19 pandemic complicated the execution of this study, I enjoyed every step of the process. It cannot be stressed enough that the latter would not have been possible without the people around me, to whom I would like to express my gratitude.

First of all, I would like to thank my committee members from TU Delft. Dr. Stefano Fazi has been an excellent first supervisor, who showed genuine interest in the subject and was always available to respond to questions, even in the late hours or during the weekends. Furthermore, I would like to thank Dr. Robert Verburg, not only for being my second supervisor and chairman, but also for helping out with all the bureaucratic difficulties that came with setting up the double degree programme.

The supervision I received from Seaway7 was provided by Edgar Steinebach and Alexander Mitterfellner, and it has to be mentioned that I could not have been more lucky. Although it took months before I would finally meet them in person, as we were all working from home, I never felt a lack of opportunities to ask all the questions I had. They would always make time to have a meeting or to bring me into contact with the right people within the company. Edgar, Alexander and my other colleagues at Seaway7 always made me feel welcome, for which I am thankful.

Last but not least, I would like to thank my friends, family and (ex-)roommates for providing the positive energy and distractions I needed during this graduation project. Special thanks go to my parents, brother and Demi for their unconditional love and support, but also for slowing me down every now and then.

Jorick Tjaberings
Delft, January 31st, 2022

Executive summary

The ever-increasing size of offshore wind turbine substructures and the development of wind farms at sites further offshore, with greater water depths and with extremer weather conditions, raise logistical challenges that have never been faced before. Additionally, the offshore wind industry has to deal with governments cutting subsidies, small profit margins and limited practice guidelines, while it is expected to lower the associated levelised cost of energy to a competitive level in the market. Scientific studies have identified room for optimisation in the substructure (the focus is laid on Monopiles (MPs) with Transition Pieces (TPs) and pre-piled jackets) transportation and installation phases. However, no studies that evaluate the performance of strategies for these phases are identified. Hence, the objective of this study is to "*generate insights into the complex system of interdependent strategies for the installation of offshore wind turbine substructures, and to identify and quantify cost-reduction opportunities.*" The considered strategies are formed by combinations of transportation and installation strategies, which differentiate based on the number and type of the deployed vessels and the sequence in which the operations are performed.

To quantitatively compare the strategies, and to consider stochastic processes (e.g., weather conditions), a discrete-event simulation modelling approach is adopted. To arrive at substantiated conclusions, the framework by Manuj et al. (2009) is followed, which provides a roadmap and rigour criteria for the design, implementation and evaluation phases. First, a conceptual model is developed and face validated. Next, a numerical "base model" is constructed, which describes the most basic strategy. This model is face validated by industry experts and evaluated by parameter variability, convergence and historical data validation tests. It is concluded that the base model is structured according to shared practical experiences, responds satisfactory to parameter changes, requires 35 simulation runs to converge, and has good predictive capabilities. Hence, it is deemed suitable to function as a "template" for the modelling of the other strategies.

The simulation results are evaluated for each of the considered substructures separately. **(i) MP – TP installation.** In general, assembly-line installation strategies, in which two Heavy Lift Vessels (HLVs) are deployed, are associated with the shortest installation time. The shuttling – assembly-line and the shuttling–alternating (in which MPs and TPs are installed alternatingly) strategies are associated with the lowest costs. Both involve a shuttling transportation strategy, in which the HLV(s) ensure(s) both the transportation and installation of the components. The mooring of barges alongside an HLV in feeder strategies (feeder vessels supply components to an HLV, which stays at the wind farm under development) and the installation of TPs by a relatively small HLV in assembly-line strategies are identified as the main bottlenecks. Reducing these by relatively simple solutions can result in significant performance increases. Lastly, the project start date is found to be a strong determinant of strategy performance. **(ii) Jacket – foundation pile installation.** The assembly-line strategies are found to result in the shortest jacket installation times as well. However, only the shuttling – assembly-line strategy is additionally associated with the lowest costs. Furthermore, it is found that a separate pile-dredging vessel can help to reduce the time and costs associated with separate phases installation strategies, in which jackets and their foundation piles are installed in different phases. Also for jackets, the barge mooring alongside the HLV is identified to be the largest bottleneck. Reducing this bottleneck can result in significant performance benefits. Lastly, a relationship is found between the performance of jacket installation strategies and the project start date, although weaker than for MP installation.

The developed decision support tool can provide a platform for further research into the logistics of offshore wind and other industries, whereas the obtained results are only valid within the set boundaries. To widen the applicability, it is recommended to perform follow-up studies in which a stochastic mechanical failure component is included, and the sensitivity to the wind farm size and port-to-farm distance is tested. Furthermore, it is advised to extend this study to investigate the potential of the industry adopting a more holistic process or market point of view.

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Glossary

Feeder	A feeder is defined as a transportation barge or vessel, which supplies components to an at the wind farm staying installation vessel (a tugboat towing a floating monopile could also be considered a feeder).
Foundation	A foundation is defined as a structure which is in direct contact with the seabed and provides a firm supportive ground to the substructure.
Jacket	A jacket is defined as a welded type of substructure, mostly consisting of three or four “legs” (at the corners), which are interconnected by diagonal (and horizontal) “bracings”.
Monopile	A monopile is defined as a tubular type of substructure with a diameter of up to 11 meters.
Peak wave period	The peak wave period is defined as the wave period corresponding to the waves with the highest energy density in the wave spectrum.
Significant wave height	Significant wave height is a statistical parameter to describe the random waves in a sea state. It is defined as the average height of the highest one-third of the waves observed in a certain period.
String	A string is defined as a series of (approximately ten) offshore wind turbines, which are connected by inter-array electrical cables.
Substructure	A substructure is defined as the structure between the seabed and the structure it is designed to keep above the waterline.
Superstructure	A superstructure is defined as the part of an offshore wind turbine above the waterline, which is a combination of the tower, the nacelle, the hub and the blades.
Wave encounter angle	The Wave Encounter Angle (WEA) is defined as the angle between the vessel heading and the wave heading.
Workability	Workability is defined as a concept which describes the environmental conditions for which an offshore operation can be performed safely.

Acronyms

DES	Discrete Event Simulation
DP	Dynamic Positioning
EPCI	Engineering, Procurement, Construction and Installation
FMP	Floating Monopile
GOF	Goodness-Of-Fit
HLV	Heavy Lift Vessel
MP	Monopile
NSE	Nash-Sutcliffe Efficiency coefficient
O&M	Operations and Maintenance
OSV	Offshore Support Vessel
PIF	Pile Installation Frame
RMSE	Root Mean Square Error
SMDP	Simulation Model Development Process
SPMT	Self-Propelled Modular Transporter
T&I	Transport and Installation
TP	Transition Piece
WEA	Wave Encounter Angle
WOW	Waiting On Weather

1 Introduction

In the last few decades, the global installed offshore wind power capacity has been growing exponentially. In 2007, the contribution of offshore wind to the global energy market was 1 GW, whereas in 2018, this contribution had grown to 23 GW (Fernández-Guillamón et al., 2019; IRENA, 2019). The growth of the cumulative installed offshore wind power capacity is visualised in Figure 1.1a. In 2019, an energy generating capacity of 6.1 GW was added to the global capacity, which described the largest growth in the history of global offshore wind. Furthermore, at the end of 2019, 75% of the installed offshore wind capacity was attributed to the European market. However, it is expected that the development of the markets in North America, China, Taiwan, Vietnam, Japan and South Korea will accelerate in the coming years, which is predicted to result in a new annual added global capacity of 20 GW in 2025 and 30 GW in 2030 (J. Lee et al., 2020). A key driver of these rapid developments is the signing of the Paris Agreement in 2015, which initiated a global movement of many countries cooperating to combat climate change. In this agreement, decarbonisation of the energy supply is considered crucial to achieving the set targets and offshore wind technology is a proposed key contributor to this process (Lacal-Arántegui & Jäger-Waldau, 2018).

The growth of the global installed capacity is not only the result of the increasing number of turbines being installed but also of the increasing size and capacity of the individual turbines. Since the first offshore wind farm, constructed in 1991 and with an average capacity of 450 kW per turbine, the global average capacity has grown to 1.5 MW in 2000 and to 7.2 MW in 2019. In May 2020, a turbine model with a capacity of 15 MW was announced to enter the commercial market in 2024 (J. Lee et al., 2020). However, increasing the capacity of wind turbines involves increasing the size of both the "superstructures" and the "substructures". Moreover, as more wind farms are being developed, further offshore sites, with greater waters depths and with extremer environmental conditions are appointed as construction areas (Chartron, 2018). These trends raise logistical challenges that have never been faced before, in an industry where subsidies are being cut by European governments, profit margins are small and extensive practice guidelines are non-existent due to limited experience (Barlow et al., 2015). While these challenges lie ahead, the offshore wind industry is expected to lower the associated levelised cost of energy to a competitive position in the energy market (Ram et al., 2018), which increases the need for innovative development. Such improvements can be made regarding the Transport and Installation (T&I)-phase, as this describes a relatively long period of time, which accounts for about 18% of the capital expenditures (Sarker & Faiz, 2017; Shafiee et al., 2016). More specifically, a supply chain readiness analysis by Poulsen and Lema (2017) indicates that the offshore wind industry in the EU primarily requires attention to the installation procedures of substructures. They expect challenges regarding the logistics and cost-effectiveness of these structures, due to their increasing size and the changing environments in which wind farms are being installed. Additionally, Koch et al. (2017) exemplify the challenges of limited availability of assets with sufficient capacity, and increasing weather sensitivity for the handling of larger substructures.

In the literature on the logistics of offshore wind farm installation projects, a strong tendency can be recognised towards the installation of superstructures. Various studies compare or describe the effectiveness of installation strategies for these structures (e.g., Oelker et al. (2018) compare different transportation strategies and Vis and Ursavas (2016) do this for installation strategies). The installation of substructures is occasionally part of the presented models, but the depth of analysis regarding strategies for this process is limited in those cases. For instance, Barlow et al. (2015) include both super- and substructures in their research on the impact of the weather dependency of offshore operations on the project duration, but limit their research to a single installation method for every phase. To the writer's knowledge, no study has been performed investigating and comparing the effectiveness of substructure installation strategies.

This thesis concentrates on contributing to the process of gaining insights into the installation logistics of offshore wind turbine substructures and identifying cost reduction opportunities. In particular, it focuses on the installation process of jackets and monopiles, which are the most common types of substructures (see Figure 1.1b). The general installation process for these structures includes transporting components from a base port to the wind farm area, driving the foundation into the seabed ("piling") and installing the substructure itself. Each phase of this process can be realised through different strategies. However, deciding upon a certain strategy is complicated as often the suitability of that strategy is dependent on the strategies adopted for the other phases (e.g., the chosen installation sequence of components influences the requirements for the transportation phase). Moreover, other factors such as weather limitations of offshore operations and the project start date may also influence the effectiveness of the strategies. Hence there is the need for a detailed decision support tool that takes these (inter)dependencies into account and helps to identify cost reduction opportunities.

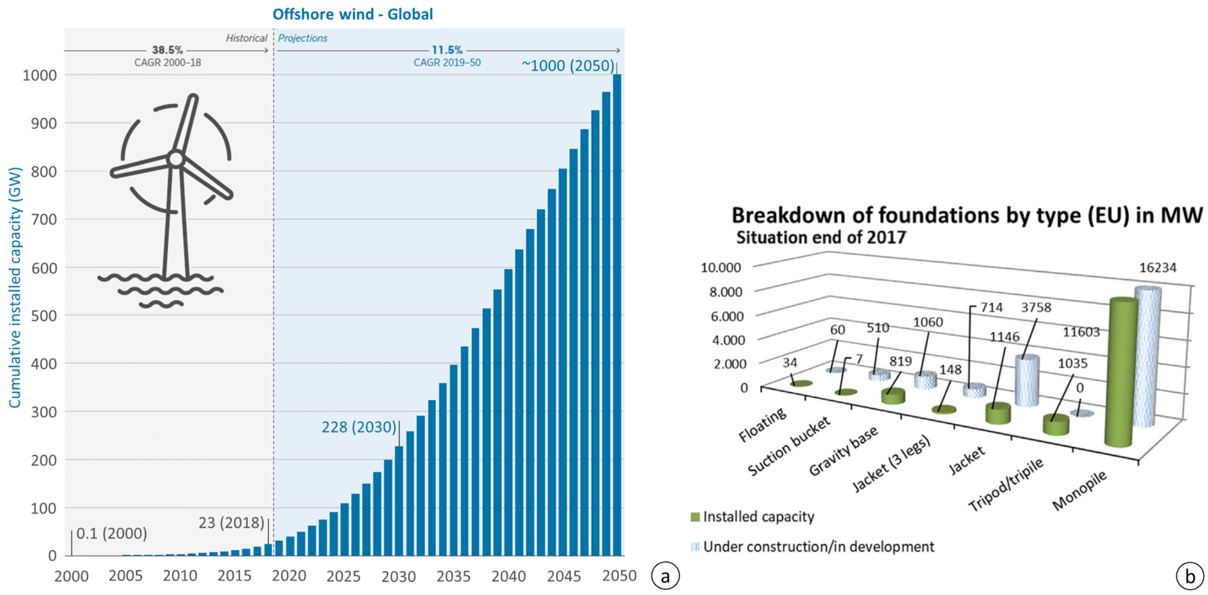

Figure 1.1: (a) Global cumulative installed wind capacity (IRENA, 2019); (b) Breakdown of offshore wind capacity per substructure type in the EU (Lacal-Arántegui et al., 2018)

The objective of this study is to generate insights into the complex system of interdependent strategies for the installation of offshore wind turbine substructures, and to identify and quantify cost-reduction opportunities. To provide such managerial insights, a quantitative modelling approach is followed. More specifically, Discrete Event Simulation (DES)-models are constructed, following the eight-step Simulation Model Development Process (SMDP) designed by Manuj et al. (2009). These models enable to compare different substructure installation strategies in varying environments of external factors.

This thesis comprises nine chapters, the first of which is an introduction into the topic, as presented above. Chapter 2 explains the terminology used in this study, discusses the available scientific literature on the considered topic and identifies a scientific knowledge gap from which the main research question is formulated. Chapter 3 defines the system of analysis and summarises the strategies evaluated in this study. Next, Chapter 4 discusses the methodology that is followed in order to find an answer to the main research question. In Chapter 5, a conceptual model is designed, and in Chapter 6 the collection of the input data for the numerical models is described. Chapter 7 describes the development and validation process of the developed models, and Chapter 8 presents and discusses the numerical simulation results. Finally, in Chapter 9, conclusions are drawn and recommendations for future research are made.

2 Theoretical background

This chapter discusses the research that has been performed on the logistical installation processes of various sets of offshore wind turbine components. The components regarded in those studies are introduced in Section 2.1. Subsequently, in Section 2.2, a literature review is performed considering (modelling) studies focused on the logistics around offshore wind farms. Finally, based on this review, a scientific knowledge gap is identified in Section 2.3.

2.1 Terminology

Although floating offshore wind turbines are mentioned in the industry with increasing frequency, the vast majority of the turbines being installed is still bottom-founded (Lacal-Arántegui et al., 2018). Bottom-founded means that a "substructure" is positioned on the seabed, to keep the "superstructure" above the water line (see Figure 2.1a). There are various types of substructures applied in the offshore wind industry, but the vast majority of these structures is a "monopile" or a "jacket", and it is expected that this tendency will only intensify in the near future (Lacal-Arántegui et al., 2018). A Monopile (MP) is the "simplest" substructure, which can be described as a tubular structure with a large diameter of up to 11 meters (IX Wind, 2021). A jacket is a truss type of structure, mostly consisting of three or four "legs" (at the corners), which are interconnected by diagonal (and sometimes horizontal) "bracings". These structures are displayed in Figure 2.1b and 2.1c. The term "foundation" is often used interchangeably with "substructure". However, for this study, foundation refers to the structure that is in direct contact with the seabed, providing firm supportive ground to the substructure. In the case of monopiles, the substructure also provides the foundation as it is the tubular structure of the monopile itself that is driven into the seabed. For jackets, however, separate foundation piles are installed. This is done either after ("post-piling", with piles driven through "pile sleeves") or before the jacket is installed ("pre-piling", piles driven into the seabed on top of which the jacket is installed). Figure 2.1c displays a post-piled jacket. The part connecting the substructure with the tower is called the Transition Piece (TP). Apart from transferring loads from the superstructure to the substructure, transition pieces also have other functionalities, such as: providing access platforms and boat landings, accommodating electrical components, and offering corrosion protection. All components above the transition piece (the tower, nacelle, hub and three blades) are considered components of the superstructure.

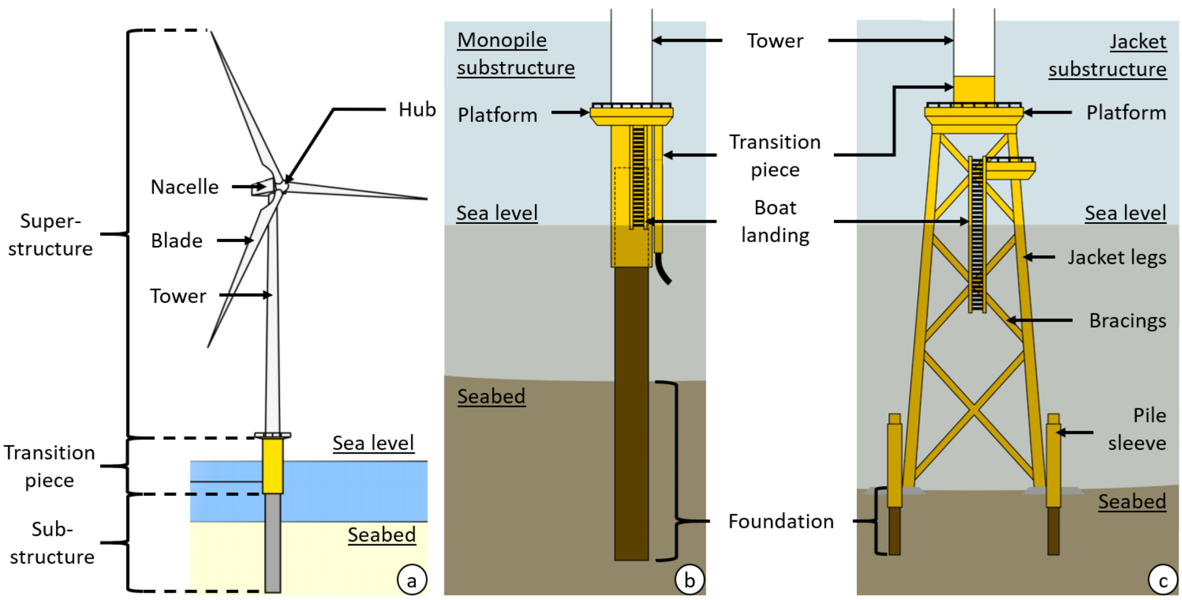

Figure 2.1: Offshore wind turbine terminology breakdown. (a) adapted from (Bhattacharya et al., 2017); (b) and (c) adapted from (IX Wind, 2021)

2.2 Research on installation logistics of offshore wind farms

According to Vis and Ursavas (2016), relatively few scientific studies concentrate on the logistical aspects of offshore wind farms. Moreover, they state that among those studies, the focus is mostly on the Operations and Maintenance (O&M)-phase, and less attention is given to the logistical aspects of the installation phase. Although researching the O&M-phase involves encountering some similar challenges (e.g., the weather dependency of the analysed operations), the corresponding system of analysis is significantly different, especially in terms of the predictability and repetitiveness of the operations. Therefore, these studies are not considered here, however, the reader is referred to (Shafiee, 2015) for an exhaustive review. In this literature review, the available studies considering the installation logistics of offshore wind turbine substructures are explored first, in Section 2.2.1. Next, in Section 2.2.2, studies analysing superstructure installation strategies are discussed, in order to consider their applicability to the installation of substructures.

2.2.1 Studies considering the logistics of substructure installation

According to Conconi et al. (2014), logistical improvements in the installation phase of offshore wind farms are vital to the goal of realising cost reductions. Moreover, they state that the trends of turbines increasing in size and wind farms being developed further offshore in greater water depths require substructures to increase in size and weight as well. To overcome the challenges associated with these developments, the transport and installation system of substructures must develop accordingly (Conconi et al., 2014; Poulsen & Lema, 2017). Conconi et al. propose to tackle these challenges by adapting the installation strategy to the project-specific circumstances. For MPs, they propose three transportation methods: wet towed (floating monopiles, towed by tugboats), by installation vessel and by feeder vessels (which supply the installation vessel at the wind farm with components). The latter two also hold for jacket transportation. Similar considerations can be made regarding the installation of jacket foundations (which can be facilitated by pre-piling, post-piling or suction buckets, and performed by the same or a different vessel than the one that installs the jacket) and the installation of MPs and TPs (which can be performed alternatingly, in separate phases or by different installation vessels). Each of these strategies has its advantages and disadvantages, which are discussed in Section 3.2, and their suitability is likely to depend on factors such as the weather limitations of the involved operations and the project start date. However, Conconi et al. do not quantify these dependencies.

The research by Lange et al. (2012) is among the earliest studies to quantify the logistical processes of offshore wind turbine super- and substructures. They develop a tool to simulate the supply chain of a wind farm development project, from the manufacturing to the offshore installation phase. Their findings indicate that disruptions from weather conditions can result in a sharp increase in the transportation and installation costs. However, this study only assesses a single installation strategy and provides little detail within its broad scope. Relative to this study, Barlow et al. (2015) provide a more focused analysis, covering solely the super- and substructure installation processes. By applying their discrete-event simulation tool, they identify the installation duration resulting from varying levels of weather severity, and they conclude that the installation processes of both structure types are significant contributors to the total delays. Specifically for jacket installation operations, most of these delays are due to the wind limitations and required weather window length of in-port loading of a jacket from the quayside onto a barge, and due to the wind and wave limitations of the offshore installation. Moreover, Barlow et al. (2015) describe a relationship between the installation time and operational limits of vessels or barges, and state that increasing the number of supply barges can increase the functional time of the installation vessel, which would reduce the installation time. Although the latter study does not describe the effectiveness of the various installation strategies proposed by Conconi et al. (2014), it does characterise relationships between operational parameters (e.g., wave limitations) and performance indicators (e.g., installation time).

In (Barlow et al., 2018), a hybrid framework is developed, whose first component is a discrete-event simulation tool based on the model by Barlow et al. (2015), which enables wind farm developers to assess the expected cost and duration of the installation process. The second component is based on the model by Tezcaner Öztürk et al. (2017) and focuses on the optimisation of the installation schedule and making it robust to changes in the duration of weather-dependent activities. Barlow et al. (2018) apply the hybrid framework in a case study on the installation of superstructures, but mention that it is also applicable to the installation of all other wind farm assets, as for instance substructures. Similar to Tezcaner Öztürk et al., Ursavas (2017) develops an offshore wind farm installation scheduling model, but based on a "partial Benders decomposition" approach. The model by Ursavas incorporates weather-related disturbances for the installation processes of both superstructures and substructures and is applied to two wind farm cases located in the North Sea. Muhabie et al. (2018) develop a discrete-event simulation tool focused on superstructure installation, but in which they also include the installation process of jackets. However, the jacket transportation and installation strategies are pre-determined and fixed. Muhabie et al. implement the effect of environmental conditions by both a deterministic and a probabilistic approach, whose results appear to be well aligned. Moreover, they find a correlation between the project starting date, the number of structures to be installed and the resulting required operational days. The studies in this paragraph provide insights into optimally aligning the offshore operations within the installation process of an offshore wind farm. However, taking the operational alignment to the next step of optimised scheduling is outside the scope of this thesis.

Beinke et al. (2017b) perform a resource sharing analysis for the construction of three offshore wind farms simultaneously (covering both super- and substructures). By conducting a discrete-event simulation study, they conclude that weather limitations have a considerable impact on the resources' degree and time of utilisation. Additionally, they state that the resource sharing principle encompasses a large cost-saving potential. In two follow-up studies, it is concluded that also information sharing (e.g., weather data, port capacity and vessel availability) has the potential to increase the project performance (increased production with the limited available resources and decreased installation costs) (Beinke et al., 2017a; Quandt et al., 2017). These studies provide strategies, but on a different project level than the focus of this thesis. Where these studies describe strategies for getting access to project assets, the focus of this thesis is on the deployment strategies of these assets.

Conclusively, although this section is specifically dedicated to research considering the installation logistics of substructures, in all of the discussed studies these structures play an accessory role. No logistical study thoroughly analysing the installation of substructures was encountered. Moreover, to the writer's knowledge, no study describing the effectiveness of different substructure installation strategies has been published so far. However, this has been done for superstructures, as is discussed in the next section.

2.2.2 Studies describing superstructure installation strategies

O'Sullivan et al. (2011) and Oelker et al. (2018) both compare two transportation concepts for superstructure installation. In the first concept, the turbine components are transported from the base port to the wind farm by the installation vessel itself, whereas in the second the components are fed to the installation vessel by commuting feeder barges or vessels. However, where the first study implements the effect of environmental conditions by a probabilistic approach, the second does this by incorporating a deterministic method. Both studies develop a discrete-event simulation model to indicate under what conditions feeders can be a viable alternative. These conditions relate to the port-to-farm distance, the size of the wind farm and the weather limitations of the used equipment. The superstructure installation strategies considered here are also applicable to substructures. However, the effectiveness might be totally different, as substructures generally include less fragile, larger and heavier components, which impacts the offshore operations. The fact that this thesis investigates the applicability of these transportation strategies to substructures, as was already proposed by Conconi et al. (2014), could therefore be a helpful scientific contribution.

Vis and Ursavas (2016) also focus on the superstructure installation process and provide an overview of the logistical principles applied in various wind farm installation projects in the North Sea. They name the pre-assembly strategy as the main differentiating factor. Pre-assembly refers to the process of assembling components already onshore, such that the number of operations to be performed offshore (which are more expensive) is reduced. One form of pre-assembly is attaching the three blades to the hub onshore (the "rotor-star assembly"), such that the complete rotor can be installed in a single lift once it is transported offshore. Likewise, the nacelle, hub and two blades can be pre-assembled into a "bunny-ear assembly". Vis and Ursavas (2016) recommend a strategy in which the number of onshore pre-installed components and the number of turbines loaded on a vessel (negatively correlated) are maximised. Furthermore, Sarker and Faiz (2017) perform a superstructure installation and transportation cost minimisation analysis, in which they also include onshore pre-assembly, but ignore the impact of weather conditions. They show that the turbine size relative to the deck area, port-to-farm distance, learning rates of repetitive work and pre-assembly strategy influence the total costs significantly. The application of pre-assembly strategies to substructures is less evident, as these structures consist of fewer separate components than superstructures. Moreover, the fact that components are currently being installed separately (e.g., the MP and the TP) is not the result of an overlooked opportunity, but of technical limitations.

2.3 Identification of knowledge gap and research question

Table 2.1 provides an overview of the reviewed studies. It indicates whether these studies include the installation of superstructures, substructures or both, and whether the impact of weather conditions, pre-assembly strategies, feeders, the piling process or the deployment of additional installation vessels are included in the analysis. Barlow et al. (2015) and Barlow et al. (2018) include four of the five factors in some form. However, while their models include most components, their focus is on identifying the impact of stochastic weather conditions on the duration of various offshore operations. Installation strategies are not varied or compared. A similar conclusion can be drawn for (Muhabie et al., 2018). However, the latter study does propose for future research to explore the logistical potential of increasing the limiting environmental conditions of offshore operations. O'Sullivan et al. (2011) and Oelker et al. (2018) compare the strategies of transportation by installation vessel and transportation by feeders, but only consider superstructure components. Lastly, while studies analysing the addition of feeders are occasionally encountered in the literature, no research analysing the deployment of additional installation vessels (HLVs) or other support vessels was identified.

From the literature review presented in this chapter can be concluded that no study analysing potentially cost-cutting strategies for the installation logistics of offshore wind turbine substructures has been identified, which leaves a scientific knowledge gap. This gap may be explained by a similar lack of knowledge in the offshore wind industry. Many of the contractors that take care of the installation of offshore wind turbine substructures originate from the oil and gas sector. These companies have a lot of experience regarding tackling the technical challenges of offshore construction projects. However, since these projects generally only involve a relatively small amount of installation activities, most of them have limited experience with long-lasting projects requiring the repetitive installation of many substructures (Drunsic et al., 2016). Only in the recent years, the relatively new industry of offshore wind has become aware of the importance of logistics in such projects. Little acknowledgement of the relevance of a topic in the industry provides little incentive for research in the scientific community, which might explain the low interest in the literature. Another reason may be the unusual combination of the knowledge in logistics and offshore hydrodynamics, which is required to be present in the team of researchers. However, this knowledge is accessible in this study. Therefore, this research aims to fill the defined knowledge gap by answering the following main research question:

What logistical strategies that can be implemented for the installation of offshore wind turbine substructures are most competitive in terms of operational costs?

Table 2.1: Content overview of the reviewed articles focused on the installation phase, including the contribution of this thesis. Abbreviations: Superstructure (T), Substructure (S)

		Considers the impact of:				
Selected articles	**Structure**	**Weather**	**Pre-assembly**	**Feeders**	**Piling**	**Add. HLVs**
• (O'Sullivan et al., 2011)	T	✓	✗	✓	✗	✗
• (Lange et al., 2012)	T & S	✓	✗	✗	✗	✗
• (Barlow et al., 2015)	T & S	✓	✓	✓	✓	✗
• (Vis & Ursavas, 2016)	T	✓	✓	✗	✗	✗
• (Ursavas, 2017)	T & S	✓	✓	✗	✗	✗
• (Sarker & Faiz, 2017)	T	✗	✓	✗	✗	✗
• (Beinke et al., 2017b)	T & S	✓	✗	✗	✗	✗
• (Quandt et al., 2017)	T & S	✓	✗	✗	✗	✗
• (Beinke et al., 2017a)	T & S	✓	✗	✗	✗	✗
• (Tezcaner Öztürk et al., 2017)	T & S	✓	✗	✓	✗	✗
• (Barlow et al., 2018)	T & S	✓	✓	✓	✓	✗
• (Muhabie et al., 2018)	T & S	✓	✓	✗	✓	✗
• (Oelker et al., 2018)	T	✓	✗	✓	✗	✗
→ **This thesis**	S	✓	✗	✓	✓	✓

3 | Defining the system of analysis

Before getting into the details of strategies for the installation of offshore wind turbine substructures (as requested in the main research question, posed in Section 2.3), first, a general overview of the various life cycle phases of offshore wind farms is provided in Section 3.1. Next, in Section 3.2, a more in-depth analysis of the substructure installation process is provided. This analysis results in an enumeration of strategies to perform the load-out, transportation and installation operations of jackets, monopiles and transition pieces.

3.1 General system description

The installation of substructures is only a part of the offshore wind farm installation process, and the Transport and Installation (T&I)-phase is only one of the phases in the development of offshore wind farms (see Figure 3.1). In this section, all the life cycle phases of offshore wind farms are described, in order to provide context around the narrowed down focus of this study.

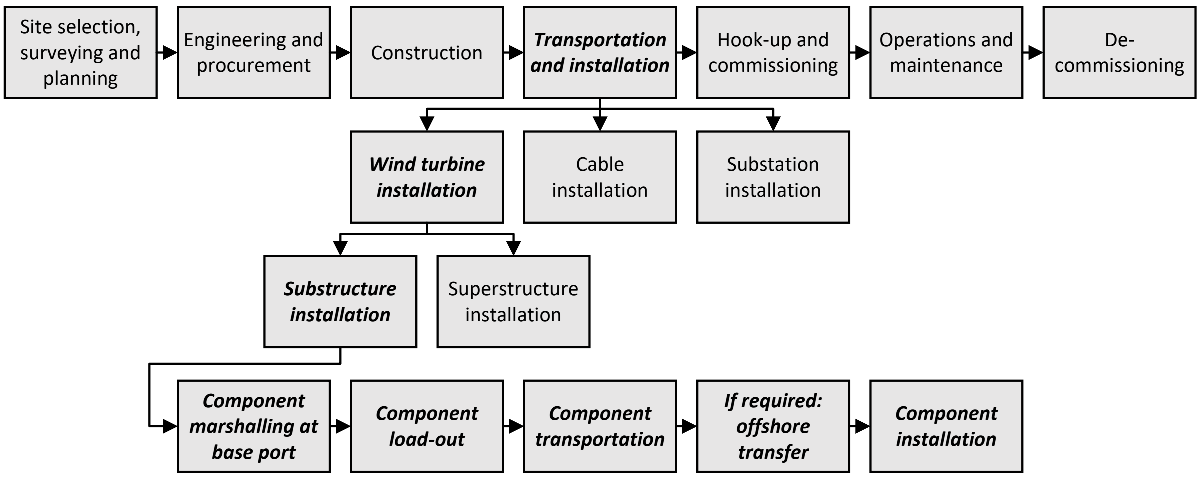

Figure 3.1: The general offshore wind farm life cycle stages, considering the phases of development, installation (with a focus on substructures), operations and maintenance, and decommissioning

The top row of Figure 3.1 provides a generalised sequence of phases in the development, installation, maintenance and decommissioning of offshore wind farms. The first phase of "**site selection, surveying and planning**" normally starts about five years before the actual installation is commenced (Shafiee et al., 2016). Site selection is generally a complex process, in which factors such as wind potential, shipping routes and aquatic life have to be accounted for (Vagiona & Kamilakis, 2018). Once the site is known, a developer is selected (often by the corresponding government organising a tender), and in-depth surveys are performed (e.g., regarding soil conditions) to support the engineering phase (Steen, 2016). Furthermore, this stage is characterised by extensive planning of smooth operations, as profit margins in the industry are small and there is little room for delays (Li, 2016). In the subsequent phase of "**engineering and procurement**", the wind farm is designed, including the selection of the type of substructure, the structural design, the optimisation of the wind farm layout and the design of the electrical infrastructure (Shafiee et al., 2016). Although procurement can be started concurrently with the engineering phase, this can be a risk as the preliminary designs, and therefore the required materials, might change. The "**construction**" phase has a lot of interdependencies with procurement, as components and equipment required in the early construction phase, should arrive accordingly early to prevent delays. Often the manufacturing of structures, such as Monopiles (MPs), Transition Pieces (TPs) and components of the superstructure, is not performed at the base port (from which components are transported to the wind farm location), meaning that the transportation from the construction yard to the base port is also included in this phase.

Once the constructed components start to arrive at the base port and all the required installation equipment is available, the offshore "**transportation and installation**" phase can commence. As indicated by the accentuated processes in Figure 3.1, this is the phase of focus in this thesis. Not only the installation of wind turbines is performed at this stage, but also the electrical infrastructure, including offshore cables and substations, is constructed (see Figure 3.2). Regarding offshore cables, the distinction can be made between "inter-array cables" (which connect the individual turbines) and "export cables" (which connect offshore with onshore substations). Offshore substations collect the energy produced by the wind turbines and increase the voltage, in order to increase the energy transportation efficiency of the generally very long export cables. Some substations additionally perform an AC to DC conversion with the same purpose (S. Rodrigues et al., 2016). Although the installation processes of offshore substations and subsea cables provide complex logistical challenges, these are outside the scope of this thesis. The considered processes regarding the transportation and installation of substructures are further discussed in Section 3.2.

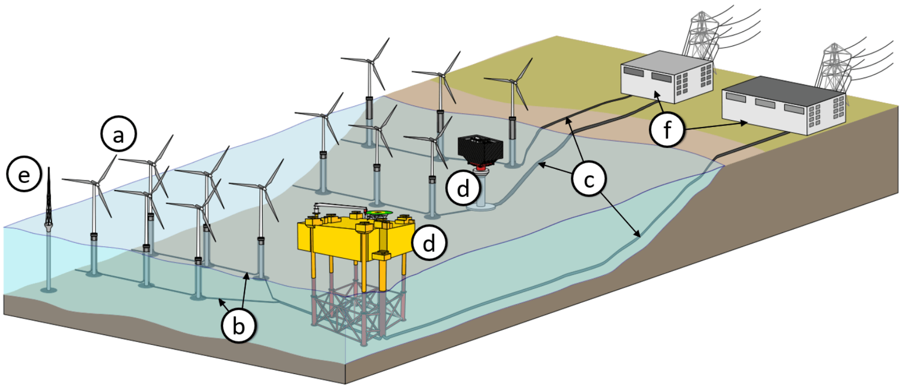

Figure 3.2: (a) Offshore wind turbines with monopile substructures, (b) Inter-array cables, (c) Export cables, (d) Offshore substations, (e) Meteorological mast (f) Onshore substations (S. Rodrigues et al., 2016)

The "**hook-up and commissioning**" phase comprises the activities after the installation of the turbines, cables and substations, with the intention to operationalise the wind farm. This includes realising the connection between the subsea cables and the substations, and extensive testing to assure high performance and reliability (Asgarpour, 2016). It should be noted that large wind farms are sometimes delivered in phases, meaning that finished sections can be commissioned before the complete farm is installed. Once operational, it is key to minimise the wind farm's downtime, and therefore profitability loss, by performing structured "**operations and maintenance**" activities. However, this proves to be a challenge as the accessibility of the offshore infrastructure is limited by the weather conditions at hand (Dewan & Asgarpour, 2016). The complexities and challenges that lie within the maintenance phase explain the relatively high interest of researchers in investigating these operations (uit het Broek et al., 2019). "**Decommissioning**" is the last phase in a wind farm's life cycle, and can be considered as a reversed installation process. In the relatively young industry of offshore wind, little experience has been built up regarding decommissioning, as the first dismantling project was only executed in 2016. Therefore, challenges may arise regarding, for instance, vessel limitations, preservation of marine life and recyclability of decommissioned components. For these reasons, Topham and McMillan (2017) recommend to consider the decommissioning process already in the design phase of offshore wind farms.

Although Figure 3.1 presents the life cycle phases of offshore wind farms in a sequential order, it should be mentioned that in practice these phases can overlap. For instance, while MPs or jackets are still being produced at the construction yard, earlier finished structures can already be installed. Similarly, while wind turbines are still being placed, ones that were installed earlier can already be hooked-up to the electrical infrastructure.

3.2 Substructure installation: procedures and strategies

As can be deduced from the bottom row of Figure 3.1, the first phase of the substructure installation phase is the arrival of substructure components at the base port. These components can arrive by different means of transportation, depending on the location of fabrication and the size of the components. Large and heavy components, such as jackets, MPs and TPs, are mostly transported over water, whereas smaller components, such as ladders and platforms, can be transported over land more easily. Ideally, base ports are facilitated with a large “marshalling yard”, providing sufficient room to line up the received constructed components (see Figure 3.3a). Moreover, the final assembly of delivered components can take place at this yard. The subsequent phases in the T&I-procedure of substructures describe the main focus of this study and comprise the load-out, transportation and installation phases. The latter are described in Section 3.2.1 to 3.2.3 respectively.

3.2.1 Load-out methodologies

Once the T&I-phase commences, the first point of action is to bring the components to be installed from the quayside onto the transportation vessel or barge. Such an operation is called a “load-out” and can be completed in different ways. The load-out of MPs, TPs, and jackets destined for offshore wind farms, is generally performed by deploying either cranes or Self-Propelled Modular Transporters (SPMTs), which are trailers with a built-in propulsion system. Figure 3.3b and 3.3c display the load-out of monopiles by a Heavy Lift Vessel (HLV)-crane and SPMTs respectively. Figure 3.3d depicts a jacket load-out by a crawler crane, with a jacket marshalling yard in the background. The choice for the type of load-out is generally dependent on the availability, costs and capacity of equipment, and the dimensions and weight of the structure to be transferred. Hence, in this study, the method applied to perform the load-out operation is considered as a given input for the system of analysis (and not varied to test the effectiveness of each methodology). If the transportation vessel is an HLV, it performs the load-out itself, otherwise, it is assumed that a suitable crane is available at the quayside.

Figure 3.3: (a) Marshalling yard storing monopiles and transition pieces (Jan De Nul Group, 2019), (b) Lifted load-out of a monopile and a transition piece by the Seaway Yudin (ALE, n.d.), (c) Load-out of monopiles by SPMTs (ALE, n.d.), (d) Lifted load-out of jackets, from a jacket marshalling yard (Crane Market, 2017)

3.2.2 Transportation strategies

The transportation of the components to be installed, from the quayside of the marshalling yard to the wind farm location, can be realised by different strategies. In the first strategy, the HLV that takes care of the installation activities is additionally deployed for the transportation activities. In those cases, the load-out is usually performed by the crane of the vessel, as is depicted in Figure 3.3b. Subsequently, the components loaded on the HLV-deck are rigidly secured to prevent them from moving during offshore transportation (in the industry generally referred to as "seafastening"). Next, the vessel sets sail to the destined location of the next component to be installed. After performing the installation activities, the HLV returns to the base port to pick up the following components. In the industry, this method is referred to as the "shuttling"-strategy.

In the second strategy, the HLV is solely deployed for installation activities, while transportation barges or vessels supply it with components. Figure 3.3c and 3.3d depict load-out operations of components onto such transportation vessels. These vessels (or barges) are often called "feeders" as they "feed" components to the installation vessel. Including a feeder to the logistical operation involves adding two critical offshore activities to the installation system: the mooring of the feeder alongside the installation vessel, and the "offshore transfer". The latter means that, once a feeder is moored to the installation vessel, the transported components have to be lifted off the vessel or barge deck. Both the feeder mooring process as well as the offshore transfer operation are often a limiting factor regarding workability (the environmental conditions for which an offshore operation can be performed safely), and can therefore be considered potential bottlenecks of the deployment of this strategy. A feeder that has been released from all its components heads back to the base port to pick up a new load, after which the cycle repeats.

The third option is performing the "wet tow method". With respect to bottom founded (non-floating) offshore wind turbines, this method has only been applied to monopiles. It comprises a situation in which the MP itself is floating and towed. To provide these tubular structures with sufficient buoyant capacity, the open ends are closed with so-called "end-caps" or "plugs". One large advantage of this method is that no transportation vessels with large deck storage capacities are required. To increase the transportation capacity of the towing vessel (often a tug boat), in theory multiple monopiles may be lined up in series, assuming a proper connection between the monopiles (Li, 2016). However, in practice, a tug boat usually only tows one monopile.

Table 3.1 compares the three transportation strategies by summarising their individual advantages and disadvantages. The main advantage of deploying feeders over transportation by the installation vessel, is the resulting high availability of the HLV for installation activities, while transportation is taken care of by feeders with a generally lower day rate (as discussed by Conconi et al. (2014), O'Sullivan et al. (2011) and Oelker et al. (2018)). Moreover, transportation barges and vessels often have a relatively large deck available for transportation, whereas HLVs also require space to store lifting and installation equipment. However, in the case of the HLV taking care of both the transportation and installation activities the day rate costs of transportation vessels or barges are absent, and offshore operations can be performed with tougher weather conditions. The latter is the case as HLVs generally have a higher workability than transportation vessels or barges, and also because no offshore feeder mooring and component transfer operations are required. Furthermore, barges often have a lower sailing speed than vessels. The main advantage of the transportation of monopiles by the wet tow method is the possibility to perform transportation and installation operations in parallel, while no large feeders are required. Furthermore, by making use of the buoyant effect of the floating monopile, only a relatively small crane is required to install it. However, apart from the fact that this method is only applicable to monopiles, it also comes with a relatively low sailing speed and workability, and the requirement to construct watertight plugs.

Table 3.1: Summary of the advantages and disadvantages of component transportation by the installation vessel and by feeders, and of monopile transportation by wet towing

	Advantages	**Disadvantages**
Transportation by the installation vessel (shuttling)	• No additional transportation vessels • No load-out facilities required • No offshore transfer required • Relatively high sailing speed • Relatively high workability	• No parallel installation and transportation operations • Relatively expensive transportation • Relatively little deck space
Transportation by feeders	• Number of feeders can be altered to optimise HLV occupancy • Parallel installation and transportation operations • Relatively large deck space availably • Transportation vessels have a lower day-rate than HLVs, barges have a lower day-rate than transportation vessels	• Additional transportation vessels • Barges generally have a lower sailing speed than vessels • Barges generally have a lower sailing workability than vessels • Barges require two tug boats • Offshore barge mooring required • Offshore transfer required
Monopile transportation by wet towing	• No large transportation vessels • Parallel installation and transportation operations • Relatively small crane required	• Fabrication plugs required • Relatively low sailing speed • Relatively low workability • Solely applicable to monopiles

3.2.3 Installation strategies

To accurately install substructures, the HLV should be able to keep its position with narrow margins. Generally, there are two principles for a floating vessel to do this: by deploying anchors and by Dynamic Positioning (DP). DP refers to a system that coordinates the activation of a set of engines, thrusters and rudders to automatically let the corresponding vessel keep its position. The main difference between both systems is the requirement of the first to position a number of anchors (often eight or more), generally with the help of anchor handling support vessels, for every installation location. The availability of a DP-system can therefore potentially save a lot of installation time for both jackets and monopiles. In this study, the availability of a DP-system is considered as a given input for the project of analysis (which influences the time it takes to position the installation vessel), and not as a strategy.

Contrary to the load-out, transportation and vessel positioning operations, which have a lot of similarities for jackets and monopiles, the installation procedures of these structures are significantly different. A description for the installation of these substructures is provided next.

Monopile installation procedures and strategies

Since MPs are normally transported horizontally (see Figure 3.3c), the first operation after hooking in the structure is to bring it to a vertical position. In the industry, this operation is called “upending”. Once vertical, the MP is brought to the “outrigger” (also called “pile gripper”) and lowered onto the seabed. An outrigger is a frame around the vertical MP, which provides stability while the substructure is driven into the seabed. Driving an MP into the seabed is usually performed by positioning a “hammer” (generally a hydraulic impact hammer, a vibratory hammer or a combination of both) on top of the tubular structure.

Once the MP has been driven into the seabed to its design depth, the TP can be placed on top. This is traditionally done immediately after the MP has been installed, which is referred to as the “alternating” installation strategy. However, in another strategy, first a batch of MPs is installed, and in a subsequent phase an equally large batch of TPs is installed on top. Moreover, when two installation vessels (HLVs) are deployed, an “assembly-line” installation strategy can be employed in which a larger vessel installs the MPs, after which a second, smaller, installation vessel places the TPs (which are typically smaller and lighter than MPs) on top (Kaiser & Snyder, 2012).

TPs are often fitted with "secondary steel", which refers to components such as boat landings, ladders and access platforms (see Section 2.1). With the use of traditional hydraulic impact hammers, these components cannot be installed on the MP itself, as they would simply come off due to the vibrations induced by the hammer. Therefore, they are installed after the hammering process with the placement of the TP (see the three strategies named in the previous paragraph). However, in the near future, it may be possible to drive MPs into the seabed with much less induced vibrations, due to a newly developed hammering technique. The developers expect to be able to install MPs without having to install secondary steel in a separate phase, meaning that MPs and TPs (including its secondary steel components) can be integrated into one structure (IQIP, 2020). Since these integration activities are performed onshore, and reduce the required offshore lifts, they can be considered as a strategy similar to the "pre-assembly"-strategy applied to superstructures (see Section 2.2.2, described by Vis and Ursavas (2016) and Sarker and Faiz (2017)). However, little is known about the technical feasibility and side processes of this strategy, and hence this approach is not considered in this study.

Table 3.2 provides an overview of the advantages and disadvantages of the discussed MP- and TP-installation strategies. The strategy of alternating installation requires the HLV to position at each turbine location only once, but the lifting equipment has to be changed for every lift. The installation of MPs and TPs in separate phases can be performed with minimal lifting equipment changes, however, the HLV has to be positioned at each location twice. The main advantage of the assembly-line strategy over the first two methodologies, is the deployment of an additional TP installation vessel conform to the required capacity (and day rate), which also results in the ability to install more components within a given weather window. However, deploying two installation vessels, both with a certain day rate, also results in a more complex logistical operation. Moreover, for both the separate phases and the assembly-line strategies holds that an installed MP without a TP on top can only be left alone for a certain amount of time (generally in the order of 24-48 hours, varying per location) without taking collision-preventing measures (such as installing a warning light). Finally, integrating TPs in MPs eliminates the requirement of various (offshore) operations, which could result in significant cost reductions. However, this method is still under development and requires an investment in new equipment.

Table 3.2: Summary of the advantages and disadvantages of alternating monopile (MP) - transition piece (TP) installation, MP and TP installation in separate phases, the MP-TP assembly-line strategy and MP-TP integration

	Advantages	**Disadvantages**
Alternating MP-TP installation	• Day rate of one installation vessel • Mooring at each location once • Sailing to each location once	• Continuous change of lifting equipment • Overcapacity vessel for installing TP
MP and TP installation in separate phases	• Day rate of one installation vessel • No continuous change of lifting equipment	• Ensuring safety when leaving MP • Mooring at each location twice • Overcapacity vessel for installing TP • Sailing to each location twice
MP-TP "assembly-line" strategy	• Capacity second installation vessel conform required capacity to install TP • No change of lifting equipment • Two vessels enable to install more parts within given weather window	• Day rate of two installation vessels • Ensuring safety when leaving MP • More complex logistical operation • Second, smaller vessel may have lower workability
TP integrated in MP (not included in this study)	• Day rate of one installation vessel • Installation in one lift • Less load-out operations • Mooring at each location once • No connection between MP and TP to be realised offshore • Sailing to each location once	• Larger transportation deck space required • Method still under development • Purchase new type of hammer required

Jacket installation procedures and strategies
Jackets destined for the offshore wind industry are mostly transported vertically (see Figure 3.3d). This can be recognised as an advantage over monopiles, as the deck space of transportation vessels can be used more efficiently (depending on the jacket and vessel dimensions). Moreover, no upending operation is required. However, vertical transportation reduces the stability and therefore the workability of the transport. Apart from these small differences in the transport arrangements of jackets and MPs, another distinction can be recognised regarding their foundation. An MP itself is driven into the seabed, meaning that it functions as a substructure as well as a foundation. The piled foundation of jackets is formed by separate foundation piles, which typically have a significantly smaller diameter than monopiles and can therefore be driven into the seabed with a smaller pile-driving device. Another option to realise a jacket foundation is by "suction buckets", which are large-diameter caissons in which a "vacuum" can be created once the jacket is positioned on the seabed, resulting in the bucket "sucking" itself into the soil. However, this type of foundation is only applicable to specific soil types.

Jacket foundation piles can be installed according to the principles of pre-piling or post-piling (as discussed by Conconi et al. (2014)). With pre-piling, the piles are driven into the seabed in a separate phase, before the jacket itself is installed. In a subsequent phase, the jacket is positioned with the bottom of its legs on top of these piles, requiring the piles to be positioned with high accuracy. To ensure this precision, the piles are normally installed through a Pile Installation Frame (PIF), which can afterwards be removed and reused. With post-piling, the jacket and its foundation piles are installed in a single phase. In that case, the piles are driven through the "pile sleeves" or the legs of the already positioned jacket (see Section 2.1). Although post-piling is the standard in the oil and gas industry, pre-piling is prevailing in the recent wind farm development projects. This is mostly due to the requirement for post-piled jackets to be able to stand stably on the seabed by itself until the piles are installed, requiring additional steel ("mud-mats") to provide this stability (Latini, 2018). Although comparing pre-piled, post-piled and suction bucket jackets could be enlightening from a purely logistical point of view, making a genuine comparison would require including location-dependent technical details (such as soil conditions), which is outside the scope of this thesis. Therefore, following the industry's clear preference, this thesis only considers the widely applicable pre-piled jacket foundation.

Pre-piled jackets can be installed by different strategies, as listed in Table 3.3. Similar to the separate phases strategy for the installation of MPs and TPs, jackets and their foundation piles can also be installed in individual sequential phases. This strategy requires minimal lifting equipment changes during the phase of pile installation. However, to realise proper jacket installation, the pre-installed piles have to be cleaned and dredged using a "pile dredging tool", for which lifting equipment has to be changed. Secondly, an assembly-line strategy (similar to the one described for MP-TP) can be applied, in which a smaller vessel (generally with a lower day rate) installs the piles, after which a larger vessel installs the corresponding jacket. This strategy enables to install more components within a given weather window, however, the day rate of the second vessel has to be accounted for. The third strategy in Table 3.3 is similar to the first, however, the pile cleaning and dredging activities are taken over by a smaller vessel (which can be a so-called "Offshore Support Vessel (OSV)") conform to the required capacity to perform this activity. This reduces the costs associated with these cleaning activities and minimises the required lifting equipment changes. However, the day rates of two vessels have to be accounted for, and the pile cleaning activities have to be performed not too long before the jacket is installed (otherwise the removed marine fouling grows back), increasing the complexity of the logistical system. The alternating installation strategy proposed for MP-TP installation is normally not applied to jackets, as the transportation of both jackets and foundation piles on one deck generally does not provide sufficient room to upend the piles. Therefore, this strategy is not considered here.

Table 3.3: Summary of the advantages and disadvantages of the separate phases, assembly-line and separate pile dredger strategies for the installation of pre-piled jackets

	Advantages	Disadvantages
Piles and jacket installation in separate phases	• Day rate of one installation vessel • Limited changes of lifting equipment during pile installation	• Mooring at each location twice • Overcapacity vessel for installing piles and pile dredging / cleaning • Sailing to each location twice
Piles-jacket "assembly-line" strategy	• Capacity second installation vessel conform required capacity to install piles • Limited changes of lifting equipment during pile installation • Two vessels enable to install more parts within given weather window	• Day rate of two installation vessels • More complex logistical operation • Overcapacity vessel for pile dredging / cleaning • Second, smaller vessel may have lower workability
Pile dredging and cleaning with separate vessel (installation in separate phases)	• Additional vessel enables to install more jackets within given weather window • Capacity cleaning vessel conform required capacity to clean piles • Limited changes of lifting equipment	• Day rate of two vessels • More complex logistical operation • Overcapacity vessel for installing piles • Second, smaller vessel may have lower workability

3.3 Strategies of analysis

To summarise Section 3.2, this section lists the introduced transportation and installation strategies and puts them into their sequential perspective, following Figure 3.4. Corresponding to Table 3.1, this figure lists the three transportation strategies: transportation by installation vessel (shuttling), by feeders and by wet towing. However, the wet tow strategy is only applicable to monopiles. The subsequent strategies of installation are dependent on the type of substructures to be installed: MPs (see Table 3.2) or pre-piled jackets (see Table 3.3). For both MPs and jackets, the separate phases and assembly-line strategies can be deployed. The alternating strategy is only applicable to the MP-TP installation process, whereas deploying a separate pile cleaning OSV is only applicable in the case of pile-jacket installation. Hence, 9 unique combinations of strategies for MPs, and 6 for pre-piled jackets can be identified, assuming that one transportation and one installation strategy is adopted in the project's T&I-phase. The number of deployed feeders and Floating Monopile (FMP)-towing tug boats can be varied (e.g., in a sensitivity analysis) when these are deployed as transportation strategies, which makes the total number of logistical set-ups analysed in this study to amount 22.

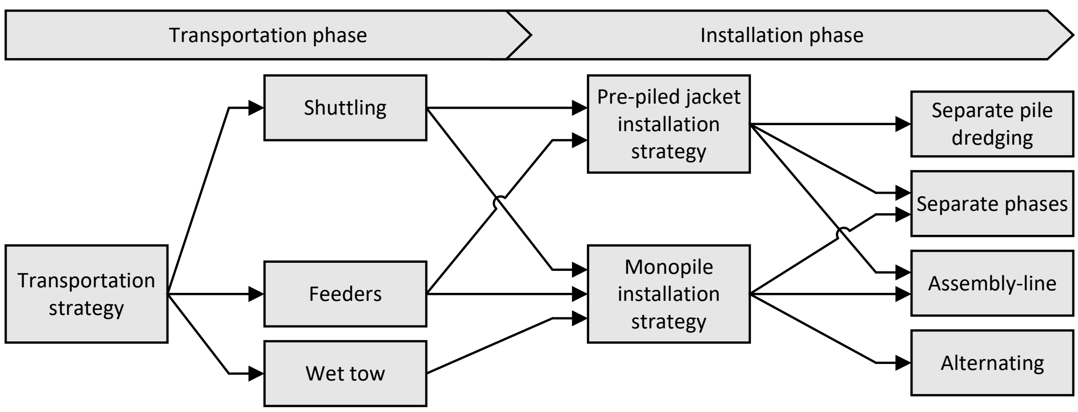

Figure 3.4: Summary of the strategies of analysis in a sequential perspective

4 | Methodology

As discussed in Section 2.3, wind turbine substructure installation strategies are occasionally mentioned in the scientific literature, but no research was encountered describing the effectiveness of these strategies. Based on research focused on superstructure installation, it is expected that this effectiveness is dependent on factors like weather conditions, operational weather limits and vessel characteristics. Quantitative and causal relationships have to be formulated to describe the impact that these factors have on the installation costs, as is requested in the main research question. These relationships form the basis for, and can be analysed in, a quantitative model (Bertrand & Fransoo, 2008). A simulation model enables to evaluate process developments without having to include practical experiments (Balogh et al., 2020), saving the large investments of offshore operations. In particular, Discrete Event Simulation (DES) is preferred if stochastic processes, like weather conditions, should be included in a model (Y. H. Lee et al., 2002; Tako & Robinson, 2012). Therefore, DES is considered a suitable research method, which can contribute to the understanding of the variables involved. However, this method has limited capabilities to function as a decision support tool in itself. To add this function, an evaluation phase is required (Brito et al., 2012).

To systematically construct a thorough decision support tool, the eight-step Simulation Model Development Process (SMDP) by Manuj et al. (2009) is followed. This framework provides a roadmap and rigour criteria for each step in the design, implementation and evaluation of DES-models. The first of the eight phases encompasses the formulation of the problem of analysis and its context, which is considered to be covered by Chapter 3. Therefore, in the remainder of this chapter, seven sub-questions are formulated, corresponding to the seven remaining steps of the SMDP-framework, and focused on answering the main research question.

Phase 1: Definition of variables. This phase is characterised by determining the simulation model's independent and dependent variables, as requested in sub-question 1, which requires to define the boundaries of the model. Independent variables are altered to study their relationship with the dependent variables. The latter are analogous to the measurement of "performance" and, therefore, components of the in the main research question targeted installation costs. Once listed, the specified variables are assessed and complemented by experts from the offshore wind industry, to perform a first verification of the simulation model (Manuj et al., 2009; V. S. Rodrigues et al., 2010). The results of this phase can be found in Chapter 5.

(1) What independent and dependent variables should be included in the model, to characterise the relationship between the substructure installation strategies and the installation costs?

Phase 2: Model conceptualisation. The validity of the simulation output depends on the system description. Constructing a conceptual model helps to validate the simulation model before further investments are made (Manuj et al., 2009; Robinson, 2008a), and is therefore requested in sub-question 2.1. Robinson provides a conceptual modelling framework in (Robinson, 2008a) and (Robinson, 2008b), which guides the processes of selecting a suitable diagramming technique and constructing a fundamentally sound model representation. To subsequently validate the conceptual model, as requested in sub-question 2.2, industry experts are consulted. By systematically going through the model, the experts get an impression of the performance indicators, model structure and the defined relationships within the model. Interviewing helps to collect, and if necessary implement, these impressions (Manuj et al., 2009; V. S. Rodrigues et al., 2010). The results of this phase can be found in Chapter 5.

(2.1) How can the relationship between the substructure installation strategies and the installation costs be conceptualised?

(2.2) How do experts from the offshore wind sector describe the validity of the conceptualised substructure installation process?

Phase 3: Data collection. The reliability of the output data of a simulation model is very much dependent on the quality of the input data (Manuj et al., 2009). Therefore, the collection of the numerical input data for the quantitative model (e.g., vessel and cargo parameters, and numerical information about stochastic weather conditions at the location of analysis), as requested in sub-question 3, is performed with care. The required data are identified based on the listed independent variables and the conceptual model, after which the corresponding values are sought, or generated, by consulting the literature and company documentation. Involved industry experts are asked to validate the reliability of the used data. The results of this phase can be found in Chapter 6.

(3) How can high-quality data, required to model the installation system layout and to quantify the model parameters, be collected and provided to the model?

Phase 4 & 5: Model development, verification and validation. Following the conceptual model and the collected input data, a computer-based simulation model is built, as requested by sub-question 4.1. The software of Simio is considered suitable for this purpose, as it provides an extensive platform for constructing DES-models, including a library of intelligent objects and graphical functionalities to visually justify the correctness of the model structure (Pegden, 2007). Manuj et al. (2009) propose to subsequently investigate the legitimacy of the created model by verification and validation. Verification is accomplished by examining the alignment of the software implementation with the validated conceptual model (see sub-question 4.2), and by analysing the modelling results of straightforward cases. Next, model validation is realised by an expert panel going through the created model (face validity), and by comparing modelling results to data of historical projects, as requested in sub-question 5. For the latter validation technique, an acceptable level of confidence and precision, and the corresponding required number of simulation runs are determined. The results of this phase can be found in Chapter 7.

(4.1) How can the conceptualised substructure installation process be implemented in a discrete-event simulation model?

(4.2) To what extent is the implemented simulation model in line with the conceptual model?

(5) How do experts from the offshore wind sector and data from historical installation projects relate to the validity of the simulation model?

Phase 6 & 7: Simulation and analysis. In the sixth phase, the validated simulation model is applied for its intended purpose: to evaluate various substructure installation strategies. To determine the scenarios of which the results are required to provide a well-substantiated answer to the main research question (requested by sub-question 6), the available strategies are identified (see Section 3.3) and the validated base model is supplemented with the required components. Furthermore, the bottlenecks are identified and the potential of solving these is investigated. Before the subsequent phase of analysis is started, a suitable analysis technique is identified, which is required to answer sub-question 7. Manuj et al. (2009) exemplify the techniques of visual inspection of graphical outputs and variability indicators (such as standard deviation and boxplots). The results of this phase can be found in Chapter 8.

(6) What scenarios need to be run through the model to reliably determine the effect of the considered substructure installation strategies on the installation costs, and to identify the effect of future (technological) developments on the results?

(7) How can the modelling results be analysed, such that a well-founded, conclusive statement on the monetary aspects of the considered substructure installation strategies results?

5 Model conceptualisation

In order to develop a structurally sound simulation model, first a conceptual model is designed. This allows for industry experts to validate the system description before further investments are made. The high-level design process, which follows the framework by Robinson (2008b), is described in Section 5.1. Next, in Section 5.2, the low-level design of the model logic is discussed. Finally, in Section 5.3 the main assumptions and simplifications made are enumerated.

5.1 High-level conceptual model development

According to Robinson (2008a), a conceptual model can be defined as "*a non-software specific description of the computer simulation model that will be developed, considering the objectives, inputs, outputs, content, assumptions and simplifications of the model.*" He states that the *objectives* of a simulation project are intrinsic to the resulting model structure, and thereby to the structure of the conceptual model. Moreover, the objectives assist in determining the model *outputs*, as these are measures of the system performance and give an indication of the extent of reaching the objectives. The model *inputs* and *content* are subsequently determined based on the objectives and outputs (Robinson, 2008a), as is visualised in the iterative process of Figure 5.1. The inputs, also referred to as the experimental factors, are altered to gain insights into the problem of analysis. Hence, the notion of inputs introduced by Robinson represents a similar concept as the "independent variables" referred to by Manuj et al. (2009). Similarly, the description of the outputs by Robinson is in line with the "dependent variables" defined by Manuj et al. Therefore, an overlap can be recognised in sub-questions 1 and 2.1.

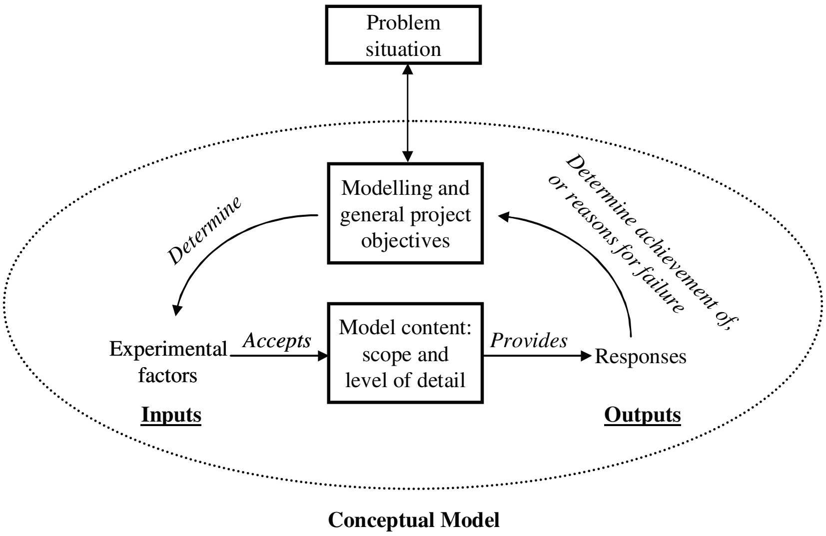

Figure 5.1: Conceptual modelling framework (Robinson, 2008b)

Following the conceptual modelling framework of Figure 5.1, a high-level model representation of the system of analysis is provided by Figure 5.2, describing the "model structure and the general project objectives." It provides some indication of the model content, but in the first place, it specifies the interaction of the model with external data supply (i.a. the inputs). Moreover, it presents the model **outputs**, which are intended to quantify the comparison of installation costs (see the main research question). Additional performance indicators could be added (e.g., the vessel utilisation rate), however, in this study only the effects of such sub-indicators (the project costs and duration) are considered of importance.

The **inputs** (or independent variables) of the system of analysis are the various strategies to adopt during the transportation and installation of offshore wind turbine substructures. Therefore, the inputs of the model cannot simply be represented by a numerical value. Instead, different combinations of data, from different sources, function as experimental factors. First, data of the vessels to be deployed in a certain strategy are required. The type of data in those cases is relatively constant (e.g., sailing speed, transportation capacity, workability, etc.), but the type, amount and function of the deployed vessels vary per strategy. Second, location data of the base port and the individual turbines are supplied to the model (from which the mutual distance is determined). Since various proposed strategies are based on variations in the installation sequence of components, the sequence of sailing destinations for transportation and installation vessels are also varied. Hence, the individual turbine locations are not experimental conditions, but their sequence of visitation. Third, time duration data are required, which refer to the duration of various operations other than sailing (e.g., the time it takes to perform a load-out or install a monopile). Considering the fact that such activities generally vary in the time they take to perform, suitable probability distributions are fitted to describe their stochastic nature, which is discussed more extensively in Chapter 6. Finally, cost data are varied with the deployment of extra vessels (in addition to the main installation vessel) with different day rates.

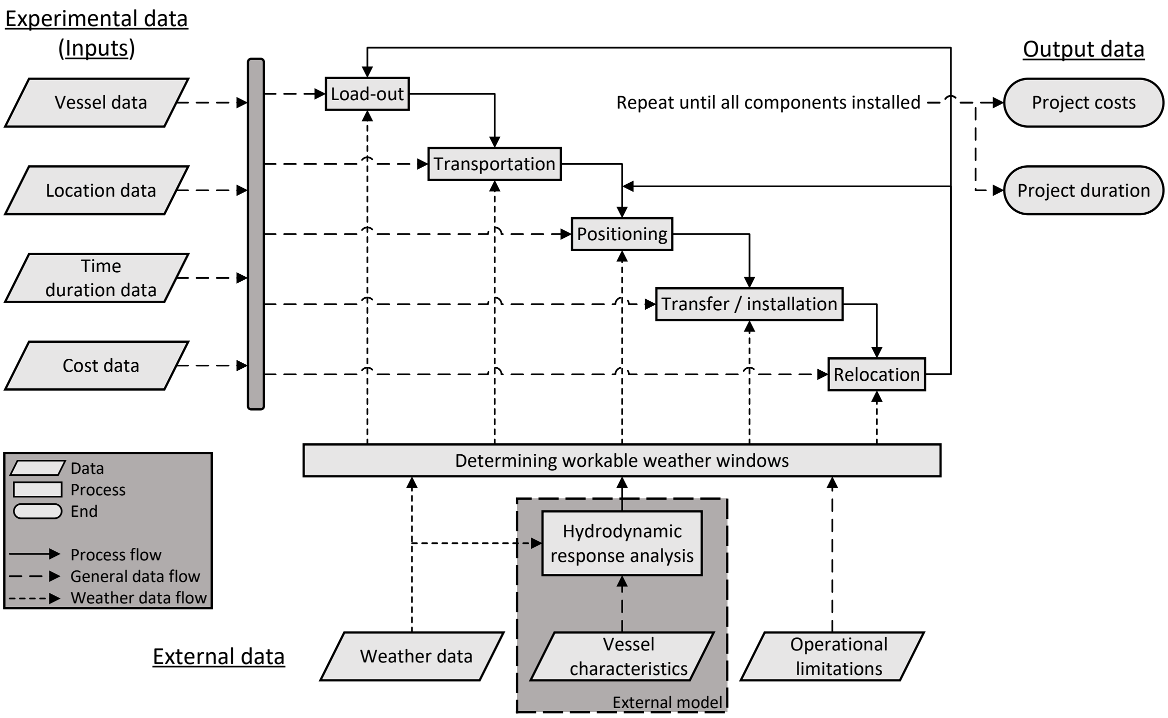

Figure 5.2: High-level conceptual model for the installation of offshore wind turbine substructures

In addition to the experimental data, also weather- and workability-related external data is supplied to the model to determine the “workable weather windows”, a process which is represented by the lower part of Figure 5.2. Workable weather windows indicate if the weather conditions at hand allow for a certain operation to be performed at a particular moment in time, or that the planned activities have to be delayed until more favourable weather arrives. The transportation, positioning and relocation operations are generally considered non-critical (based on experience) and are therefore considered only limited by the significant wave height and the wind speed. The same holds for load-outs, however, as these are often performed inside the sheltered area of a port, only the wind speed at the particular location is accounted for as a limiting factor. The transfer and installation operations are deemed more refined operations, and it is therefore necessary, with regard to the precision of analysis, to include the dependency on peak wave periods and wave encounter angles. To establish the weather windows for the transfer and installation activities, the equipment responses to the weather conditions at hand are determined in an external model, and compared to their operational limitations. A more detailed description of this external model, and its outputs, is provided in Chapter 6.

5.2 Low-level conceptual model development

Regarding the model **content**, Figure 5.2 provides a relatively low-detail overview of the considered repetitive sequential phases that were introduced in Section 3.2. Additionally, it indicates that all four types of experimental data function as input for all of the phases in the process. However, it does not provide details of the process logic or decisions that are made inside the model. According to Robinson (2008b), such details may be necessary to provide industry experts with sufficient insights to constructively validate the model structure. Various diagramming techniques can be used to provide these details. Since Figure 5.2 already visualises the general process flow and interaction with (external) data, a technique merely focused on the model's internal architecture would be most suitable. In such cases, Robinson (2014) proposes a "logic flow diagram". Additionally, he considers this diagramming technique to be clear and easily comprehensible, which is convenient when industry experts with different backgrounds are involved in the validation process. Following this reasoning, a logic flow diagram of the system of analysis is provided in Figure 5.3, which is an extension to Figure 5.2.

Since the experimental conditions require the implementation of various strategies with slightly varying logistical structures, the model structure in Figure 5.3 is presented in a general fashion, covering all proposed strategies and substructure types. The left column describes the process and decision steps from the moment that the components are lined up at the marshalling yard until the installation vessel arrives at the next location of installation. These steps include the load-out, transportation and pile dredging (only for jackets) operations. The vessels performing these operations vary per strategy (transportation can be performed by the Heavy Lift Vessel (HLV) or by feeders, and pile dredging by the HLV or by a separate Offshore Support Vessel (OSV)), and are therefore not specified. This column ends with the question about the requirement of an offshore transfer operation, implying the dependency of the installation procedure on the means of transportation described in the next two columns. The diagram continues with the middle column for situations in which a transfer operation is not required (i.e., for shuttling transportation strategies), and with the right column for strategies involving feeders (including the wet-tow strategy for monopiles). The repetitive nature of this diagram is followed until all components are installed and the project is completed.

5.3 Assumptions and simplifications

Although efforts are made to let the discrete-event simulation model under development represent reality as closely as reasonably practicable, **assumptions and simplifications** are made out of time and complexity constraints, and relevance considerations. Some simplifications (regarding the weather dependency) were already discussed following Figure 5.2. The other assumptions and simplifications that are expected to be most impacting on the model accuracy are listed here and discussed more extensively in Chapter 6. **(i)** The predicted weather conditions and vessel responses and limitations are assumed to be correct (once started, weather-dependent operations do not have to be aborted). **(ii)** Learning effects are not accounted for separately but are considered to be incorporated in the probability distributions of the duration of the corresponding operations. **(iii)** The vessel day rates and marshalling yard rent last exactly until the end of the project, unless a particular vessel is only required in a certain phase of the project (e.g., due to a separate phases or assembly-line strategy). **(iv)** Vessels travel at a constant speed. **(v)** Delays not induced by weather limitations (such as mechanical breakdowns) are not considered. **(vi)** The wind farm to be installed is simplified to have an "entry point" at a certain distance from the base port, from which the distance to the first turbine in each "string" (the string entry) is defined. A string is a series of approximately ten turbines, which are connected by inter-array electrical cables (see Figure 3.2). The distance between each individual turbine within a string is also specified as a single constant. A vessel travelling from the base port to a specific turbine location passes the wind farm entry point and associated string entry point.

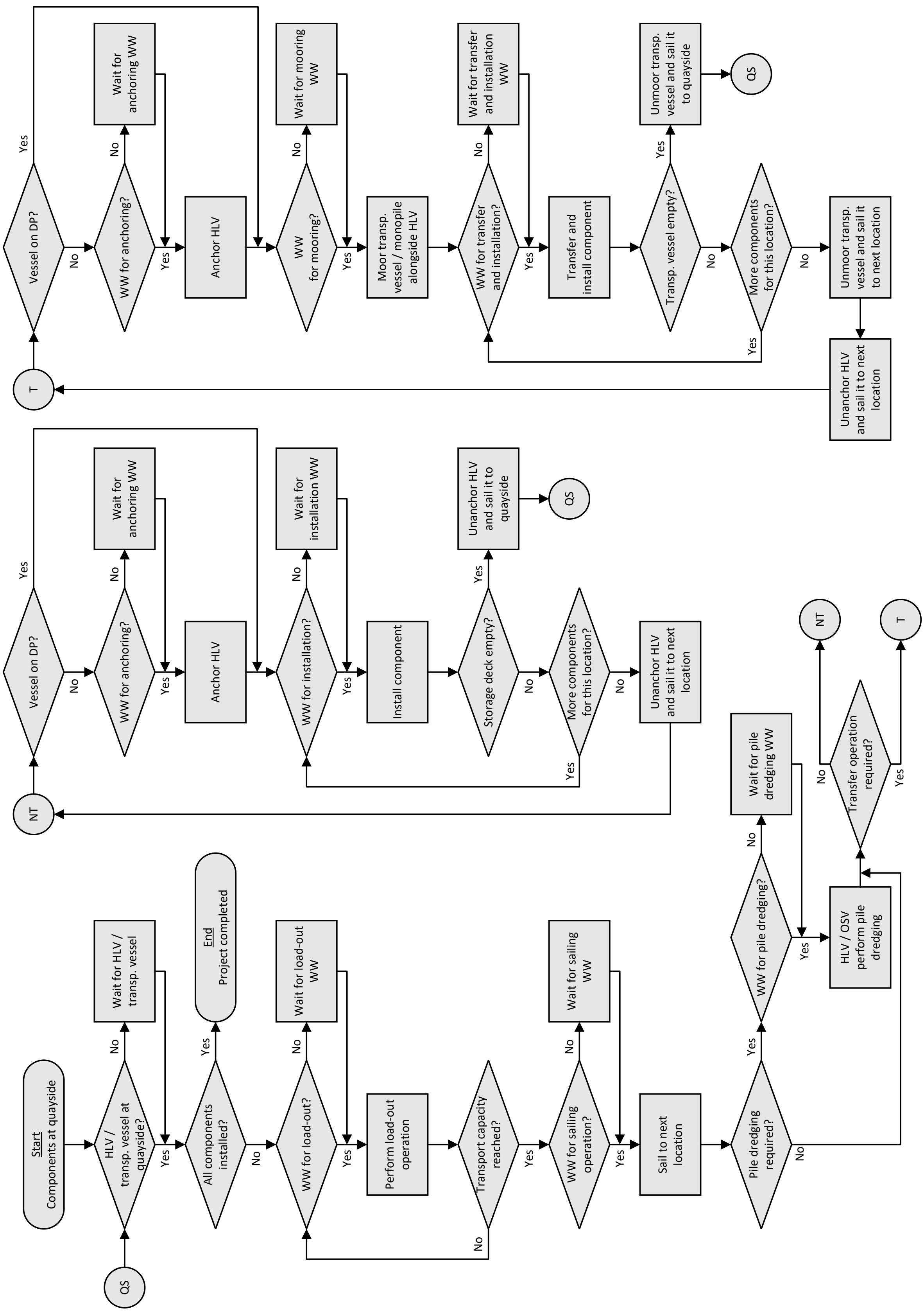

Figure 5.3: Logic flow diagram conceptualising the model content (WW = Weather Window)

6 Data collection

In order to let the modelling results resemble real-world situations, realistic (historical) data need to be supplied to the model. Since these data may vary depending on the considered location and deployed vessels, the obtained simulation results are case specific, and hence this research is considered to be a case study. The data collection is performed following Figure 5.2 and is discussed for each category of input data in Section 6.1 to 6.5.

6.1 Vessel data

In each strategy, the same primary Heavy Lift Vessel (HLV) is deployed, either for the transportation and/or installation of Monopiles (MPs), Transition Pieces (TPs), jackets or jacket foundation piles. This vessel is capable of transporting three MPs, six TPs, two jackets or twelve jacket foundation piles (see Table 6.1). In the case of an alternating installation strategy, three MPs and three TPs can be transported simultaneously. The sailing speed is considered to be constant, as was mentioned in Section 5.3. This simplification is justified based on an analysis of 45 sailing trips between a wind farm in the North Sea and a base port in the south of The Netherlands, performed by the considered vessel, which resulted in an average velocity of 7.7 knots and a coefficient of variation of 7.3%. The latter corresponds to a relatively low variability of the velocity around the mean. Additionally, Table 6.1 provides the relevant vessel capacities for the second HLV (which is deployed in assembly-line strategies), a feeder barge and a tug boat towing a Floating Monopile (FMP). For these vessels, the sailing speed is assumed to be constant as well, although this is not numerically substantiated due to the limited availability of data. The properties of the vessels regarding workability are discussed in Section 6.5.

Table 6.1: Properties of vessels deployed in the considered strategies

Vessel	Cap. MP	Cap. FMP	Cap. TP	Cap. MP/TP	Cap. Jacket	Cap. Jacket found. pile	Sailing speed [kn]
HLV	3	N/A	6	3/3	2	12	7.7
HLV2	N/A	N/A	8	N/A	N/A	12	11.9
Barge	3	N/A	8	3/3	2	12	5.0
Tug	N/A	1	N/A	N/A	N/A	N/A	5.0

6.2 Location data

Since the sailing destination sequence may vary per project, the distances between the base port and every installation location, and between each individual installation location, are required modelling data. Providing all the direct distances would require a lot of pre-processing work every time the simulation model is used for a different project. Therefore, simplified distance approximations are proposed. First of all, a "wind farm entry point" is assumed at a location between the base port and the wind farm, as is displayed in Figure 6.1. The distance between the base port and this entry point ($D_{BP\text{-}EP}$) is used as the largest distance input value. Furthermore, the values for $D_{EP\text{-}ES}$ represent distances between the wind farm entry point and the first turbine of every string (the "string entry"). Next, it is assumed that the distance between each subsequent turbine in a string is constant and that travelling from one string to another requires covering the same distance. However, the latter is only possible between the first and last turbines of each string (see Figure 6.1), which is a reasonable assumption as operations in the next string are generally started only after the operations in the previous are (almost) finished. In the case study to be performed (further introduced in Section 7.2), the location data of a wind farm in the North Sea relative to a base port located in the south of The Netherlands function as input. The reference project requires the installation of 67 substructures at a wind farm situated 256 km from the base port ($=D_{BP\text{-}EP}$). It is assumed that the wind farm layout can be described by six strings of ten and one string of seven turbine locations, separated by a constant distance of 1 km. $D_{EP\text{-}ES1}$ to $D_{EP\text{-}ES3}$ are approximated as 7 km and, $D_{EP\text{-}ES4}$ to $D_{EP\text{-}ES7}$ as 2 km.

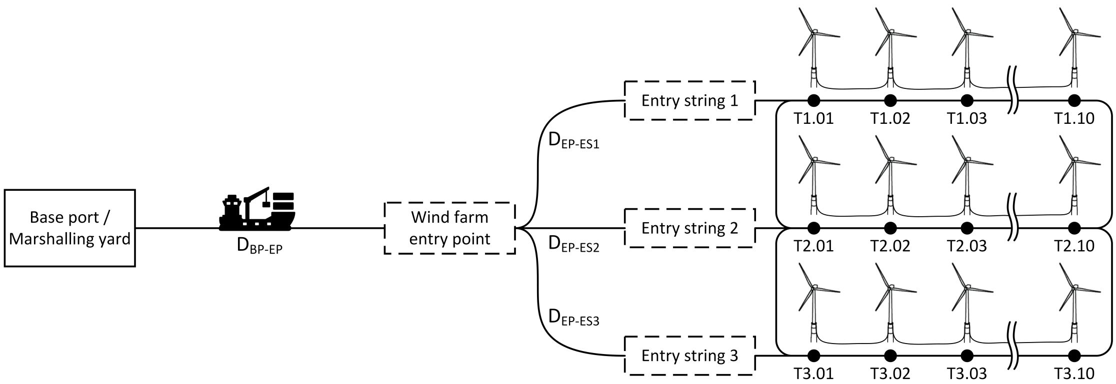

Figure 6.1: Visualisation of the assumptions made regarding the distances to be covered

6.3 Duration data

Duration data refers to data indicating the time it takes to perform operations other than sailing and waiting on suitable weather windows. The considered operations are listed in Table 6.2 and 6.3. Repetitive offshore operations vary in their duration, which means that it is not preferable to assign these activities a deterministic time value. Hence, random durations are generated, following a suitable probability distribution for each operation. Preferably, these distributions are fitted to data. The duration data used in this case study were generated by recording the time each operation performed aboard the vessel takes. To the data of most of the operations, a lognormal distribution is fitted. Only in the case of "miscellaneous work" in Table 6.2, a normal distribution is considered more suitable. Both the lognormal and the normal distribution are two-parameter distributions, which can be described by a mean and a standard deviation. In the case of the lognormal distribution, these are the mean and standard deviation of the dataset that results from taking the natural logarithm of the individual values of the original dataset (in Table 6.2 and 6.3, μ_L and σ_L respectively). The parameters to describe the normal distribution are the mean and standard deviation of the original dataset (μ_N and σ_N respectively).

The suitability of each fitted distribution (normal and lognormal distributions) is examined by performing a Kolmogorov-Smirnov "Goodness-Of-Fit (GOF)" test on the provided data. This test is based on "the maximum difference between an empirical ($S_N(x)$) and a hypothetical ($F_0(x)$) cumulative distribution" (Massey, 1951). For a fitted distribution to be considered significantly accurate, this maximum difference should be less than the critical value ($d_\alpha(N)$) corresponding to the required level of significance (α) and the sample size (N). This principle is mathematically expressed in Equation 6.1 (Massey, 1951). For the level of significance of 0.05 (which is a generally accepted value (Teegavarapu, 2019)), all of the fitted distributions in Table 6.2 and 6.3 can be considered significantly accurate.

$$Pr\left[max\left|S_N(x) - F_0(x)\right| > d_\alpha(N)\right] = \alpha \tag{6.1}$$

For some operations, no (sufficient) time duration data was available to fit a statistically significant distribution. In those cases, a PERT-distribution was described and provided to the model. Such a distribution is generally used in cases of limited data availability, and is similar to a beta-distribution. However, the describing parameters are approximated by making an "optimistic" (α), a "pessimistic" (β), and a "most likely" (m) time estimate (Nafkha, 2016; Premachandra, 2001). The parameter estimates presented in Table 6.2 and 6.3 are made by experienced industry experts and are therefore considered the most reliable alternative in this case of lacking data. Table 6.2 and 6.3 additionally indicate the operations that are considered "continuous", which means that they have to be performed in the same weather window and cannot be aborted due to bad weather. The required window length equals the summation of the durations of the included operations (generally, values from the right-tail of the distributions are taken to be conservative).

Table 6.2: Operations to be performed for the installation of monopiles and transition pieces, the allocated distribution types and the fitted distribution parameters. Abbreviations: MP = monopile, TP = transition piece

	Operation	Type of distribution	Distribution parameters
At base port	Load-out single MP	Lognormal	μ_L = -x.xx, σ_L = x.xx
	Load-out single TP	Lognormal	μ_L = -x.xx, σ_L = x.xx
	Other quayside operations (HLV)	Lognormal	μ_L = x.xx, σ_L = x.xx
	Tot. time barge along quayside, loading 3 MPs	PERT	α = x.x, m = xx.x, β = xx.x
	Tot. time barge along quayside, loading 8 TPs	PERT	α = xx.x, m = xx.x, β = xx.x
At turbine location	11. Run anchors	Lognormal	μ_L = x.xx, σ_L = x.xx
	Continuous:		
	12. Install MP	Lognormal	μ_L = x.xx, σ_L = x.xx
	13. Drive MP	Lognormal	μ_L = x.xx, σ_L = x.xx
	14. Transfer MP to upend cradle	Lognormal	μ_L = x.xx, σ_L = x.xx
	Continuous:		
	15. Install TP	Lognormal	μ_L = x.xx, σ_L = x.xx
	16. Level TP	Lognormal	μ_L = -x.xxx, σ_L = x.xx
	17. Perform miscellaneous work	Normal	μ_N = x.xx, σ_N = x.xx
	18. Perform completion work	Lognormal	μ_L = x.xx, σ_L = x.xx
	19. Grout TP	Lognormal	μ_L = x.xx, σ_L = x.xx
	20. Pick-up anchors	Lognormal	μ_L = x.xx, σ_L = x.xx
	Only for feeder strategies (non-continuous)		
	2c Moor barge alongside HLV	Lognormal	μ_L = x.xx, σ_L = x.xx
	2d Transfer MP	Lognormal	μ_L = x.xx, σ_L = x.xx
	5c. Transfer TP	Lognormal	μ_L = x.xx, σ_L = x.xx
	5d. Unmoor barge	Lognormal	μ_L = -x.xx, σ_L = x.xx

Table 6.3: Operations to be performed for the installation of jackets and jacket foundation piles, the allocated distribution types and the fitted distribution parameters. Abbreviations: PIF = Pile Installation Frame

	Operation	Type of distribution	Distribution parameters
At base port	Load-out single pile	PERT	α = x.x, m = x.x, β = x.x
	Load-out single jacket	PERT	α = x.x, m = x.x, β = x.x
	Other quayside operations (HLV)	Lognormal	μ_L = x.xx, σ_L = x.xx
	Tot. time barge along quayside, loading 2 jackets	PERT	α = x.x, m = xx.x, β = xx.x
	Tot. time barge along quayside, loading 12 piles	PERT	α = xx.x, m = xx.x, β = xx.x
At turbine location	11. Run anchors	Lognormal	μ_L = x.xx, σ_L = x.xx
	12. Install PIF	Lognormal	μ_L = x.xx, σ_L = x.xx
	Continuous:		
	13. Install four piles	Lognormal	μ_L = x.xx, σ_L = x.xx
	14. Drive one pile	Lognormal	μ_L = x.xx, σ_L = x.xx
	15. Retrieve PIF	Lognormal	μ_L = x.xx, σ_L = x.xx
	16. Dredge and clean pile	Lognormal	μ_L = x.xx, σ_L = x.xx
	17. Clean pile	Lognormal	μ_L = x.xx, σ_L = x.xx
	Continuous:		
	18. Install jacket	Lognormal	μ_L = x.xx, σ_L = x.xx
	19. Grout jacket	Lognormal	μ_L = x.xx, σ_L = x.xx
	20. Pick-up anchors	Lognormal	μ_L = x.xx, σ_L = x.xx
	Only for feeder strategies (non-continuous)		
	2c Moor barge alongside HLV	Lognormal	μ_L = x.xx, σ_L = x.xx
	2d Transfer pile	Lognormal	μ_L = x.xx, σ_L = x.xx
	5c. Transfer jacket	Lognormal	μ_L = x.xx, σ_L = x.xx
	5d. Unmoor barge	Lognormal	μ_L = -x.xx, σ_L = x.xx

6.4 Cost data

Due to the fact that a variation of vessels is deployed in the strategies that are evaluated in this study, the performance of a strategy cannot solely be measured by the total project duration. The deployment of more vessels with a lower weather sensitivity would always be considered the better alternative. Hence, the strategies are additionally compared based on the operational costs of the deployed vessels and the marshalling yard rent. The rates considered in this study are presented in Table 6.4. These cost components are seen as the factors that differentiate the various strategies, which means that other expenses are assumed to be relatively constant over the strategies or deemed negligible. Furthermore, it must be noted that for the deployment of each barge in a feeder strategy, additionally two tug boats should be accounted for to sail the barge. A construction support vessel is considered suitable to perform the pile dredging operations in the jacket installation strategies that involve a separate pile dredger.

Table 6.4: The cost components considered in this study and the corresponding values

Cost component	Day rate [Euros]
HLV	xxx.000
HLV2	xxx.000
Barge	xx.500
Tugboat	xx.000
Construction support vessel	xx.000
Marshalling yard rent	xx.500

6.5 Weather data

Most of the logistical studies that have been performed on offshore wind farms let the continuity of operations depend on limitations regarding the significant wave height (H_s), and some additionally consider limitations regarding wind speed (V_w), as described in Section 2.2. However, Sperstad et al. (2014, 2017) state that more accurate predictions can be made if more limiting parameters are incorporated. This conclusion results from their comparison between the application of a simplified single-parameter wave description (in terms of H_s), and the implementation of a more complex and realistic multi-parameter wave determinant (H_s as a function of peak wave period (T_p) and Wave Encounter Angle (WEA)).

For this study, it has been decided, in consultation with experts in the field of offshore hydrodynamics, to let the selection of limiting environmental parameters depend on the phase of the installation procedure. The continuity of the load-out phase is modelled as only dependent on the wind speed at the base port location. The transportation, positioning (including running the anchors) and relocation (including picking up the anchors) phases are modelled to be limited by the H_s and V_w at the offshore wind farm location. Hence, for these phases, hourly time series of V_w at the base port and of the H_s and V_w at the wind farm location suffice as weather data input. Just before the start of the particular operations, the model checks whether the environmental conditions at hand exceed the limiting values within the maximum duration of the operation (provided in Table 6.5), and, if required, it postpones the operations to the first moment in time where the weather conditions are suitable.

Regarding the transfer and installation phases, it has been decided to follow the approach proposed by Sperstad et al. (2014, 2017) and to consider the dependency of the HLV responses on the T_p and the WEA, in addition to the H_s and V_w. This decision follows from the experience in the industry that the workability of the transfer and installation phases is generally more sensitive to the T_p and the WEA than the other operations in the process chain. By performing hydrodynamic simulations of these procedures, the limiting values for H_s can be determined as a function of T_p and WEA, as visualised for the case of MP installation in the polar plot of Figure 6.2a. From this plot can be deduced that a WEA of 180 degrees provides an “optimal” workability, and it is assumed that the installation procedure is performed under this angle (it must be mentioned that for certain environmental conditions this assumption may deviate from reality). The same assumption is made for the other operations in Table 6.5, for which the workability is described by H_s-T_p limits. Assuming optimal WEAs, the relationships between the limiting H_s and T_p are described by a curve, as visualised for MP and TP installation in Figure 6.2b. Since no hydrodynamic properties are known for the second installation vessel deployed in assembly-line strategies, in consultation with experts in hydrodynamics a three-point discrete H_s-T_p-curve is assumed for the installation of TPs by this vessel. For an operation to continue, the H_s-T_p combination should be below the corresponding curve and the wind speed below the limiting value, for the duration of the operation (see Table 6.5). In the simulations performed in this study, the discussed limits are related to hourly time series of the H_s, T_p, $V_{w,Wind\_farm}$ and $V_{w,Base\_port}$, provided over twelve years (2000-2011).

Table 6.5: Weather limitation for the operations to be performed for the installation of monopiles and transition pieces, and jackets and foundation piles. Additionally, the durations for which the environmental conditions require to stay below the limiting values for the operation to continue are specified

Operation	$H_{s,\,max}$ [m]	$T_{p,\,max}$ [m]	$V_{w,\,max}$ [m/s]	Duration [h]
HLV sailing to OWF / Base port	x	-	xx	xx
HLV2 sailing to OWF / Base port	x	-	xx	xx
Barge sailing to OWF / Base port	5	-	xx	xx
Tug – FMP sailing	3	-	xx	xx
Monopile load-out	-	-	xx	x (onto barge: x)
Transition piece load-out	-	-	xx	x (onto barge: x)
Jacket foundation pile load-out	-	-	xx	x
Jacket load-out	-	-	xx	x (onto barge: x)
Run anchors	x.x	-	xx	x
Pick-up anchors	x.x	-	xx	xx
Moor barge / FMP	x.x	-	xx	x
Unmoor barge	x.x	-	xx	x
Monopile transfer	$H_s - T_p$ limit	$H_s - T_p$ limit	xx	x
Transition piece transfer	$H_s - T_p$ limit	$H_s - T_p$ limit	xx	x
Jacket foundation pile transfer	$H_s - T_p$ limit	$H_s - T_p$ limit	xx	x
Jacket transfer	$H_s - T_p$ limit	$H_s - T_p$ limit	xx	x
Monopile installation	$H_s - T_p$ limit	$H_s - T_p$ limit	xx	x
Transition piece installation	$H_s - T_p$ limit	$H_s - T_p$ limit	xx	xx
Transition piece installation by HLV2	[1.5, 1.0, 0.5]	[6.0, 8.0, 12.0]	xx	x
Transition piece securing by HLV2	1.5	-	xx	xx
PIF installation	$H_s - T_p$ limit	$H_s - T_p$ limit	xx	x
Jacket foundation pile installation	$H_s - T_p$ limit	$H_s - T_p$ limit	xx	x
Pile dredging / cleaning by HLV	x.x	-	xx	xx
Pile dredging by support vessel	1.5	-	xx	xx
Jacket installation	$H_s - T_p$ limit	$H_s - T_p$ limit	xx	x

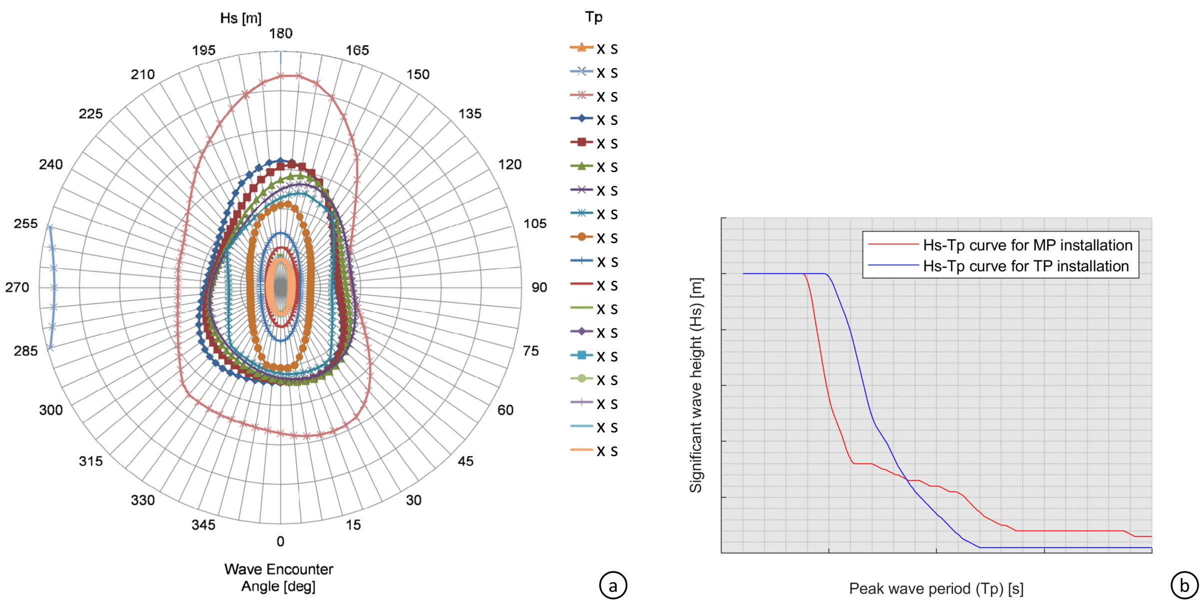

Figure 6.2: (a) A polar plot of the limiting significant wave height (H_s), as a function of the peak wave period (T_p) and the wave encounter angle, for the installation of monopiles, (b) The limiting significant wave height for the installation of monopiles and transition pieces, as a function of the corresponding peak wave period

7 | Model structure and validation

This chapter is focused on the phase of translating the conceptual model developed in Chapter 5 into a discrete-event simulation "base model", which forms the basis for the modelling of the other strategies, and supplying this model with the data collected in Chapter 6. This process is described in Section 7.1. Subsequently, the developed base model is validated in Section 7.2.

7.1 Model structure development process

The "base model" in this study simulates the combination of the shuttling transportation strategy and the alternating installation strategy for the installation of Monopiles (MPs) and Transition Pieces (TPs). This is a relatively simple strategy, for which sufficient validation data are available. Since this strategy includes, but is limited to, the basic principles of substructure installation, it is deemed a suitable "template" for the modelling of the other strategies. For instance, the shuttling – separate phases strategy can be modelled by changing the sequence of certain operations, and the shuttling – assembly-line strategy by assigning the TP-installation processes to a different model entity (a vessel). However, additional constraints and logic may have to be implemented. For the shuttling MP-TP transportation strategy, these constraints are discussed in Figure A.1 in Appendix A. To develop the model structures describing the feeder and wet tow transportation strategies, the transportation tasks of the shuttling models are assigned to additional entities representing barges and Floating Monopile (FMP)-towing tugs. Furthermore, the logic to describe the processes of offshore transfer of components and of the barge and FMP-mooring alongside the Heavy Lift Vessel (HLV) are supplemented to the models. Schematic overviews of the modelling constraints applicable to MP-TP feeder and wet tow transportation strategies can be found in Figure A.2 and A.3 respectively. The foundation pile – jacket transportation and installation strategies are similar to the MP-TP installation strategies, and hence limited adaptations to the developed model structures are made. The most impacting factors are the implementation of the required actions to install the considered structures, the corresponding durations and the operational weather limitations. Furthermore, the installation strategy of appointing a dedicated dredger Offshore Support Vessel (OSV) to perform the pile dredging process is modelled by assigning this operation to an additional entity representing this vessel and letting it operate in a time window resulting in zero waiting time for the HLV. The schematic overviews and modelling constraints for the foundation pile–jacket transportation and installation strategies are provided in Figure A.4 and A.5.

7.2 Model validation

There are various ways to "operationally validate" a simulation model, which means to determine if the model's output is sufficiently accurate for its intended purpose. However, these processes take time, which is a resource that is limited available in this study. Therefore, it is decided to only validate the model structure of the base model, as introduced above. Additions to this "template" to model the other strategies are not included in the validation process, and therefore form a risk for inaccuracies. However, since these additions are small relative to the base model, the introduced effect is expected to affect the general conclusions only to a limited extent. The base model developed for this study is tested by the validation techniques of a "face validity test", "parameter variability test", and "historical data validation test", as described by Sargent (2010). Face validity was ensured by discussing the various components within the model's structure, and the assumptions made, with experienced industry experts from both the field and the office environment. Regarding the parameter variability and the historical data test, a historical project (which forms the basis for the case study performed in Chapter 8) is taken for reference. This project involved the installation of 67 MPs and TPs in the North Sea, using a base port situated in the south of The Netherlands. The considered components were installed by a shuttling transportation strategy and an alternating installation strategy, using the primary HLV as introduced in Section 6.1. The project was performed in 2016 and started on the eighteenth of March. Hence, for the validation, this same start date was used. However, as the model is validated for its predicting capabilities, only weather data of years before 2016 were used.

7.2.1 Parameter variability test

The parameter variability test is based on the variation of input or internal parameters of the created model, to subsequently analyse the resulting output (Sargent, 2010). Following the analysis of the model behaviour, conclusions are drawn about the model representing reality as intended. One of the critical components in the developed model is the implementation of the weather dependency of various operations. This model component is therefore evaluated in this section. Figure 7.1a provides an "S-curve" of the progress of the validation project. For every installed MP and TP, the curve goes one step up. Once this curve reaches 100%, all of the components are installed. To plot this curve, only one set of random values and the weather data of the year 2000 were used as input, since the intention of this curve is solely to validate the functioning of the model, and not to test its predictive capabilities. Furthermore, the limiting significant wave heights (H_s-limit) for the sailing and anchor handling operations are plotted, as well as the corresponding H_s time series for the year 2000. To test the effect of varying these limiting values, the H_s-limit of the sailing operation is lowered from [redacted] m to [redacted] m and of the anchor handling operations from [redacted] m to [redacted] m. The resulting S-curve is provided in Figure 7.1b. Logically, the point at which 100% completion is reached is shifted to a later date as a result of the parameter change. Furthermore, longer horizontal parts of the curve can be recognised at times where the limiting values are exceeded (meaning that the operations are postponed until better weather arrives), which also suggests a good implementation of the H_s-dependency.

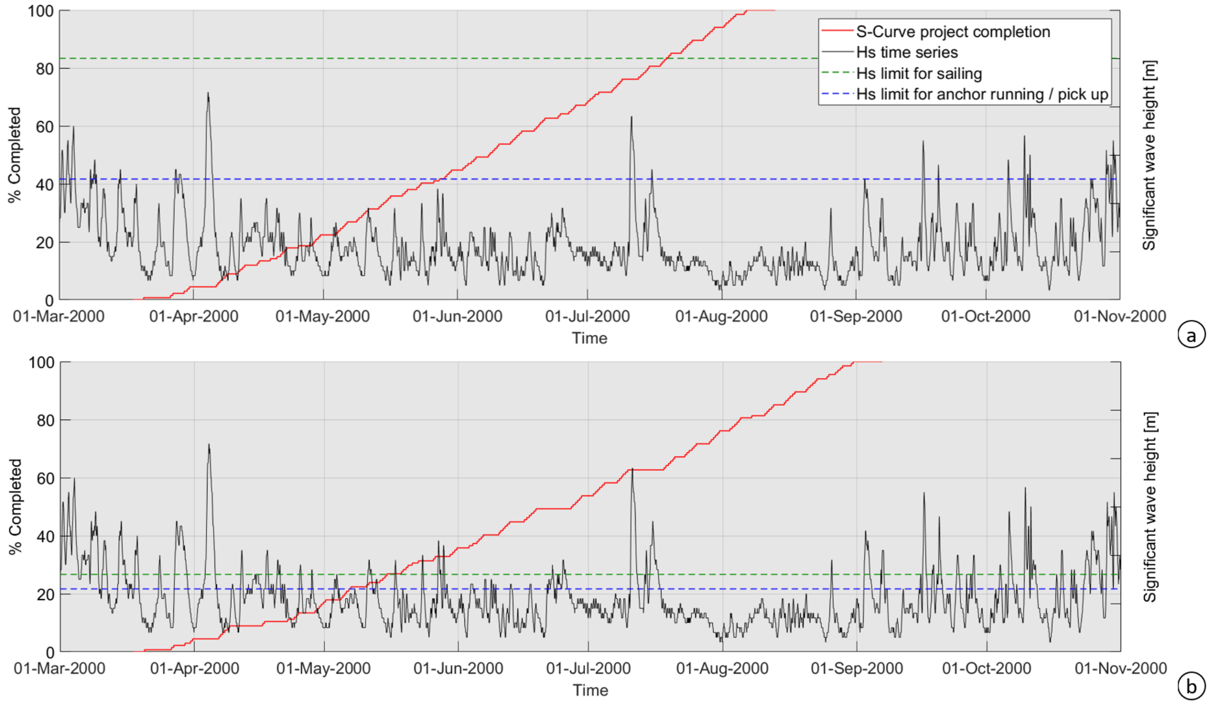

Figure 7.1: Simulated project completion S-curves, for weather data from the year 2000 and one seed of random values. In (a), weather-limited parameters are kept at their operational values, in (b) the H_s-limit for sailing/transportation is lowered to [redacted] m and for anchor handling operations to [redacted] m

A similar test is performed for the implementation of the wind speed limit (V_w-limit). For the same operations and time period, Figure B.1a in Appendix B provides the S-curve, the V_w time series at the wind farm location and the V_w-limits. In Figure B.1b, the V_w-limit for sailing is lowered from [redacted] m/s to [redacted] m/s and for the anchor handling operations from [redacted] m/s to [redacted] m/s. This, once more, results in a later 100%-completion date and postponed operations when the limiting values are exceeded (recognised by longer horizontal parts in the S-curve). The same conclusions can be drawn for Figure B.2, in which the V_w-limit for the load-out operations is lowered from [redacted] m/s to [redacted] m/s. It should be noted that for the latter figure, the wind speed time series is taken for the location of the project-specific base port.

The implementation of the H_s-T_p curves presented in Figure 6.2b is tested in Figure 7.2. This figure once more provides the original S-curve, and one for the situation in which the H_s-T_p curves for the installation of MPs and TPs are lowered to a level of 60% of the original curves. Furthermore, the time series for the H_s and T_p are provided, which, combined with the H_s-T_p-curve and the duration of the operations (see Table 6.5), allow to determine the moments in time the operations can be performed. Similar to the other parameter variability tests, relatively long horizontal sections in the S-curve can be recognised, indicating postponement of operations due to H_s-T_p-combinations located above the corresponding limiting curve. Conclusively, also this test provides results that are in line with a correct implementation of the used theory.

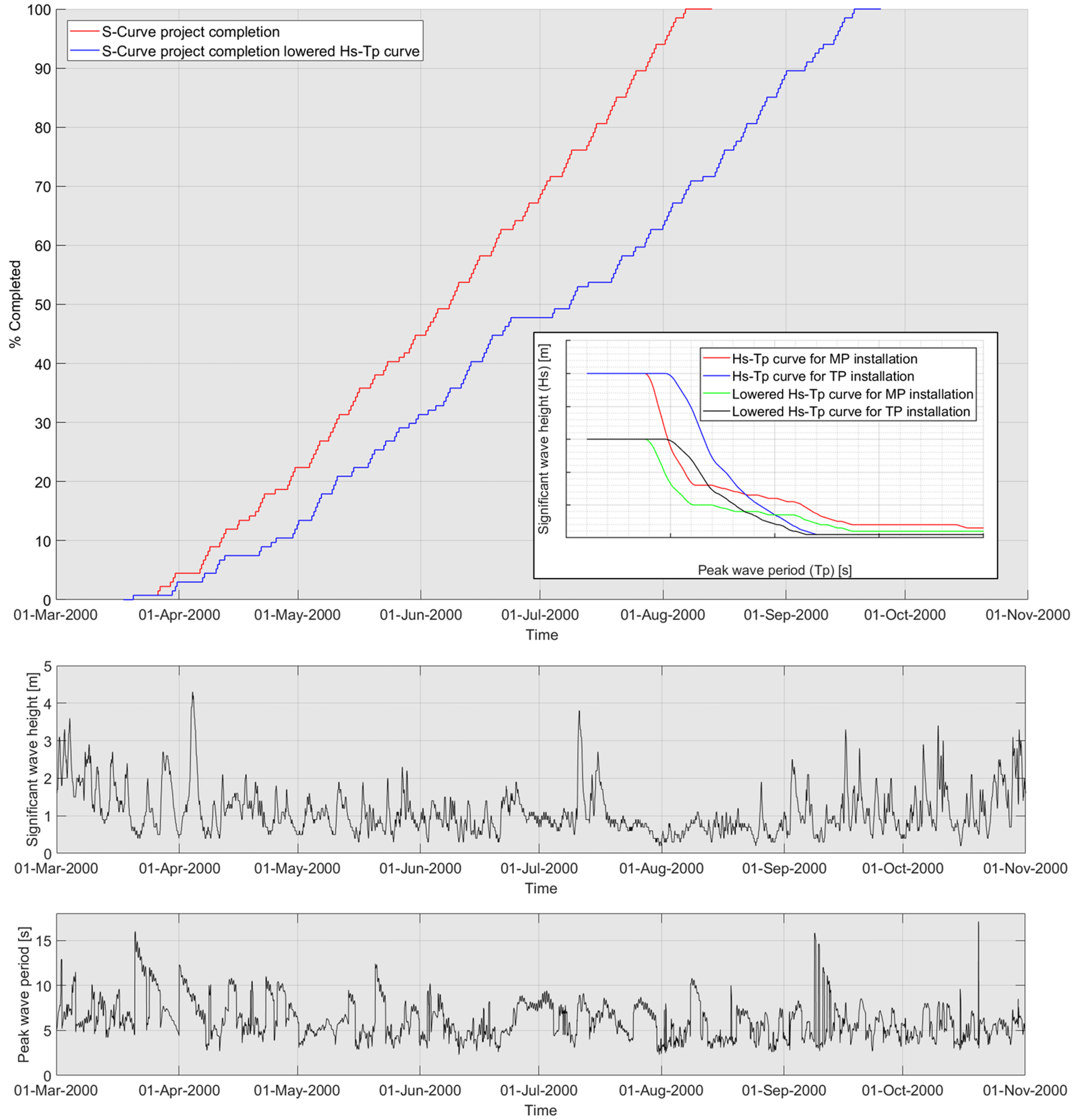

Figure 7.2: Simulated project completion S-curves, for weather data from the year 2000 and one seed of random values. The curve representing the completion process with lowered workability is based on an H_s–T_p-curve at 60% of the level of the (normal) operational curve (both provided in this figure). Additionally, the H_s and T_p time series are provided

7.2.2 Historical data validation test

According to Sargent (2010), historical data validation tests require to use a part of the available data to develop the model and another part to test the behaviour of the model. The base model considered in this validation study is built based on input data from two projects, while the validity of the model output is tested with data from a third project (i.e., the validation or case study project). However, location, vessel and weather data (e.g., sailing distances, workability figures and weather time series) are project-specific and hence correspond to the validation project. Moreover, in the validation project, a different type of anchors was deployed than in the project on which the values in Table 6.2 are based. Hence, the difference in installation time of approximately one hour was corrected by a constant value. Since the model developed in this study is of a stochastic nature, simulation results vary depending on the values included in the sets of generated random values. These sets of random values are known as “seeds”. The fact that the results vary per seed limits the ability to validate the model based on a single simulation run. Furthermore, there is the intention to provide the developed model with capabilities to predict the project progress over time, which means that weather data from the past function as input. Since the weather is a variable phenomenon, the predicted project duration does not only vary with seed numbers, but also with the year from which weather data is retrieved. Therefore, the model is validated based on the average of multiple simulation runs.

To determine the required number of simulation runs to let the average project duration converge to a stable value, a convergence test is performed for every year of available weather data (2000-2011, see Section 6.5). Appendix C provides for every considered year the plots that indicate the resulting total project duration per seed, the cumulative averaged duration and the duration averaged over 50 simulation runs. As a targeted convergence accuracy, a 24-hour bound around the 50-run average result is provided. Once the cumulative averaged value stays within these bounds, the model output is considered “converged”. Hence can be concluded that the results of the simulations performed with the weather data of 2000 and 2008 require the largest amount of runs to converge. To simplify the further validation process, and to be conservative, this largest number is considered to be guiding, and it is decided that, regardless of the year, 35 runs is the norm. Figure 7.3 shows the total installation time for each of the 35 runs per year in box plots. From this figure can be concluded that the total installation time can vary significantly for simulations with the same year of weather data (due to the stochastic nature of the operations), but also that the results are very much dependent on the yearly-varying weather conditions (the years 2002 and 2011 can be associated with the most favourable weather conditions, whereas the opposite can be stated about the year 2000). Hence, it should be noted that validating the model based on the average results has the limitation of only considering the variability of the results to a limited extent.

The actual historical data validation test is performed by comparing the average S-curve generated by the simulation model with an S-curve from empirical data of a project performed in 2016. Both curves are plotted in Figure 7.4. A notable difference between the simulation S-curve in this figure, and the curves in Section 7.2.1 is the repetitive pattern and the relatively short weather-induced horizontal parts of the curve in Figure 7.4. This difference can be explained by the fact that curves in Section 7.2.1 and Appendix B are the result of one simulation run, with one set of random values (one seed) and one year of weather conditions, whereas the curve in Figure 7.4 is the average S-curve of 420 simulation runs (twelve years of weather data multiplied by 35 runs with different seeds). Hence, weather-induced irregularities are averaged out.

Based on visual inspection, it is concluded that the simulation model predicts the project completion progress satisfactory. The deviation from the empirical curve can at least partly be explained by the unforeseen repairs that were performed, and which were not accounted for in the simulation model (see Section 5.3). In addition, the effect of weather-induced delays in 2016 could be different from the average effect of the weather conditions in the years 2000-2011. Towards

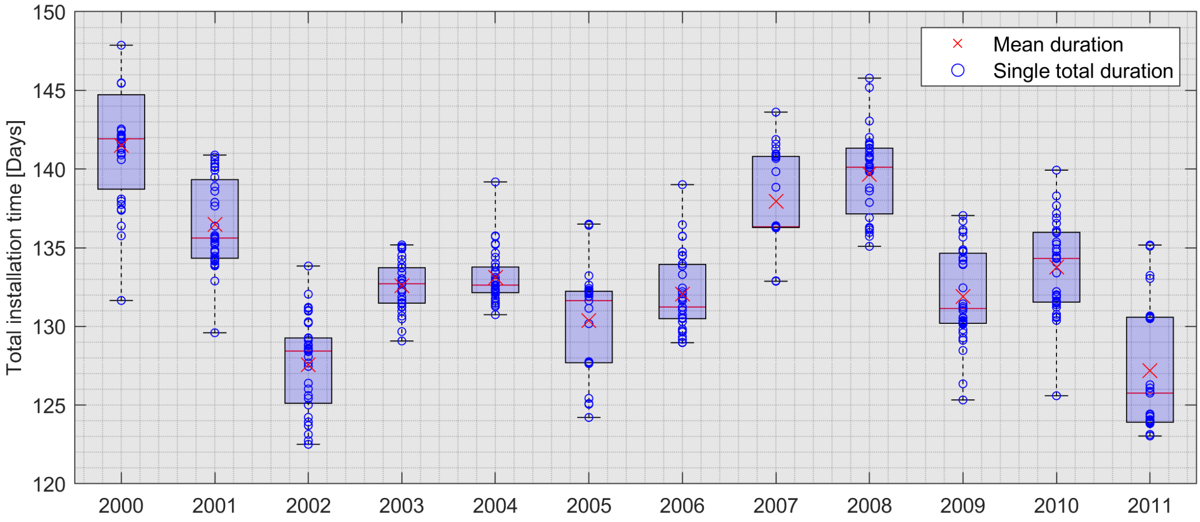

Figure 7.3: Boxplot describing the simulated total installation time per year, for the shuttling-alternating monopile-transition piece installation strategy

the 100%-completion date, the deviation reduces due to an increased rate of completion of the empirical curve. This could be explained by learning effects (which in this study are assumed to be incorporated in the randomly generated durations of operations, but in reality effectuate in the latter project phases) or by favourable weather conditions towards the summer of 2016.

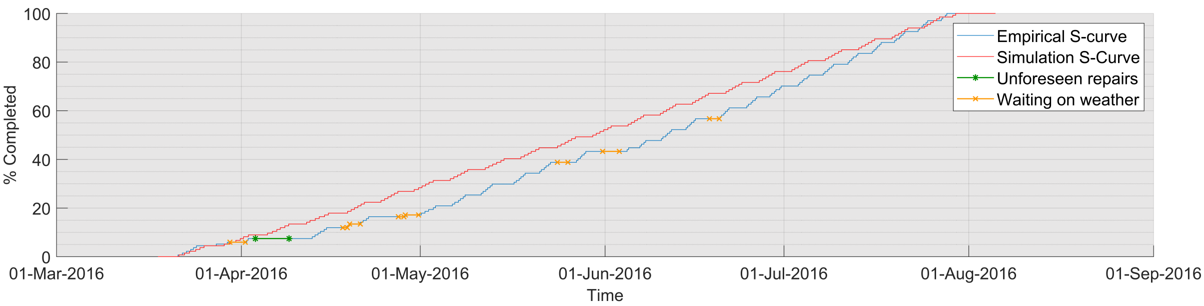

Figure 7.4: The empirical validation S-curve and the predicted S-curve (the average result of 420 simulation runs)

In addition to the subjective visual inspection described above, the model's predictive capabilities are quantified, as recommended by Sargent (2010). In order to do this, the method proposed by Ritter and Muñoz-Carpena (2013) is followed. This method combines graphical results with "absolute value error statistics", in this case the Root Mean Square Error (RMSE), and "normalised Goodness-Of-Fit (GOF) statistics", for which the Nash-Sutcliffe Efficiency coefficient (NSE) is used. The equation for the RMSE is provided by Equation 7.1, from which can be deduced that a value for RMSE of zero represents a perfect fit. The NSE includes the ratio between the mean square error of the predicted values and the variance of the observed values, as mathematically expressed in Equation 7.3. Hence, a value of one for the NSE represents a perfect fit.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{N}} \tag{7.1}$$

$$n_t = \frac{SD}{RMSE} - 1 \tag{7.2}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O})^2} = 1 - \left(\frac{RMSE}{SD}\right)^2 = 1 - \left(\frac{1}{n_t + 1}\right)^2 \tag{7.3}$$

In these equations:

- N represents the sample size
- O_i represents the observed values
- P_i represents the model estimates
- n_t represents the frequency of the observations variability being greater than the mean error
- $\overline{O}$ represents the mean of the observed values
- SD represents the standard deviation of the observations

Regarding the GOF of the S-curves in Figure 7.4, the following values were calculated: 189 hours for RMSE, 885 hours for SD, 3.69 for n_t and 0.95 for NSE. Hence, the GOF is rated as "very good", according to the classification presented in Table 7.1. Although this classification was originally designed for a different field of application (hydrology), Ritter and Muñoz-Carpena (2013) state that the proposed methodology (in which equations Equation 7.1 to 7.3 are included) was developed independently of the application. Since the in this study developed model meets the criteria for a very good performance rating with considerable margin, it is considered safe to assume that it would also score well in a classification specifically designed for logistical models.

Table 7.1: Classification of goodness-of-fit, according to Ritter and Muñoz-Carpena (2013)

Performance rating	Model efficiency interpretation	n_t	NSE
Very good	SD ≥ 3.2 RMSE	≥ 2.2	≥ 0.90
Good	SD = 2.2 RMSE – 3.2 RMSE	1.2 - 2.2	0.80 – 0.90
Acceptable	SD = 1.2 RMSE – 2.2 RMSE	0.7 - 1.2	0.65 – 0.80
Unsatisfactory	SD < 1.7 RMSE	< 0.7	< 0.65

8 | Numerical results and discussion

This chapter presents the numerical simulation results of the implementation of the strategies of analysis into the case study project that was used for validation in Section 7.2. In Section 8.1, the performance of the Monopile (MP) - Transition Piece (TP) installation strategies is evaluated and process improvements are considered. Furthermore, the dependency of the strategy performance on the project start date is investigated. A similar procedure is followed for the analysis of the installation of jackets and their foundation piles in Section 8.2. In Section 8.3, the findings of the numerical simulations, and the implications for related work and the industry are discussed.

8.1 Monopile – transition piece installation strategies

This section presents the numerical simulation results regarding MP-TP installation strategies. First, in Section 8.1.1, the performance of the proposed strategies is compared, based on the input data presented in Chapter 6. Furthermore, the bottlenecks of the most promising strategies are identified. Next, in Section 8.1.2, measures to reduce these bottlenecks are proposed and the potential improvement in the project performance is discussed. In Section 8.1.3, the dependency of the performance on the project start date is examined.

8.1.1 MP-TP installation strategy performance evaluation

The nine unique combinations of MP-TP transportation and installation strategies introduced in Section 3.3 are numerically evaluated in this section. Furthermore, a sensitivity analysis is performed with regard to the number of deployed feeder barges and Floating Monopile (FMP)-towing tugboats. Hence, fourteen logistical set-ups are compared. These set-ups and the corresponding abbreviations are presented in Table 8.1.

Table 8.1: Overview of the logistical set-ups for the installation of MPs and TPs, and the corresponding abbreviations

Abbreviation	Strategy	Vessels		Abbreviation	Strategy	Vessels	
MP_S_Alt	Shuttling – Alternating	1 HLV		MP_2F_AL	Feeders – Assembly-line	2 HLVs	2 Barges
MP_S_Sep	Shuttling – Separate phases	1 HLV		MP_4F_AL			4 Barges
MP_S_AL	Shuttling – Assembly-line	2 HLVs		MP_2T1F_Alt	Wet tow – Alternating	1 HLV	2 Tugs, 1 Barge
MP_1F_Alt	Feeders – Alternating	1 HLV	1 Barge	MP_2T2F_Alt			2 Tugs, 2 Barges
MP_2F_Alt			2 Barges	MP_2T2F_Sep	Wet tow – Separate phases	1 HLV	2 Tugs, 2 Barges
MP_1F_Sep	Feeders – Separate phases	1 HLV	1 Barge	MP_3T2F_Sep			3 Tugs, 2 Barges
MP_2F_Sep			2 Barges	MP_3T2F_AL	Wet tow – Assembly-line	2 HLVs	3 Tugs, 2 Barges

In order to quantify the performance of the strategies and the sensitivity of various strategies to the number of deployed feeders, in the first place the average S-curves are provided in Figure 8.1. This type of curve was already introduced in Section 7.2.2, and regarded as suitable to provide a general overview of the project completion progress over time. The curves of the strategies MP_S_AL, MP_4F_AL and MP_3T2F_AL reach the 100%-completion first and approximately at the same time. MP_1F_Sep and MP_2T2F_Sep take the longest to reach full completion. The latter can in the first place be explained by a relatively low occupancy rate of the Heavy Lift Vessel (HLV) due to no continuous supply of components (the vessel is idle while waiting for components). By increasing the number of feeders, this rate can be boosted (regard the steeper S-curves of MP_2F_Sep and MP_3T2F_Sep). However, once an HLV reaches 100% occupancy (which is the case for the latter two strategies), adding feeders does not add to the installation rate anymore, which sets a limit to the size of the feeder fleet. This also explains why MP_3T2F_AL is only evaluated for one composition of feeders: MP_3T2F_Sep already shows that the first HLV performs optimally with three FMP-tugs and MP_4F_AL shows that the second HLV operates most efficiently with two TP-supplying barges (both in terms of time and costs, as elaborated below). Furthermore, Figure 8.1 shows that the curve corresponding to strategy MP_1F_Sep is characterised by a reducing installation rate above the 50%-completion line (which is when the TPs are being installed). This can be explained by the months towards the end of the year this part of the curve is corresponding to, which are generally associated with unfavourable weather.

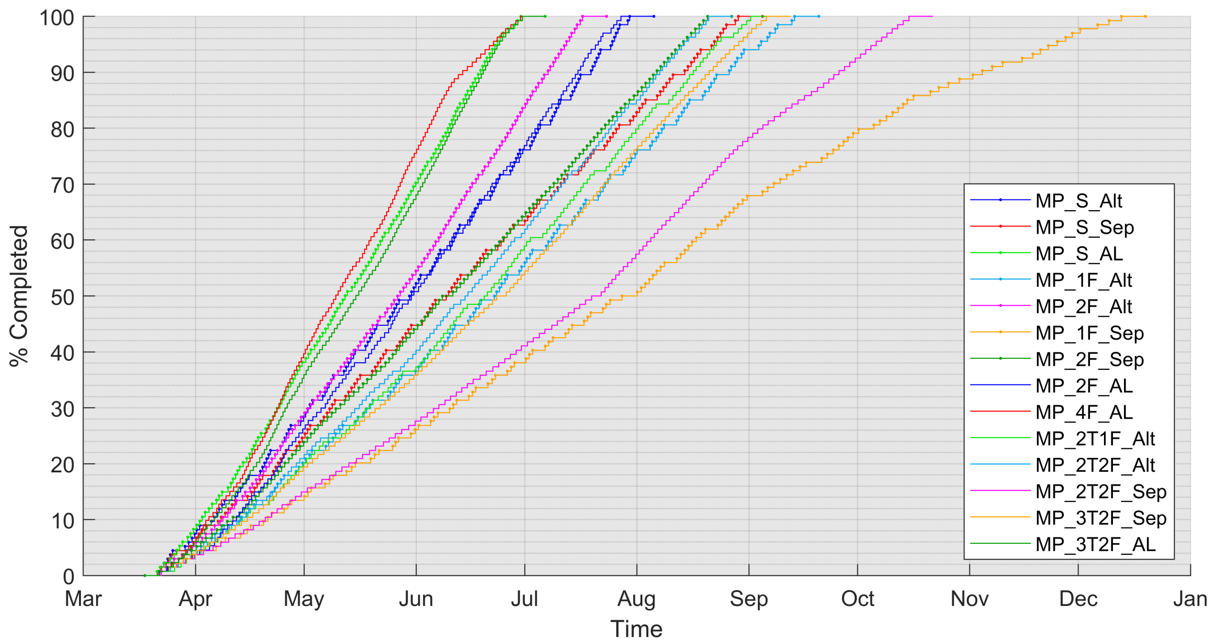

Figure 8.1: S-Curves of the fourteen considered logistical set-ups for the installation of MPs and TPs

Figure 8.2 is complementary to Figure 8.1, as it provides insights into the variability of the installation duration around the progress S-curves. In particular, it presents a single boxplot of the total installation duration for each strategy (representing the results of all 35 × 12 simulation runs). Hence, from this figure can be concluded that of the three strategies that on average reach the 100%-completion level the fastest, MP_S_AL is associated with the lowest variability around the average (or in the case of the boxplot, the median) installation time. Furthermore, the strategy associated with the largest average installation time (MP_1F_Sep) additionally appears to be related to the largest variability. This is considered to be weather-induced and again linked to the generally unfavourable weather associated with the months a large part of the operations of this strategy are performed in.

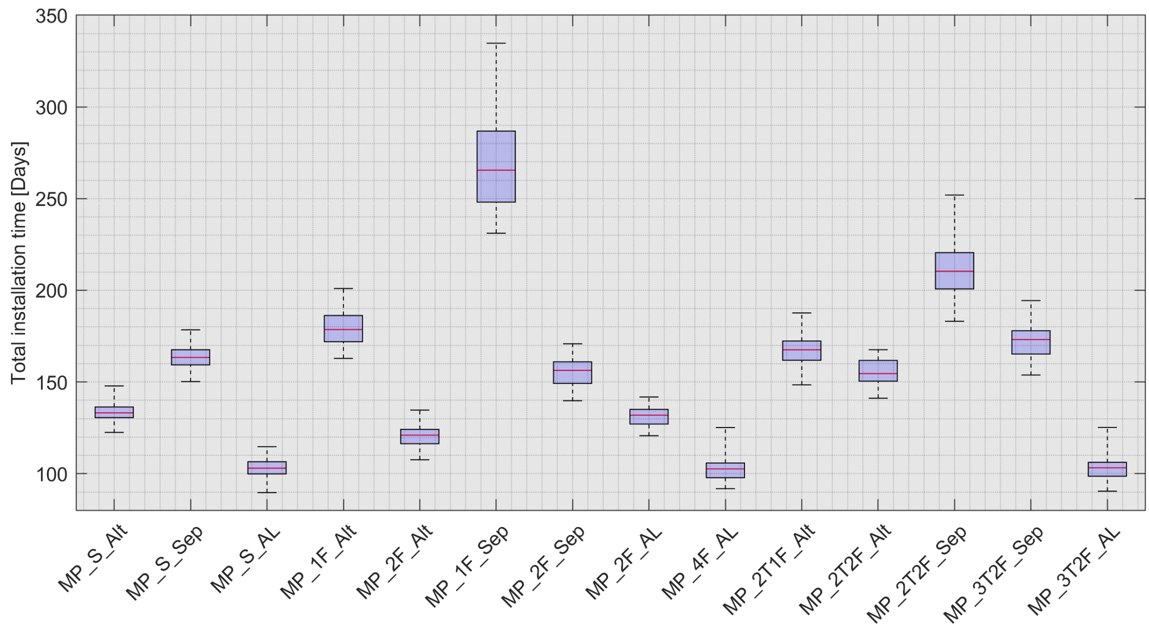

Figure 8.2: Boxplot describing the simulated total installation time per considered strategy

Although the total installation time is an important performance indicator, the costs associated with a strategy is considered more decisive. The boxplots in Figure 8.3 compare the various strategies in terms of costs, only including the components introduced in Section 6.4. Notable is that the MP_S_Alt strategy corresponds to the lowest costs, although the completion time of this strategy is not among the shortest. This result can be explained by the relatively low total day rate due to the deployment of only a single vessel. However, the difference with MP_S_AL is marginal. The strategies of MP_4F_AL and MP_3T2F_AL, which correspond to a relatively low installation time, are not among the strategies with the lowest associated costs. This indicates that the reduction of the installation time achieved by the deployment of additional vessels in these strategies does make up for the extra introduced costs. Finally, it can be stated that the strategies with the lowest installation rate are also among the approaches with the highest associated costs.

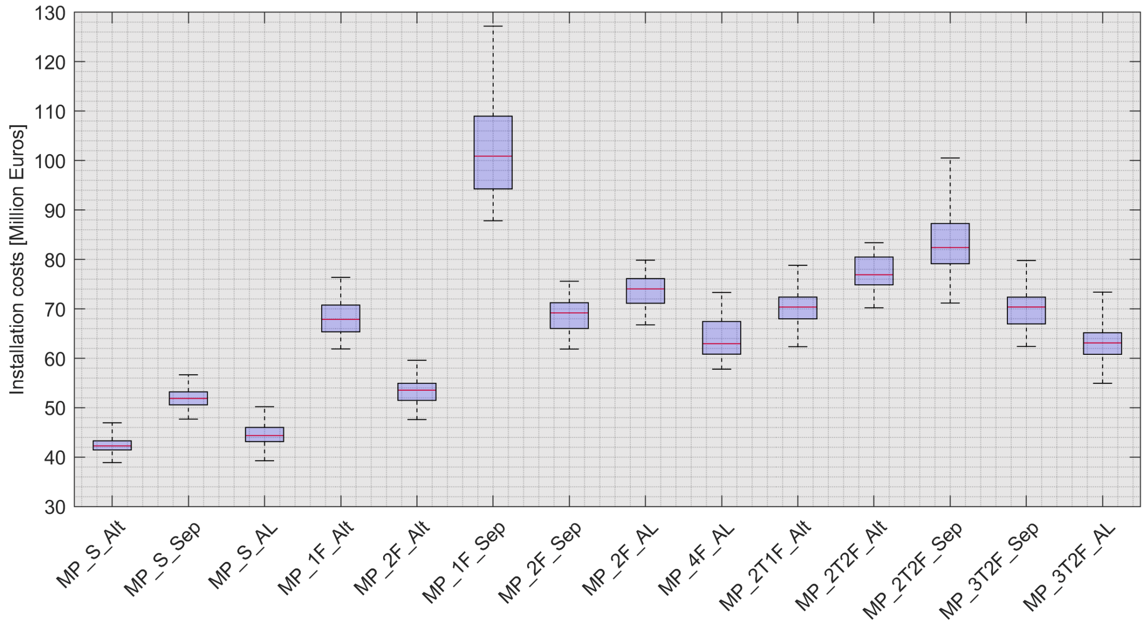

Figure 8.3: Boxplot describing the simulated installation costs per considered strategy, only including the cost components discussed in Section 6.4

Another noteworthy result is that despite the deployment of additional vessels relative to the base strategy MP_S_Alt, the installation time is regularly not reduced or only marginally (see Figure 8.2). A similar conclusion can be drawn when comparing MP_S_AL to MP_4F_AL and MP_3T2F_AL, and MP_S_Sep to MP_2F_Sep and MP_3T2F_Sep. These remarks can at least partly be explained by the lower workability of the additional HLV (deployed in assembly-line strategies) compared to the original HLV, and by the weather-sensitive operations that are introduced when feeders are deployed (e.g., barge mooring and transfer operations). Both result in additional Waiting On Weather (WOW)-days, during which operations are postponed until more favourable weather conditions arrive. Figure 8.4 presents the total number of WOW-days, averaged over 35 runs, for each year of weather data and for each strategy. It shows that the strategies only involving the original HLV (MP_S_Alt and MP_S_Sep) correspond to the lowest number of WOW-days (although these are not among the strategies with the lowest installation time). MP_1F_Sep is associated with the largest number of WOW-days, which can for a large part be explained by the large share of activities being performed in months associated with unfavourable weather. Furthermore, strategies involving both feeders (i.e., feeder barges or tugboats towing FMPs) and a second, smaller, HLV result in relatively many WOW-days. Hence, there is some margin available to improve the cost-effectivity of these strategies, which can be accessed if the number of WOW-days can be reduced.

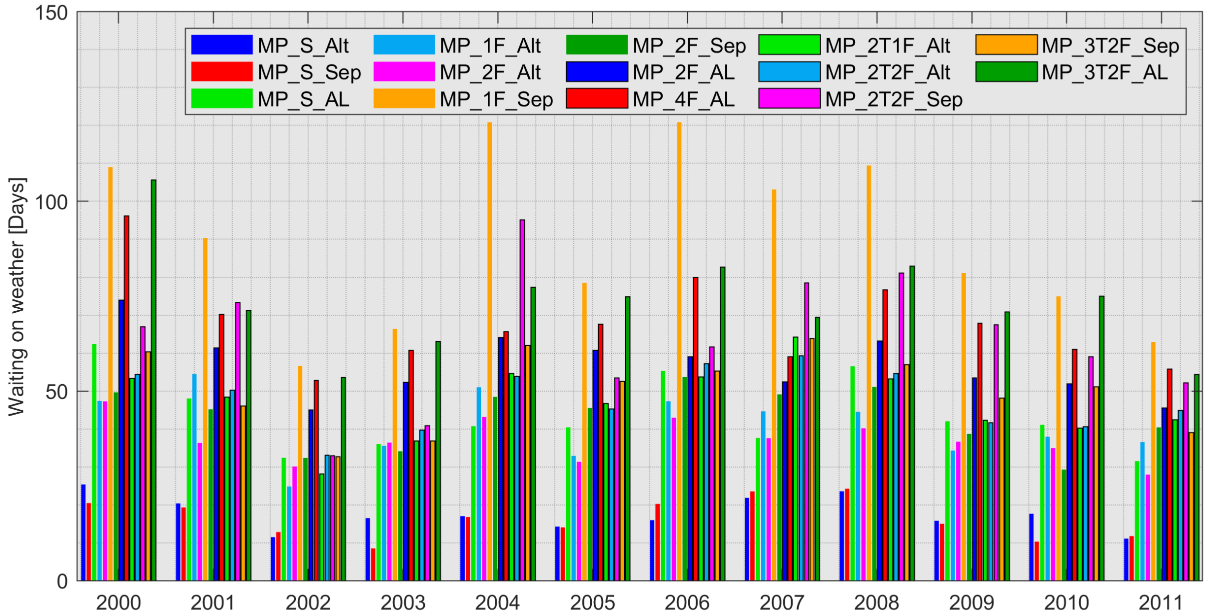

Figure 8.4: Average total number of WOW-days during an MP-TP installation project, per year and per strategy

Table 8.2 provides the contribution of the weather-dependent operations to the total number of WOW-days, for the five most promising strategies. For MP_S_Alt, the largest contributors are the installation operations of MPs and TPs. However, these operations are not perceived as bottlenecks, since the total number of WOW-days corresponding to this strategy is relatively low (see Figure 8.4). Regarding MP_S_AL, the number of WOW-days is significant and, contrary to MP_S_Alt, there exists a strong skewness towards the contribution of TP-installation. This is due to the fact that for this strategy TPs are installed by a smaller HLV with a higher weather sensitivity. In the case of MP_2F_Alt, the largest contribution to the WOW-days is induced by the barge (un)mooring activities. To understand the lower percentages corresponding to the installation activities compared to the preceding strategies, it should be realised that if the operations are postponed until suitable weather arrives to perform the barge mooring operation, the probability that the environmental conditions are also below the limits for the installation operations increases. The discussed reasoning behind the main contributors of MP_2F_Alt also holds for MP_4F_AL and MP_3T2F_AL. However, for the latter two, the share of WOW-days induced by TP-installation is significantly larger, as these are installed by the smaller HLV.

Table 8.2: Contributions of weather-limited MP-TP installation operations to the total number of WOW-days

	MP load-out	TP load-out	Sailing	Anchor running	Barge / FMP mooring	MP Transfer	TP Transfer	MP installation	TP installation	Barge unmooring	Anchor pick-up
• MP_S_Alt	0.6%	0.1%	0.0%	3.0%	-	-	-	48.3%	44.0%	-	3.9%
• MP_S_AL	0.2%	0.1%	0.0%	2.1%	-	-	-	22.6%	72.5%	-	2.6%
• MP_2F_Alt	0.5%	0.0%	0.9%	0.4%	37.7%	3.9%	2.9%	7.4%	19.2%	26.2%	0.9%
• MP_4F_AL	0.3%	0.1%	0.5%	0.2%	34.0%	5.0%	3.5%	5.8%	34.6%	15.2%	0.8%
• MP_3T2F_AL	0.3%	0.1%	5.6%	0.0%	36.5%	11.2%	3.2%	5.5%	32.6%	3.6%	1.4%

8.1.2 MP-TP installation bottleneck reduction sensitivity analysis

This section investigates the potential of increasing the workability of the operations that manifest themselves as bottlenecks in Table 8.2. This is done by performing three experiments, in which the weather limits are increased for:

(i) The mooring of feeder barges alongside HLVs. In this experiment, the corresponding limiting significant wave height is increased from [redacted] m to [redacted] m. This increase is considered reasonable by experts in hydrodynamics, and can in practice be realised by the deployment of a different crew transfer vessel (crew transfer is the limiting factor in this operation). The strategies in Figure 8.5 and 8.6 indicated by "Impr_BM" are the result of simulations with increased barge mooring workability. This experiment is performed on MP_2F_Alt, MP_4F_AL and MP_3T2F_AL.

(ii) The installation of TPs by the second HLV. For this experiment, the same experts consider an increase of the TP-installation limits presented in Table 6.5 to [H_s, T_p] = [(2.0 m, 6.0 s); (1.5 m, 8.0 s); (1.0 m, 12.0 s)] (each H_s-limit is increased by 0.5 m) reasonable. In practice, this improvement can be accomplished by deploying a motion compensation system. In Figure 8.5 and 8.6 this improvement is indicated by "Impr_TPInst". This experiment is performed on MP_S_AL, MP_4F_AL and MP_3T2F_AL.

(iii) Both the mooring of feeder barges alongside HLVs and TP-installation by the second HLV. Here, both the improvements of **(i)** and **(ii)** are implemented, which is referred to as "Impr_BM_TPInst" in Figure 8.5 and 8.6. This experiment is performed on MP_4F_AL and MP_3T2F_AL.

From Figure 8.5 and 8.6 can be concluded that Impr_TPInst results in such a significant cost reduction that MP_S_AL becomes the most favourable strategy, although the installation time on average slightly increases. The latter can be explained by the resulting higher installation rate of the second HLV, which creates room for optimisation by deploying this vessel at a later stage in the project. For MP_2F_Alt, Impr_BM results in a significant reduction of both installation time and costs, but not sufficient to become competitive with the shuttling strategies. Regarding MP_4F_AL, it can be concluded that Impr_TPInst results in a larger reduction of the total installation time than Impr_BM, and therefore the TP-installation by the second HLV could be considered the largest bottleneck. However, due to the fact that Impr_BM improves the installation rate of both HLVs, this improvement results in a larger cost reduction. Hence, when identifying process improvements to eliminate bottlenecks, it is recommendable to base decisions on a broader perspective than just the reduction of total installation time. Considering MP_3T2F_AL, Impr_BM results in the largest reduction of installation time and costs, and barge mooring can therefore be named the largest bottleneck of this strategy. Impr_TPInst is less effective than for the previous strategy because FMP-transfer is more weather-sensitive than MP-transfer from a barge, which means that both barge mooring and FMP-transfer are remaining bottlenecks if Impr_TPInst is realised, rather than just the mooring of the barge. As could be expected, implementing both Impr_TPInst and Impr_BM results in the largest reduction of installation time and costs for both MP_4F_AL and MP_3T2F_AL. Nevertheless, it should also be noted that the "basic" MP_S_Alt strategy, without any workability improvements, remains a very competitive strategy in terms of installation costs.

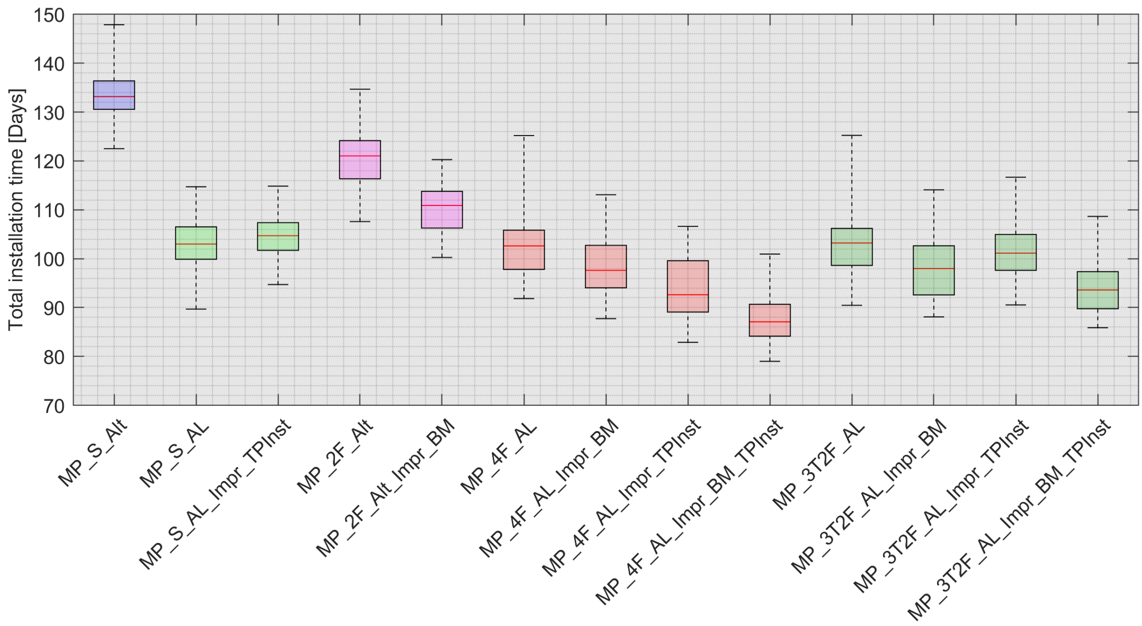

Figure 8.5: Comparison between the installation time of the five promising initial MP-TP-installation strategies and of those strategies with improved workability

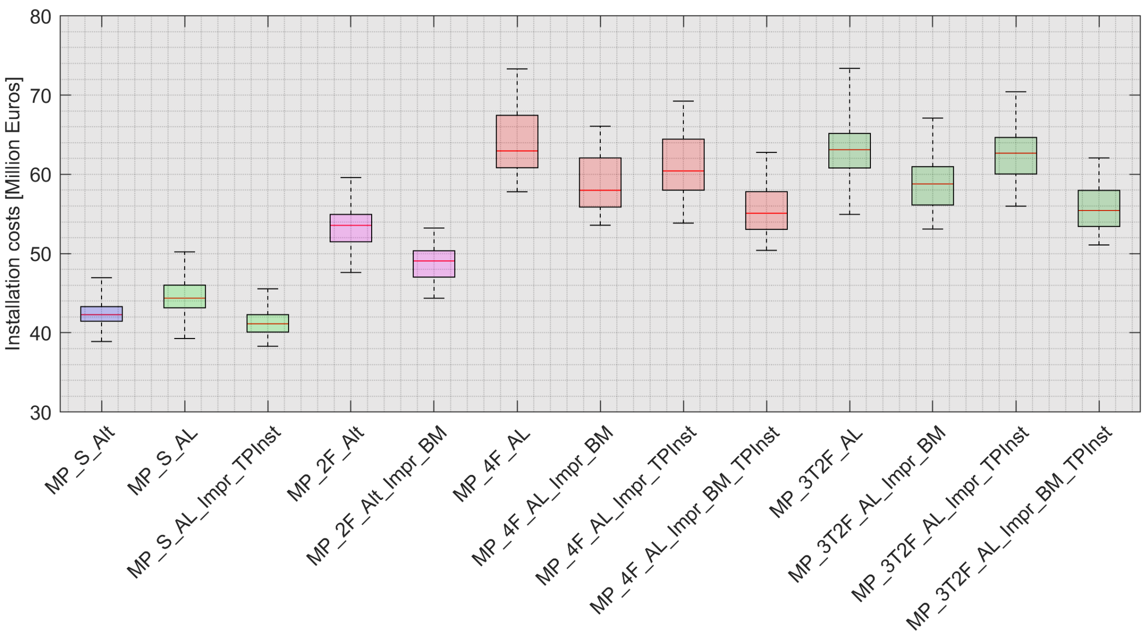

Figure 8.6: Comparison between the installation costs of the five promising initial MP-TP-installation strategies and of those strategies with improved workability

8.1.3 MP-TP installation performance as a function of the start date

Figure 8.7 and 8.8 display the maximum, mean and minimum installation time and costs respectively, for the promising initial (without workability improvements) MP-TP-installation strategies as a function of the start date. Based on these figures it can be stated that regardless of the strategy the project start date can have a significant impact on both the installation time and costs. Start dates which result in more operations being performed in the winter season, result in higher mean installation times and costs, and maxima and minima deviating more from the mean. As a result of this trend, the "optimal" start date (associated with the shortest installation time and lowest costs) is earlier for strategies that require more time to complete the project.

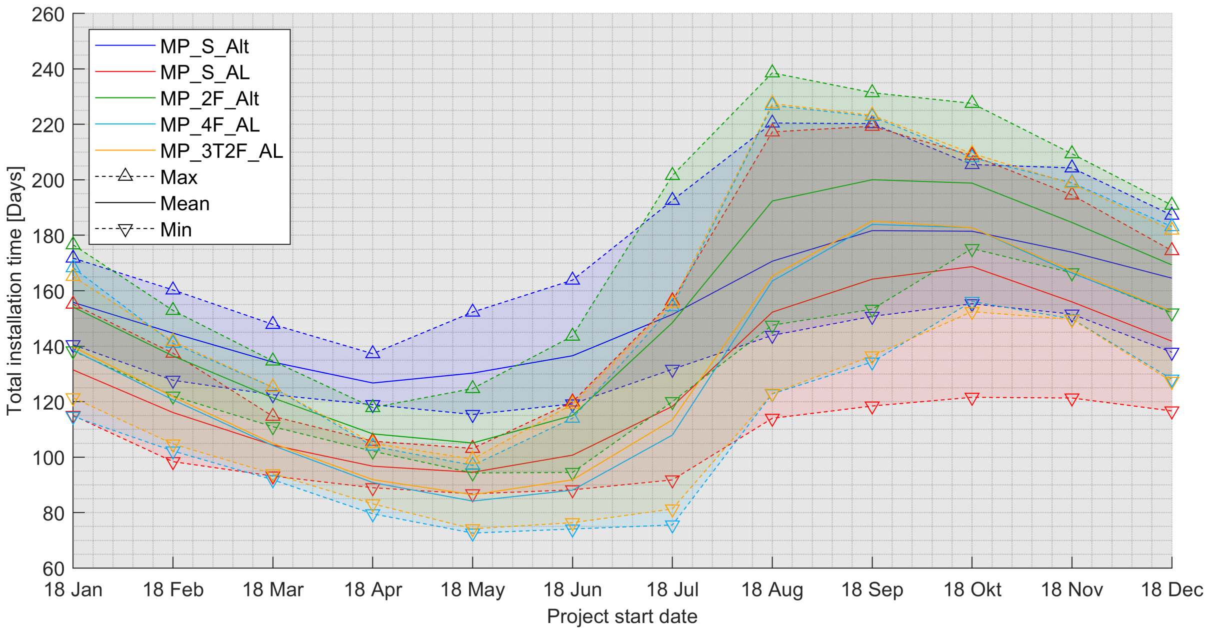

Figure 8.7: The maximum, mean and minimum installation time as a function of the project start date per MP-TP installation strategy (**note** that for visibility reasons the colours per strategy are different w.r.t. the figures above)

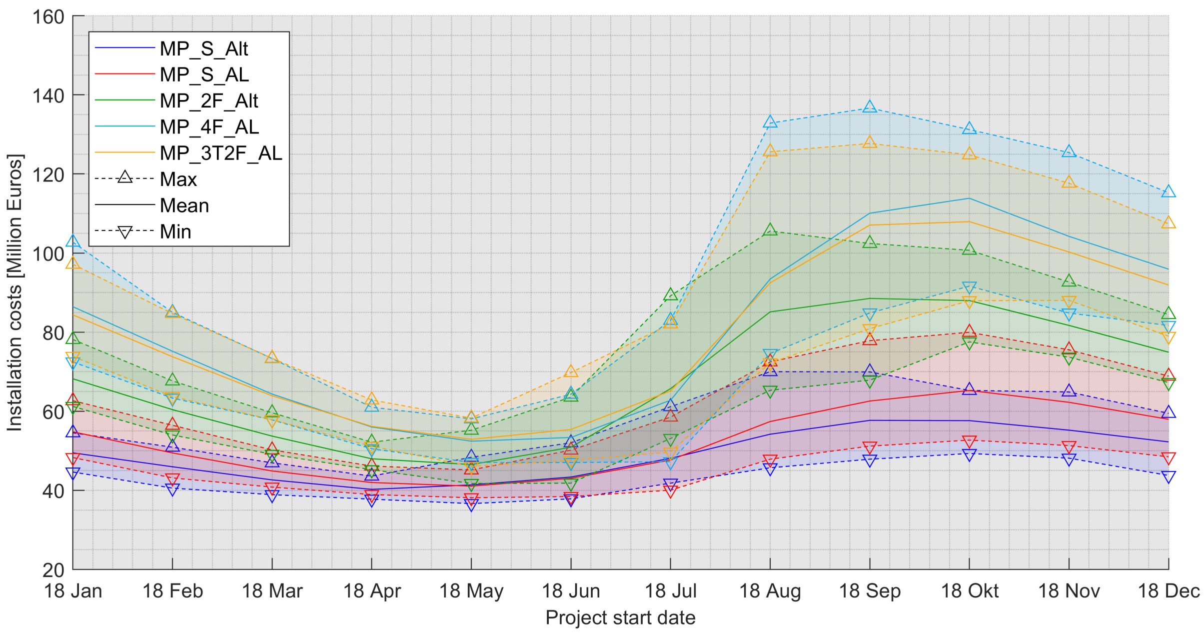

Figure 8.8: The maximum, mean and minimum installation costs (only including the cost components discussed in Section 6.4) as a function of the project start date per MP-TP installation strategy (**note** that for visibility reasons the colours per strategy are different w.r.t. the figures above)

Nevertheless, it must be noted that there are certain risks associated with starting an installation project on the "optimal" date. The model developed in this study does not account for unexpected events such as mechanical failures that require repairs. The delays as a result of such events may push the project's operations into the months with less favourable weather, due to which the installation time and costs can increase quickly, as can be deduced from Figure 8.7 and 8.8. Hence, it can be considered to start a project before the "optimum", which may reduce the project's risk. Additionally, the risks associated with the choice for a certain strategy must be evaluated. From a cost perspective, the performance of MP_S_Alt and MP_S_AL is comparable and higher than of the other strategies for a certain range of start dates. However, for start dates towards the winter season, MP_S_Alt starts to outperform MP_S_AL. A similar situation may be encountered due to the influence of unexpected delays. Also, looking at the installation time, the variability of the latter strategy increases significantly, which may become troublesome when certain contractual milestones are to be met.

8.2 Jacket – foundation pile installation strategies

In this section, the numerical simulation results regarding jacket installation strategies are presented. Section 8.2.1 compares the performance of the proposed strategies based on the input data presented in Chapter 6. Additionally, the bottlenecks of the most promising strategies are identified. Subsequently, in Section 8.2.2, actions that can be taken to reduce these bottlenecks are proposed and the potential improvement in the project performance is discussed. Finally, in Section 8.2.3, the dependency of the performance on the project start date is evaluated.

8.2.1 Jacket installation strategy performance evaluation

Similarly to what was done for the simulations of MP-TP installation feeder strategies, the number of component-supplying barges is varied in the simulations of the installation of jackets and their foundation piles. Hence, based on the six considered strategies, eight different logistical set-ups are analysed, as can be deduced from Table 8.3. The eight corresponding project completion S-curves are plotted in Figure 8.9, which shows that Ja_4F_AL on average reaches 100%-project completions first, shortly followed by Ja_S_AL. Ja_1F_Sep results in the only curve for which on average operations are performed throughout the whole winter. This is mainly the result of the low occupancy rate of the HLV due to the usage of only one barge (compare to Ja_2F_Sep), but also the delaying effect of the unfavourable weather is clearly visible. When comparing Ja_2F_AL and Ja_4F_AL, a similar effect of the HLV occupancy rate is visible. However, for this strategy, the project is completed before the winter season and therefore the “flattening” of the S-curve is largely avoided.

Table 8.3: Overview of the logistical set-ups for the installation of jackets and the corresponding abbreviations

Abbreviation	Strategy	Vessels	Abbreviation	Strategy	Vessels	
Ja_S_Sep	Shuttling – Separate phases	1 HLV	Ja_1F_Sep	Feeders – Separate phases	1 HLV	1 Barge
Ja_S_AL	Shuttling – Assembly-line	2 HLVs	Ja_2F_Sep			2 Barges
Ja_S_Dredg	Shuttling – Separate pile dredging	1 HLV, 1 OSV	Ja_2F_AL	Feeders – Assembly-line	2 HLVs	2 Barges
			Ja_4F_AL			4 Barges
			Ja_2F_Dredg	Feeders – Separate pile dredging	1 HLV, 1 OSV	2 Barges

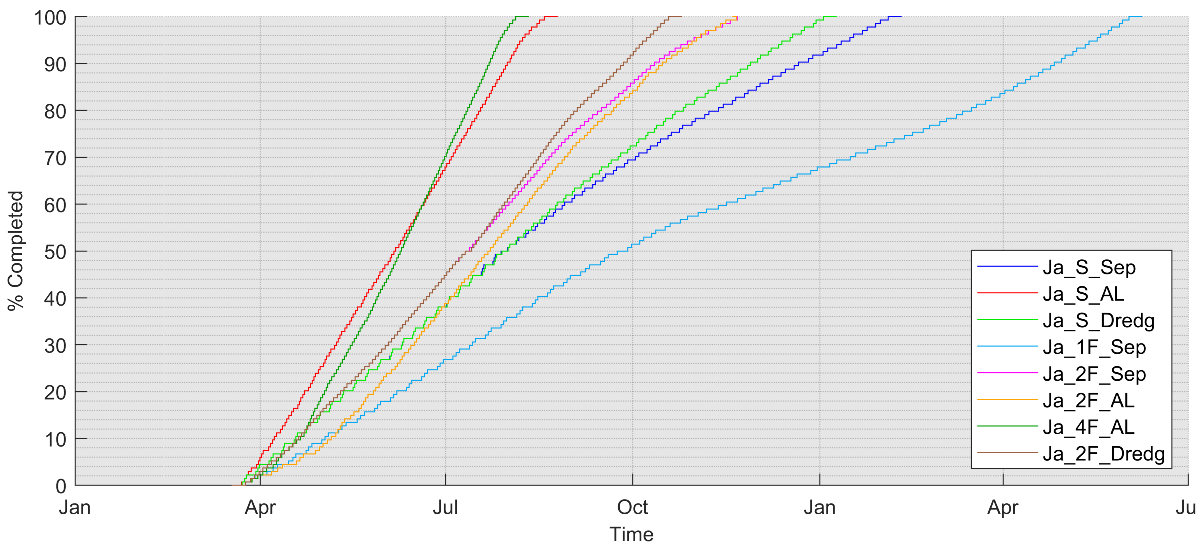

Figure 8.9: S-Curves of the eight considered logistical set-ups for the installation of jackets and foundation piles

Figure 8.10 shows the boxplots of the installation time and costs for the eight considered logistical set-ups, each based on 11 × 35 simulation runs. Simulations with the start date in 2011 could not be performed for all strategies, as for some the completion time is more than a year and no weather data was available for 2012. Therefore, it was decided not to include this start date for any of the simulations. In terms of installation time, Ja_4F_AL can be considered the most advantageous, although Ja_S_AL is a competitive alternative. When additionally installation costs are evaluated, a clear preference goes out to the latter option. The time reduction realised with the deployment of four additional feeder barges in Ja_4F_AL does not make up for the additional introduced costs. Another notable result is the effectiveness of the strategies in which a separate dredger vessel is deployed. It should be realised that these strategies are based on the separate phases strategies, but with an additional Offshore Support Vessel (OSV) to perform the pile dredging. Comparing Ja_S_Sep with Ja_S_Dredg and Ja_2F_Sep with Ja_2F_Dredg results in the conclusion that significant time and cost reductions can be achieved by deploying an OSV.

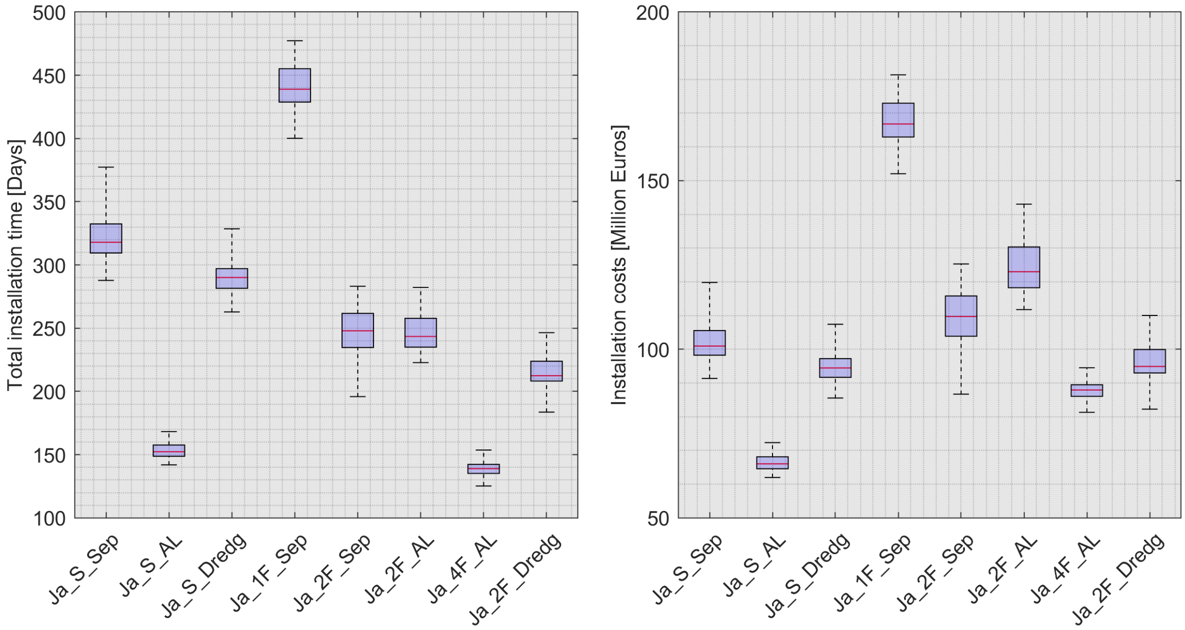

Figure 8.10: Boxplots describing the simulated installation time and costs (only including the cost components discussed in Section 6.4) per considered strategy,

In order to research the influence of WOW-days on the project performance, Figure 8.11 provides for each logistical set-up the number of WOW-days, averaged over 35 runs, per year. As could be expected based on the results derived for the installation of MPs and TPs presented in Section 8.1, logistical set-ups including feeder barges generally result in relatively many WOW-days. Also, the total project duration has a positive effect, which means that strategies including feeder barges with a low total installation time (e.g., Ja_4F_AL) can have fewer WOW-days than strategies excluding feeders (e.g., Ja_S_Sep). Accordingly, the reduction of the installation time due to the addition of a separate dredger OSV can result in a reduction of the number of WOW-days (compare Ja_2F_Sep with Ja_2F_Dredg).

In addition to the overview of the total weather-induced delays presented in Figure 8.11, Table 8.4 specifies the average contribution per weather-dependent operation. Just as was concluded for the installation of MPs and TPs, barge (un)mooring operations (if present in the strategy) provide a relatively large contribution to the total number of WOW-days. For Ja_S_AL, two of the main contributors are Pile Installation Frame (PIF)-installation and pile dredging. However, by experimentation, it was found that increasing the limits corresponding to these operations shifts the cause of postponement to pile and jacket installation respectively. Therefore, Section 8.2.2 only discusses the effect of increasing the workability of the barge (un)mooring operation.

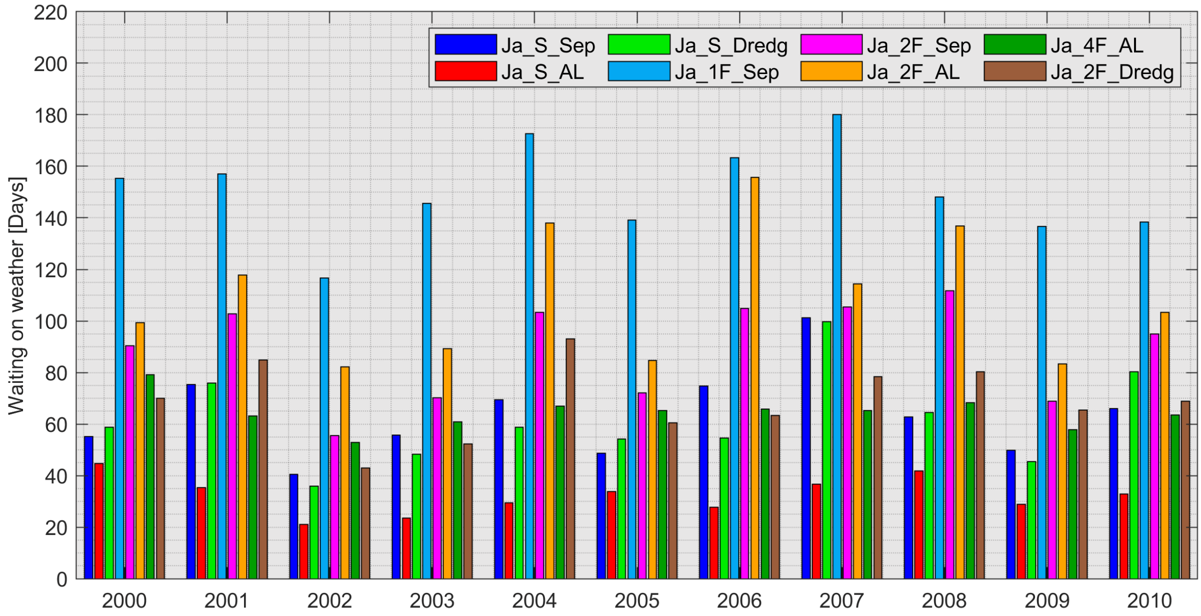

Figure 8.11: Average total number of WOW-days during a jacket installation project, per year and per strategy

Table 8.4: Contributions of weather-limited jacket installation operations to the total number of WOW-days

	Pile load-out	Jacket load-out	Sailing	Anchor running	PIF installation	Barge mooring	Pile Transfer	Pile installation	Pile dredging	Pile cleaning	Jacket transfer	Jacket installation	Barge unmooring	Anchor pick-up
• Ja_S_AL	1.3%	0.6%	0.0%	2.1%	20.7%	0.0%	0.0%	13.3%	22.3%	0.0%	0.0%	35.5%	0.0%	4.4%
• Ja_2F_Sep	0.8%	0.4%	0.1%	0.0%	3.4%	37.1%	4.7%	3.0%	8.8%	0.0%	2.7%	8.1%	30.9%	0.0%
• Ja_4F_AL	0.8%	0.5%	0.1%	0.3%	5.2%	34.0%	6.0%	3.2%	4.5%	0.0%	1.6%	11.9%	31.5%	0.6%
• Ja_2F_Dredg	1.0%	0.3%	0.1%	0.0%	4.3%	37.4%	6.0%	3.8%	5.4%	3.0%	2.0%	7.3%	29.3%	0.0%

8.2.2 Jacket installation bottleneck reduction sensitivity analysis

As discussed in Section 8.1.2, it can be considered reasonable to increase the significant wave height limit of the barge mooring operation from [redacted] m to [redacted] m. This is due to the fact that crew transfer from the HLV to the barge is limiting in this operation, and hence the limit can be increased by the deployment of a crew transfer vessel that is less weather sensitive. Figure 8.12 shows that significant reductions in the installation time and costs can be realised if this relatively marginal increase in weather resistance is put into practice. However, it should also be pointed out that even if this increase in performance is realised, Ja_S_AL remains the best performing strategy in terms of costs.

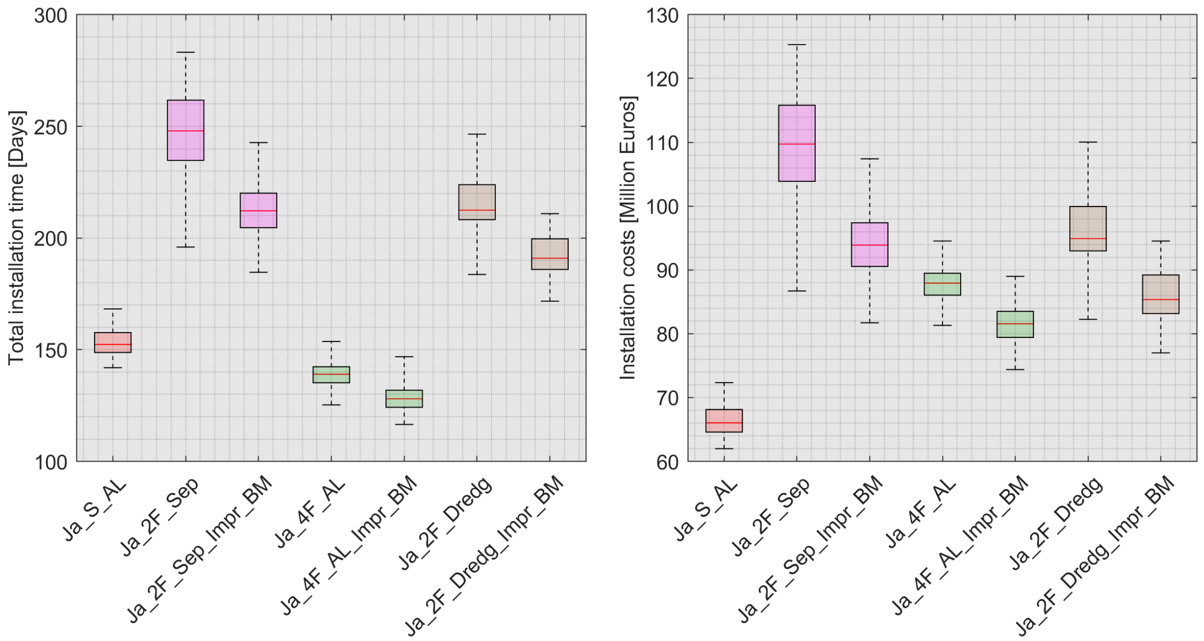

Figure 8.12: Comparison between the installation time of the four promising initial jacket-installation strategies and of those strategies with improved workability

8.2.3 Jacket installation performance as a function of the start date

For the four promising jacket installation strategies, the effect of the start date on the project performance is investigated. Figure 8.13 and 8.14 present the maximum, mean and minimum installation time and costs respectively, as a function of the start date. When these figures are related to Figure 8.7 and 8.8, it can be stated that considering relative numbers the jacket installation strategies are less sensitive to the start date. However, when looking at absolute numbers, the sensitivity is comparable. Among the strategies compared, the results of Ja_4F_AL are most affected by varying the start date, especially regarding the associated costs. Hence, when applying this strategy, special attention should be given to the risks of having delays and ending up in a period of the year for which costs increase rapidly.

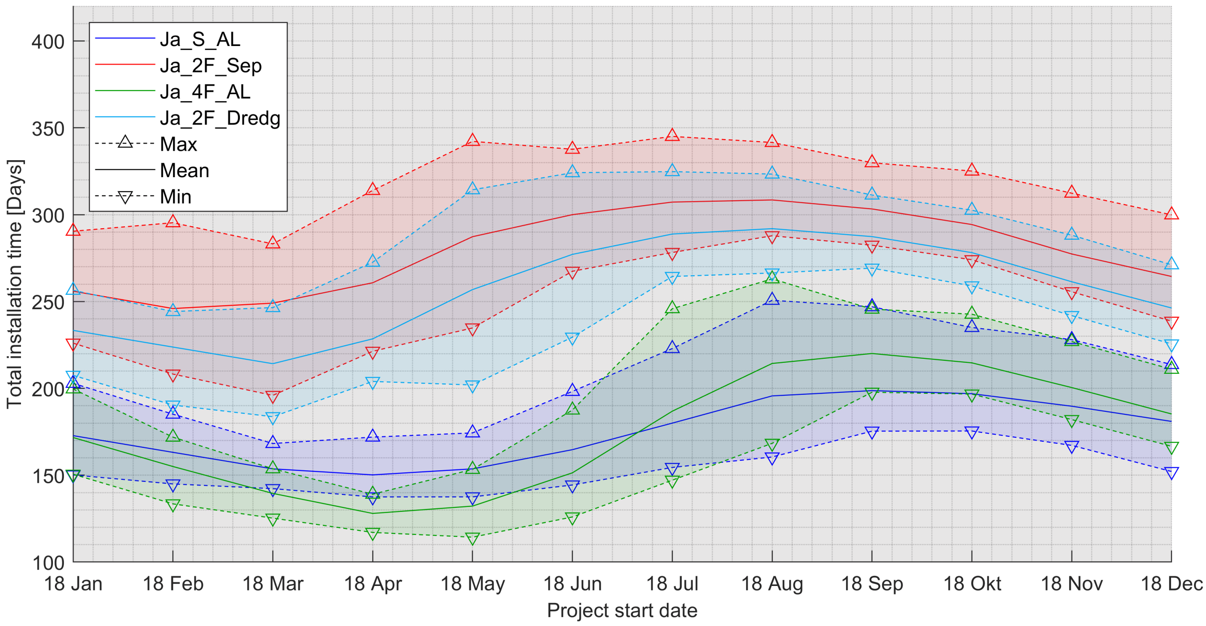

Figure 8.13: The maximum, mean and minimum installation time as a function of the project start date per jacket installation strategy (**note** that for visibility reasons the colours per strategy are different w.r.t. the figures above)

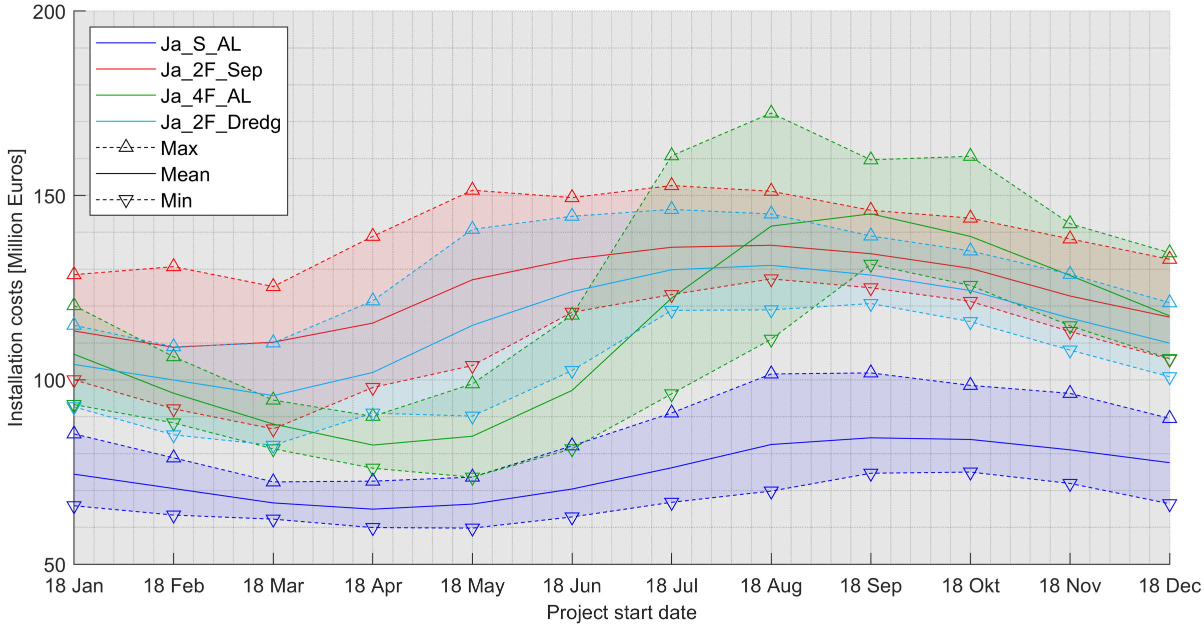

Figure 8.14: The maximum, mean and minimum installation costs (only including the cost components discussed in Section 6.4) as a function of the project start date per jacket installation strategy (**note** that for visibility reasons the colours per strategy are different w.r.t. the figures above)

8.3 Discussion

This section discusses the main findings presented in Section 8.1 and 8.2 and evaluates them in the context of the related fields of science and industries. First, in Section 8.3.1, the main findings from the numerical simulations are discussed in the context of recent and expected market developments. Next, the potential effect of technological developments on the obtained results is evaluated in Section 8.3.2. In Section 8.3.3, a holistic market perspective for the companies involved in the development of offshore wind farms to adopt is proposed and the associated advantages and obstacles are discussed. Subsequently, in Section 8.3.4, the generalisability of the findings in and outside of the offshore wind industry is evaluated. Finally, the limitations of the performed study are discussed in Section 8.3.5.

8.3.1 Numerical results w.r.t. market developments

Section 8.1 and 8.2 have shown that for the current market, and within the boundaries of this study, shuttling transportation strategies generally outperform feeder strategies. However, for various market development scenarios shuttling may not be a viable alternative. One of those is the continuous increase in the size of substructures. This may lead to a situation in which many of the current installation vessels do not have the capacity to transport the substructures on their transportation deck or to lift them from the deck and bring them in a vertical position onto the seabed. Feeder barges can in those cases provide additional deck space, whereas towing FMPs does not require deck space at all and reduces the required crane capacity as use can be made of the MP's buoyant effect. Another market development scenario in which shuttling strategies may not be a viable alternative is induced by the expansion of the focus of the offshore wind market from Europe to other continents. According to Gilman et al. (2016), the U.S. is planning to have installed 86 GW of offshore wind power by 2050, which is more than 2.5 times the current global installed capacity. This perspective of rapid development is an interesting opportunity for European contractors. which are relatively experienced in the offshore wind industry. However, the U.S. Jones Act restricts these contractors in deploying shuttling strategies, as this act requires the vessels that transport goods (such as wind turbine components) between ports in the U.S. to be built in the U.S. (which they generally are not). A potential solution might be to deploy feeder strategies, using barges, feeder vessels or FMP-towing tugboats which are constructed in the U.S.

Since it can be expected that the feeder alternatives are more expensive than shuttling transportation strategies, a competitive disadvantage could arise w.r.t. companies with large installation vessels capable of installing the next-generation substructures or companies that operate Jones Act compliant vessels. European offshore contractors should use this knowledge to prepare themselves with a competitive position in these expected market developments. Various alternatives are to be evaluated, such as building larger installation vessels, potentially on U.S. soil (to step into the U.S. market of large foundations in a shuttling strategy), or investing in methods to be competitive with the currently available vessels. Many contractors are expected to first investigate the latter option, as this avoids large investments. The main identified bottleneck of feeder strategies is the lower workability as a consequence of the introduction of weather-sensitive operations. Hence, to increase competitiveness this disadvantage should be mitigated. Recent technological developments may contribute to solving this issue, as discussed in the next section.

8.3.2 Numerical results w.r.t. technological developments

In the last few years, various motion compensation systems have been introduced in the market of offshore wind. Such devices compensate for the motions that are induced by the offshore environmental conditions (e.g., wave-induced motions), which enables contractors to install components with the required accuracy at higher sea states. The increasing availability of such devices indicates that the potential of increasing offshore workability is recognised. The in this study developed decision support tool has shown to be capable of estimating the reduction in installation time and costs resulting from a workability increase. This expected cost reduction forms the basis for establishing a budget for investments in workability-increasing systems. When larger investments are required, it is preferable to investigate the applicability of the investment in follow-up projects. The developed tool may then be used to estimate the payback period, which potentially covers multiple projects.

Another technological development in the field of substructure installation was already discussed in Section 3.2.3. It concerns a new type of hammer that is used to drive MPs into the seabed, which has the potential to introduce much less vibrations into the substructure than the traditional impact hammer. These vibrations are the reason why boat landings, ladders and access platforms (in the industry referred to as "secondary steel") are generally attached to the TPs, and installed after the MP is driven into the soil. If they were installed on the MP, they would simply vibrate off during the pile driving process. According to IQIP (2020), the vibrations induced by the newly developed hammer may be sufficiently low to enable the installation of secondary steel on the MP. Furthermore, the design of the turbines in the Hollandse Kust Zuid wind farm, of which the installation has recently commenced, shows that the electrical components traditionally housed by the TP can also be positioned in the turbine tower. The combination of these developments shows the potential to completely leave TPs out of turbine design (or to "integrate" TPs into MPs). Looking at Table 6.2, these developments would at least take operations 5, 6 and 9 out of the process. Apart from the direct time saving, this may also result in a reduction in the number of WOW-days, as TP-installation proved to be a weather-sensitive operation. However, integrating the TP in the MP also encompasses some disadvantages. If the TP is taken out of the turbine design, it is expected that the length of the MP has to compensate for the height traditionally provided by the TP. This would mean that MPs become longer and heavier, which intensifies the limitations discussed in Section 8.3.1 regarding vessel deck space and crane capacity. Nevertheless, it can be stated that if this scenario becomes reality, the attractiveness of additionally investing in motion compensation systems to improve the in this study considered processes would reduce, as the application of such systems was primarily focused on TP-installation. The developed decision support tool can be of assistance in determining the most cost-effective alternative.

8.3.3 Numerical results w.r.t. alternative market perspectives

Section 8.1 and 8.2 showed that installation strategies associated with a short installation time often do not correspond to low installation costs, and therefore are not preferred. However, it may be that if a more holistic market perspective would be adopted, the preferences would shift towards the strategies associated with short installation times. One of the main advantages of these strategies is that they provide the opportunity to operationalise the wind farm earlier, and therefore to generate revenue earlier. An important requirement towards adopting such a perspective is the alignment of the (financial) interests of the involved stakeholders. Contractors have to be compensated for selecting a fast rather than a cheap strategy, based on the additionally generated revenue. The option of the developed decision support tool to present the expected performance as a function of the start date (see Section 8.1.3 and 8.2.3) may be of help in the alignment process. It could be used to find a combined performance optimum for the various contractors sequentially installing different types of components (substructures, superstructures, cables, etc.). A similar concept of information sharing was already investigated by Beinke et al. (2017a), and was shown to have the potential to significantly reduce installation times. However, it must be noted that this approach would require a considerable change of culture among the currently individually operating contractors (the current culture can be characterised by the increasing number of contractors signing up for Engineering, Procurement, Construction and Installation (EPCI)-projects, in which a single company manages four phases of the development process, and hence avoids the requirement of aligning processes with other parties).

8.3.4 Generalisability

It must be realised that the developed models and the results obtained from this study are based on a certain case (i.e., it is a case study). This means that the results can not be generalised without evaluating the boundary conditions. However, the developed models are applicable to other cases, even to the installation of superstructures, as long as suitable input data are provided.

- The number of each type of vessel, and their transportation capacity and sailing speed.
- The number of strings, the number of turbines aligned in each string, the distance between the base port and the wind farm entry point, the distance between the wind farm entry point and the string entry points and the distance between each turbine in a string.
- The considered installation activities and the corresponding durations. Section 6.3 provides a foundation for this. Adding operations requires fitting distributions to suitable data.
- The day rates of the significant cost components, as exemplified in Section 6.4.
- The vessel-specific weather limitations, and the location-specific weather time series.

While feeder transportation strategies have been researched to some extent (e.g., in the study by Oelker et al. (2018)), approaches such as the assembly-line strategy have never been studied for the case of superstructures. Hence, applying the developed models to superstructure installation would tackle another scientific knowledge gap. The results of this study are not expected to be directly generalisable to the case of superstructures, as these are generally not installed by floating vessels but by jack-ups. Jack-ups normally have a higher workability during installation, as they do not experience wave-induced motions when the hull is lifted out of the water.

Although the models developed in this study are purpose-built for the analysis of the installation of offshore wind farms, the underlying principles are applicable in many industries. One upcoming industry to which also the weather-limited principles in the models are applicable is the deep-sea mining industry. In the near future, the terrestrial mining industry might not be able to keep up with the continuously growing worldwide consumption of mineral resources anymore. Hence, deep-sea mining may be a good alternative, preferably with minimal associated costs. For this industry, different transportation strategies are available to bring the extracted minerals to the shore. According to Ecorys (2014), this can be done by the mining vessel itself (similar to the shuttling strategies in this study) or by barges or bulk carriers (similar to the feeder strategies).

Another example is the offshore oil and gas industry, which operates many offshore extraction facilities and therefore has to deal with logistical problems such as the supply of spare parts and the discharge of produced hydrocarbons.

8.3.5 Limitations

Considering the time available to perform this study, the scope has been limited. The numerical simulations have only been performed on a single wind farm size, at a single distance from the base port, at a single location. Although it is expected that the general conclusions drawn in this study are not very sensitive to the variation of the first two parameters, this has not been confirmed. The fact that this study has been limited to a single location may represent a larger limitation, as results have only been obtained for the environmental conditions at this particular location. Since most of the delays considered in this study are weather-induced, this may affect the general conclusions. In addition to the weather conditions considered in this study being case-specific, some other weather-related limitations have to be mentioned.

- Recently acquired insights show that current may be a limiting factor for FMP transportation. This condition has not been included in the analysis of this study and could limit the effectiveness of this transportation strategy and thereby the accuracy of the obtained results.
- Climate change is expected to affect the predictive capabilities of the produced models. The increasing severity of the offshore weather conditions may intensify the impact of the identified bottlenecks or create new obstacles, which could influence the selection of strategies. Hence, it is preferable to provide the models with weather data of recent years, or with weather forecasts that account for the development of climate change (which is not the case for this study, as weather data from the years 2000-2011 was used).
- This study considers the weather dependency in a simplified manner (although more accurate than most other scientific studies, as explained in Section 6.5). The sea state is described by a time series of significant wave heights and peak wave periods. However, this principle does not cover both principles of sea and swell waves. Especially the latter can be limiting for the operations, due to the relatively long waves which excite the natural frequencies of floating vessels. To include both types of waves, workable weather windows could be produced based on 2D-spectral weather data. This would increase the accuracy, but also the complexity and the required pre-processing work.

In addition to the weather-induced delays, in practice, significant delays may result from mechanical failures requiring repairs. However, such events are not included in the developed models. Apart from making the models more accurate, including a stochastic failure component in the models would be of assistance in reliability analyses or in the justification of investments in spare parts. Another limitation of this study is its focus on the phases between the load-out and the actual installation of substructures (see Section 3.1). In practice, the considered processes may be dependent on additional external factors. One example is the supply of components to the marshalling yard and the availability of storage capacity. In this study, it has been assumed that independent of the installation rate of a strategy, the components to be installed are always available to be loaded on the transportation vessels. In reality, the onshore supply of components is a complex logistical process that may not be as perfectly aligned as assumed. Similarly, the effects of quayside availability and the interaction with processes after substructure installation (e.g., superstructure and cable installation) are not considered.

It must also be mentioned that the convergence and validation tests were only performed on the base model, representing the shuttling–alternating strategy for the transportation and installation of MPs and TPs. The other strategies were modelled by adding components to this base model. This way, it has been tried to provide results representing reality as close as possible, without having to perform convergence and validation tests on every produced model. However, with the addition of these components, errors or variability may have been introduced into the results.

9 Conclusion

The conclusions that can be drawn from the process towards reaching the research objective are discussed in Section 9.1. Also, the main research question is answered in this section. In Section 9.2, the scientific implications of this study are discussed and recommendations are made for future research. Finally, in Section 9.3, it is described how the results of this research can be applied in an organisational or managerial environment.

9.1 General conclusions

The literature review performed in this study revealed that the availability of scientific studies on the logistics of the installation of offshore wind farms is limited. Most of the available studies only consider the installation of wind turbine superstructures, and some include the installation of substructures as an accessory process. Furthermore, while a few studies analyse the effectiveness of superstructure installation strategies, no study was encountered doing this for substructures. Hence, the objective of this study was to "*generate insights into the complex system of interdependent strategies for the installation of offshore wind turbine substructures, and to identify and quantify cost-reduction opportunities*". In pursuing this objective, first, offshore installation strategies were identified by a literature study. It was concluded that the strategies can be categorised in transportation and installation strategies, from which combinations can be formed. Nine different combinations were identified to be applicable to Monopile (MP)-Transition Piece (TP) installation and six to jacket-foundation pile installation. A Discrete Event Simulation (DES)-modelling approach was considered most suitable to quantitatively evaluate the strategies. To arrive at conclusions in a rigorous manner, the eight-step Simulation Model Development Process (SMDP) by Manuj et al. (2009) was followed. The phases *definition of variables* and *model conceptualisation* were merged since the experimental conditions in this study are not simply variations in the values of input parameters, but different sets of input data corresponding to the strategies of analysis. Hence, the experimental data were categorised in "vessel data", "location data", "time duration data", "cost data" and "weather data". The numerical model output was expressed in two variables: the project costs and duration. Next, model conceptualisation was performed at a high level (to provide insights into the interaction of the models with external data) and at a low level (to conceptualise the decision logic). These conceptual models were face validated by industry experts, to provide a solid guideline for the construction of the numerical models. In the *data collection* phase, the input data were collected and reviewed by industry experts to ensure their quality. Moreover, probability distributions fitted to time duration data were statistically tested by a Kolmogorov-Smirnov test.

In the *model development* phase, a base model was constructed, which describes the combination of a shuttling transportation and an alternating installation strategy for MPs and TPs. This was considered the most "basic" strategy, and suitable to be used as a "template" to construct the models for other strategies. Next, it was face validated by industry experts and evaluated by parameter variability, convergence and historical data validation tests. The conclusions were drawn that the base model is structured according to the practical experience of industry experts, responds to parameter changes according to expectations, requires 35 simulation runs for the average result to converge between a 24-hour bound, and has good predictive capabilities. Next, the base model was used to develop the model structures corresponding to the other strategies of analysis. In the evaluation of the results obtained in the *simulation and analysis* phase, a distinction was made between MP and jacket installation strategies. **(i) MP and TP installation.** It was concluded that an assembly-line strategy is most suitable if a low installation time is required (assuming a high occupancy rate for the Heavy Lift Vessel (HLV) in the case of feeder strategies). However, when also costs are considered, only the shuttling–assembly-line strategy can compete with the least expensive alternative: the shuttling–alternating strategy. Furthermore, it was found that alternating installation strategies, in general, outperform separate phases strategies. Barge mooring and the installation of TPs by a smaller HLV in an assembly-line strategy were identified as the main bottlenecks. Reducing these can result in significant installation time and cost reductions. Also, the strategy performance was found to be strongly dependent on the project start date. Performing operations in the winter season can lead to significant performance reduction, especially for strategies involving operations with relatively low workability limits. **(ii) Jacket and foundation pile installation.** Also for jacket installation, it was observed that the assembly-line strategies are associated with the shortest installation time. The shutting–assembly-line strategy was found to be the alternative with the lowest costs by a significant margin. Another finding is that the deployment of a separate pile-dredging Offshore Support Vessel (OSV) can help to reduce the installation time and costs of separate phases installation strategies. Once more, the barge mooring process was appointed as the main bottleneck. Reducing this bottleneck with relatively simple solutions can result in large performance benefits. Lastly, the performance of jacket installation appeared to be less sensitive to the project start date than MP installation (considering relative numbers).

Based on the findings discussed above, an answer is formulated to the main research question: "*What logistical strategies that can be implemented for the installation of offshore wind turbine substructures are most competitive in terms of operational costs?*" Within the boundaries set in this study, the answer to this question can be formulated relatively straightforward. For the installation of MPs and TPs, the most cost-effective strategies are the shuttling–alternating and the shuttling–assembly-line strategies. For jacket installation, shuttling–assembly-line is the best performing strategy. However, the validity of this conclusion is dependent on its context and technological developments, as discussed in Section 8.3. In the U.S.-market, none of these strategies may be applicable due to the Jones Act, which would result in very different conclusions. Similarly, adopting a more holistic market point of view, and considering the effect of collecting revenue earlier when a wind farm is operational earlier, may shift the preference towards strategies with a short installation time.

9.2 Scientific implications and future research

A review of the state-of-the-art literature showed that studies considering offshore logistical strategies are very limited available and that this research is unique in its focus on the logistics of offshore wind turbine substructures. Hence, with this study, an attempt has been made to cover a significant scientific knowledge gap. Additionally, this study contributes to the process of improving strategic (cost) management regarding the installation of offshore wind farms and it may provide a foundation for the logistical development of other (offshore) industries. Also, it must be stated that the writer's experiences from a close collaboration with industry experts and the fact that the performance of a strategy has shown to be sensitive to the set operational limits emphasize the great importance of the interaction between the fields of offshore logistics and vessel hydrodynamics. This conclusion was also drawn by Sperstad et al. (2014). Hence, it is recommended to further integrate these fields in future studies. Furthermore, it is encouraged to investigate opportunities to reduce the limitations of this study (see Section 8.3.5) and to further develop the decision support tool. Some suggestions to this end are provided below.

- The effect of the wind farm size and port-to-farm distance on the strategy performance might be of relevance and is therefore recommended to be investigated.
- To make the models more realistic, it is advised to include a stochastic failure component.
- Regarding the identification of new cost-reduction opportunities, it is recommended to investigate the adoption of more holistic process and market approaches. The first could mean to extend the supply chain of analysis upstream towards procurement and construction, and downstream towards hook-up and commissioning (see Section 3.1), which allows for optimal alignment of processes and strategies. The second could mean to investigate the alignment of the interests of the involved parties. An example of misalignment of interests

described in this study, is that the installation strategies with the shortest installation time are currently not favoured (partly) because they introduce additional costs for the contractor whereas the benefits go to the wind farm owner. Also, the opportunity for the contractor to start earlier with a new project is not evaluated. Aligning such interests might result in a shift of preference, e.g., towards strategies with shorter installation times.
- To further refine the models, it is advised to determine workable weather windows based on 2D-spectral weather data. However, this significantly intensifies the pre-processing work.
- Since little is known about the development of climate change in the coming decades, it is recommended to investigate the sensitivity of the offshore wind farm installation performance to various scenarios of the increasing severity of the offshore conditions.
- It is recommended to consider the CO_2 -emissions as a performance indicator of the considered strategies (in addition to installation time and costs). This enables a contractor to quantify its contribution to combat climate change, which may be a competitive advantage during the tendering process, and to substantiate investments in CO_2 -reduction systems.

9.3 Managerial implications

It is evident that the results in this study were obtained by the development of a decision support tool. While in this study this tool has only been applied to compare the performance of strategies for the installation of a certain wind farm layout, it can also be applied to other layouts (see Section 8.3.4). Hence, for any installation project, the tool can provide support in making decisions regarding strategy selection and vessel deployment. Moreover, the moments at which the developed models can be consulted stretches over the whole spectrum of phases.

- **Business development and tendering**. When bidding on new projects, contractors have to find a balance between the risk they take and the probability of winning a project. A high bid reduces the internal risk but also reduces the chances of winning the project, and vice versa. The developed decision support tool can be of assistance with the internal risk analysis. Due to its stochastic nature, many scenarios are automatically evaluated, and statistical analysis can be performed on its output (e.g., by determining the P50 or P90 value of the expected installation costs). Moreover, the tool can provide support in finding the right partners at an early stage and estimating the offer a competitor will make.
- **Investment decisions**. The added value of technological innovations (such as motion compensation systems) can be investigated and investments substantiated. Therefore, the developed tool can be regarded as an innovation management tool, which can provide support in responding to internal and external opportunities.
- **Operational**. Once a project is won, the detailed preparations for execution commence. Within the boundaries of the agreement with the client, installation strategies can be compared and evaluated as was done in this study. Also, during projects, the performance can be tracked and new knowledge can be implemented in the model to substantiate adjustments in the original execution plan. Furthermore, the developed tool could function as a platform to which processes upstream and downstream can be supplemented (as suggested in Section 9.2). This could provide support in aligning processes when managing large Engineering, Procurement, Construction and Installation (EPCI) projects.
- **Project evaluation**. By gathering data over the execution of a project, the actual and the expected project performance can be compared. This allows for bottleneck identification, but also for improving the extent to which the model represents reality for following projects.

Conclusively, the developed tool can be integrated in many layers of an organisation to provide support in making the most cost-effective decisions. It must be realised that putting this integration process into practice requires the alignment of various disciplines, which may come with challenges. However, if these are managed well, the combination of the different expertises in a single tool is also expected to lead to novel insights.

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Appendices

A Model structure development

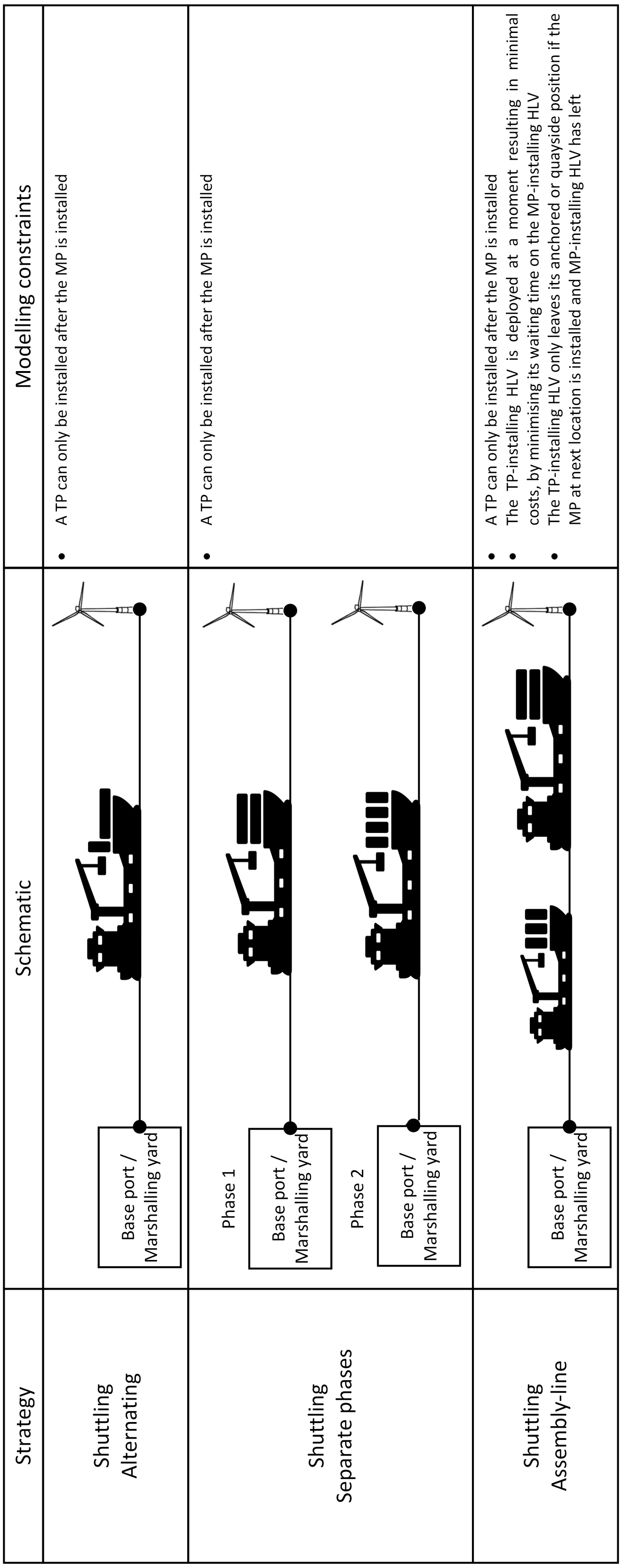


Figure A.1: Description model structure development for shuttling MP-TP transportation

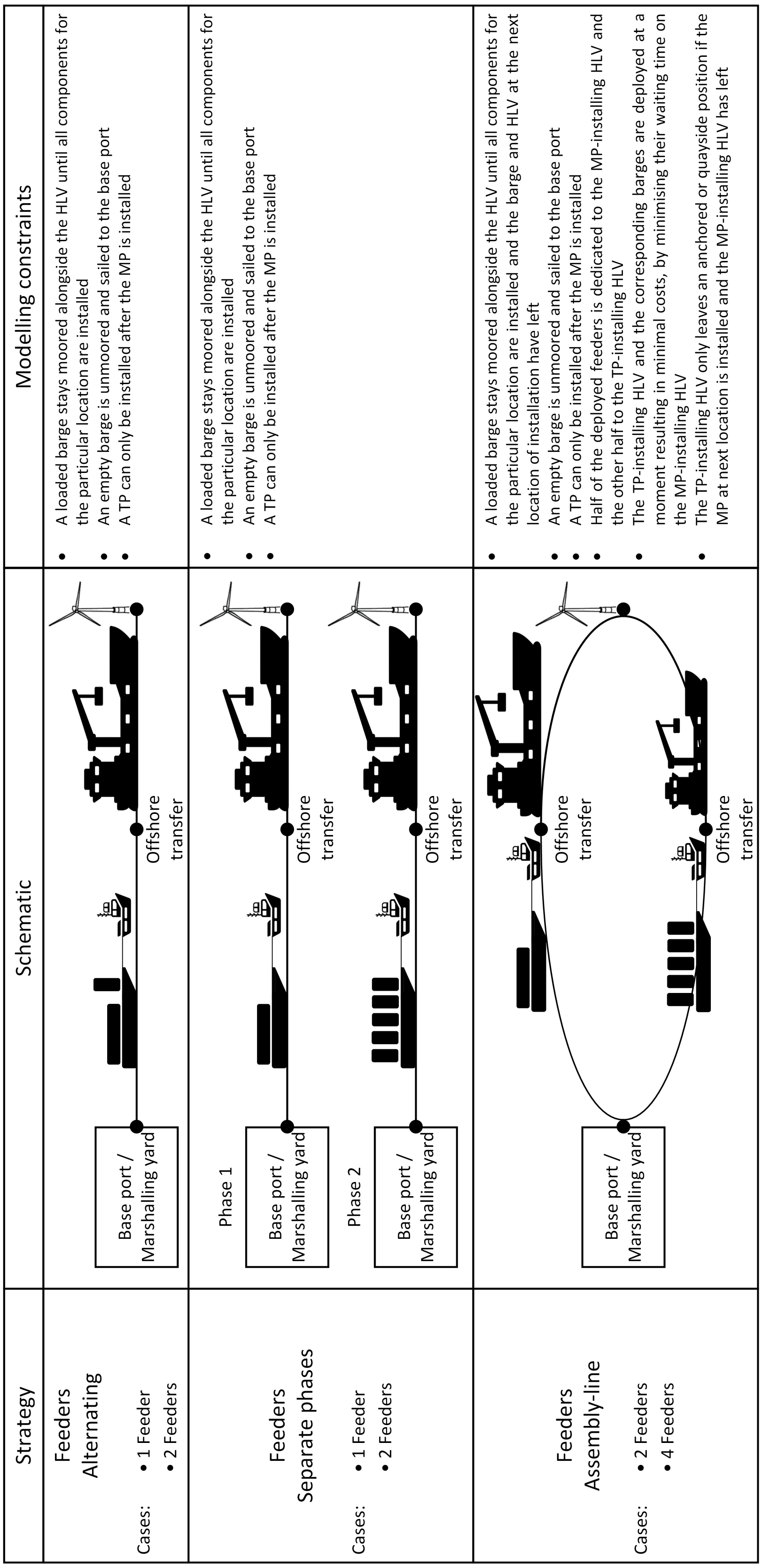


Figure A.2: Description model structure development for feeder MP-TP transportation

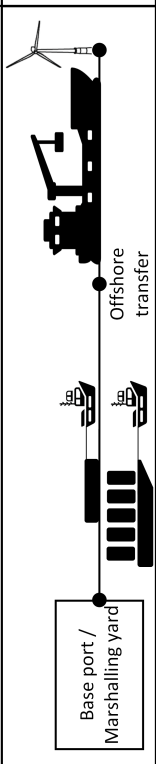
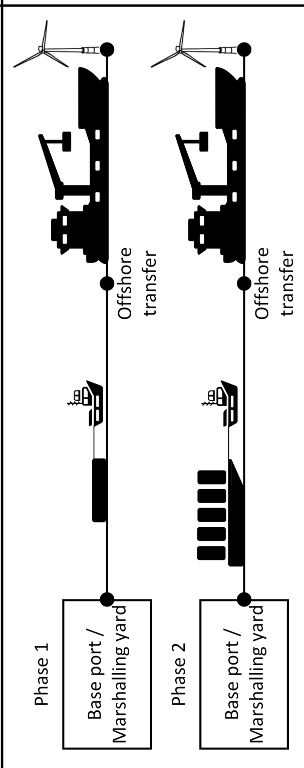
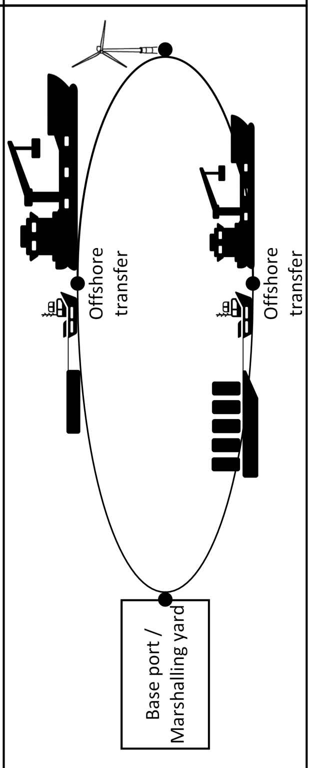
Strategy	Schematic	Modelling constraints
Wet tow Alternating Cases: • 2 Tugs, 1 Barge • 2 Tugs, 2 Barges		• A barge is moored alongside the HLV after the MP is installed • A loaded barge stays moored alongside HLV until all components for the particular location are installed • An empty barge is unmoored and sailed to the base port • An FMP-tug returns to the base port after transferring an MP to the HLV • A TP can only be installed after the MP is installed
Wet tow Separate phases Cases: • 2 Tugs, 2 Barges • 3 Tugs, 2 Barges		• After all MPs have been installed, the FMP-tugs are withdrawn from the cost-system and the barges are inserted • A loaded barge stays moored alongside HLV until all components for the particular location are installed • An empty barge is unmoored and sailed to the base port • An FMP-tug returns to the base port after transferring an MP to the HLV • A TP can only be installed after the MP is installed
Wet tow Assembly-line Cases: • 3 Tugs, 2 Barges		• A loaded barge stays moored alongside HLV until all components for the particular location are installed and the HLV at the next location of installation has left • An empty barge is unmoored and sailed to the base port • An FMP-tug returns to the base port after transferring an MP to the HLV • A TP can only be installed after the MP is installed • The TP-installing HLV and the corresponding barges are deployed at a moment resulting in minimal costs, by minimising their waiting time on the MP-installing HLV • The TP-installing HLV only leaves an anchored or quayside position if the MP at next location is installed and the MP-installing HLV has left

Figure A.3: Description model structure development for wet tow MP-TP transportation

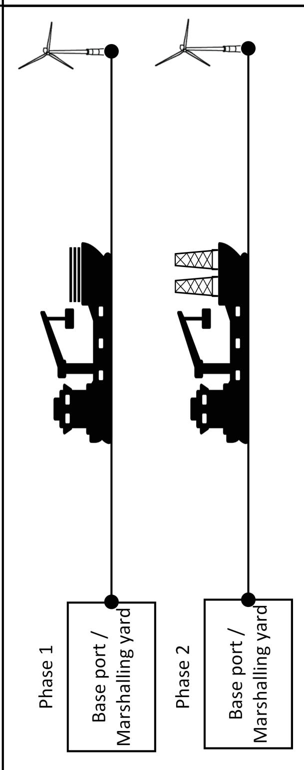
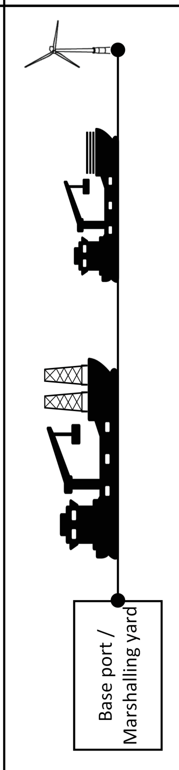
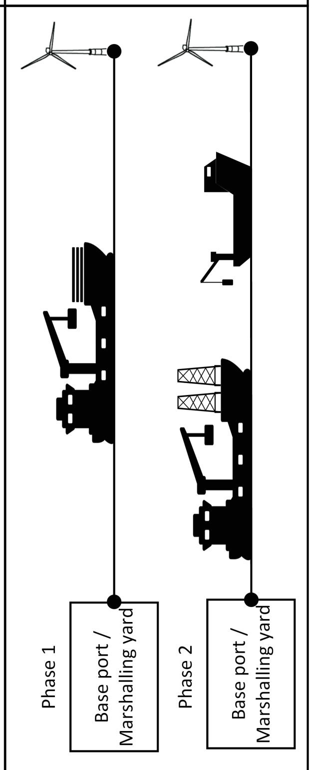
Strategy	Schematic	Modelling constraints
Shuttling Separate phases		• Jacket can only be installed if its piles are installed, dredged and cleaned • Jacket must be installed less than 48 hours after the piles have been cleaned. If this requirement is not met, the piles have to be re-cleaned
Shuttling Assembly-line		• Jacket can only be installed if its piles are installed, dredged and cleaned • Jacket must be installed less than 48 hours after the piles have been cleaned. If this requirement is not met, the piles have to be re-cleaned • The jacket-installing HLV is deployed at a moment resulting in minimal costs, by minimising its waiting time on the pile-installing HLV • The jacket-installing HLV only leaves an anchored or quayside position if the piles at next location are installed and the pile-installing HLV has left
Shuttling Separate dredger		• Jacket can only be installed if its piles are installed, dredged and cleaned • Jacket must be installed less than 48 hours after the piles have been cleaned. If this requirement is not met, the piles have to be re-cleaned • Pile dredging by the OSV is performed after the pile installation, but before pile cleaning and jacket installation, and scheduled such that none of the HLVs have waiting time due to the OSV

Figure A.4: Description model structure development for shuttling jacket-foundation pile transportation

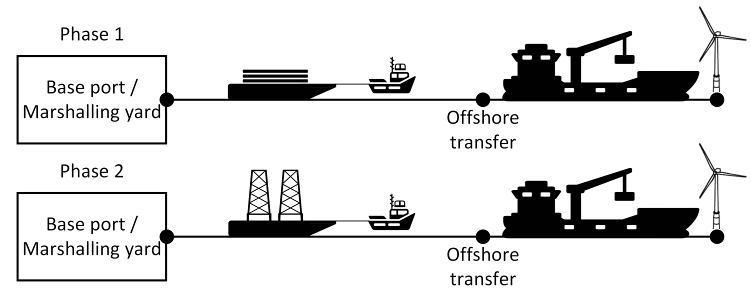
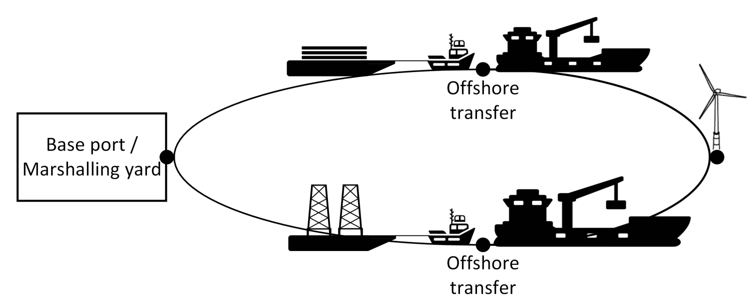
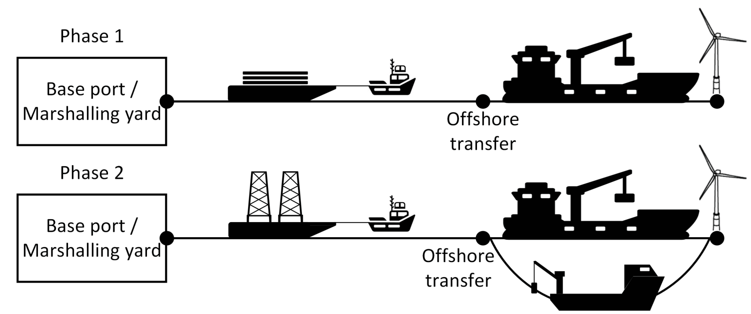
Strategy	Schematic	Modelling constraints
Feeders Separate phases Cases: • 1 Feeder • 2 Feeders		• A loaded barge stays moored alongside HLV until all components for the particular location are installed • An empty barge is unmoored and sailed to the base port • Jacket can only be installed if its piles are installed, dredged and cleaned • Jacket must be installed less than 48 hours after the piles have been cleaned. If this requirement is not met, the piles have to be re-cleaned
Feeder Assembly-line Cases: • 2 Feeders • 4 Feeders		• A loaded barge stays moored alongside HLV until all components for the particular location are installed and the barge and HLV at the next location of installation have left • An empty barge is unmoored and sailed to the base port • Half of the deployed feeders is dedicated to the pile-installing HLV and the other half to the jacket-installing HLV • Jacket can only be installed if its piles are installed, dredged and cleaned • Jacket must be installed less than 48 hours after the piles have been cleaned. If this requirement is not met, the piles have to be re-cleaned • The jacket-installing HLV only leaves an anchored or quayside position if the piles at next location are installed and the pile-installing HLV has left
Feeders Separate pile dredger Cases: • 2 Feeders, 1 dredger		• A loaded barge stays moored alongside HLV until all components for the particular location are installed • An empty barge is unmoored and sailed to base port • Jacket can only be installed if its piles are installed, dredged and cleaned • Jacket must be installed less than 48 hours after the piles have been cleaned. If this requirement is not met, the piles have to be re-cleaned • Pile dredging by the OSV is performed after the pile installation, but before pile cleaning and jacket installation, and scheduled such that none of the HLVs have waiting time due to the OSV

Figure A.5: Description model structure development for feeder jacket-foundation pile transportation

B | Parameter variability test

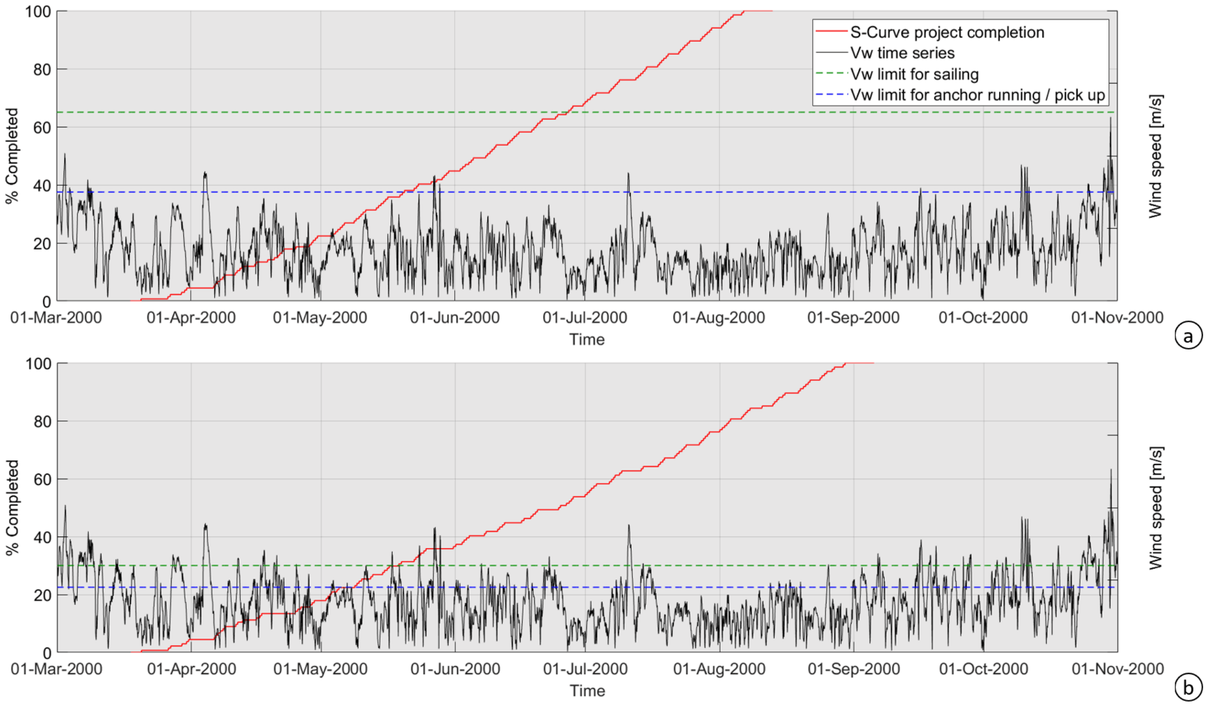


Figure B.1: Simulated project completion S-curves, for weather data from the year 2000 and one seed of random values. In (a), weather-limited parameters are kept at their operational values, in (b) the V_w-limit for sailing/transportation is lowered to [redacted] m/s and for anchor handling operations to [redacted] m/s

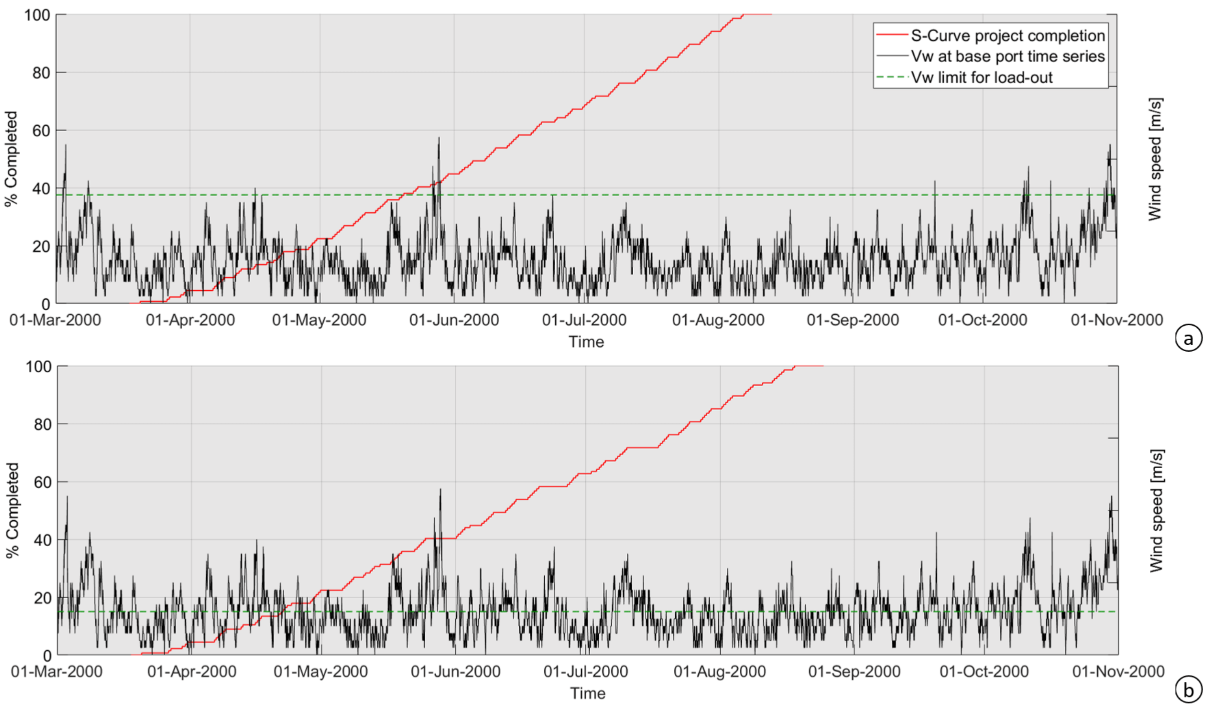


Figure B.2: Simulated project completion S-curves, for weather data from the year 2000 and one seed of random values. In (a), weather-limited parameters are kept at their operational values, in (b) the V_w-limit for the load-outs of both monopiles and transition pieces is lowered to [redacted] m/s. It should be noted that the wind speed time series provided here corresponds to the location of the project-specific base port

C | Convergence test

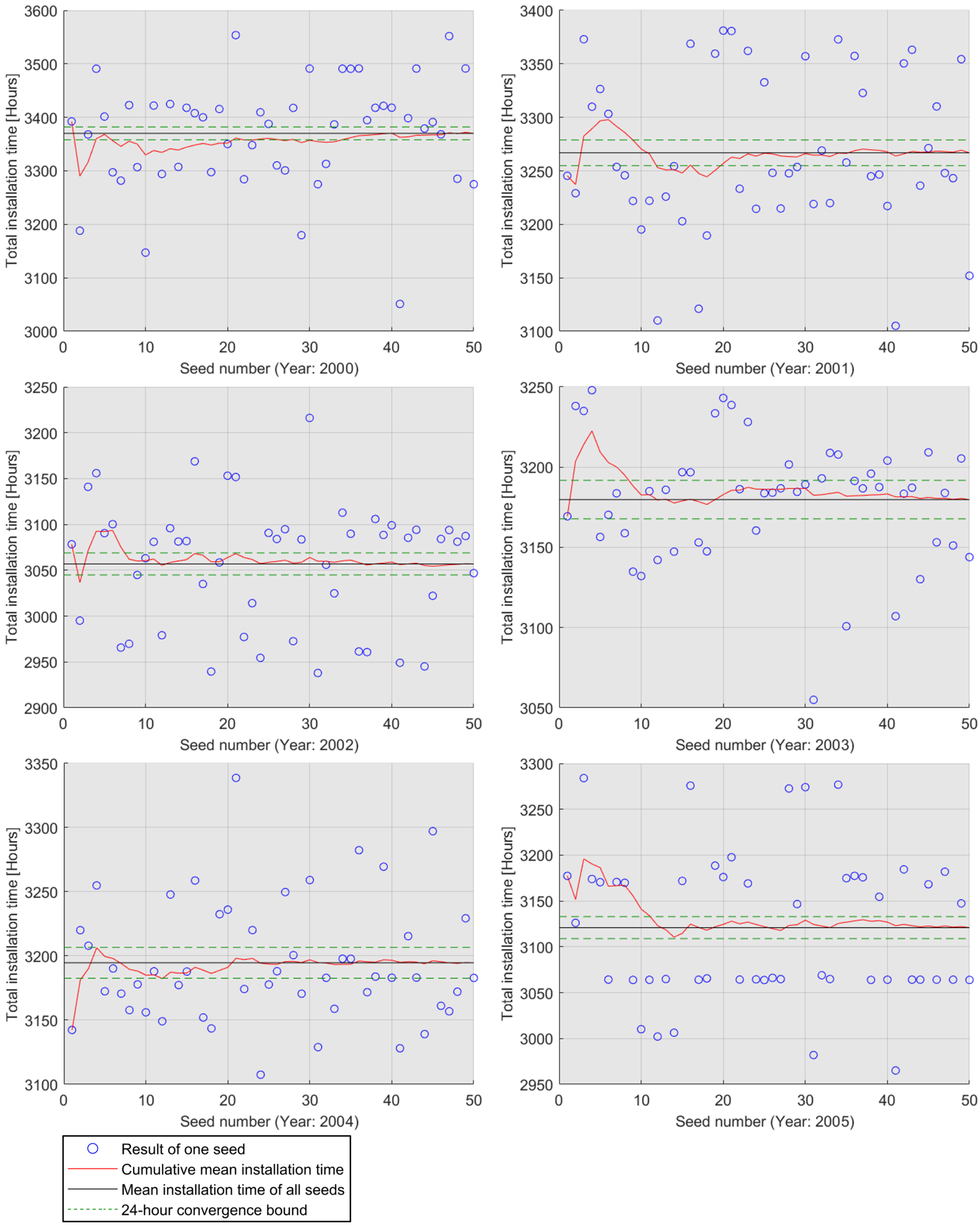


Figure C.1: Convergence test results for simulation runs with as a start date the eighteenth of March, in the years 2000 to 2005

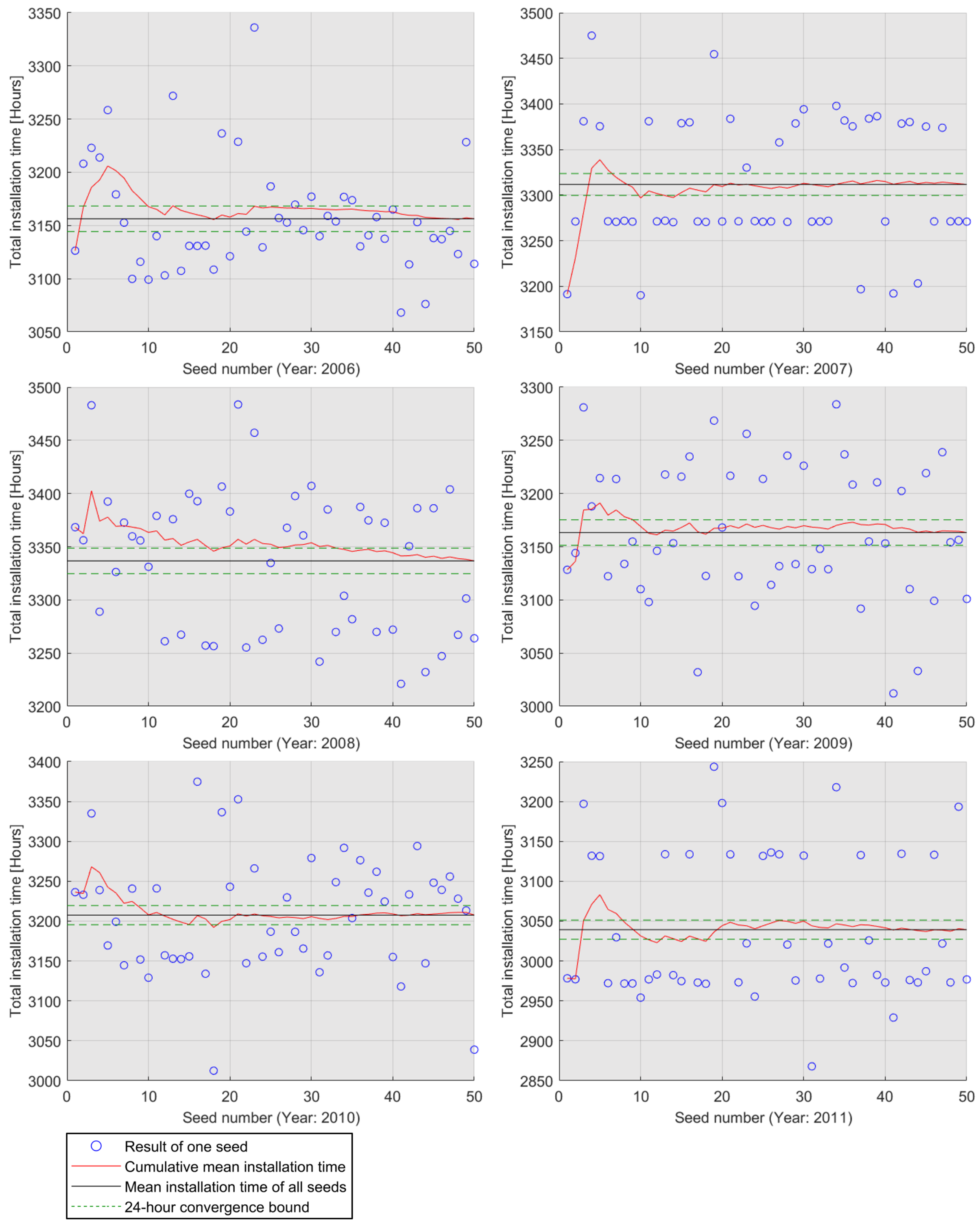


Figure C.2: Convergence test results for simulation runs with as a start date the eighteenth of March, in the years 2006 to 2011