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Original research article

Evaluating operational strategies for the installation of offshore wind turbine substructures

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ABSTRACT

The construction of offshore wind farms requires solving more and more complex logistical problems due to the increasing sizes of turbines and changing environments. In particular, the installation of substructures requires attention due to their significant impact on capital expenditures and the limited literature and guidelines available. In this paper, we develop a decision support tool consisting of a discrete-event simulation that allows for comparing strategies for the installation of offshore wind turbine substructures in terms of time and costs. We identify several combinations of transportation and installation strategies for monopile and for jacket substructures. The differentiation is based on the deployed vessels and the installation sequence of the components. The strategies are applied to the case of a wind farm in the North Sea. For both substructure types, we find that strategies involving a second installation vessel result in the shortest installation times, and those in which the installation vessel(s) take(s) care of both transportation and installation result in the lowest costs. Additionally, we quantify the performance increases as a result of a reduction of the most prominent bottlenecks and the sensitivity of the project performance to the start date. Finally, the results are discussed in relation to future market and technological developments in the field.

1. Introduction

The global installed offshore wind power capacity has been growing exponentially in the last two decades due to the rising demand for renewable energies. In 2007, the contribution of offshore wind to the global energy market was 1 GW and increased to 23 GW in 2018 [1]. 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 offshore wind. Such a growth is not only the result of the increasing number of turbines being installed but also of their increase in size and capacity. Since the first offshore wind farm, constructed in 1991 and with an average capacity of 450 kW per turbine, the 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 [2]. Inevitably, this raises logistical challenges in an industry where extensive practice guidelines are non-existent due to limited experience [3].

A supply chain readiness analysis by Poulsen and Lema [4] indicates that the offshore wind industry in the EU primarily requires attention to the installation procedures of substructures. They expect challenges regarding the logistics activities for these structures, due to their increasing size and the changing environments in which wind farms are being installed. Additionally, Koch et al. [5] exemplify the challenges of limited availability of assets with sufficient capacity, and increasing weather sensitivity for the handling of larger substructures. Moreover, as more and more wind farms are being built further offshore, at sites with greater waters depths and with extremer environmental conditions, challenges arise especially in the Transport and Installation (T&I)-phase. This phase is lengthy and costly accounting for about 18% of the capital expenditures [6,7].

In this paper, we focus on the T&I process of jackets and monopiles, which are the most common types of substructures. The general installation process consists of three main steps: transporting components from a base port to the wind farm area, driving the foundation into the seabed and installing the substructure. Each phase of this process can be realised through different strategies that differentiate based on the type and number of deployed vessels and the installation sequence

Abbreviations: T&I, Transport and installation; DES, Discrete-event simulation; MP, Monopile; FMP, Floating monopile; TP, Transition piece; HLV, Heavy lift vessel; SPMT, Self-propelled modular transporter; WOW, Waiting-on-weather; PIF, Pile installation frame; O&M, Operations and maintenance; OSV, Offshore support vessel; WEA, Wave encounter angle

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of the components. However, the suitability of a certain strategy is dependent on the strategies adopted for the other phases (i.e., 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 affect the effectiveness of the selected strategies. Therefore, our goal is to develop a decision support tool that takes these inter-dependencies into account and helps to identify cost reduction opportunities. To provide such managerial insights, we develop a Discrete-Event Simulation (DES) model to compare different substructure T&I strategies in varying environments and external factors. Moreover, we are able to ensure the validity of the results by using empirical data for the input and validation of the model. We apply the resulting tool to the case of a wind farm in the North Sea, which consists of 67 turbines and is located approximately 250 km from the considered base port.

Literature on T&I strategies for offshore wind farms have focused mainly on the installation of superstructures. See for example, Oelker et al. [8] and Vis and Ursavas [9] comparing installation and transportation strategies respectively. The installation of substructures is occasionally part of the presented models, but the analysis is rather limited. For instance, although Barlow et al. [3] consider the impact of the weather dependency in the installation of super- and substructures they limit their research to a single installation method for every phase. As underlined by Poulsen and Lema [4] and Koch et al. [5] the substructure installation phase is critical with the challenges associated with their installation ever growing due to extremer weather conditions and greater water depths. To this end, careful analysis of these substructure installation strategies is becoming more and more important. To our knowledge, no study has yet been performed investigating and comparing the effectiveness of different substructure installation strategies. This study aims to fill this gap by focusing on the most common types of substructures and their different installation methods. Moreover, the study provides further insights into the challenges the companies are nowadays confronted with due to the characteristics of larger turbines and analyses different strategies to overcome these, such as deploying additional installation vessels, feeders and workability improving systems.

This paper is structured as follows. Section 2 presents the terminology used in this study and discusses the available scientific literature on the topic. Section 3 defines the system of analysis and summarises the strategies evaluated in this study. Next, Section 4 discusses the development of the decision support tool. In Section 5, the collection of the input data for the numerical models is described. Section 6 presents and discusses the numerical simulation results. Finally, in Section 7, we draw our conclusions and present recommendations for future research.

2. Background

In this section, we first introduce the terminology. Next, a literature review is performed on relevant studies focusing on the logistics around offshore wind farms. Finally, based on this review, a scientific knowledge gap is identified.

2.1. Terminology

Although floating offshore wind turbines are mentioned in the industry with increasing frequency, the vast majority being installed is still bottom-founded. Bottom-founded means that a substructure is positioned on the seabed to keep the superstructure above the water line (see Fig. 1a). Among others, the most common substructures are *monopiles* and *jackets*, and it is expected that their use will only intensify in the near future [10]. A monopile (MP) is a tubular structure with a large diameter of up to 11 m [11]. A jacket is a truss type of structure, mostly consisting of three or four legs, which are interconnected by diagonal bracings. These structures are displayed in Fig. 1b and 1c.

The term foundation refers to the structure that is in direct contact with the seabed, providing firm, supportive ground to the substructure. In the case of MPs, their tubular structure provides the foundation once driven into the seabed. For jackets, however, separate foundation piles are installed. This is done either after (post-piling) or before the jacket is installed (pre-piling). Fig. 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, TPs also have other functionalities, such as: providing access platforms and boat landings, accommodating electrical components, and offering corrosion protection. In the case of MPs, TPs are generally installed as separate structures since the fragile components housed by the TPs cannot cope with the accelerations induced by the hammering process. However, for jackets, the separate installation of the foundation piles allows for constructing jackets and TPs as a single structure. All components above the TP (the tower, nacelle, hub and three blades) are considered components of the superstructure. Work by Jiang [12] provides a comprehensive technical overview for offshore wind turbines.

2.2. Research on installation logistics of offshore wind farms

Only a few scientific studies concentrate on the logistical aspects of offshore wind farms [9]. Their focus is mostly on the Operations and Maintenance (O&M)-phase, while less attention is given to the installation phase. Although the O&M-phase involves 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 in detail here, but, the reader is referred to [14,15] for exhaustive reviews. In this paper, the available studies considering the installation of substructures are explored 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. Research on installation strategies for substructures

According to Conconi et al. [16], improvements in the installation phase of offshore wind farms are vital to the goal of realising cost reductions, especially in view of their increase in size and weight. To overcome the challenges associated with these developments, the transport and installation system of substructures must develop accordingly Poulsen and Lema [4],Conconi et al. [16]. They propose to tackle these challenges by adapting the installation strategy to the project-specific circumstances. For MPs, they propose three transportation methods: wet towed (i.e., floating monopiles towed by tugboats), installation vessel and feeder vessels (which supply the installation vessel at the wind farm with components). The latter two methods also hold for jacket transportation. The suitability of each strategy is likely to depend on factors such as the weather limitations and the project start date. However, Conconi et al. do not quantify these dependencies.

The research by Lange et al. [17] 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. Barlow et al. [3] provide a more focused analysis, covering solely the super- and substructure installation processes. By means of a discrete-event simulation tool, they identify the installation duration resulting from different 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 and wave limitations. Moreover, Barlow

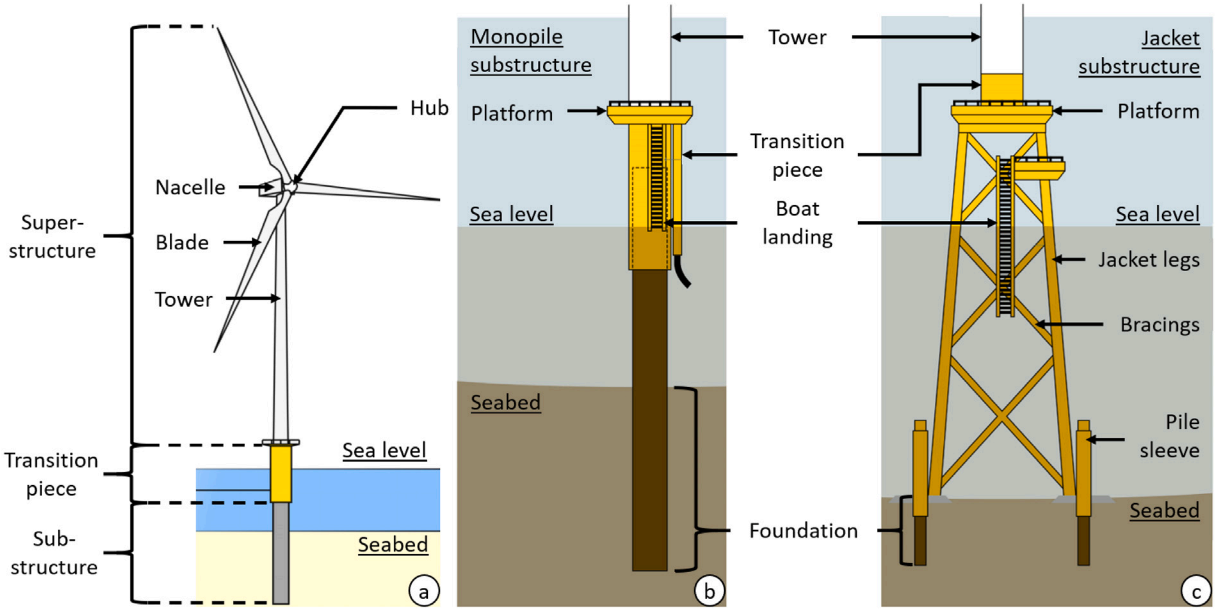

Fig. 1. Offshore wind turbine terminology breakdown. (a) adapted from [13]; (b) and (c) adapted from [11].

et al. [3] 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 characterises the relationships between operational parameters and performance indicators, it does not describe the effectiveness of the various installation strategies proposed by Conconi et al. [16] and their impact when dealing with different substructure types.

In Barlow et al. [18], a hybrid framework is developed, whose first component is a discrete-event simulation tool based on the model by Barlow et al. [3], 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. [19] 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. [18] apply the hybrid framework in a case study on the installation of superstructures but mention that it is also applicable to substructures. Similar to Tezcaner Öztürk, Ursavas [20] develops an offshore wind farm installation scheduling model that incorporates weather-related disturbances for the installation of both superstructures and substructures and is applied to two cases in the North Sea. Finally, Muhabie et al. [21] 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. Moreover, they find a correlation between the project starting date, the number of structures to be installed and the resulting required operational days.

Beinke et al. [22] perform a resource sharing analysis for the construction of three offshore wind farms. 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 via increased production with the limited available resources and decreased installation costs [23,24]. These studies provide analysis into the strategies regarding getting access to project assets. With respect to the last part of the offshore wind farm life cycle, among others, Topham and McMillan [25] perform a cost analysis for different transport strategies, whereas Irawan et al. [26] proposes an optimisation approach for scheduling the decommissioning activities of an offshore wind farm in order to minimise the total cost for the jack-up vessel, barge vessel, inventory, processing and on-land transportation costs.

Conclusively, although this section is specifically dedicated to research considering the installation of substructures, in all of the discussed studies these structures play an accessory role. Moreover, to our 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. Research on installation strategies for superstructures

O'Sullivan et al. [27] and Oelker et al. [8] 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 feeders. 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.

Vis and Ursavas [9] also focus on the superstructure installation process and provide an overview of the logistical principles applied in various 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. Vis and Ursavas [9] recommend a strategy in which the number of onshore pre-installed components and the number of turbines loaded on a vessel are maximised. Furthermore, Sarker and Faiz [7] 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, 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.

Table 1
Content overview of the reviewed articles focused on the installation phase, including the contribution of this study.

		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	✓	✗	✓	✗	✗
→ **Our study**	S	✓	✗	✓	✓	✓

Abbreviations: Superstructure (T), Substructure (S).

2.3. Knowledge gap

Table 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, piling process or the deployment of additional installation vessels are included in the analysis.O'Sullivan et al. [27] and Oelker et al. [8] compare the strategies of transportation by installation vessel and transportation by feeders, but only consider superstructure components. Although Barlow et al. [3,18] include most components in some form, their focus is on identifying the impact of stochastic weather conditions on the duration of various offshore operations and not on different installation strategies and type of substructure installed. A similar conclusion can be drawn for Muhabie et al. [21]. However, the latter study does propose for future research to explore the logistical potential of increasing the limiting environmental conditions of offshore operations. 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. Therefore, this research aims to fill the defined knowledge gap by analysing the different installation strategies for substructures, their interdependencies and impacts on costs and project duration together with various policies such as additional vessel deployment to overcome installation bottlenecks.

3. System of analysis

The focus of this paper is the Transportation and Installation (T&I) of substructures of a wind farm. Considering the life cycle of a wind farm in general, this phase begins after a site has been selected and the components have been engineered, procured and constructed. See Fig. 2 for an overview. Once the constructed components start to arrive at the base port and all the required installation equipment is available, the T&I phase can commence.

The first phase of the substructure installation phase is the arrival of substructure components at the base port, where "marshalling yards" typically provide sufficient room for lining up and assembly (see Fig. 3a). 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. These are described in Section 3.1 to 3.3, respectively.

3.1. Load-out methodologies

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 monopiles (MPs), Transition Pieces (TPs), and jackets is generally performed by deploying either cranes or Self-Propelled Modular Transporters (SPMTs), which are trailers with a built-in propulsion system. Fig. 3b and 3c display the load-out of MPs by a Heavy Lift Vessel (HLV)-crane and SPMTs, respectively. Fig. 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.

3.2. 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 performs the installation activities is additionally deployed for the transportation. In those cases, the load-out is usually performed by the crane of the vessel, as is depicted in Fig. 3b. Subsequently, the components loaded on the HLV-deck are secured to prevent them from moving during offshore transportation (sea fastening). 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 barges or vessels, called feeders, supply it with components. Fig. 3c and 3d depict load-out operations of components onto these feeders. Including a feeder in 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 its deck. Both the feeder mooring process and 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

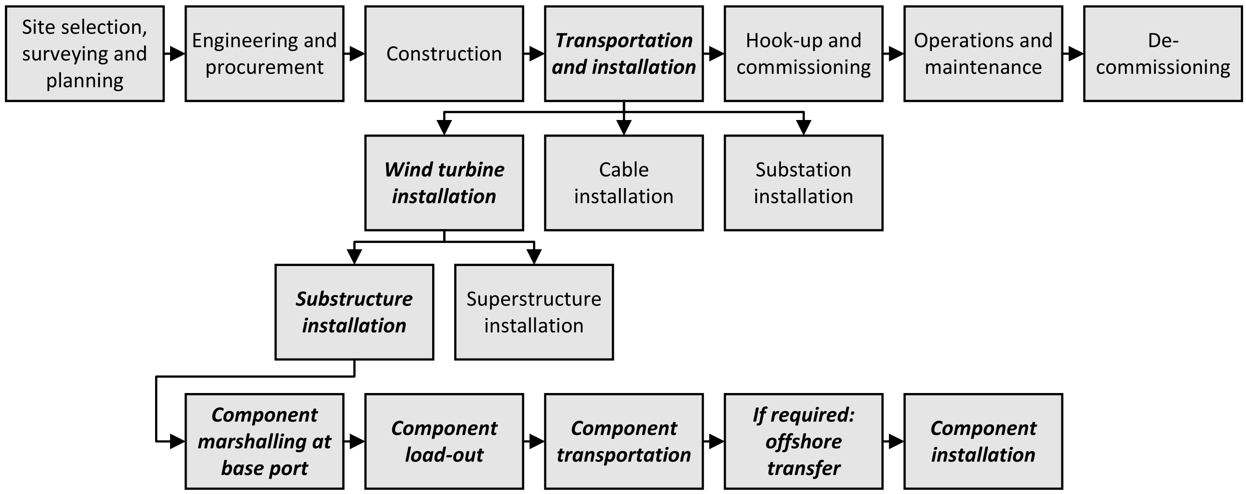

Fig. 2. The general offshore wind farm life cycle stages, considering the phases of development, installation (with a focus on substructures), operations and maintenance, and decommissioning. Although the figure presents the life cycle phases of offshore wind farms in a sequential order, in practice, these phases can overlap.

Fig. 3. (a) Marshalling yard storing monopiles and transition pieces [28], (b) Lifted load-out of a monopile and a transition piece [29], (c) Load-out of monopiles by SPMTs [29], (d) Lifted load-out of jackets, from a jacket marshalling yard [30].

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 MPs. 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". 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 tug boat, multiple MPs may be lined up in series, assuming a proper connection between the MPs [31]. However, in practice, a tug boat usually only tows one MP.

Table 2 compares the three transportation strategies by summarising pros and cons. The main advantage of deploying feeders for transportation is their lower day rate and the higher availability of the HLV for installation activities [8,16]. Moreover, feeders often have a 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, given the higher workability of HLVs. Furthermore, feeder barges typically have a lower sailing speed than vessels. The main advantage of the transportation of MPs by the wet tow method is the possibility to perform transportation and installation operations in

Table 2
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 • High sailing speed • High workability	• No parallel installation and transportation operations • Expensive transportation • Little deck space
Transportation by feeders	• Number of feeders can be altered to optimise HLV occupancy • Parallel installation and transportation operations • 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 • Small crane required	• Fabrication plugs required • Low sailing speed • Low workability • Dedicated to monopiles

parallel, while no large feeders are required. However, apart from the fact that this method is only applicable to MPs, it also comes with a low sailing speed and workability.

3.3. Installation strategies

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

3.3.1. Monopile installation procedures and strategies

Since MPs are normally transported horizontally (see Fig. 3c), the first operation after hooking in the structure is to bring it to a vertical position (upending). Once the MP has been driven into the seabed to its designed 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 the so-called “separate phases” 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 [32].

Table 3 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 with just sufficient capacity to install TPs, 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 h, varying per location) without taking collision-preventing measures (such as installing a warning light).

3.3.2. Jacket installation procedures and strategies

Jackets destined for the offshore wind industry are mostly transported vertically (see Fig. 3d). This can be recognised as an advantage over MPs, as the deck space of transportation vessels can be used more efficiently. Moreover, no upending operation is required. However, vertical transportation reduces the stability and, therefore, the workability of the transport. Another distinction between jackets and MPs 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 MPs and can be driven into the seabed with a smaller pile-driving device.

Generally, jacket foundation piles that support wind turbines are installed according to the principles of pre-piling [16]. First, piles are driven into the seabed. 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).

Pre-piled jackets can be installed by different strategies, as listed in Table 4. 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, but the day rate of the second vessel has to be accounted for. The third strategy in Table 4 is similar to the first; however, the pile cleaning and dredging activities are taken over by a smaller Offshore Support Vessel (OSV) with just sufficient capacity to perform this activity. This reduces the costs associated with these cleaning activities and minimises the required lifting equipment changes. Then again, 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

Table 3
Summary of the advantages and disadvantages of alternating monopile (MP) - Transition Piece (TP) installation, MP and TP installation in separate phases and the MP–TP assembly-line strategy.

	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	• Small second vessel with just enough capacity to install TP • No change of lifting equipment • Two vessels enable to install more parts within a given weather window	• Day rate of two installation vessels • Ensuring safety when leaving MP • More complex logistical operation • Small second vessel may have lower workability

Table 4
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	• Small second vessel with just enough capacity to install piles • Limited changes of lifting equipment during pile installation • Two vessels enable to install more parts within a given weather window	• Day rate of two installation vessels • More complex logistical operation • Overcapacity vessel for pile dredging / cleaning • Small second vessel may have lower workability
Pile dredging and cleaning with a separate vessel (installation in separate phases)	• Additional vessel enables to install more jackets within a given weather window • Small cleaning vessel with just sufficient capacity to clean the piles • Limited changes of lifting equipment	• Day rate of two vessels • More complex logistical operation • Overcapacity vessel for installing piles • Small second vessel may have lower workability

of both jackets and foundation piles on one deck generally does not provide sufficient room to upend the piles.

3.4. Strategies of analysis

This section summarises the introduced transportation and installation strategies and puts them into their sequential perspective, following Fig. 4. Corresponding to Table 2, 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 MPs. The subsequent strategies of installation are dependent on the type of substructures to be installed: MPs (see Table 3) or pre-piled jackets (see Table 4).

Hence, nine unique combinations of strategies for MPs and six 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.

4. Methodology

Based on research focused on superstructure installation, it is expected that the effectiveness of Transport and Installation (T&I) strategies 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. In this respect, a Discrete-Event Simulation is typically a preferred approach, especially when stochastic processes should be included in a model [33]. In this section, we first provide a high-level design process, followed by the main assumptions and simplifications.

The simulation framework has been developed in Simio, and the post-processing of results has been automated using the Matlab coding environment. Reports are based on 35 simulation runs for each year of available weather data (eleven years in total). Hence, in total 35 × 11 simulations, whose results are averaged out. This value of 35 runs was determined by performing a convergence test. 50 runs were performed for each year of weather data. In the worst case (i.e., year of weather data), it took 35 runs for the average installation time to converge within a 24-hour bound around the 50-run average.

4.1. High-level conceptual model development

A high-level model representation of the system of analysis is provided in Fig. 5, describing the model structure and the general project objectives. It specifies the interaction of the model with external data supply (i.e., the inputs). Moreover, it presents the model outputs, which are intended to quantify the comparison of installation costs. A more detailed description of the model's internal architecture is provided by the logic flow diagram in Appendix A.

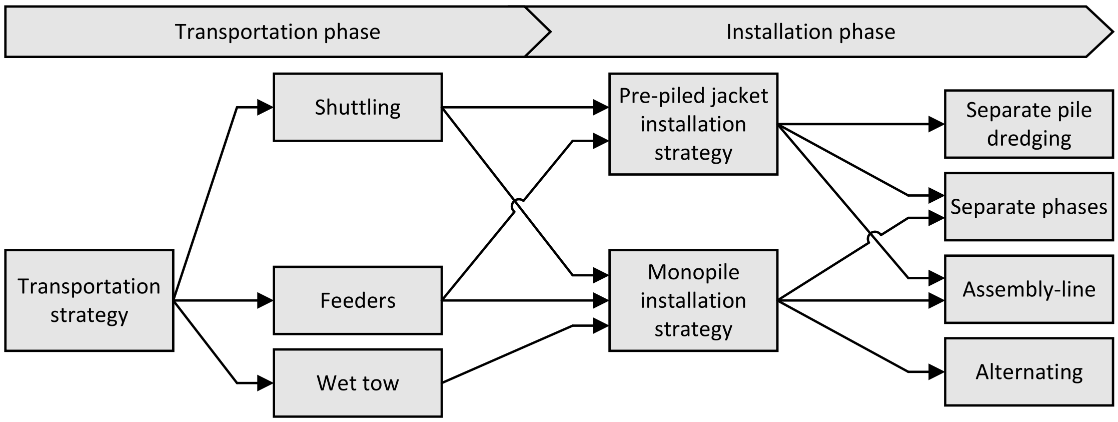

Fig. 4. Summary of the strategies of analysis in a sequential perspective.

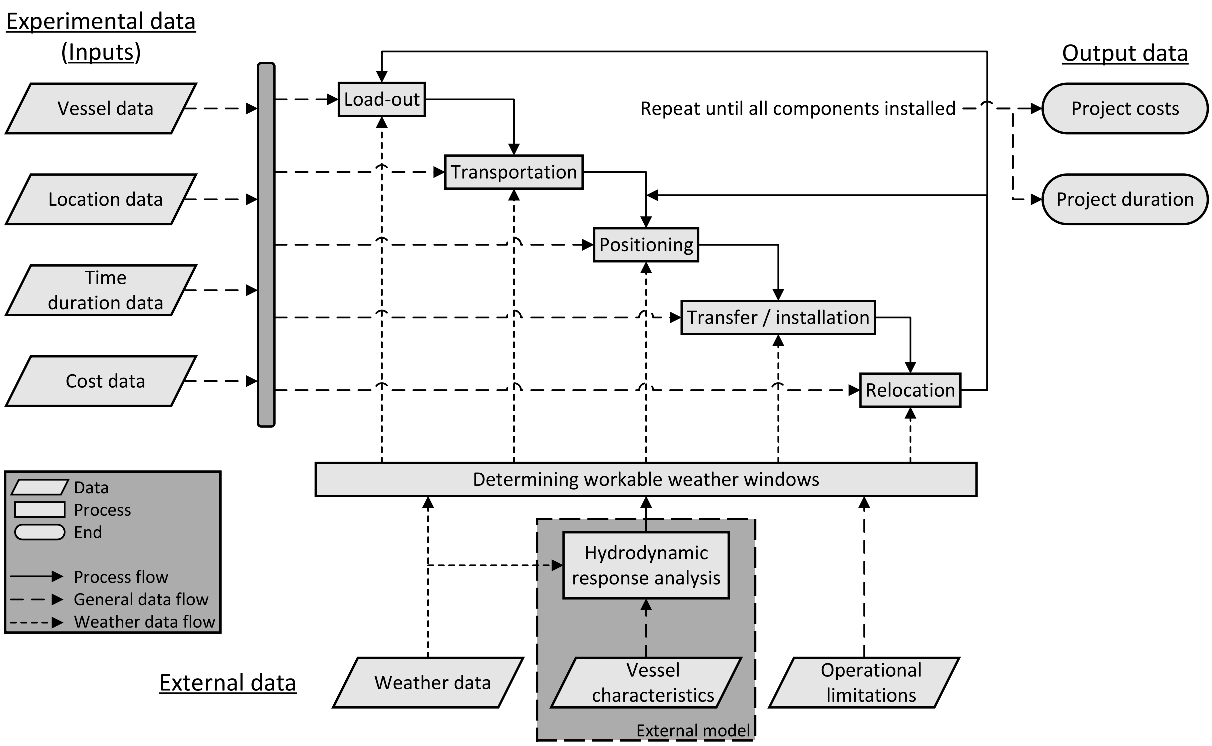

Fig. 5. High-level conceptual model for the installation of offshore wind turbine substructures.

Some of the inputs of the system of analysis depend on the various strategies to adopt during the transportation and installation phase, such as vessel and time duration data. Although data of the vessels is quite constant (e.g., sailing speed, transportation capacity, workability, etc.), the type, amount and function of the deployed vessels vary per strategy. Location data of the base port and the individual turbines is fixed, but the sequence of sailing destinations for transportation and installation vessels are varied based on the adopted strategy. Hence, the individual turbine locations are not experimental conditions, but their sequence of visitation is.

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 Fig. 5. 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. In the majority of logistical studies on offshore wind farms, the continuity of operations depends on limitations regarding the significant wave height (H_s), and some also consider limitations regarding wind speed (V_w). However, Sperstad et al. [34] 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).

To accurately establish the weather windows for the transfer and installation activities, an external model is used. This model follows the methodology proposed by [35]. It consists of a hydrodynamic model of the considered HLV, by which the responses of the system to incident waves can be determined. To these responses, limits are set (e.g., the maximum crane load or the maximum HLV roll motion). Next, the limiting H_s-value for which one of the responses reaches its limit is determined, for a series of T_p-values. This way, H_s- T_p curves are constructed (see also Appendix B), which express the H_s-limit as a function of T_p. Just before the start of the particular operations, the

Table 5
Properties of vessels deployed in the considered strategies. MP/TP relates to alternating installation strategy, where MPs and TPs can be transported simultaneously.

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

model checks whether the environmental conditions at hand exceed the limiting values within the maximum duration of the operation, and, if required, it postpones the operations to the first moment in time where the weather conditions are suitable. The transportation, positioning and relocation operations are generally considered non-critical and are therefore considered only limited by the H_s and V_w. 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 more refined operations, and it is therefore deemed necessary, with regard to the precision of our model, to deploy the hydrodynamic analysis as described above.

4.2. Assumptions and simplifications

Other assumptions and simplifications concerning the model are listed here. **(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 (introduced in Section 5.3) 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 phase 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.

5. Data collection

In this study, we consider a typical setting for wind farms installation in the North Sea relative to a base port located in the south of The Netherlands, whose data is available from a case company. Although restrictions due to non-disclosure agreements between the company and the research team allow only non-sensitive to be disclosed we provide representative proportional data which is further supported by literature. This data is presented in Appendix B. The data collection is described following Fig. 5 and is discussed for each category of input data.

5.1. Vessel data

Table 5 provides an overview of the transportation capacities and sailing speed for each type of vessel. HLV2 is a second Heavy Lift Vessel (HLV) deployed in assembly-line strategies. The sailing speed of an HLV is considered to be constant 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, which resulted in an average speed of 7.7 knots and a coefficient of variation of 7.3%. For the feeder barge and the tug boat, the sailing speed is assumed to be constant as well.

5.2. Location setting

The system is composed of a base port, a wind farm entry point, and strings of wind turbines. The reference project requires the installation of 67 substructures at a wind farm situated ≈250 km from the base port. The considered 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. Distances between the wind farm entry point and the first turbine of every string of wind turbines are approximated to 7 km for the first three strings and to 2 km for the others. Next, it is assumed that travelling from one string to another is 1 km; however, this is only possible between the first and last turbines of each string, which is a reasonable assumption as operations in the next string are generally started only after the operations in the previous are finished.

5.3. Duration data

The considered operations are listed in Table 6. Random durations are generated for each operation, following suitable probability distributions fitted to the available data. A lognormal distribution was the most common selection, except in the case of "miscellaneous work", where a normal distribution is found to be more suitable. The suitability of each fitted distribution was examined by performing a Kolmogorov–Smirnov Goodness-Of-Fit test on the provided data [36]. For a level of significance of 0.05 (which is a generally accepted value [37]), all of the fitted distributions in Table 6 can be considered significantly accurate.

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. The parameter estimates are made by experienced industry experts. Table 6 additionally indicates 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 duration of the included operations.

5.4. Cost data

The rates considered in this study concern the daily rates of HLV, HLV2, barges, tugboats, construction support vessels and marshalling yard rents. 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. Other expenses are assumed to be constant over the strategies or deemed negligible. Table B.12 in Appendix B provides ranges for the costs considered in this study. However, in the numerical results we will provide the total cost of each strategy.

5.5. Weather data

The operational limits for weather-sensitive operations are expressed in terms of H_s, T_p and V_w. To determine workable weather windows, these limits are related to hourly time series of these parameters, provided over twelve years of weather data (2000–2011). Weather data at the location of the base port was accessed from [38], and at the wind farm location from [39].

Table 6
Operations to be performed for the installation of monopiles and transition pieces, jackets and jacket foundation piles. Also, the allocated distribution types are provided.

	Operation (Monopile – transition piece)	Type of distribution	Operation (Jacket – foundation piles)	Type of distribution
At base port	Load-out single monopile	Lognormal	Load-out single pile	PERT
	Load-out single transition piece	Lognormal	Load-out single jacket	PERT
	Other quayside operations (HLV)	Lognormal	Other quayside operations (HLV)	Lognormal
	Tot. time barge along the quayside, loading 3 monopiles	PERT	Tot. time barge along the quayside, loading 2 jackets	PERT
	Tot. time barge along the quayside, loading 8 transition pieces	PERT	Tot. time barge along the quayside, loading 12 foundation piles	PERT
At turbine location	01. Run anchors	Lognormal	01. Run anchors	Lognormal
	Continuous:		02. Install PIF	Lognormal
	02. Install monopile	Lognormal	**Continuous:**	
	03. Drive monopile	Lognormal	03. Install four piles	Lognormal
	04. Transfer monopile to upend cradle	Lognormal	04. Drive one pile	Lognormal
	Continuous:		05. Retrieve PIF	Lognormal
	05. Install transition piece	Lognormal	06. Dredge and clean pile	Lognormal
	06. Level transition piece	Lognormal	07. Clean pile	Lognormal
	07. Perform miscellaneous work	Normal	**Continuous:**	
	08. Perform completion work	Lognormal	08. Install jacket	Lognormal
	09. Grout transition piece	Lognormal	09. Grout jacket	Lognormal
	10. Pick-up anchors	Lognormal	10. Pick-up anchors	Lognormal
	Only for feeder strategies (non-continuous)		**Only for feeder strategies (non-continuous)**	
	2a. Moor barge alongside HLV	Lognormal	2a. Moor barge alongside HLV	Lognormal
	2b. Transfer monopile	Lognormal	2b. Transfer pile	Lognormal
	5a. Transfer transition piece	Lognormal	5a. Transfer jacket	Lognormal
	5b. Unmoor barge	Lognormal	5b. Unmoor barge	Lognormal

Abbreviations: HLV = Heavy Lift Vessel, PIF = Pile Installation Frame.

6. Numerical results and discussion

This section presents the numerical simulation results of the implementation of the strategies of analysis into the case study project. Section 6.1 presents relevant technical details and explains the model validation. In Section 6.2, 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 6.3. In Section 6.4, the findings of the numerical simulations and the implications for the industry are discussed.

6.1. Model validation

A base model was used to simulate the combination of the shuttling transportation strategy and the alternating installation strategy for the installation of MPs and TPs. For this strategy sufficient validation data is available from the case study at hand, involving the installation of 67 MPs and TPs. Since this strategy includes the basic principles of substructure installation, it is deemed a suitable template for the modelling of the other strategies.

The base model developed for this study was tested by the validation techniques of a face validity test, parameter variability test, and historical data validation test, as described by Sargent [40]. 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, the historical project from the case study is taken for reference. 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. Details of the validation can be found in Appendix C. Both a visual inspection and a statistical analysis on of the result confirmed that the simulation model predicts the project completion progress satisfactorily.

6.2. Monopile–transition piece installation strategies

This section presents the simulation results for the 9 MP–TP related strategies introduced in Section 3.4. First, in Section 6.2.1, the performance of the proposed strategies is compared, based on the input data presented in Section 5. Furthermore, the bottlenecks of the most promising strategies are identified. Next, in Section 6.2.2, measures to reduce these bottlenecks are proposed and discussed. In Section 6.2.3, the dependency of the performance on the project start date is examined.

6.2.1. MP-TP installation strategy performance evaluation

Out of the nine strategies, we analyse fourteen logistical set-ups, since a sensitivity analysis is performed with regard to the number of deployed feeder barges and floating monopile (FMP)-towing tugboats. These set-ups and the corresponding abbreviations are presented in Table 7.

We provide S-curves in Fig. 6 to analyse the project completion progress over time for a selection of strategies. These curves are the result of averaging all S-curves that result from the 35 simulation runs for each year of weather data (see the methodology section). The curves of the strategies MP_S_AL, MP_4F_AL and MP_3T2F_AL on average 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. From the analysis of the simulation output, the latter

Table 7
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

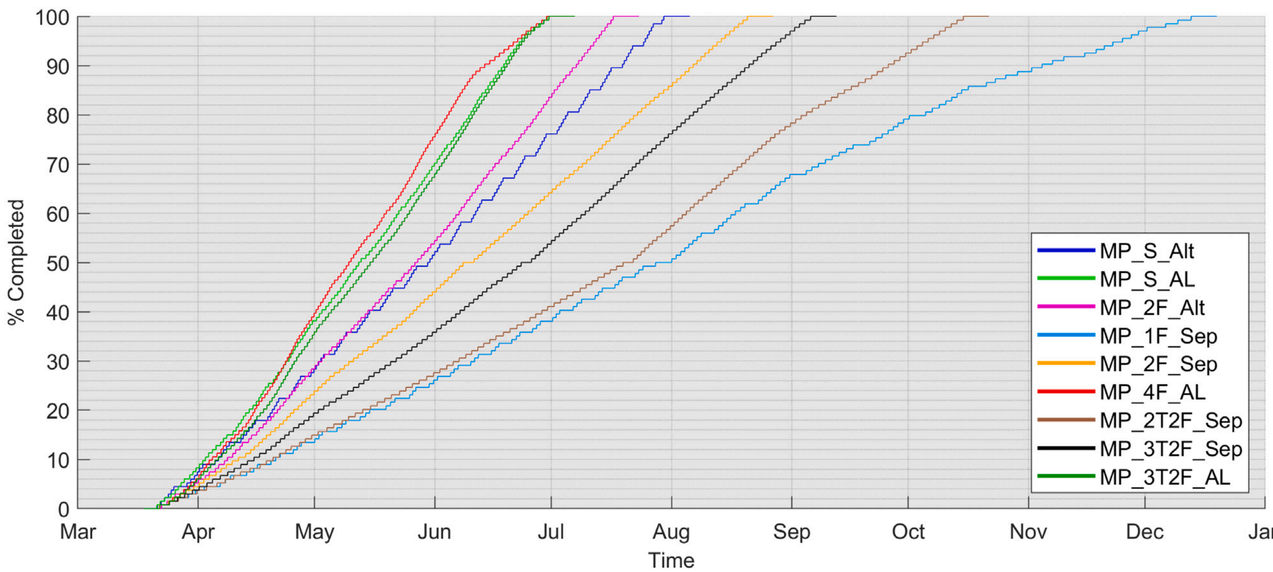

Fig. 6. A selection of nine average S-curves of the in total fourteen considered logistical set-ups for the installation of MPs and TPs.

can be explained by a low occupancy rate of the Heavy Lift Vessel (HLV) due to non-continuous supply of components. By increasing the number of feeders, this rate can be boosted (see the steeper S-curves of MP_2F_Sep and MP_3T2F_Sep). However, once an HLV reaches 100% occupancy (a vessel with 100% occupancy is never idle except for when it is waiting for the weather to improve, which is the case for the latter two strategies), adding feeders does not add to the installation rate anymore. This limit to the size of the feeder fleet also explains why MP_3T2F_AL is only evaluated for one composition of feeders: MP_3T2F_Sep already shows that the first HLV performs adequately 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, Fig. 6 shows that the curve corresponding to strategy MP_1F_Sep is characterised by a reducing installation rate above the 50%-completion line (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. Although strategy MP_2F_Sep involves the same types of system components, the second feeder results in such a reduction of the installation time that the total project can be finished before months of unfavourable weather arrive. Hence, the described effect MP_1F_Sep is not visible in the latter case.

Fig. 7 is complementary to Fig. 6, as it provides insights into the variability of the installation duration. It can be concluded that of the fastest three strategies, MP_S_AL is associated with the lowest variability around the average installation time. Furthermore, the strategy associated with the largest average installation time (MP_1F_Sep) appears to be related to the largest variability.

The boxplots in Fig. 8 compare the various strategies in terms of costs. The MP_S_Alt strategy corresponds to the lowest costs, but the completion time of this strategy is not among the shortest. This result can be explained by the 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 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.

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 Fig. 7). 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 (HLV2) 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 and for which further chartering costs have to be considered.

Table 8 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. 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

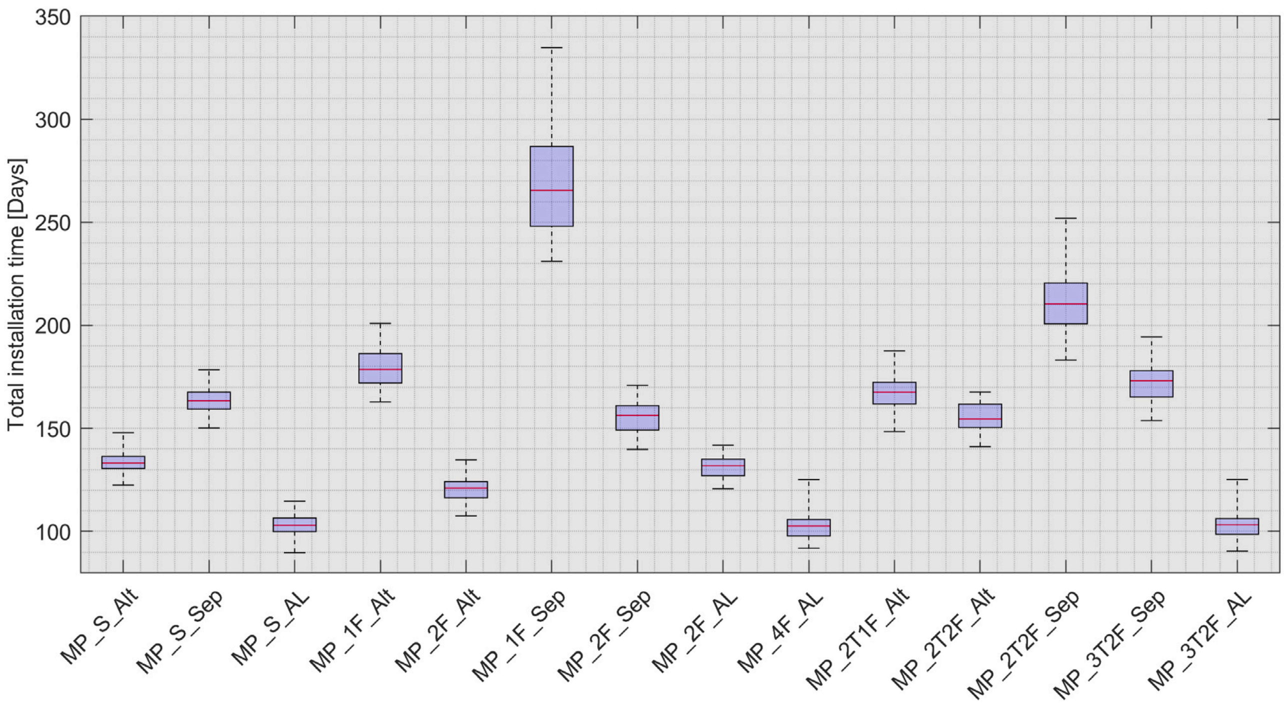

Fig. 7. Boxplots describing the simulated total installation time per considered strategy. The boxplots represent the results of 35 simulation runs for each considered year of weather data.

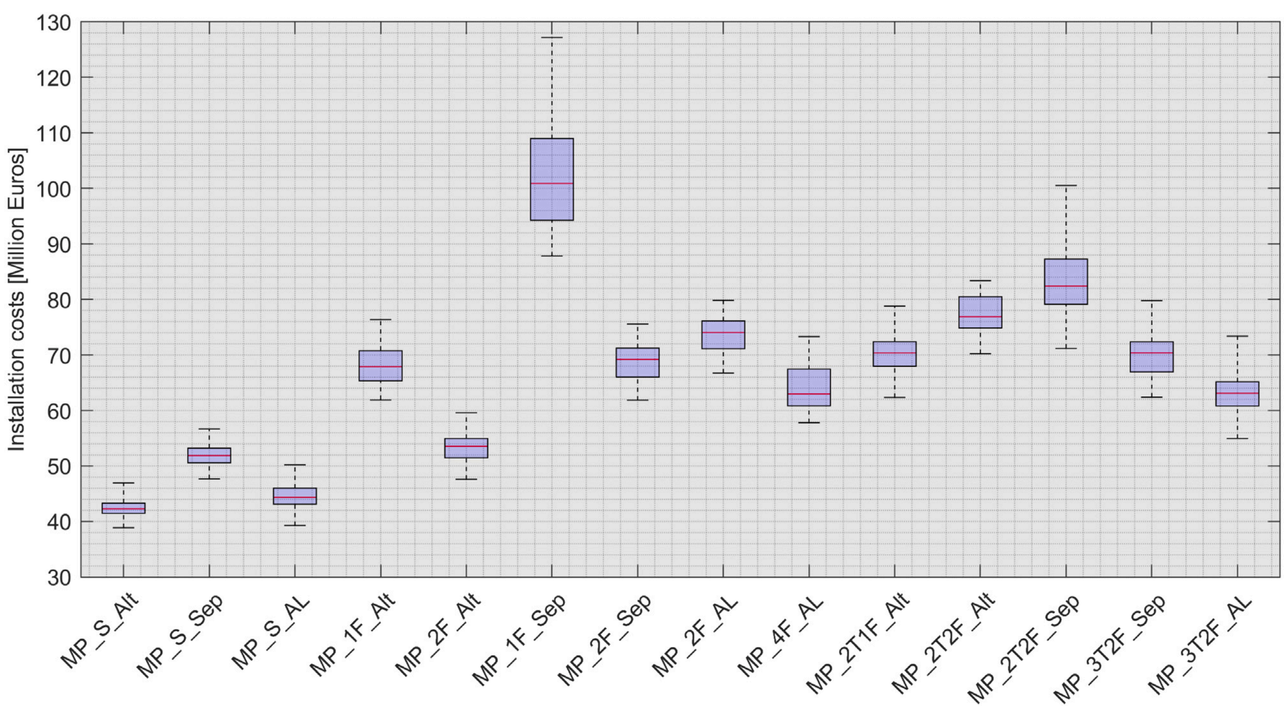

Fig. 8. Boxplot describing the simulated installation costs per considered strategy, only including the cost components discussed in Section 5.4.

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.

6.2.2. MP-TP installation bottleneck reduction sensitivity analysis

This section investigates the potential of increasing the workability of the operations that are considered bottlenecks in Table 8. This is done by performing three experiments, in which the weather limits are increased for:

Table 8
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	Project WOW-days (average)
• MP_S_Alt	0.6% 0.1d	0.1% 0.0d	0.0% 0.0d	3.0% 0.5d	-	-	-	48.3% 8.5d	44.0% 7.7d	-	3.9% 0.7d	17.6d
• MP_S_AL	0.2% 0.1d	0.1% 0.0d	0.0% 0.0d	2.1% 0.9d	-	-	-	22.6% 9.9d	72.5% 31.7d	-	2.6% 1.1d	43.7d
• MP_2F_Alt	0.5% 0.2d	0.0% 0.0d	0.9% 0.3d	0.4% 0.1d	37.7% 14.0d	3.9% 1.4d	2.9% 1.1d	7.4% 2.8d	19.2% 7.1d	26.2% 9.7d	0.9% 0.3d	37.1d
• MP_4F_AL	0.3% 0.2d	0.1% 0.1d	0.5% 0.3d	0.2% 0.1d	34.0% 23.1d	5.0% 3.4d	3.5% 2.4d	5.8% 3.9d	34.6% 23.5d	15.2% 10.3d	0.8% 0.6d	67.8d
• MP_3T2F_AL	0.3% 0.2d	0.1% 0.1d	5.6% 4.1d	0.0% 0.0d	36.5% 26.8d	11.2% 8.2d	3.2% 2.3d	5.5% 4.0d	32.6% 23.9d	3.6% 2.7d	1.4% 1.1d	73.4d

(i) The mooring of feeder barges alongside HLVs. In this experiment, the corresponding limiting significant wave height is increased by 0.3 m for strategies MP_2F_Alt, MP_4F_AL and MP_3T2F_AL. In practice, this increase can be realised by the deployment of a different crew transfer vessel. For this, it must be understood that to moor a barge alongside an HLV, personnel have to be brought from the HLV to the barge, for which crew transfer vessels are used. The wave height limit of these vessels is governing in the barge mooring operation. Hence, a larger crew transfer vessel can increase the wave height limit of the barge mooring operation. See the strategies in Figs. 9 and 10 indicated by "Impr_BM".

(ii) The installation of TPs by the second HLV. For this experiment, experts consider shifting the limiting Hs-Tp curve for the TP-installation up by 0.5 m reasonable. In practice, this improvement can be accomplished by deploying a motion compensation system. In Figs. 9 and 10 this improvement is indicated by "Impr_TPInst". This experiment is performed on MP_S_AL, MP_4F_AL and MP_3T2F_AL. Note that the investment cost for such a system is not considered in the computation.

(iii) Both the improvements of **(i)** and **(ii)** are implemented, which is referred to as "Impr_BM_TPInst" in Figs. 9 and 10. This experiment is performed on MP_4F_AL and MP_3T2F_AL.

From Figs. 9 and 10, it 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 allows for deploying this vessel at a later stage while avoiding waiting time on the first HLV. 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. Considering MP_3T2F_AL, Impr_BM results in the largest reduction of installation time and costs, and barge mooring can therefore be considered 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. 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.

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

Figs. 11 and 12 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 consequence 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.

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. Hence, starting a project before the "optimum" may reduce the project's risk. From a cost perspective, the performance of MP_S_Alt and MP_S_AL is comparable and higher than that 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. 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.

6.3. Jacket – foundation pile installation strategies

In this section, the numerical simulation results regarding jacket installation strategies are presented. Section 6.3.1 compares the performance of the proposed strategies. Additionally, the bottlenecks of the most promising strategies are identified. Subsequently, in Section 6.3.2, actions to reduce these bottlenecks are discussed. Finally, in Section 6.3.3, the dependency of the performance on the project start date is evaluated.

6.3.1. Jacket installation strategy performance evaluation

Based on the six considered strategies, eight different logistical setups are analysed, displayed in Table 9. The eight corresponding project completion S-curves (which represent the average output of 35 runs for each year of weather data) are plotted in Fig. 13, which shows that Ja_4F_AL on average reaches 100%-project completions first. 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, but

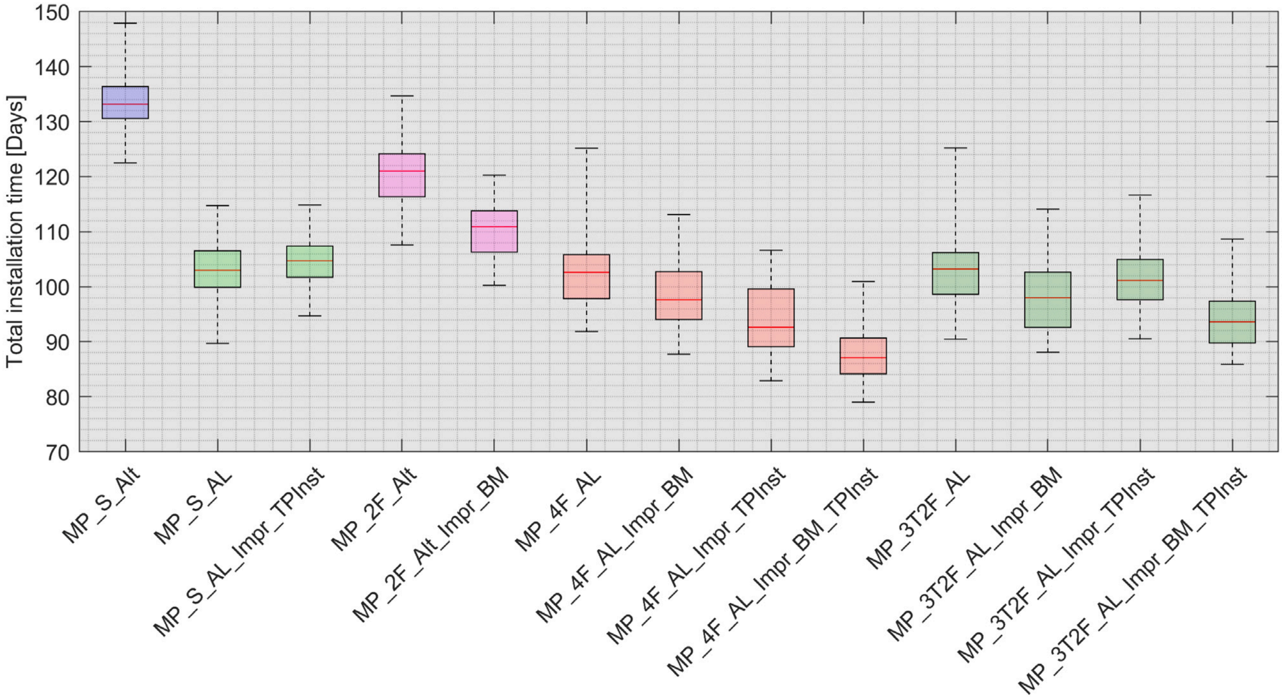

Fig. 9. Comparison between the installation time of the five promising initial MP–TP-installation strategies and of those strategies with improved workability.

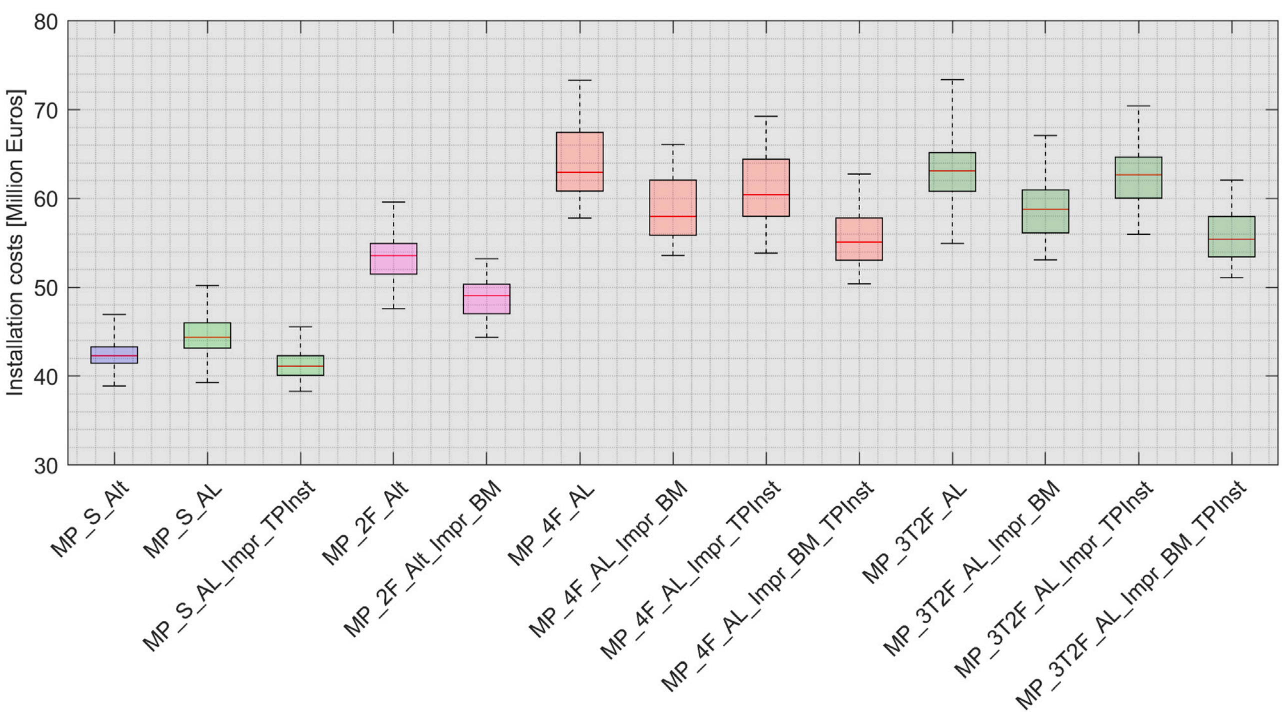

Fig. 10. Comparison between the installation costs of the five promising initial MP–TP-installation strategies and of those strategies with improved workability.

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.

Fig. 14 shows the boxplots of the installation time and costs for the eight set-ups. In terms of installation time, Ja_4F_AL can be considered the most advantageous, although Ja_S_AL is a competitive alternative (the difference in medians is 13 days). When also 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

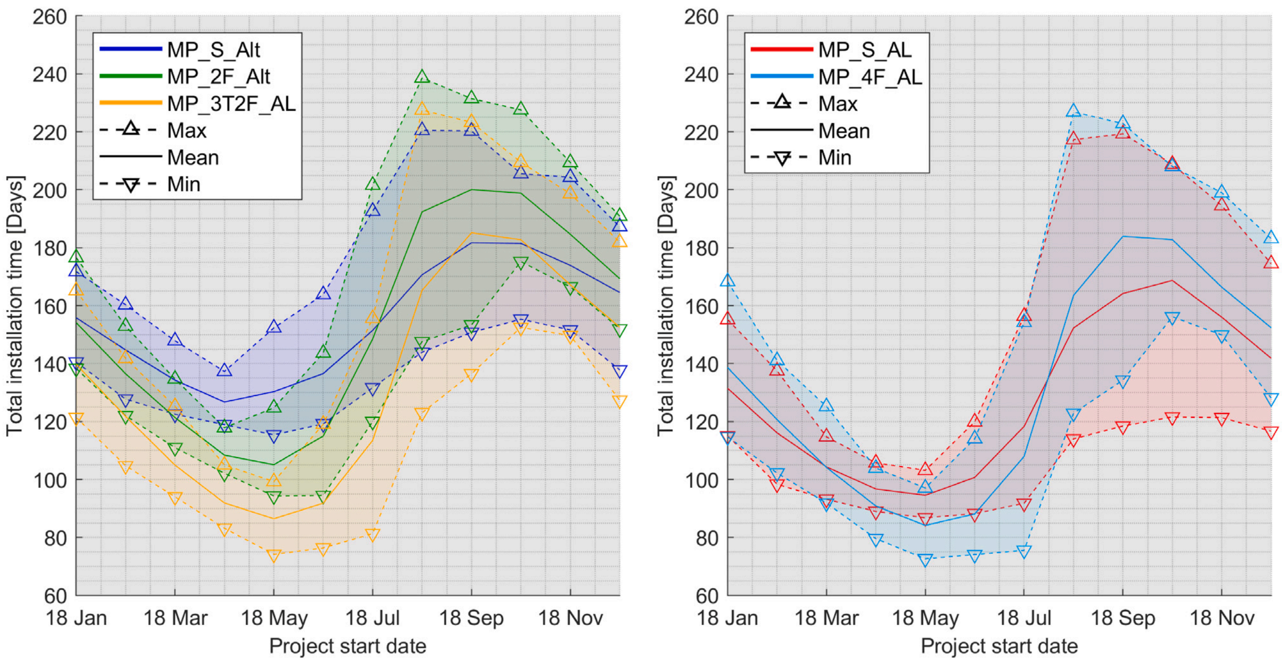

Fig. 11. The maximum, mean and minimum installation time as a function of the project start date per MP–TP installation strategy (**note** that for visibility reasons the colours per strategy are different w.r.t. the figures above).

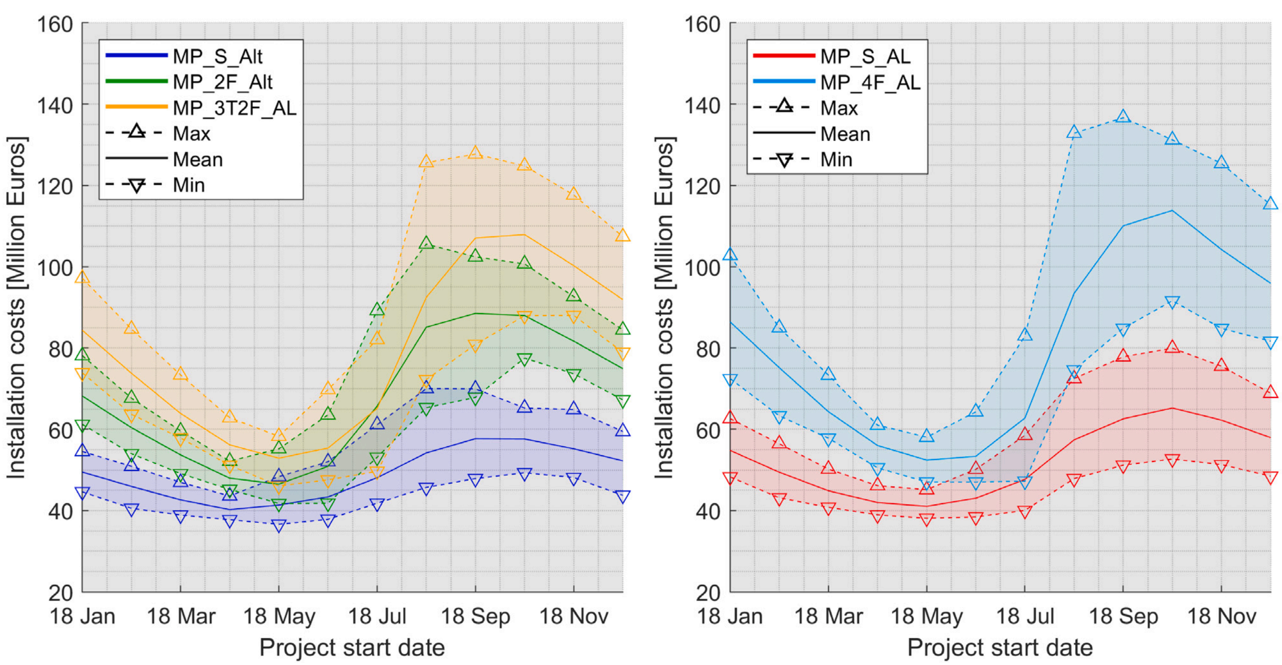

Fig. 12. The maximum, mean and minimum installation costs (only including the cost components discussed in Section 5.4) as a function of the project start date per MP–TP installation strategy (**note** that for visibility reasons the colours per strategy are different w.r.t. the figures above).

Table 9
Overview of the logistical set-ups for the installation of jackets and the corresponding abbreviations.

Abbreviation	Strategy	Vessels
Ja_S_Sep	Shuttling – Separate phases	1 HLV
Ja_S_AL	Shuttling – Assembly-line	2 HLVs
Ja_S_Dredg	Shuttling – Separate pile dredging	1 HLV, 1 OSV

Abbreviation	Strategy	Vessels	
Ja_1F_Sep	Feeders – Separate phases	1 HLV	1 Barge
Ja_2F_Sep			2 Barges
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

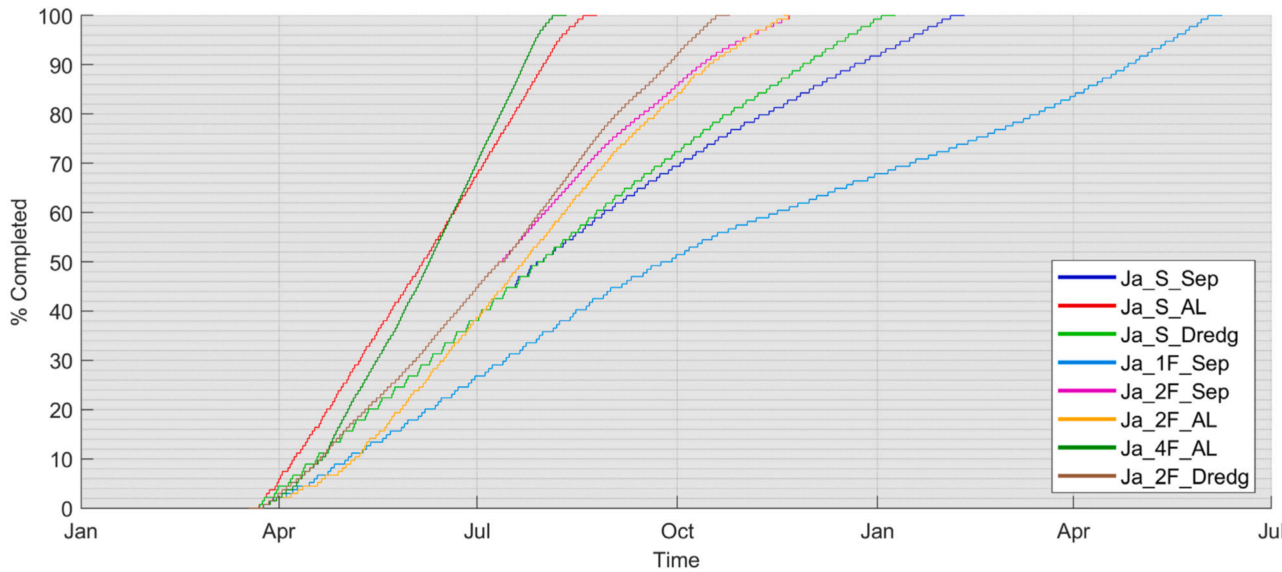

Fig. 13. Average S-curves of the eight considered logistical set-ups for the installation of jackets and foundation piles.

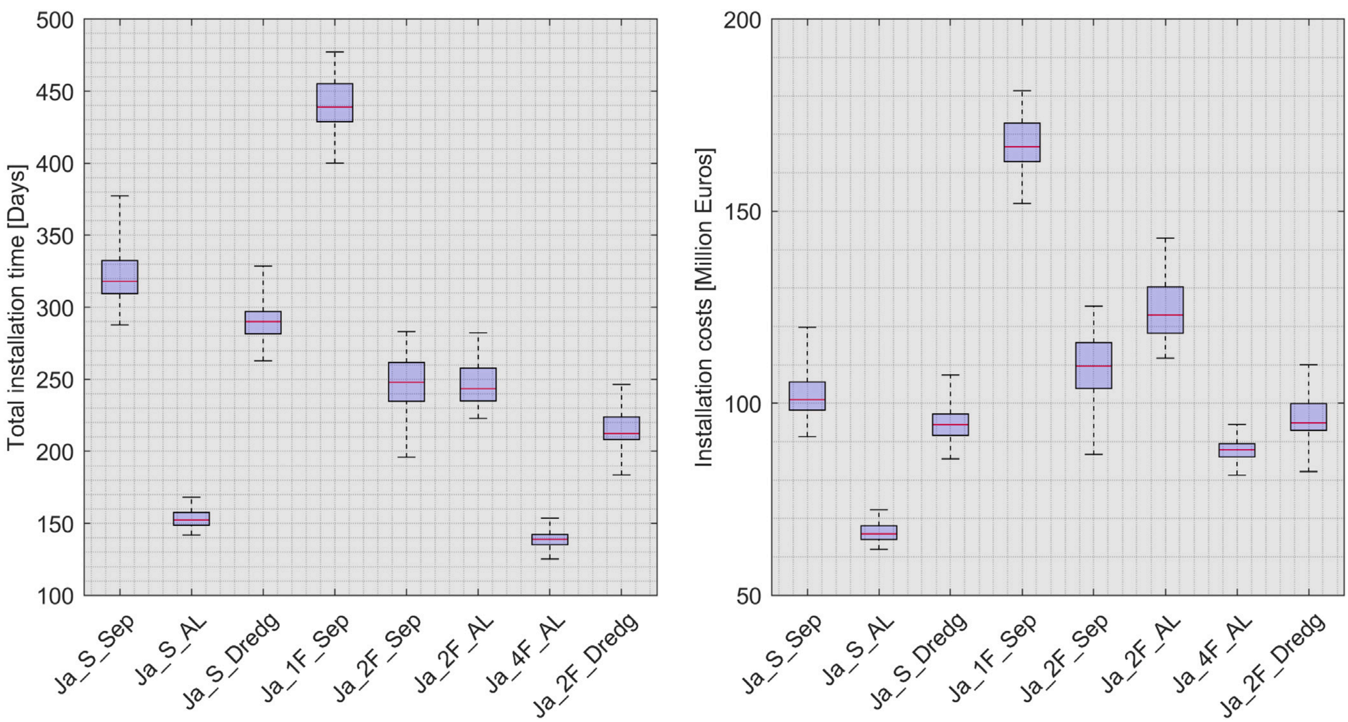

Fig. 14. Boxplots describing the simulated installation time and costs (only including the cost components discussed in Section 5.4) per considered strategy.

results in the conclusion that significant time and cost reductions can be achieved by deploying an OSV.

Table 10 specifies the average contribution to the number of WOW-days 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 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 6.3.2 only discusses the effect of increasing the workability of the barge (un)mooring operation.

6.3.2. Jacket installation bottleneck reduction sensitivity analysis

As discussed in Section 6.2.2, it can be considered reasonable to increase the significant wave height limit of the barge mooring operation by 0.3 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. Fig. 15 shows that significant reductions in the installation time and costs can be realised if this marginal increase

Table 10
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	Project WOW-days (average)
• Ja_S_AL	1.3% 0.4d	0.6% 0.2d	0.0% 0.0d	2.1% 0.7d	20.7% 6.7d	0.0% 0.0d	0.0% 0.0d	13.3% 4.3d	22.3% 7.2d	0.0% 0.0d	0.0% 0.0d	35.5% 11.5d	0.0% 0.0d	4.4% 1.4d	32.4d
• Ja_2F_Sep	0.8% 0.7d	0.4% 0.3d	0.1% 0.1d	0.0% 0.0d	3.4% 3.0d	37.1% 33.0d	4.7% 4.2d	3.0% 2.7d	8.8% 7.8d	0.0% 0.0d	2.7% 2.4d	8.1% 7.2d	30.9% 27.5d	0.0% 0.0d	89.1d
• Ja_4F_AL	0.8% 0.5d	0.5% 0.3d	0.1% 0.1d	0.3% 0.2d	5.2% 3.3d	34.0% 21.9d	6.0% 3.9d	3.2% 2.0d	4.5% 2.9d	0.0% 0.0d	1.6% 1.0d	11.9% 7.7d	31.5% 20.3d	0.6% 0.4d	64.5d
• Ja_2F_Dredg	1.0% 0.7d	0.3% 0.2d	0.1% 0.1d	0.0% 0.0d	4.3% 3.0d	37.4% 25.8d	6.0% 4.2d	3.8% 2.7d	5.4% 3.7d	3.0% 2.1d	2.0% 1.4d	7.3% 5.0d	29.3% 20.3d	0.0% 0.0d	69.1d

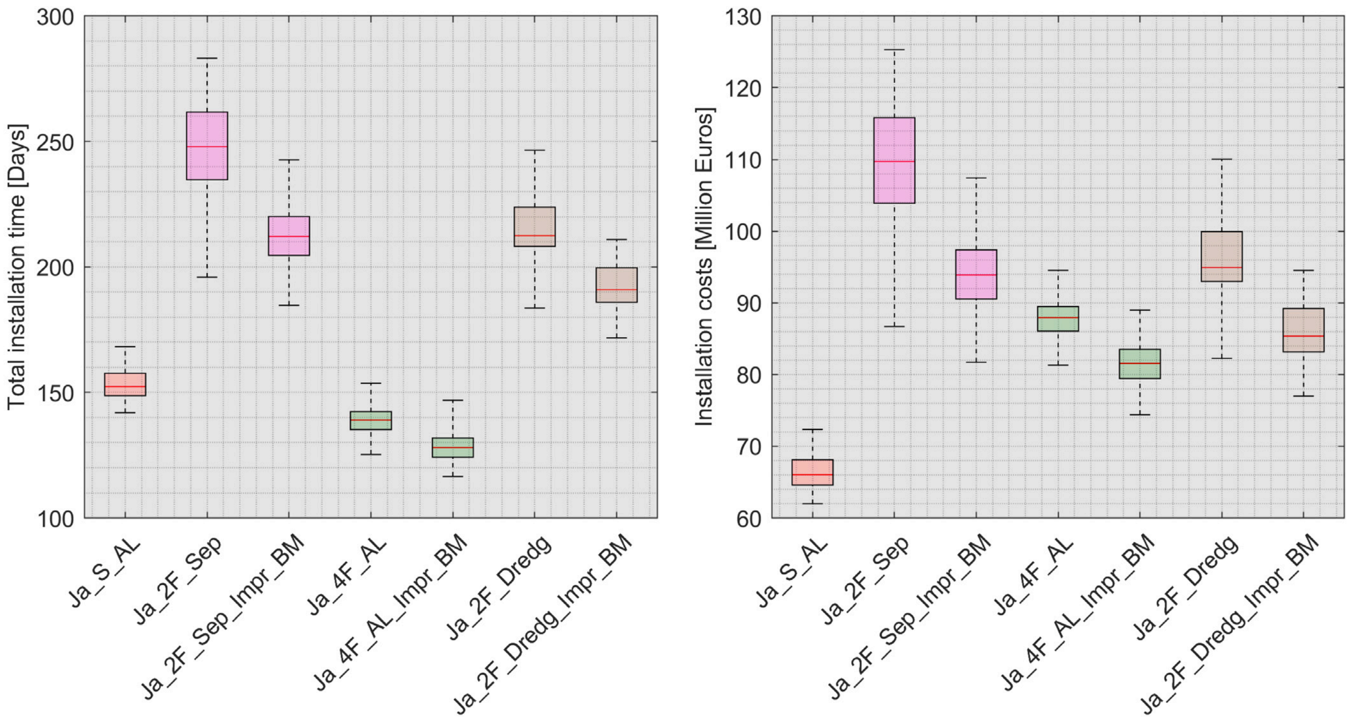

Fig. 15. Comparison between the installation time of the four promising initial jacket-installation strategies and of those strategies with improved workability.

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.

6.3.3. *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. Figs. 16 and 17 present the maximum, mean and minimum installation time and costs, respectively, as a function of the start date. When these figures are related to Figs. 11 and 12, 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 compared strategies, 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.

6.4. *Discussion*

6.4.1. *Numerical results w.r.t. market developments*

The numerical results have shown that for the current market 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 handle the substructures. In those cases, feeder barges can provide additional deck space, whereas towing FMPs does not require deck space at all and reduces the required crane capacity.

Another complex scenario for shuttling strategies may be related to the expansion of the offshore wind market from Europe to other continents. According to Gilman et al. [41], the US 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. However, the U.S. Jones Act restricts these contractors from deploying

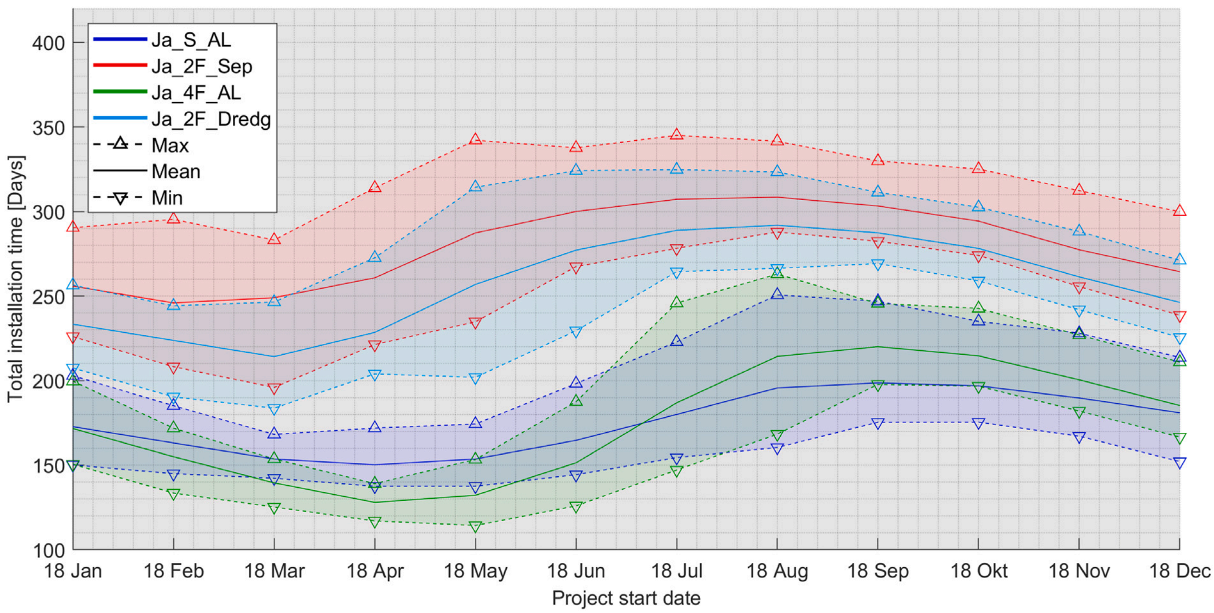

Fig. 16. The maximum, mean and minimum installation time as a function of the project start date per jacket installation strategy (**note** that for visibility reasons, the colours per strategy are different w.r.t. the figures above).

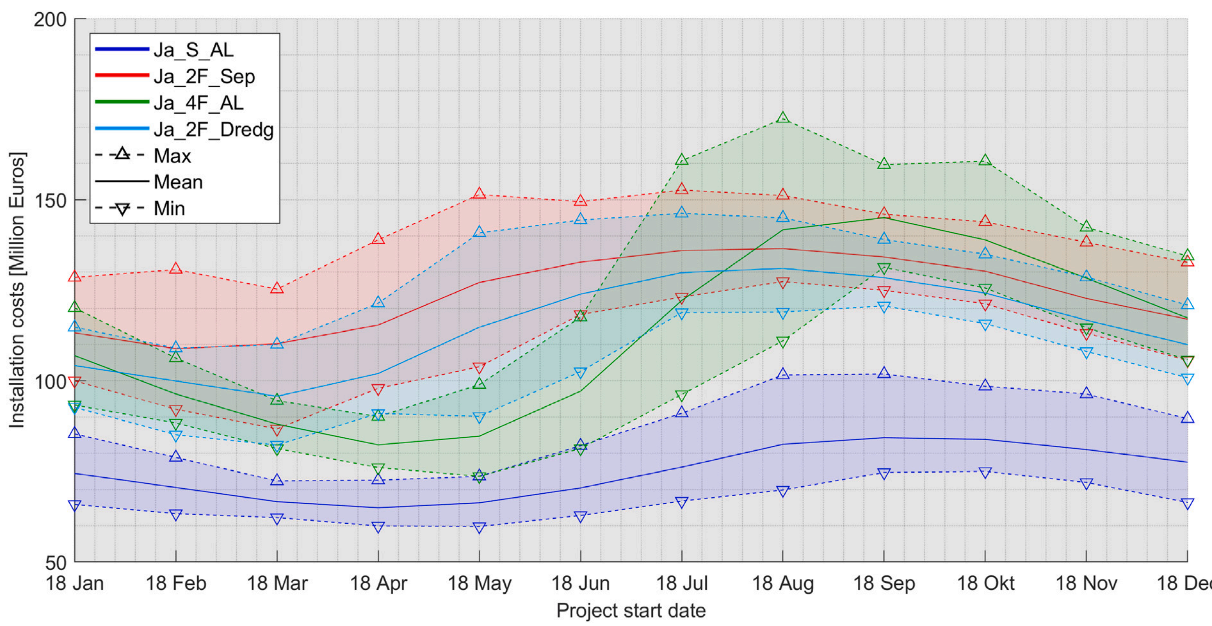

Fig. 17. The maximum, mean and minimum installation costs (only including the cost components discussed in Section 5.4) as a function of the project start date per jacket installation strategy (**note** that for visibility reasons, the colours per strategy are different w.r.t. the figures above).

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.

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, or investing in methods to be competitive with the currently available vessels. Many contractors are expected first to investigate the latter option, as this avoids large investments.

6.4.2. *Numerical results w.r.t. technological developments*

The main identified bottleneck of feeder strategies is the lower workability as a consequence of the introduction of weather-sensitive operations. Recent technological developments may contribute to solving this issue. 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, 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. Our analysis showed a 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 simulation tool may then be used to estimate the payback period, which potentially covers multiple projects.

Another technological development in the field of substructure installation 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 [42], the vibrations induced by the newly developed hammer may be sufficiently low to enable the installation of secondary steel on the MP. Furthermore, if the electrical components traditionally housed by the TP can also be positioned in the turbine tower, there is the potential to completely leave TPs out of turbine design or to "integrate" TPs into MPs. Looking at Table 6, 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, if the TP is taken out of the turbine design, MPs should become longer and heavier, which intensifies the limitations discussed in Section 6.4.1 regarding vessel deck space and crane capacity.

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

Sections 6.2 and 6.3 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 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.). However, it must be noted that this approach would require a considerable change of culture among the currently individually operating contractors.

7. Conclusions

In this study, we aimed 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 strategies can be categorised in transportation and installation strategies, from which 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.

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. In the U.S., 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.

The literature review revealed that while a few studies analyse the effectiveness of superstructure installation strategies, no study was encountered doing this for substructures. Available studies only include the installation of substructures as an accessory process. For future research, it is recommended to investigate the alignment of the interests of the involved parties. An example of misalignment of interests 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 could be evaluated. Aligning such interests might result in a shift of preference. Finally, considering CO_2 -emissions as a performance indicator of the considered strategies (in addition to installation time and costs), would enable a contractor to quantify its contribution to combat climate change, which may be a competitive advantage during the tendering processes, and to substantiate investments in CO_2 -reduction systems.

CRediT authorship contribution statement

Jorick Tjaberings: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Stefano Fazi:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Evrim Ursavas:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Model logic flow diagram

See Fig. A.18.

Appendix B. Input data

This study was performed in collaboration with a commercial party. The advantage of such a cooperation for our research is the availability of realistic input data for the developed models. However, also non-disclosure agreements had to be signed regarding these data. In order to enable tractability, we provide openly available data which are proportional to a factor close to one to the values actually used.

Table B.11 shows the durations of the most relevant operations performed during the installation of monopile and jacket substructures. For the duration of a load-out operation, a general value is given, as this was found not to vary much depending on the component. Additionally, we provide the sources from which these values are derived, which can be consulted if further clarification is required.

Table B.12 provides day rates for the major cost components in this study. It has to be noted that these values are location, time and vessel-specific. Lower availability and larger sizes of the vessels will drive

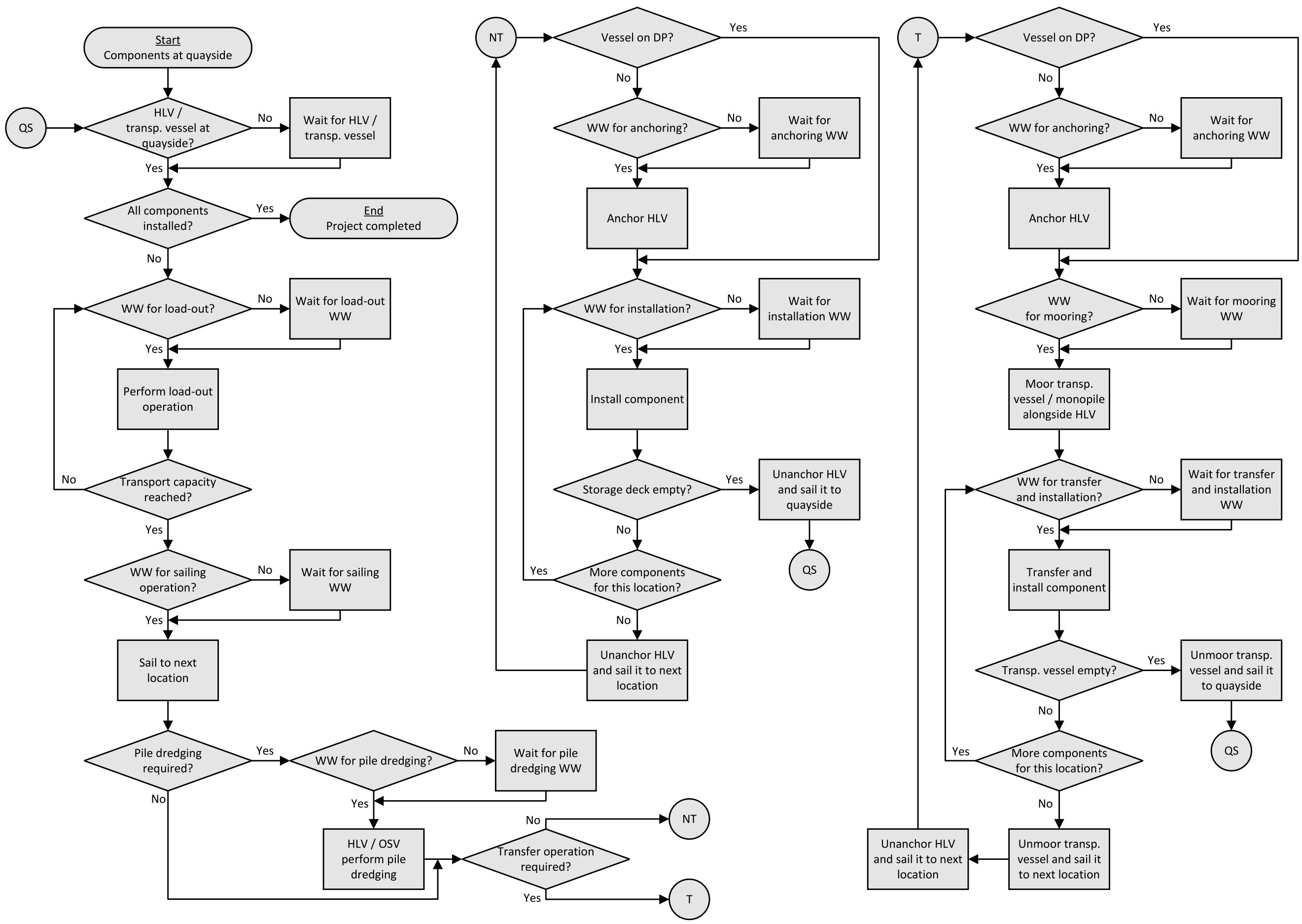

Fig. A.18. Logic flow diagram conceptualising the model content (WW = Weather Window).

Table B.11
Durations of the main operations.
Source: source 1: [8], source 2: [43], source 3: [44].

Operation	Duration [hours]	Source
Load-out of a component	2-3	1
Monopile installation times		
Install monopile	5	2
Drive monopile	5	2
Install transition piece	4	2
Grout transition piece	2	3
Jacket installation times		
Install template	4	2
Install one pile	3	2
Drive one pile	1.5	2
Remove template	4	2
Install jacket	6	2
Grout jacket	8	2

Table B.12
Day rates of the considered major cost components.
Source: source 1: [45], source 2: [46].

Cost component	Day rate [Euro / day]	Source
HLV	150,000 – 250,000	1
Barge	30,000 – 50,000	1
Tugboat	1,000 – 5,000	1
Construction support vessel	14,400	2

Table B.13
Weather limits of various operations.
Source: source 1: [8], source 2: [47], source 3: [35], source 4: [21].

Operation	Hs [m]	Vw [m/s]	Source
Load-out of components	-	14	1
Sailing	3	21	1
Barge mooring (feeder transportation) Limited by crew transfer operation	1.5	12	2
Monopile / jacket installation	Hs-Tp	12	3, 4
Driving monopile / jacket piles into soil	Hs-Tp	12	3, 4
Transition piece / jacket pile installation	Hs-Tp	12	3, 4

the prices up. However, larger vessels can result in larger workability, which makes it a complex problem to identify the ideal investment.

Table B.13 shows the weather limits for the major weather-dependent operations in terms of significant wave height (H_s) and wind speed (V_w). Once again, it must be mentioned that these values vary with the size of the vessel and only provide an indication. Load-out operations are generally performed in sheltered port areas, and therefore only a wind speed limit is set. The operations of monopile and jacket installation, driving monopiles and jacket piles into the soil and installing transition pieces and jacket foundation piles are considered sensitive operations. Therefore, the corresponding H_s-limits are expressed as a function of the peak wave period (T_p). For a certain vessel and substructure size, these H_s-T_p limits were derived by [35]. The resulting plots are shown in Fig. B.19. The angles mentioned in the legends relate to the angle between the vessel and the wave heading, which affect the responses of the vessel.

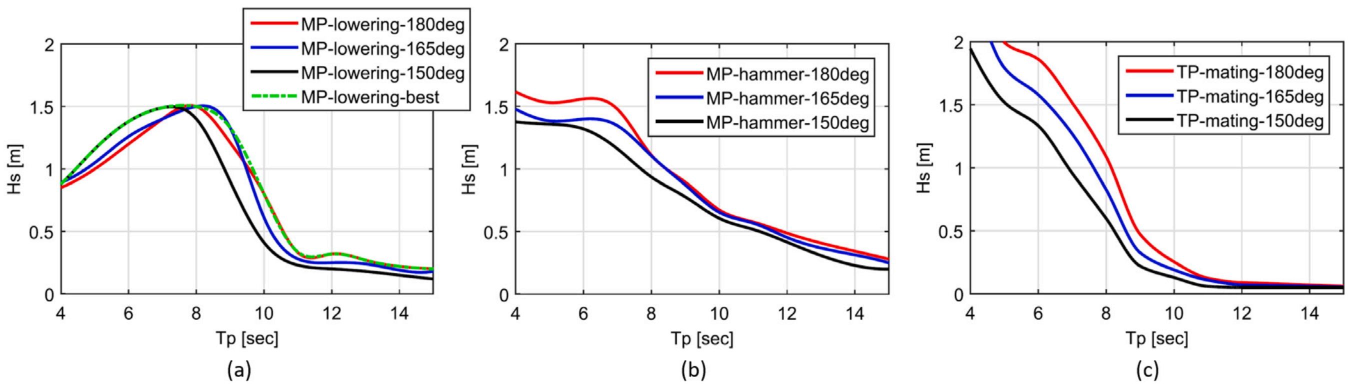

Fig. B.19. H_s-T_p limit curves for the lowering and driving of monopiles and the installation of transition pieces [35].

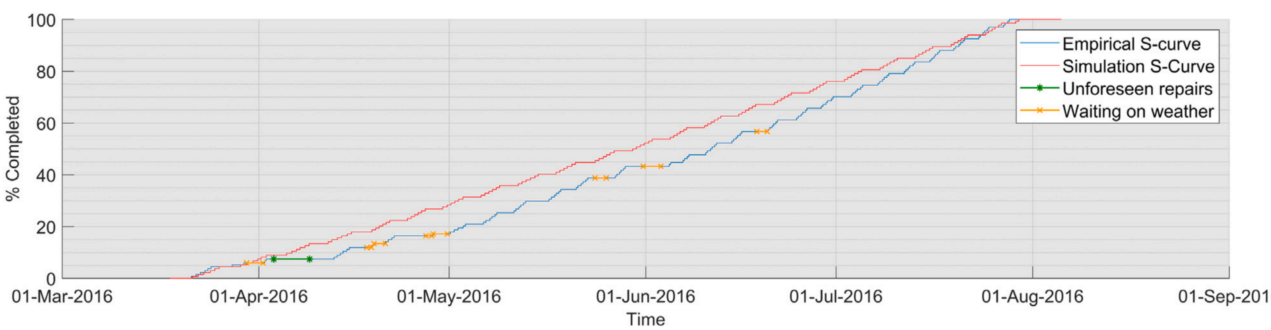

Fig. C.20. The empirical validation S-curve and the predicted S-curve.

Table C.14
Classification of goodness-of-fit, according to [48].

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

Appendix C. Validation

The actual historical data validation test is performed by comparing the S-curve generated by the simulation model with an S-curve from empirical data of a project performed in 2016. The simulated S-curve is the result of averaging the outputs of 35 runs for each year of available weather data (see Section 5.5). Both curves are plotted in Fig. C.20.

Based on visual inspection, it is concluded that the simulation model predicts the project completion progress satisfactorily. 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 4.2). 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 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.

In addition to the subjective visual inspection described above, the model's predictive capabilities are quantified, as recommended by Sargent [40]. In order to do this, the general method proposed by Ritter and Muñoz-Carpena [48] 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–SutcliffeEfficiency coefficient (NSE) is used. The equation for the RMSE is provided by Eq. (C.1), from which it 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 Eq. (C.3). Hence, a value of one for the NSE represents a perfect fit.

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

$$n_t = \frac{SD}{RMSE} - 1 \tag{C.2}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O})^2} = 1 - \left(\frac{RMSE}{SD}\right)^2 = 1 - \left(\frac{1}{n_t + 1}\right)^2 \tag{C.3}$$

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 Fig. C.20, the following values were calculated: 189 h for RMSE, 885 h 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 C.14. Although this classification was originally designed for a different field of application (hydrology), Ritter and Muñoz-Carpena [48] state that the proposed methodology (in which equations Eq. (C.1) to (C.3) are included) was developed independent of the application.

References

[1] Fernández-Guillamón Ana, Das Kaushik, Cutululis Nicolaos A, Molina-García Angel. Offshore wind power integration into future power systems: Overview and trends. J Mar Sci Eng 2019;7(11). http://dx.doi.org/10.3390/jmse7110399.

[2] Lee Joyce, Feng Zhao, Dutton Alastair, Backwell Ben, Qiao Liming, Lim Shuxin, Lathigaralead Anjali, Liang Wanliang. Global Offshore Wind Report 2020. Global Offshore Wind Report 2020, Brussels: Global Wind Energy Council (GWEC); 2020.

[3] Barlow Euan, Öztürk Diclehan Tezcaner, Revie Matthew, Boulougouris Evangelos, Day Alexander H, Akartunali Kerem. Exploring the impact of innovative developments to the installation process for an offshore wind farm. Ocean Eng 2015;109:623–34. http://dx.doi.org/10.1016/j.oceaneng.2015.09.047.

[4] Poulsen Thomas, Lema Rasmus. Is the supply chain ready for the green transformation? The case of offshore wind logistics. Renew Sustain Energy Rev 2017;73:758–71. http://dx.doi.org/10.1016/j.rser.2017.01.181.

[5] Koch Christian, Baluku Joseph, Habakurama Issa Ibrahim, Mathern Alexandre. The challenges of building inner sea offshore wind farms - the cases of lillgrund and anholt. In: Proceedings of the 9th Nordic Conference on Construction Economics and Organization. 2017, p. 307–17.

[6] Chartron Sylvain. Evaluating and improving logistics costs during offshore wind turbine construction. Sci Publ Group 2018;4(4):65–74. http://dx.doi.org/10.11648/j.ijtet.20180404.11.

[7] Sarker Bhaba R, Faiz Tasnim Ibn. Minimizing transportation and installation costs for turbines in offshore wind farms. Renew Energy 2017;101:667–79. http://dx.doi.org/10.1016/j.renene.2016.09.014.

[8] Oelker Stephan, Ait-Alla Abderrahim, Lütjen Michael, Lewandowski Marco, Freitag Michael, Thoben Klaus Dieter. A simulation study of feeder-based installation concepts for offshore wind farms. In: Proceedings of the International Offshore and Polar Engineering Conference. 2018, p. 578–83.

[9] Vis Iris FA, Ursavas Evrim. Assessment approaches to logistics for offshore wind energy installation. Sustain Energy Technol Assess 2016;14:80–91. http://dx.doi.org/10.1016/j.seta.2016.02.001.

[10] Lacal-Arántegui Roberto, Yusta Jose M, Domínguez-Navarro Jose Antonio. Offshore wind installation: Analysing the evidence behind improvements in installation time. Renew Sustain Energy Rev 2018;92:133–45. http://dx.doi.org/10.1016/j.rser.2018.04.044.

[11] Wind IX. Sif offshore foundations. 2021, https://www.ixwind.com/services/sifoffshorefoundations/. [Accessed 17 December 2021].

[12] Jiang Zhiyu. Installation of offshore wind turbines: A technical review. Renew Sustain Energy Rev 2021;139:110576.

[13] Bhattacharya Subhamoy, Nikitas Georgios, Arany Laszlo, Nikitas Nikolaos. Soil-structure interactions (SSI) for offshore wind turbines. Inst Eng Technol 2017;1–23. http://dx.doi.org/10.1049/etr.2016.0019.

[14] Shafiee Mahmood. Maintenance logistics organization for offshore wind energy: Current progress and future perspectives. Renew Energy 2015;77(1):182–93. http://dx.doi.org/10.1016/j.renene.2014.11.045.

[15] Ren Zhengru, Verma Amrit Shankar, Li Ye, Teuwen Julie JE, Jiang Zhiyu. Offshore wind turbine operations and maintenance: A state-of-the-art review. Renew Sustain Energy Rev 2021;144:110886.

[16] Conconi Manuela, Corbetta Giorgio, D'Amico Federico, Goormachtig Jan, Hajjar Rachelle, Halvorsen-Weare Elin E, Moccia Jacopo, Norstad Inge, Pineda Ivan, Rialland Agathe, Reig Elena, Rodriguez Mar. Logistic efficiencies and naval architecture for wind installations and novel developments. Technical report, Leanwind; 2014.

[17] Lange Kerstin, Rinne Andre, Haasis Hans-Dietrich. Planning maritime logistics concepts for offshore wind farms: A newly developed decision support system. In: International Conference on Computational Logistics, vol. 7555. 2012, p. 142–58. http://dx.doi.org/10.1007/978-3-642-33587-7{_}11.

[18] Barlow Euan, Öztürk Diclehan Tezcaner, Revie Matthew, Akartunali Kerem, Day Alexander H, Boulougouris Evangelos. A mixed-method optimisation and simulation framework for supporting logistical decisions during offshore wind farm installations. European J Oper Res 2018;264(3):894–906. http://dx.doi.org/10.1016/j.ejor.2017.05.043.

[19] Tezcaner Öztürk D, Barlow E, Akartunali K, Revie M, Day AH, Boulougouris E. Robust rolling horizon optimisation model for offshore wind farm installation logistics. 2017.

[20] Ursavas Evrim. A benders decomposition approach for solving the offshore wind farm installation planning at the North ssea. European J Oper Res 2017;258(2):703–14. http://dx.doi.org/10.1016/j.ejor.2016.08.057.

[21] Muhabie Y Tekle, Rigo P, Cepeda M, D'Agosto Mde Almeida, Caprace J-D. A discrete-event simulation approach to evaluate the effect of stochastic parameters on offshore wind farms assembly strategies. Ocean Eng 2018;149:279–90. http://dx.doi.org/10.1016/j.oceaneng.2017.12.018.

[22] Beinke Thies, Ait Alla Abderrahim, Freitag Michael. Resource sharing in the logistics of the offshore wind farm installation process based on a simulation study. Int J E-Navigation Mar Econ 2017;7:42–54. http://dx.doi.org/10.1016/j.enavi.2017.06.005.

[23] Beinke Thies, Ait Alla Abderrahim, Freitag Michael. Resource and information sharing for the installation process of the offshore wind energy. IFIP Adv Inf Commun Technol 2017;514:268–75. http://dx.doi.org/10.1007/978-3-319-66926-7.

[24] Quandt Moritz, Beinke Thies, Ait-Alla Abderrahim, Freitag Michael. Simulation based investigation of the impact of information sharing on the offshore wind farm installation process. J Renew Energy 2017;2017:1–11. http://dx.doi.org/10.1155/2017/8301316.

[25] Topham Eva, McMillan David. Sustainable decommissioning of an offshore wind farm. Renew Energy 2017;102:470–80.

[26] Irawan Chandra Ade, Wall Graham, Jones Dylan. An optimisation model for scheduling the decommissioning of an offshore wind farm. OR Spectrum 2019;41(2):513–48.

[27] O'Sullivan James, Arjona Juan F, Aghili Michael. Comparison of installation scenarios for offshore wind farms using operations simulator with Markov wind & wave weather model. Proc Off Technol Conf 2011;4:3265–9. http://dx.doi.org/10.4043/22176-ms.

[28] Jan De Nul Group. All foundations on formosa 1 phase 2 installed. 2019, https://www.jandenul.com/news/all-foundations-formosa-1-phase-2-installed. [Accessed 25 January 2021].

[29] Mammoet. Multi-sector expertise key to one of Asia's most ambitious wind projects. 2022, https://www.mammoet.com/cases/multi-sector-expertise-key-to-one-of-asias-most-ambitious-wind-projects/. [Accessed 04 March 2022].

[30] Market Crane. ALE has performed the final load-out for the Wikinger OWF project in ferrol, Spain. 2017, https://cranemarket.com/blog/ale-completes-wikinger-project-scope-back-to-newsoverview-ale-has-performed-the-final-load-out-for-the-wikinger-owf-project-in-ferrol-spain/. [Accessed 26 January 2021].

[31] Li Lin. Dynamic analysis of the installation of monopiles for offshore wind turbines (Ph.D. thesis), Trondheim: Norwegian University of Science and Technology; 2016, p. 1–88.

[32] Kaiser Mark J, Snyder Brian F. Installation strategies and options. In: Offshore wind energy cost modelling. green energy and technology. London: Springer; 2012, p. 69–89. http://dx.doi.org/10.1007/978-1-4471-2488-7.

[33] uit het Broek Michiel AJ, Veldman Jasper, Fazi Stefano, Greijdanus Roy. Evaluating resource sharing for offshore wind farm maintenance: The case of jack-up vessels. Renew Sustain Energy Rev 2019;109:619–32. http://dx.doi.org/10.1016/j.rser.2019.03.055.

[34] Sperstad Iver Bakken, Stålhane Magnus, Dinwoodie Iain, Endrerud Ole-Erik V, Martin Rebecca, Warner Ethan. Testing the robustness of optimal access vessel fleet selection for operation and maintenance of offshore wind farms. Ocean Eng 2017;145:334–43. http://dx.doi.org/10.1016/j.oceaneng.2017.09.009.

[35] Guachamin Acero Wilson, Li Lin, Gao Zhen, Moan Torgeir. Methodology for assessment of the operational limits and operability of marine operations. Ocean Eng 2016;125:308–27. http://dx.doi.org/10.1016/j.oceaneng.2016.08.015.

[36] Massey Frank J. The Kolmogorov-Smirnov test for goodness of fit. J Amer Statist Assoc 1951;46(253):68–78. http://dx.doi.org/10.2307/2280095.

[37] Teegavarapu Ramesh SV. Methods for analysis of trends and changes in hydroclimatological time-series. In: Teegavarapu Ramesh, editor. Trends and Changes in Hydroclimatic Variables. Elsevier; 2019, p. 1–89. http://dx.doi.org/10.1016/B978-0-12-810985-4.00001-3.

[38] KNMI. Uurgegevens van het weer in nederland. 2021, https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens/. [Accessed 04 March 2021].

[39] MetoceanView. MetoceanView hindcast app. 2021, https://metoceanview.com/. [Accessed 01 March 2021).

[40] Sargent Robert G. Verification and validation of simulation models. In: Proceedings of the 2010 Winter Simulation Conference. 2010, p. 166–83.

[41] Gilman Patrick, Maurer Ben, Golladay Jennifer, Stromberg Jessica. National offshore wind strategy - Facilitating the development of the offshore wind industry in the United States. Technical report, U.S. Department of Energy; 2016.

[42] IQIP. Quietly pushing the XXL monopile to new limits. 2020, https://www.ihciqip.com/en/news/quietly-pushing-the-xxl-monopile-to-new-limits. [Accessed 27 January 2021].

[43] Semenyuk Maksym. Offshore Wind Farm Installation Planning. Decision-support tool for the analysis of new installation concepts. Technical report, 2019.

[44] Verhaegh Max. Modelling the manufacturing and installation costs of offshore wind farm substructures for a micro siting model. Technical report, 2014.

[45] Ahn Dang, Shin Sung-chul, Kim Soo-young, Kharoufi Hicham, Kim Hyun-cheol. Comparative evaluation of different offshore wind turbine installation vessels for Korean west–south wind farm. Int J Nav Archit Ocean Eng 2017;9:45–54. http://dx.doi.org/10.1016/j.ijnaoe.2016.07.004.

[46] Santos Fernando, Teixeira Angelo P, Soares C Guedes. Modelling and simulation of the operation and maintenance of offshore wind turbines. Proc Inst Mech Eng O 2015;229(5):385–93. http://dx.doi.org/10.1177/1748006X15589209.

[47] TNO. Innovations for Port of Den Helder Infrastructure following offshore wind developments. (Technical Report 2). Petten, The Netherlands; 2019, https://repository.tno.nl/islandora/object/uuid%3Aec19a1e4-9e7c-42c0-b19e-15daccdd440f. [Accessed 09 July 2022].

[48] Ritter Axel, Muñoz-Carpena Rafael. Performance evaluation of hydrological models: Statistical significance for reducing subjectivity in goodness-of-fit assessments. J Hydrol 2013;480:33–45. http://dx.doi.org/10.1016/j.jhydrol.2012.12.004.