Delft University of Technology
MSc thesis Management of Technology

Evaluating the cost effectiveness of logistic strategies for onshore monopile handling in marshalling ports

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Evaluating the cost effectiveness of logistic strategies for onshore monopile handling in marshalling ports

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Management of Technology**

Faculty of Technology, Policy and Management

by

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To be defended in public on August 28th 2023

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Executive summary

The global ever growing energy demand, quest for renewable alternatives for fossil fuels and desire to reduce dependency on single countries has driven the increasing demand for offshore wind energy production. The advancing technologies that enable offshore wind turbines to gain efficiency go hand in hand with increasing sizes of components and foundations. Deeper waters can be entered, but the accompanied size and weight increase poses various challenges. Fixed-bottom structures such as monopiles reach diameters of 10m and lengths up to 110m, which complicates the onshore handling of those monopiles in marshalling ports. This study identified a gap in the existing literature regarding marshalling ports and their role in supporting offshore wind farm construction.

Using a discrete event simulation (DES) and a case study regarding the construction of an offshore wind farm in the Baltic Sea, different scenarios have been evaluated and assessed in their resilience and performance in response to schedule changes. The findings highlight the importance of a compressed project schedule in achieving cost reductions. A strategy with approximately 75% overlap between load-in and load-out schedules was identified as the most cost-efficient approach. With this approach, cost savings are not only achieved by reducing operational expenses such as personnel and equipment rental, but most substantially by the decreased amount of demanded storage area spaces. With less storage spaces needed, both the construction costs for storage bunds and the area rental costs decrease.

The analysis of the experiment on schedule overlap revealed that a scenario with only one support for load-out and zero supports for the load-in exhibited higher average waiting times and total maximum fines. However, this scenario still performed best in terms of total costs, as the waiting times for ships did not outweigh the expenses associated with additional supports.

The study also examined the timing of arrivals and found that when a barge arrives the day after the installation vessel departs, the waiting time for unloading significantly decreases. Considering both the maximum fine related to delays, the total project costs and the waiting times for ships weighted on their day rate, the preferable order of arrival of the barge is after, at the same day and before the installation vessel arrives, contrary to the ideal outcome based solely on barge time.

To be able to implement these desires regarding schedule changes to decrease costs, subcontractors such as heavy lifting companies who are responsible for the onshore handling of monopiles, must collaborate with other actors in an early stage of the project. Collaboration among stakeholders is emphasized as a key recommendation stemming from the study. Involving all relevant actors in offshore wind projects from an early stage can yield extensive mutual benefits. By establishing an overarching supply chain management, coordinated by the project developer, overall construction costs can be reduced without harming any particular party.

The developed discrete event simulation might be applied to other projects to extend the research, under the requirement that the included assumptions are structurally evaluated. Investigating different project sizes, schedule variations and load-out methods could improve the overall understanding of the system dynamics and parameters. In combination with a discrete event simulation, a mathematical layout optimization might enable decision makers to make choices regarding the location and priority of placing wind turbine components in marshalling port, based on the installation variability. This could eventually lead to a decision making tool suitable for cost-optimising marshalling activities and installation strategies for wind farm constructions globally, contributing to the acceleration of the energy transition.

Acknowledgements

This thesis has been written to obtain the degree of Master of Science in Management of Technology, at the faculty of Technology, Policy and Management at Delft University of Technology. The writing process has been quite a journey, which could not have been completed successfully without the help of several people. In this section, I want to take the opportunity to express my gratitude to everyone that helped me accomplish this.

I am very grateful that Mammoet offered me the opportunity to conduct research on a very relevant and interesting topic in the rapidly changing offshore wind market. The practical application and relevance has certainly helped to keep me motivated throughout the project.

Therefore, I would first like to thank Leo Oorschot for his time, fruitful discussions and effort in guiding me within Mammoet. His support was invaluable throughout the whole thesis trajectory, but also his colleagues were always helpful with brainstorming, clarifying project details and being open for discussion.

Furthermore, I would like to thank Dr. Fazi and Dr. Verburg for their guidance and feedback from the academic point of view, being the first and second supervisors of my graduation committee.

My friends and roommates have been a great support along the way, by discussing ideas, sharing frustrations, or offering a welcome distraction during breaks.

Last but not least, I would like to thank my parents Peter and Ivonne, brother Robert and girlfriend Julia for their infinite love and support during my studies. You were always there for me and made this possible.

Sander Kassels
Delft, August 2023

Contents

1 Introduction

In comparison to the emission levels in 1990, the EU is committed to a 55% greenhouse gas reduction target by 2030, in line with the Paris Agreement objectives (WindEurope, 2023). Accelerating the clean energy transition is a hot topic on the agenda of many countries across the globe, not only limited to the EU. Wind energy, in particular offshore wind, is one of the alternatives to fossil fuels that can help to achieve the set targets: the resources are stable and abundant, and public acceptance is higher compared to onshore alternatives (European Commission, 2022). Recently revised plans push the wind energy sector even further to install an additional 57 GW by 2030 on top of the existing 453 GW target, to increase energy independency (WindEurope, 2023). These ambitions result in the projected growth in annual offshore wind farm installation that is depicted in figure 1, which includes an outlook to 2030 for Europe.

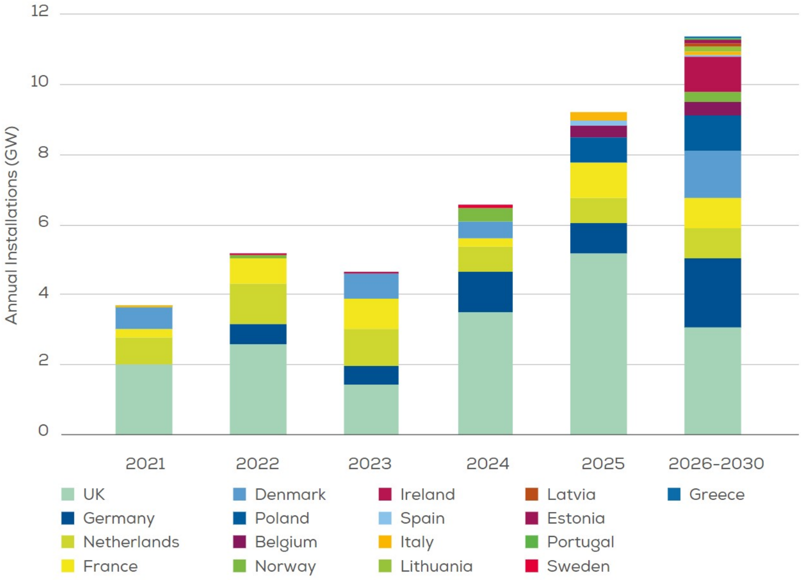


Figure 1: *Annual installations in offshore wind (GW) (WindEurope, 2021)*

One of the main issues in generating more power, especially offshore, is the lack of infrastructure needed to serve the type and volume of the work expected, especially in terms of ports. In particular, marshalling ports can be a serious bottleneck for wind energy development. Marshalling ports are used when temporary parking of equipment before deployment offshore is necessary, particularly in areas without a nearby manufacturing port (Díaz & Soares, 2022). By doing so, they form a key logistic factor in the installation process by providing a buffer between production and installation rates. Additionally, travelling times for expensive installation vessels are reduced as marshalling ports are located in the vicinity of wind farms under construction. However, if the quantity, weight and size of components present at the marshalling port is large and the assisting resources are not properly balanced, delays can occur that can compromise the smoothness of the operations.

In this thesis, the goal is to model the operations within a marshalling port. In particular, we consider that in this marshalling port monopiles are supplied and requested by ships with varying arrival rates. These monopiles need equipment such as Self Propelled Modular Transporters (SPMT) to be unloaded and positioned on the laydown area, and steel supports or sand dunes for storage. Depending on the arrival rate, the number of resources and the way they are utilized should be managed properly to reduce costs and delays.

The available literature that discusses the logistical challenges of handling offshore wind structures in marshalling ports is limited. The studied literature has been grouped in offshore installation strategies, port requirements, supply chain management and onshore logistics. For the offshore installation, several studies have evaluated different sequences, vessels or level of integration in construction (Tjaberings, Fazi, and Ursavas (2022), Barlow et al. (2015), Guo, Wang, and Lian (2022)), but either investigate only topside components, or make assumptions and simplifications regarding the load-out and onshore handling. The literature regarding port requirements agrees to the fact that marshalling port area shortage can become a serious bottleneck in the development of offshore wind farms, both in Europe and the U.S., but lack a plan for efficient land use. Rodríguez, Álvarez, and Dono (2019) and Irawan, Song, Jones, and Akbari (2017) do apply a spatial layout optimization, but either only focus on a manufacturing port for jackets (Rodríguez et al., 2019) or the layout of topside components (Irawan et al., 2017). Therefore, the studied literature has insufficient focus on the marshalling of substructures.

Hence, in this study we aim to fill the gap by carrying out a simulation study that models the aforementioned problem. This will be done by analyzing a specific case of monopile handling in a marshalling port in Denmark, conducted in 2022 by Mammoet, a heavy lifting contractor. The collected data will be applied to Discrete-Event Simulation (DES) modelling, to create a higher level of analysis of the supply chain around marshalling ports, while still taking internal activities in the marshalling port into account. Time is a crucial performance indicator in the onshore handling of components, as load-outs have to be conducted quickly to fully utilize weather windows in installation offshore. However, this can be linked to costs, as installation vessels have expensive day-rates while lying idle, equipment and personnel onshore have a price tag, port area has a rent per square meter, and contractors are limited to penalties for delays. Therefore, it is chosen to use costs as the main performance indicator. Overall, the focus of this thesis can be translated to the main research question:

Which logistic strategy in terms of resource allocation for the onshore handling of monopiles in marshalling ports is the most cost-efficient, considering the arrival rates of shipments?

This thesis is structured as follows. Chapter 2 includes a review of the current state of the available literature, identifying the knowledge gap. Chapter 3 describes the problem that this research aims to tackle in more detail and introduces the studied case. Next, the methodology on how this problem will be modelled is treated in chapter 4. The results from the model are presented in chapter 5, which are discussed in the discussion in chapter 6. The thesis is concluded with the conclusion and recommendations in chapter 7.

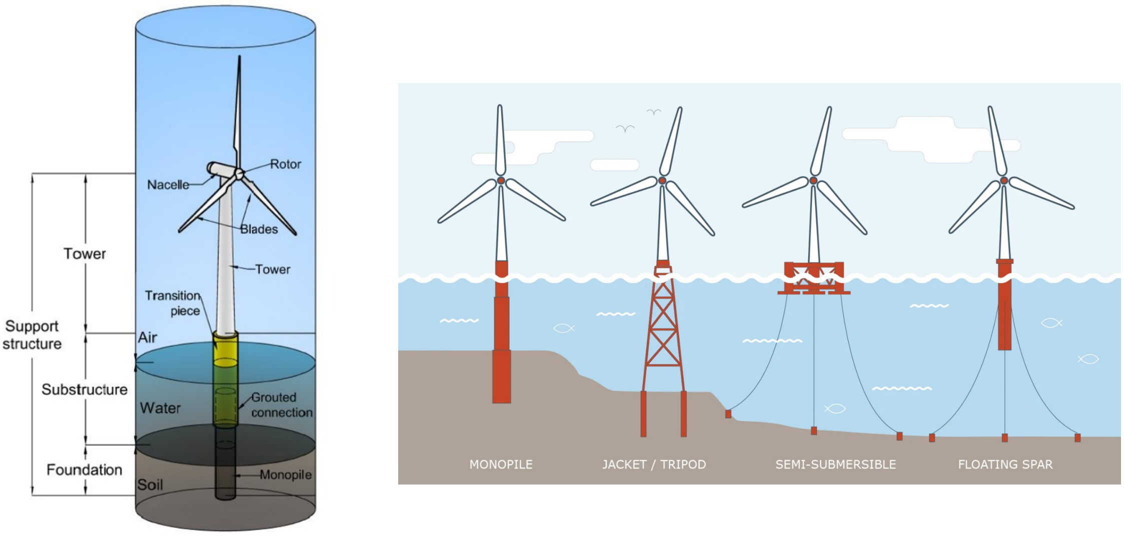
2 Theoretical background

This section first introduces some core components of offshore wind turbines in section 2.1. Furthermore, it contains an overview of the literature studied, grouped in offshore installation strategies (section 2.2), the expected port requirements for both fixed-bottom foundations (section 2.3), supply chain (section 2.4) and onshore logistics (section 2.5). It concludes with the identified knowledge gaps resulting from these studies (section 2.6).

2.1 Wind turbine components

The generator of an offshore wind turbine, being propelled by the blades, is located in the nacelle, depicted in figure 2a. This is why the blades, rotor and nacelle, together with the tower, are referred to as the wind turbine generator (WTG) components, or the superstructure. The wind turbine is built on top of a substructure, which can have a separate or integrated transition piece (TP). Furthermore, the substructure consists of a foundation, which can be found in various types, as can be seen in figure 2b.

Among those types, a distinction can be made between fixed-bottom and floating foundations. Although there are rapid developments in alternative designs, fixed-bottom foundations, especially monopile foundations, will still make up the majority of the installed foundations for the coming years (Sánchez, López-Gutiérrez, Negro, & Esteban, 2019). Monopile support structures consist of a cylindrical steel tube, which is drilled into the seabed. Therefore, those foundations are appropriate for relatively shallow waters, and deeper waters can be entered with longer monopiles. Due to its wide implementation, the focus of this thesis will center around monopile foundations. However, also studies regarding logistics for WTG components and other foundation types are considered in this section to create a complete overview of the existing literature.



(a) *Monopile foundation with topside* (b) *Foundation types offshore wind turbines*

Figure 2: *Schematic visualisation wind turbine foundations, retrieved from (Bhattacharya et al., 2017) and (Jakobsen & Ironside, 2021)*

2.2 Offshore installation strategies

Several studies have investigated logistical strategies in the installation process of offshore windfarms. Guo et al. (2022) for example, reviewed the effect of the level of integration of components in three kinds of installation methods. A useful distinction was made between the various aspects in the installation process, including onshore manufacturing, loading at dock, marine transportation, offshore assembly and installation. It was found that an integrated transportation and installation of foundation and wind turbine is most economical and efficient technology, by limiting the operations out at sea.

Vis and Ursavas (2016) came to a comparable conclusion, suggesting a pre-assembly strategy that uses a minimum number of components to be installed onsite and a maximum number of turbines on a vessel. Since offshore wind farm sites are selected especially for their high wind potentials, crane operations are limited in terms of an available time window for lifting the components safely.

Barlow et al. (2015) applied a similar scope, combining a logistical model of the offshore installation with a synthetic weather time-series model by using a simulation tool. Regarding the load-out, only activities related to the vessel are mentioned, such as preparations on deck, loading the asset from quayside to the vessel, and sea-fastening of all loaded assets. Building on this research, Barlow et al. (2018) expanded the model by adding technical information regarding the foundations of wind turbines. Tjaberings et al. (2022), on the other hand, identified several combinations of transportation and installation strategies for monopile and for jacket substructures. A differentiation of strategies was based on the deployed vessels and the installation sequence of the components. It was found that the lowest costs are achieved in a strategy where the installation vessel takes care of both transportation and installation. The load-out operation, which includes bringing the components to be installed from the quayside onto the transportation vessel or barge, was considered as a given input for the system of analysis.

The load-out operation, which is depicted in figure 3, being either simplified, viewed from the vessel perspective, or not taken into account at all, is a trend that these studies have in common.

Figure 3: *Load out by installation vessel*

2.3 Port requirements for fixed-bottom turbines

Parkison and Kempton (2022) analyzed the infrastructure needed for offshore wind power targets by U.S. state and federal policies, specifically, manufacturing, vessels, and offshore wind ports. It is mentioned that the evolving sizes of wind turbines and their components determine the infrastructure and correlating equipment required to manufacture components, marshal them to be ready for deployment, load onto installation vessels, assemble in the ocean, and maintain components over their project lifetime. The analysis of needed infrastructure shows that for reaching the federal targets, a significant bottleneck will be the availability of port area required to marshal components and load them onto installation vessels. Parkison and Kempton (2022) state that marshalling ports have the most challenging spatial and load-bearing requirements of all port types related to offshore wind. The specific technical and geographical requirements exacerbate the typical port challenges of efficient management and optimized area capacity:

1. Weight of the components leads to high load-bearing requirements for the port surface and quay.
2. Component size and count, turning radius for component movements, maneuvering for partial assembly, and load out to installation vessels determines necessary port area.
3. The logistical sequence-shipments and weather windows- determines residence time of sets of components.
4. Vessels and related quay length, channel depth etc.
5. Vertical clearance.

These requirements are also acknowledged by Akbari, Irawan, Jones, and Menachof (2017), who investigate the logistics capabilities of offshore wind ports, namely physical characteristics, connectivity and layout of the port, for supporting the installation and operation and maintenance phases of offshore wind projects. Criteria were given to evaluate suitability of ports, including quay load-bearing capacity, component handling equipment, storage space availability, component laydown (staging) area availability and potential for expansion. The results of the study suggest that the port's distance to the wind farm is an influential factor in the decision-making process, since ports located closer to the wind farm allow for weather windows to be exploited more efficiently and the transportation time and cost will hence be reduced. This emphasizes the importance of a marshalling port when the manufacturing location is not in the vicinity of the offshore wind farm location.

2.4 Supply Chain

Drunsic, Ekici, White, and Gl (2016) highlight key challenges related to supply chain management for offshore wind projects with particular focus on the installation and transportation infrastructure, equipment and logistics. The paper covers the different components, the vessels and equipment, port facilities, coordination of supply and installation and the key challenges for the U.S. market. It is concluded that the serial nature of the manufacturing and installation of offshore wind components and the intense cost reduction pressure drive a need for robust supply chain management, that is unique to offshore wind. However, Drunsic et al. (2016) remain on an exploratory level, only emphasizing the need of further investigation but not acting upon it.

Shields et al. (2023) dive deeper the offshore wind energy supply chain for the United States. An important barrier in supply chain development that is mentioned is that existing port and vessel infrastructure is inadequate to install 30 GW of offshore wind energy by 2030. The available acreage of potential U.S. marshalling ports is significantly smaller than corresponding European marshalling ports, which puts the ability of the port to support on-time project installation at risk. Such a European marshalling port is presented in figure 4. Another barrier that is mentioned regarding the further development of port and vessel infrastructure, is the investment risk that is created by the uncertainty surrounding the potential impacts of construction delays, cost overruns, legal complications, and changes in government support.

Figure 4: *Marshalling port in Rønne, Denmark*

Specific port feasibility studies, like Porter, Gostic, Philips, and MacDonald (2022), also acknowledge that large investments are required to upgrade existing marine terminals to ports suitable for supporting offshore wind farms. Rippel, Jathe, Lütjen, and Freitag (2020) conduct an optimization of a standard inventory stock problem, applied to a base-port, estimating the required in- and outflows using historical data. They present a method to estimate the required storage capacity and initial inventory levels at the base-port for an offshore installation project. A simplification applied in this research is that individual components are not distinguished. Sets consisting of one tower, one nacelle, three blades, and a connection hub including the required wiring are considered, therefore generalizing the onshore handling of components. The whole base-port is seen as one system with in- and outflows, while elements like the component layout and used equipment can be crucial for the storage capacity.

2.5 Onshore logistics

Irawan et al. (2017) proposed mathematical models for generating an optimal layout for an installation port for an offshore wind farm, with the objective to minimize the total transportation cost of the components within the port. The port area has been segmented in subareas: unloading areas, storage areas, staging areas and loading areas. The components included in the models are the nacelle, tower and blades, so the handling of foundations is left out of scope.

Rodríguez et al. (2019) evaluate the internal logistic strategy in a shipyard in terms of costs and resources in charge of the transportation to the storage area and Load-Out operations. The applied research approach is comparable to the expected approach in this thesis. However, their model on jackets doesn't consider factors relevant for the onshore handling of monopiles, such as support elements and horizontal spatial limitations in maneuvers, as jacket substructures are stored upright. Rodríguez et al. (2019) focus on the manufacturing, and load-out dates and duration are defined at the beginning of a project. A more generic simulation, including the supply and installation rate, would enable an evaluation of strategies from a broader perspective, making the research more applicable to future developments and global expansion.

2.6 Knowledge gap

From the studies related to offshore installation strategies, Vis and Ursavas (2016) and Barlow et al. (2015) only consider the installation of WTG components. Other studies (Barlow et al., 2018; Tjaberings et al., 2022), being focused on the offshore aspect of the installation process, include little detail on the type of load-out and the onshore handling in general. The assumptions that the load-out operation and accompanied storage strategy was considered a given input, can be seen as a knowledge gap, providing room for further investigation.

When it comes down to port requirements, both studies related to fixed-bottom (Akbari et al., 2017; Parkison & Kempton, 2022) and floating wind (Crowle & Thies, 2022; Díaz & Soares, 2022; Martinez & Iglesias, 2022) turbines foresee a marshalling area shortage due to the large land area required for the laying down components. Future components will demand more from marshalling ports, like higher loadbearing capacity of both quay and port surface, longer quaysides, deeper channels, and appropriate component handling equipment.

Some research has been conducted taking the supply chain of offshore wind into account, mainly for the U.S. market (Drunsic et al., 2016; Shields et al., 2023). Both studies, together with Porter et al. (2022) acknowledge the need for large investments to make current ports suitable for offshore wind facilitation. Rippel et al. (2020) optimize the inventory stock of a base-port, but without varying equipment utilizations and analyzing spatial layout. Irawan et al. (2017) does optimize this spatial layout, but only considers WTG components and given types of load-outs. The same holds for (Rodríguez et al., 2019), but then for the manufacturing of jackets in a shipyard. Therefore, this research aims to fill the knowledge gap by analyzing the various onshore handling strategies of monopile foundations in marshalling ports, interdependencies of variables, and impacts on costs and project duration.

3 Problem description

In this chapter, the scope of this research is provided in section 3.1, along with the main problem that will be investigated. Next, a case of a marshalling port is presented in section 3.2 to introduce the key concepts in onshore monopile handling and elaborate on the main cost contributors. The chapter concludes with overview of the most important assumptions that were made to enable modelling of the real life case, presented in section 3.3.

3.1 Marshalling port challenges

In this study, a marshalling port is considered, where monopiles arrive from distant manufacturing facilities and subsequently are handled by several resources until they are transshipped to installation vessels. The scope of this thesis revolves around the operations that occur within this port with the goal of reducing waiting times for the arriving barges and installation vessels, since these two share assisting handling resources. Figure 5 depicts this scope within the overall development of offshore wind farms, highlighting the marshalling port activities and its interactions with both the barge and the installation vessel.

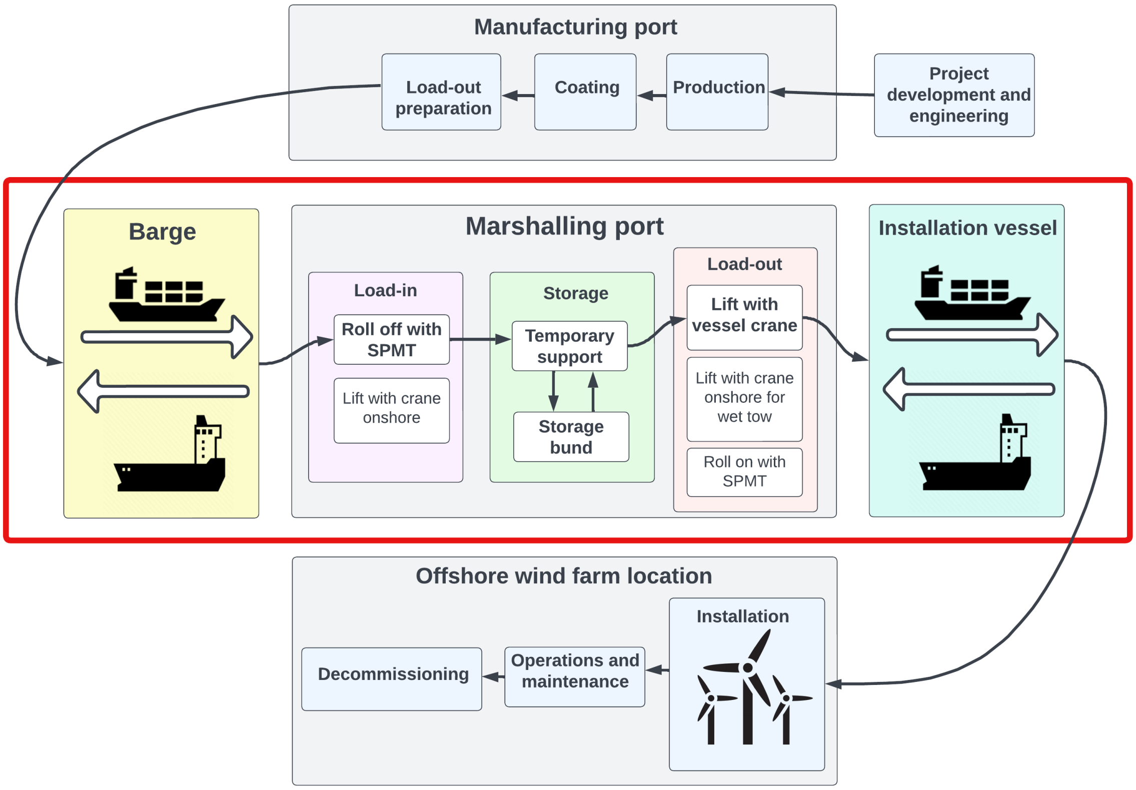


Figure 5: *Scope onshore handling in marshalling ports*

Upon arrival in the marshalling port, usually by means of barges (see figure 6), a load-in activity is performed, with the monopiles being unloaded from the barge. Mooring the barge, installing ramps and clearing the transport path from the sea fastening grillage are among the preparatory activities to be carried out before executing the load-in.

Figure 6: *Arrival barge at marshalling port*

For both the load-in and positioning on site, a Self Propelled Modular Transporter (SPMT) is used, which is a commonly used piece of equipment in heavy lifting and transport projects, including monopile handling, see figure 7. The SPMT positions the monopile on a allocated storage bund and then is free for other operations. During transport, at least two operators and a supervisor are required to ensure a safe operation, who remain on site throughout the whole project to be able to adapt to unexpected schedule changes. After the load-in the monopile remains on the long term storage location until the assigned installation vessel comes for the pickup, which is called the load-out. In this case, a SPMT collects the monopile from the storage bunds and transfers it to quayside, to enable the installation vessel to pick up the monopiles with its onboard crane.

(a) *SPMT* (b) *SPMT used for monopile transport*

Figure 7: *Self Propelled Modular Transporter (SPMT)*

In order to speed up operations, temporary steel supports could be used to ease the loading and unloading operations during the load-in and load-out phases. The supports, as depicted in figure 8, are positioned at the quayside. The SPMT can just unload the monopile from the barge putting it on the supports and then leave for other operations, freeing the barge right away. Without those supports, the SPMT would have to move the monopiles one by one to the long term storage area and in such a case, the barge is bound to remain docked for longer time. This can be detrimental to the total project duration when the barge is not able to return to the manufacturing facility in time. However, temporary steel supports are expensive compared to costs related to barge delays, which raises the concern whether its use outweighs its costs.

(a) *Bottom support* (b) *Topside support*

Figure 8: *Temporary steel supports on quayside*

For the load-out phase, a similar reasoning can be done, but an additional set of supports is needed when a different quayside is used for docking the installation vessel. Also in this case, the absence of temporary supports can cause long waiting times for installation vessels. However, the waiting time for installation vessels is more costly than the barge ones. Tjaberings et al. (2022) identified that the day rate for a heavy lift vessel (HLV) is up to €250.000, about five times as costly as the day rate for a barge and fifty times the costs of a tugboat. Therefore, it is critical to conduct the load-out as quickly as possible, in order to reduce costs. In addition, installation vessels are limited to weather windows, as the installation operations offshore are highly weather dependent (Akbari et al., 2017).

All in all, the SPMT and the operational crew can be seen as critical resources since only a single SPMT is often present in marshalling ports, due to its high costs. In this thesis we aim at modelling these marshalling port operations and understand the right configuration to minimize the overall costs, related to equipment, personnel and support structures, and reducing waiting time costs. In this respect, we take the perspective of a heavy lifting and transport specialist such as Mammoet. The case study of Arcadis Ost 1 is used to investigate the conventional way of working for monopile handling in marshalling ports, which is introduced in section 3.2. Additional pictures to clarify the core concepts from this case are provided in appendix A.

3.2 Marshalling port in the Baltic Sea

Arcadis Ost 1 is a 257 MW offshore wind farm developed in the German territorial waters of the Baltic Sea, northeast of the island of Rügen. The wind farm will begin operations in 2023 and will supply enough green energy to power an equivalent of 290,000 households (Parkwind, 2023).

For this project, the monopiles have been produced at Steelwind in Bremerhaven in Northwestern Germany, see figure 9. Since the projected wind farm is located in the Baltic Sea and production and installation rate were not aligned, an alternative laydown area had to be found nearby the wind farm. This resulted in the selection of a marshalling port located on the Danish island Bornholm in the Baltic Sea, named the port of Rønne, see figure 9. Area rental rates, costs of construction, mobilisation costs of equipment, availability of laydown area and sailing distance to the wind farm location, are all factors that contribute to such a site selection.

This project is specifically relevant to investigate as the largest monopiles ever installed formed the foundations of this wind farm. The 28 so-called XXL monopiles weighted more

Figure 9: *Location Steelwind Nordenham, port of Rønne, Arcadis Ost 1 and the related transport route*

than 2,000 tonnes each, having a diameter of 9.5m and a length of up to 110m. Marshalling activities were conducted from February 2022 to June 2022, being the first time for all parties involved to handle such large monopiles. Developing new or adapted specialised equipment was important, as similar sizes are expected for future projects. This also indicates the possibilities for improvements, as the current way of working might not be the most efficient.

In the development of offshore wind parks, there is commonly one overall client, which was Parkwind Ost GmbH in the case of Arcadis Ost 1. This client is responsible for the planning, development, establishment and operational activities related to the offshore wind project. Since the client is mainly involved on the high level perspective of the project, external parties are employed for specific phases in the project, such as installation, production and, in the case of Mammoet, the onshore handling in marshalling ports.

From internal documentation at Mammoet regarding project costs, an overview has been made of the contribution of each cost factor towards the total project costs of Arcadis Ost 1. The results are presented in figure 10, which shows that only three sources of costs contribute to almost 90% of the total costs.

This overview provides valuable insights regarding project costs, for example that equipment rates contribute for approximately 44% to the total costs. This includes among others the rental rate of 68 SPMT axles and 2 power packs, but also the monopile saddles that were required on top of the SPMTs to ensure sufficient support during transportation. An additional six SPMT axles were required to remove the grillage before the load out could be conducted. Other equipment that was included in this cost section were load-spreading mats for the load in ramp and an assisting harbour crane for installation of these ramps.

The second largest cost contribution came from the personnel rates. Continuously, a crew was onsite to be ready to accommodate the arrival of barges for the load-in and vessels for the load-out. Two transport operators and one supervisor were onsite, performing the load-in only during day time and the load-out in both day and night time. Working at night time results in a pay rate of 150%.

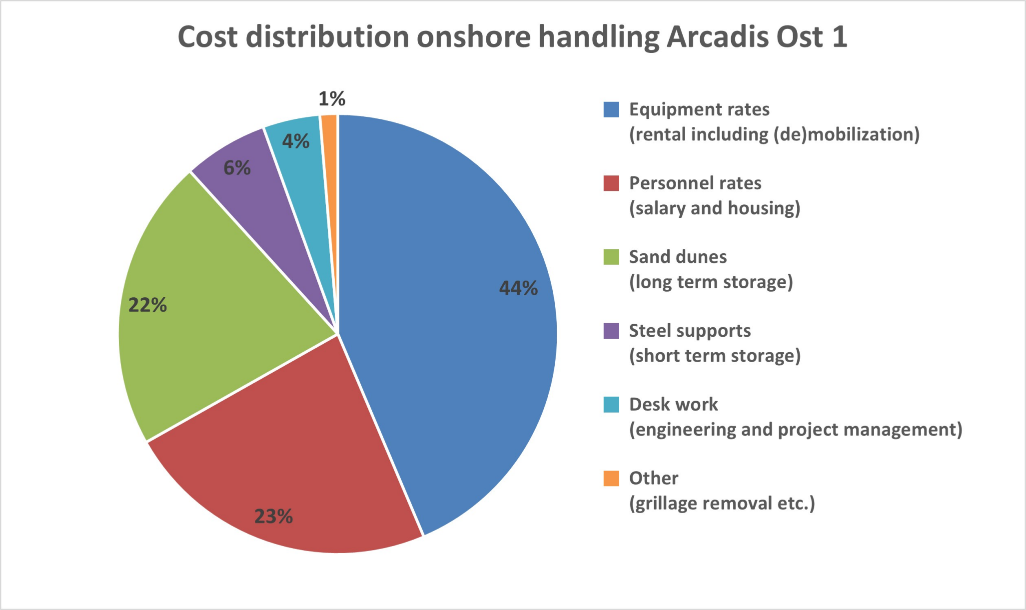


Figure 10: *Distribution project costs*

The third largest cost element was the design, construction and removal of sand dunes for monopile storage. This is not core expertise of a heavy lifting contractor, so an external local civil contractor had to be employed for the construction of these sand dunes. Large volumes of material were required for the construction of the sand dunes, to meet the load-bearing capacity of the marshalling yard. This increases the total material transport costs from the source to the marshalling yard. Also additional reinforcement layers and different materials for the top layer make the whole structure more complicated and costly then it may seem at first glance.

Since equipment, personnel and monopile storage contribute to almost 90% of the total costs, it might be most effective to start looking for cost reductions within these elements in order to reduce the total project costs. Therefore, these costs will be included as key performance indicator, on which will be further elaborated in section 4.2.

3.3 Assumptions and simplifications

Rossetti (2021) state that when developing a simulation model, the modeler attempts to represent the system in such a way that the representation assumes or mimics the pertinent outward qualities of the system. Therefore it is important to formulate the assumptions taken into account, that were required to adhere to the scope of this research. The most important ones have been listed below, in addition to the limitations in considered scenarios, presented in section 4.4. The assumptions regarding the input data has been treated separately in section 5.1 and appendix D.

- Ten supply shipments were considered, just as in the Arcadis Ost 1 project. However, in the real case not all barge transports were fully loaded, with 28 monopiles in total. For this model, both the barge and the installation vessel have a capacity of three monopiles, which are assumed to be fully utilized, summing up to a total of 30 monopiles.
- All monopiles are assumed to be identical, while in real life they have varying weight distributions, specifically designed for their assigned location, which requires more caution with the onshore transport. As a result, it is assumed schedule deviations due to for

example paint damage or defaults at sea do not affect the order of load-outs, while in the real case additional monopile movements were required upon this occasion.

- The installation vessel crane has a sufficient reach to pick up the outer one when three monopiles are positioned parallel to each other on the quayside.
- The SPMT is assumed to be immediately available when a monopile is picked up by the installation vessel crane. In reality this might take a few minutes, to be totally sure that for example the slings are secured.
- The investigated schedules and scenarios are assumed to be tight to such an extent that working at night is inevitable. In the real case, the barge was only loaded out during daytime and the installation vessel was provided with monopiles both at day and night.
- The option for steel or wooden saddles for the long term storage is not taken into consideration, although this might have benefits with regard to the currently applied sand dunes.
- It has been assumed that there was no crane onshore capable of performing load-in or load-out operations. For other projects, this might be the case as other offshore installation strategies will be applied, such as wet tow transportation.
- The quayside is assumed to enable the barge and installation vessel to arrive at the same time, see figure 11, leading to the SPMT being able to unload the barge while the installation vessel is still picking up monopiles from the supports.

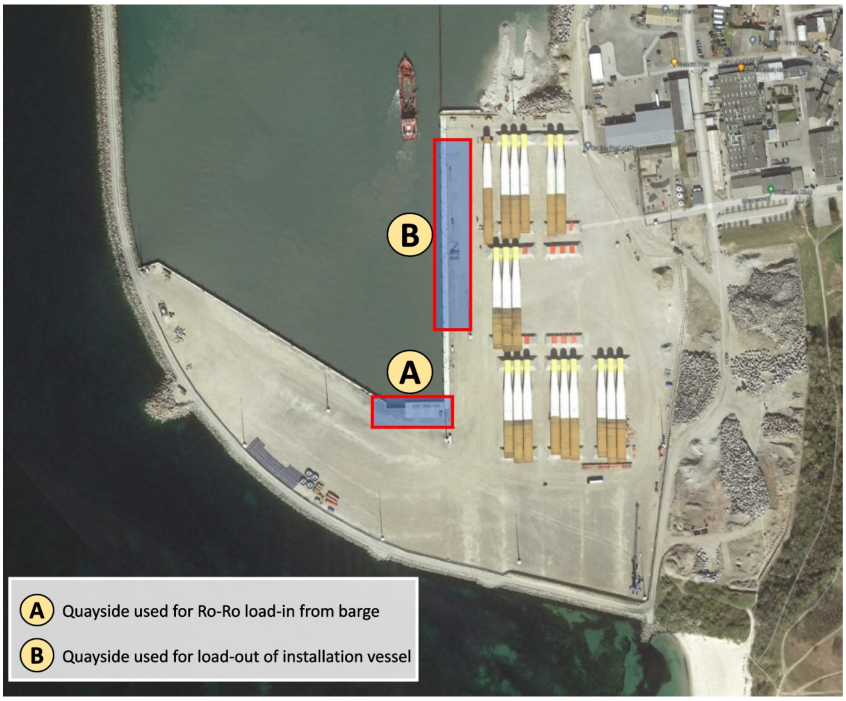


Figure 11: *Marshalling port of Rønne*

4 Methodology

This chapter starts with the clarification the choices leading to using a discrete event simulation for this study in section 4.1. Subsequently, the applied simulation methodology is introduced in section 4.2, after which section 4.3 dives deeper in the actual modelling of the simulation model. This chapter concludes with the implementing scenarios being explained in section 4.4.

4.1 Discrete Event Simulation (DES)

The problem described in chapter 3 is bounded by numbers such as component dimensions, activity durations, and transport distances, so therefore a quantitative study is adopted to solve the problem. Quantitative and causal relationships are important to formulate, to be able to describe the impact that these factors have on the onshore handling costs.

Manuj, Mentzer, and Bowers (2009) state that the size and complexity of logistics and supply chain systems, their stochastic nature, level of detail necessary for investigation, and the inter-relationships between system components make simulation modelling an appropriate modelling approach to investigate and understand such systems.

Shull, Singer, and Sjøberg (2008) identified characteristics on which simulation techniques can be distinguished, which are translated to a system classification by Rossetti (2021), presented in figure 12. Simulations that contain probabilistic components are called stochastic, in contrast to deterministic, where a fixed set of input parameter values results in output parameter values being similar for every simulation run. For the problem described in chapter 3, some of the input parameters are deterministic, such as the type and amount of resources used. Those could be seen as constraints or independent variables to the system. However, other parameters have a probabilistic component, such as mooring and transport duration and vessel arrival times, and are therefore stochastic. For stochastic simulation techniques, it is important to repeat simulation runs for a sufficient number of times in order to be able to observe the statistical distribution of output parameters. This is because the variation of input and intermediate variables is generated by random sampling from given statistical distributions (Shull et al., 2008).

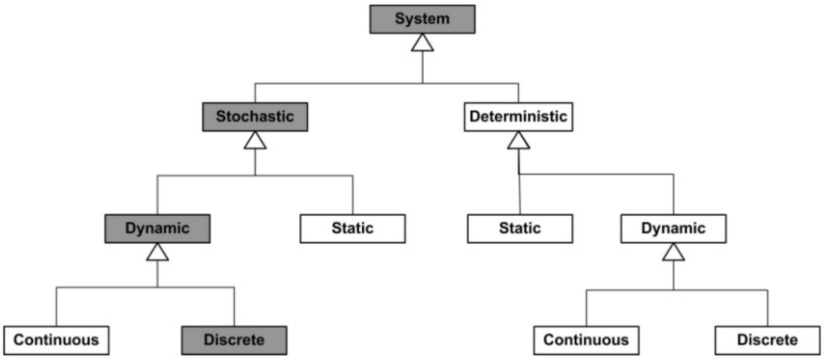


Figure 12: *System classification by Rossetti (2021)*

Dynamic simulation models, capturing the behavior of model parameters over a specified period of time, can be either continuous or event-driven. Continuous models, according to Shull et al. (2008), update the values of the model variables representing the model state at equidistant time steps based on a fixed set of well-defined model equations. However, as this study aims to investigate monopile handling from a broader perspective, only the total duration of the separate activities are relevant to determine the resulting project costs. Event-driven simulation models update the values of the model variables as new events occur (Shull et al., 2008), and is therefore appropriate to investigate logistic strategies within marshalling ports.

The most frequently used event-driven simulation technique is discrete-event simulation (DES) (Shull et al., 2008). These models are typically represented by a network of activities and items that flow through this network. The results from DES simulations are widely used for design and implementation tasks, operational analysis, resource allocation, advanced planning, and logistics management (Simio LLC, 2023). Several studies (Rodríguez et al. (2019), Barlow et al. (2015) and Tjaberings et al. (2022)) related to logistic operations have utilized this approach, supporting its effectiveness for analyzing onshore activities.

4.2 Simulation methodology

Rossetti (2021) presented a general methodology for applying simulation to problem solving, which has used for structuring the simulation process. Each phase is clarified in the section below.

Phase 1: Problem formulation

The first phase, problem formulation, not only revolves around the definition of the problem, of which the majority has been presented in chapter 3, but also around establishing measures of performance for evaluation and documenting model assumptions. Independent and dependent variables need to be specified, as dependent variables reflect the performance criteria and independent variables include the system parameters (Manuj et al., 2009). These variables have been used to construct the conceptual model presented in figure 13, in order to grasp the dependency of the inputs and the outputs of the system.

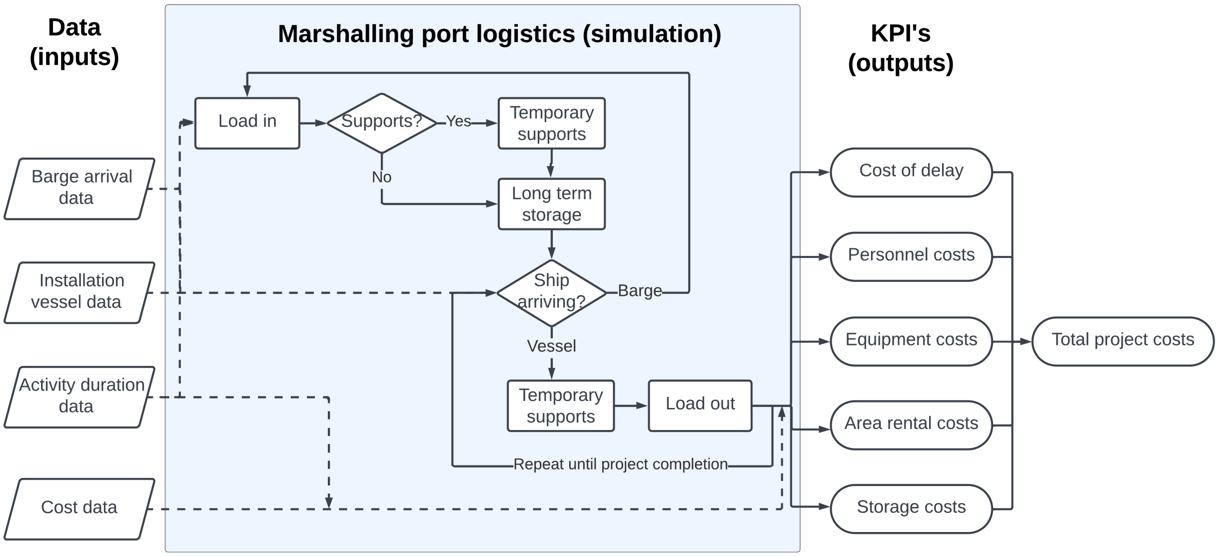


Figure 13: *Conceptual model of monopile handling in marshalling ports*

Based on the main cost contributors identified in section 3.2, key performance indicators have been established to monitor the characteristics of the system. For an analysis of the cost effectiveness of various strategies, all output values can be expressed as costs. The total project costs can be divided in total operational costs, including personnel and equipment, the total costs related to the temporary supports, and the total costs related to the long term storage bunds. The fines for the barge and vessel are taken into account, as well as their times, translated in costs. The exact computation of these KPIs will be discussed in section 5.

Phase 2: Model building
In the next phase, the conceptual model created in phase 1 has to be translated into the simulation model. Data about the system will be collected to use as input to the simulation model. Also verification and validation is performed in this phase, to determine whether or not the program performs as intended and adequately represents the real system (Rossetti, 2021). When building models, certain design alternatives are developed, either implicitly or explicitly. In this study, these are referred to as scenarios. In section 4.3, a detailed description of the modelling process is provided.

Phase 3: Experimental design and analysis
Subsequently, the worth of the alternative designs, generated in phase 2, is being evaluated with respect to problem objectives, when analysing experiments. These experiments, revolving around schedule variations in this study, are described in detail in section 5.3 and 5.4. This phase also includes conducting preliminary runs, to see how the simulation performs. When the final experiments are determined, the first results can be analysed to gather output and determine how this should be structured.

Phase 4: Evaluate and iterate
When applying the model to a real-life case study, the developed framework can be validated and the model can be improved by comparing the real-life situation with the output of the model. The process of evaluation and iteration is important to adapt the model to the desired level of complexity and realism compared to the observed case. This phase can consist of several iterative loops, before finding the right settings to conduct the final runs.

Phase 5 and 6: Documentation and implementation
Finally, the fifth and sixth phases, documentation and implementation, complete the simulation process. Documentation is essential when trying to ensure the ongoing and future use of the simulation model, and implementation recognizes that simulation projects often fail if there is no follow through on the recommended solutions (Rossetti, 2021). In this study, the implementation remains limited to recommendations, as real life implementation is within the power of heavy lifting contractors in the offshore wind industry.

4.3 Modelling

For converting the real life case study in a Discrete Event Simulation, the software Arena Simulation from Rockwell Automation was chosen, due to its wide adoption compared to other DES software. The availability of example models and literature related to this software enabled a steep learning curve while building the model, which was required with limited prior knowledge about the software. Arena is a commercial software program that provides access to an underlying simulation language called SIMAN through an environment that permits the building of models using a drag and drop flowchart methodology (Rossetti, 2021). In addition, the environment provides toolbar and menu access to common simulation activities, such as animating the model, running the model, and viewing the results.

The Arena model that has been created for the scenario with no supports for the load-in and one support for the load-out is included in appendix B. This section will go more into detail about the logistical sequence and modules that have been used to realise this simulation model.

The Arena simulation model starts with create modules where the arrival of the barge shipments is modelled. Each shipment has been represented in a separate module to be able to assign specific arrival times with the first creation entry. This is important to be able to process various schedules as described in section 5.1. The entity that is being created is a monopile, so each arrival contains three entities per arrival.

After the entities pass through the station module that marks the quayside, a timestamp is used to assign the entrance time to the system. A SPMT is modelled as a transporter, which is being requested once the entities get to the request module. The mooring of the ship is excluded in this process, since that concerns the scope of the barge operator, but the installation of the RoRo ramps, ballasting during the load-in, lifting the monopile in the SPMT saddles and removing the grillage is included in the allocated duration. The SPMT, two operators and a supervisor are included as resource for this module, in a seize delay release logic. This means that these resources are seized as long as the load in of a monopile takes, from which the related costs can be derived. These costs have been specified in the resource data definition, making a distinction between the busy/hour rate and the idle/hour rate. After the load-in, the transport of the monopile to the storage area is represented with the transport module, with the speed and distances being defined in the distance data set. At the storage area station, the transporter is “freed”, which means being released from a task and available for the transport of the next monopile. After three monopiles have been delivered, the barge is free to leave. It is being checked whether the barge has left within the predefined time limitations. If not, a fine is calculated according to the day rate of the barge and the additional hours that the barge had to stay docked. The total time is being recorded in the data output file as barge time, after which the entities are stored in the long term storage. This is inserted as a hold module, with a wait for signal condition included.

This signal is generated by a second “string” of modules, which is initiated with the arrival of the installation vessel. The installation vessel itself is modelled as an entity, with only one arrival per creation. The arrival time has been set half a day before the actual arrival, in order to generate the signal for the long term storage hold module to release three monopiles. After a 12 hour delay, the actual arrival time is marked with a timestamp module. An important note here is that the priority for the load-in is set to medium, so that using the SPMT for the load-out preparations is always a higher priority then for the load-in. What follows is the load-in, which is modelled as a process module. Once the monopiles are released from the long term storage, a SPMT is requested, this time with a high priority to be able to supply the installation vessel with monopiles as quickly as possible. After that, based on the scenario which is described in section 4.4, it is decided where the monopile has to be transported. In this case, where one support is used for the load-out, the support is filled with a monopile first. Another process and transport module are applied here, with different delay times. The monopile entity is queued in another hold module, representing the temporary support. The SPMT is “freed” and goes back to get the second monopile, which will be lifted directly from the SPMT by the installation vessel. The installation vessel will be waiting in a queue as part of a hold module itself, scanning for the condition that a monopile is available on the SPMT. Once this is the case, the installation vessel proceeds to perform the load-out. This is done with a pickup module, that collects an entity from a specified queue, in this case the hold module that represents the monopile on the SPMT. When the load-out starts, the SPMT is freed and collecting the third monopile, while in the mean time the installation vessel performs the load-out of the second monopile from the temporary supports. These load-outs are modelled as processes too, but without specific resources as that is out of the onshore handling scope. The vessel will wait for the third monopile to arrive in a similar fashion as the first monopile, in order to perform the load-out once this monopile is available. When the load-out of three monopiles is completed, it is being checked whether the installation vessel has been loaded in time, with a fine being calculated if this is not the case. The total time that the vessel has been docked, as well as the calculated fine are stored in the data output file. The whole system is concluded with a dispose module, where can be checked if indeed all the created entities have made it to the end of the simulation.

The other scenarios then the previously described one, TI0-TO1, vary in either the logistical sequence for the load-in or load-out or both. The related simulation models have been included in appendix B, while the implemented scenarios are being described in section 4.4.

4.4 Implemented scenarios

For the purpose of finding the most cost efficient strategy in the onshore handling of monopiles, three main factors that influence the system have been chosen to be varied. The amount of temporary supports, the amount of SPMTs and the choice of working only during the day or also at night time are included. By combining these variations, several scenarios (shown in figure 14) can be constructed, of which the simulation output can be compared if all other variables are being kept constant.

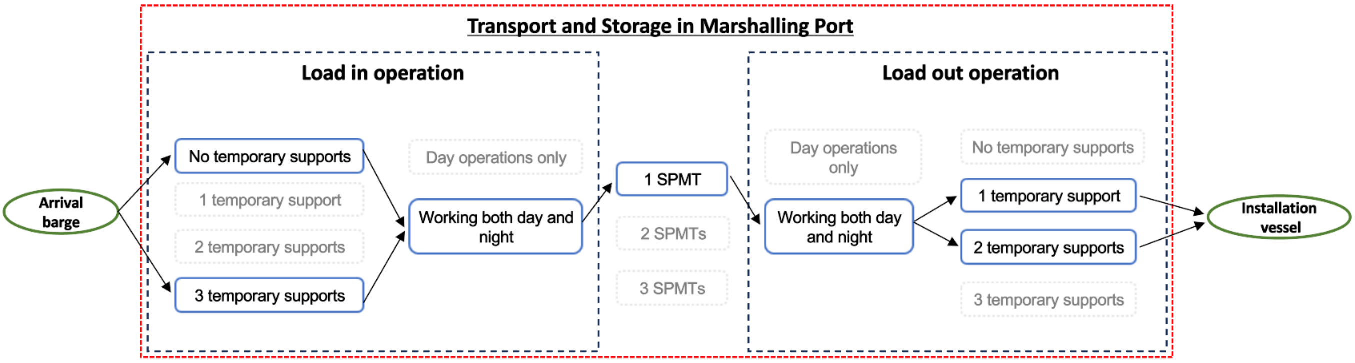


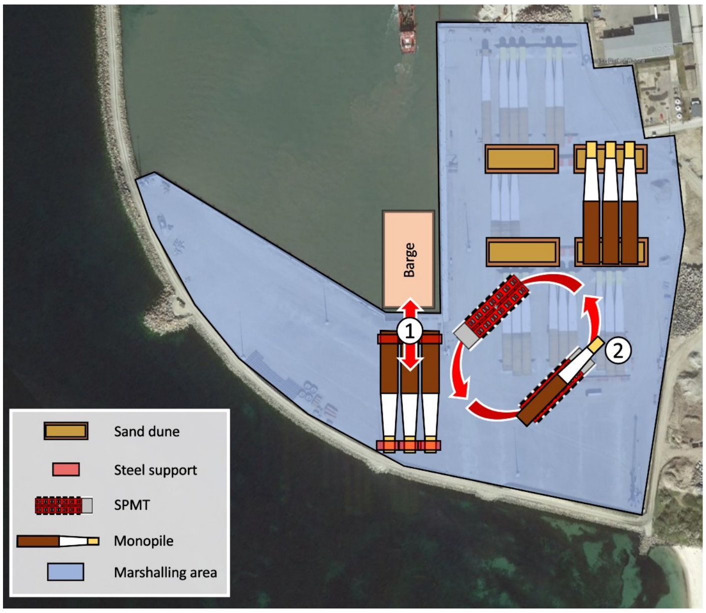
Figure 14: *Potential scenario choices*

Since variations in schedule changes will be investigated and due to time restrictions for this research, it has been decided to keep the number of scenarios limited. If all options presented in figure 14 would have been included, it would result in 192 scenarios. A selection has been made based on the effect on the logistical sequence and the feasibility. As one of the main parameters will be tightening the supply schedule, it is assumed that including features that are nice to have is unrealistic, like performing day operations only. The goal is to push the system to the limits, so therefore requiring to work at both day and night is assumed to be crucial. For understanding the dynamics of the system, only using one SPMT might be a starting point, since the current project was operated in a similar way. An extension of the research could include looking at deploying multiple SPMTs, as well as other variations of temporary supports.

For the load-in, it is believed that the main impact on the logistical sequence is achieved when comparing no temporary supports with three temporary supports. With none, the monopiles have to be transported from the barge directly to the storage bunds for long term storage, while in the mean time the barge has to wait for the SPMT to be available to pick up the next monopile. This choice is referred to as “temporary support in zero”, or TI0 in the model and experiments.

When the monopiles can be temporarily placed either directly on the quayside or relatively close by, the SPMT will be released quicker and subsequently the barge will be fully unloaded quicker, enabling it to depart earlier for a new batch of monopiles. This logistical sequence uses three supports for the load-in and therefore is referred to as TI3 in the models. Figure 15 schematically represents the order in which the operations are conducted for this scenario choice.

For the load-out, it is of importance that the monopiles are available for the installation vessel to be lifted. Therefore, having no temporary supports at all might not be a realistic option as the vessel would have wait for the SPMT to pick up monopiles one by one. Between one or two temporary supports is the most noticeable difference in sequence, as between two and three supports there is no difference in time for the installation vessel, only in availability

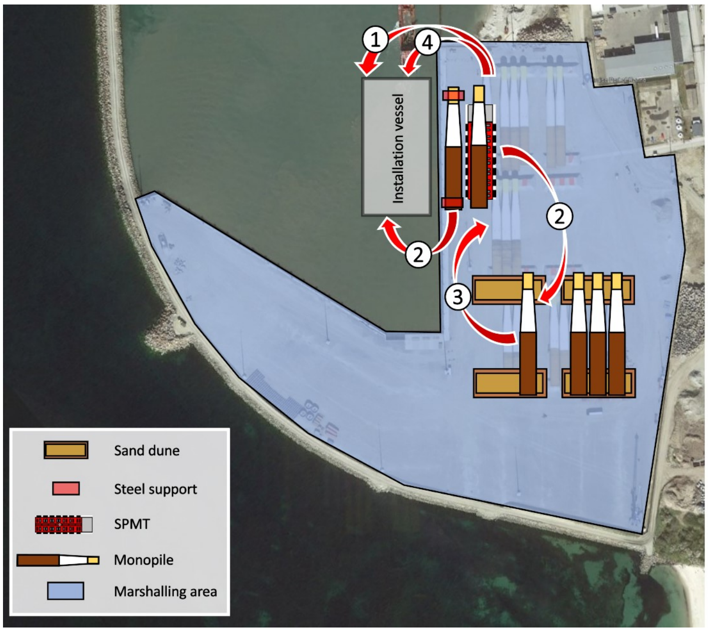


① Monopiles are being loaded in onto supports in the vicinity of the quayside to release the barge sooner.

② Once the barge has left and the SPMT is available, the monopiles will be transported from the supports to the long term storage.

Figure 15: *Logistical sequence TI3*

of the SPMT. The first option, with one support for the load-out, is referred to as TO1. This logistical sequence, in combination with zero supports for the load-in, was applied in the case of Arcadis Ost 1. Figure 16 shows the sequence in which the load-out activities are performed, with for example the load-out of the second monopile and picking up the third one by the SPMT are parallel performed activities.



① The first monopile is picked up directly from the SPMT by the installation vessel crane.

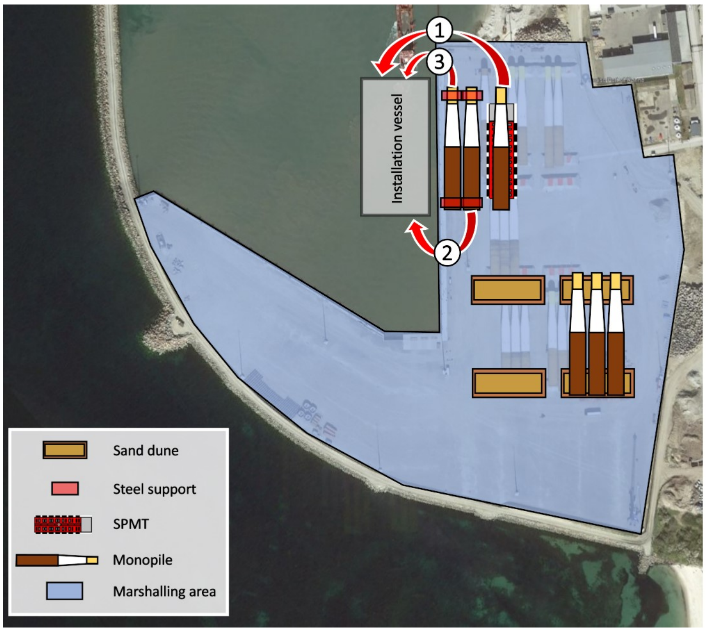
② The second monopile is picked up from the supports on the quayside. In the meantime, the SPMT goes to pick up the third monopile from the long term storage.

③ The SPMT returns with the last monopile, the installation vessel waits for the SPMT to arrive.

④ The third and last monopile is picked up directly from the SPMT by the installation vessel crane.

Figure 16: *Logistical sequence TO1*

The last scenario choice that has been considered consists of two supports for the load-out, referred to as TO2. The related logistical sequence has been graphically represented in figure 17, with the SPMT being readily available immediately after the installation vessel crane lifts the first monopile. The abbreviations of the four combinations of the presented scenario choices, namely TI0-TO1, TI0-TO2, TI3-TO1 and TI3-TO2 have been used in the remainder of this thesis to refer to specific scenarios.



① The first monopile is picked up directly from the SPMT by the installation vessel crane. This means that the SPMT is available for other tasks right away.

② The second monopile is picked up from the supports on the quayside by the installation vessel crane.

③ The third and last monopile is picked up from the second set of supports.

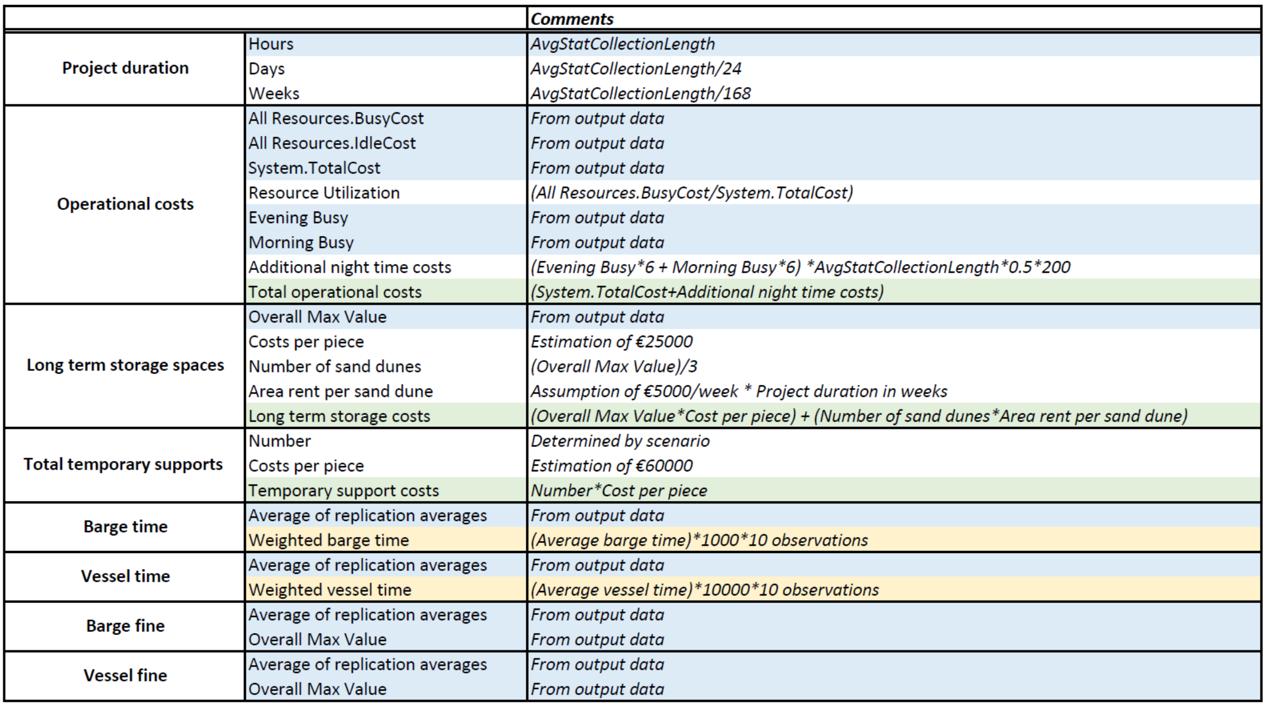
Figure 17: *Logistical sequence TO2*

5 Numerical results and data analysis

Once the simulation runs are completed, Arena Simulation collects user-defined statistics in a output data file, from which the most relevant statistics were derived. First of all, the average statistics collection length was monitored in hours, to enable calculations regarding the project duration. Furthermore, for both the installation vessel and the barge the total (waiting) time was registered. After a predefined threshold had been exceeded, a fine was calculated. For the barge, this threshold has been set at 15 hours and for the installation vessel at 5 hours. The magnitude of the fine is based on the day rate of the ship per hour. Additionally, the time and related costs for using the defined resources in the system was monitored with the .BusyCost and .IdleCost parameter. The defined resources, including the SPMT, two operators and a supervisor, contained a busy/hour cost rate and idle/hour cost rate on which the cost output was based.

In order to realistically include the night rate for the personnel, the frequency module kept track of the times that the resources were busy either before 6 A.M. or after 6 P.M. Subsequently, the percentage of the time that the resources were busy was multiplied by the total night hours and half of the day rate of the personnel. When being added to the costs from working at a day rate, this represents a realistic total including the costs from working at night time. To conclude, the required amount of long term storage spaces was determined by monitoring the overall max value for the long term storage queue.

Concerning the costs and time output data, the average of replication averages is taken as the main value, but the standard deviation of replication averages, minimum and maximum replication average and overall min and max value is registered as well. From this data, which is collected for each schedule variation, results are summarized in an overview per scenario, where additional calculations are made concerning for example area rent and resource utilization. The contents of such an overview are shown in figure 18, with in blue the data from the output file, in green the costs related to operations and storage, and in yellow the costs related to waiting times. The related computations are included in the comments column.



		Comments
Project duration	Hours	*AvgStatCollectionLength*
	Days	*AvgStatCollectionLength/24*
	Weeks	*AvgStatCollectionLength/168*
Operational costs	All Resources.BusyCost	*From output data*
	All Resources.IdleCost	*From output data*
	System.TotalCost	*From output data*
	Resource Utilization	*(All Resources.BusyCost/System.TotalCost)*
	Evening Busy	*From output data*
	Morning Busy	*From output data*
	Additional night time costs	*(Evening Busy*6 + Morning Busy*6) *AvgStatCollectionLength*0.5*200*
	Total operational costs	*(System.TotalCost+Additional night time costs)*
Long term storage spaces	Overall Max Value	*From output data*
	Costs per piece	*Estimation of €25000*
	Number of sand dunes	*(Overall Max Value)/3*
	Area rent per sand dune	*Assumption of €5000/week * Project duration in weeks*
	Long term storage costs	*(Overall Max Value*Cost per piece) + (Number of sand dunes*Area rent per sand dune)*
Total temporary supports	Number	*Determined by scenario*
	Costs per piece	*Estimation of €60000*
	Temporary support costs	*Number*Cost per piece*
Barge time	Average of replication averages	*From output data*
	Weighted barge time	*(Average barge time)*1000*10 observations*
Vessel time	Average of replication averages	*From output data*
	Weighted vessel time	*(Average vessel time)*10000*10 observations*
Barge fine	Average of replication averages	*From output data*
	Overall Max Value	*From output data*
Vessel fine	Average of replication averages	*From output data*
	Overall Max Value	*From output data*

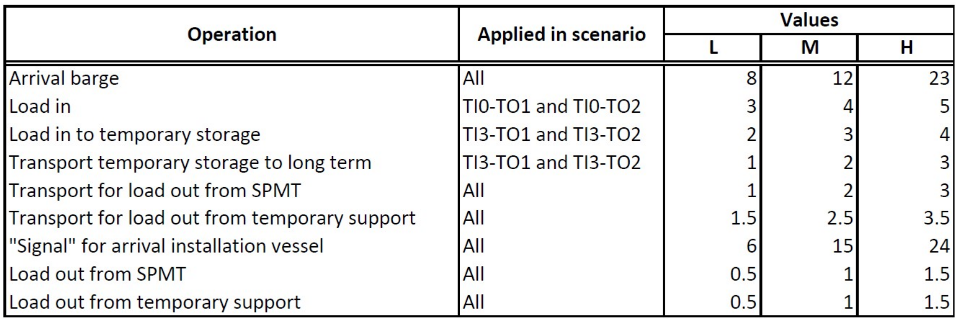
Figure 18: *Summarised output data*

5.1 Experimental setup

To analyze the effect of reducing project duration, we compare total costs and benefits across varying schedules. This involves adjusting arrival times for the barge and installation vessel while keeping other parameters constant, including arrival uncertainties. By connecting these schedule changes to the scenarios in section 4.4, we assess the resilience of each scenario to schedule adjustments. To comprehensively understand schedule impacts, two distinct experiments are conducted.

5.1.1 Data collection and system input

Most data that has been used for input in the system has been retrieved from internal documentation from Mammoet. Both current and previous projects have been analysed to gather insights in the methods and equipment that is used for load-in and load-out operations, especially for monopiles. Values that were not specifically documented, were discussed with experienced experts from Mammoet to gather realistic estimations. Estimations regarding duration of certain activities in the simulations are represented with a triangular distribution, which is often used in business decision making and project management. It is a continuous probability distribution with a minimum value (L), maximum value (H) and most likely value (M). The durations that were used in the simulation models are included in figure 19. The other assumptions that were included in the model are presented in appendix D.



Operation	Applied in scenario	Values		
		L	M	H
Arrival barge	All	8	12	23
Load in	TI0-TO1 and TI0-TO2	3	4	5
Load in to temporary storage	TI3-TO1 and TI3-TO2	2	3	4
Transport temporary storage to long term	TI3-TO1 and TI3-TO2	1	2	3
Transport for load out from SPMT	All	1	2	3
Transport for load out from temporary support	All	1.5	2.5	3.5
"Signal" for arrival installation vessel	All	6	15	24
Load out from SPMT	All	0.5	1	1.5
Load out from temporary support	All	0.5	1	1.5

Figure 19: *Overview activity duration in hours*

5.1.2 Replication parameters

Due to time limitations for conducting this study, it has been chosen to run 1000 replications per scenario per schedule variation. This comes down to 16 runs for experiment 1 and 12 runs for experiment 2. Furthermore, the base time units were set to hours, with the hours per day set to 24. The replication length was set to infinite, in order for Arena to run the simulation to completion, with the replication length based on the total project duration related to each specific schedule variation. This was done to avoid the computation of additional idle costs for the equipment and personnel on days before or after the project.

5.2 Validation and verification

The Discrete Event Simulation (DES) model assumptions, as well as parameter values, have firstly been validated by discussion with experienced experts from Mammoet. After implementation, the whole model has been walked through again, iterating values and logistical sequences that deviated from reality. To validate whether the output of the simulation is comparable to the case study of Arcadis Ost 1, a similar schedule was applied. Scenario TI0-TO1 was used here, since in the original project only one temporary support was used to facilitate the load-out operations. For the sake of including realistic costing, only the handling scope is taken into account, so the area rental costs and delay related costs are excluded. In the real case, these cost were the scope of external parties, although for this study those cost contributors are included. Nevertheless, the equipment rates and personnel rates can be compared. Combined, they contributed to 67% of the total project costs in Arcadis Ost 1, according to figure 10. The simulation results, which have been included in appendix E, present a value of 63%, by calculating the fraction of the operational costs compared to the total project costs. So although in the simulation also external costs factors are taken into account, the contribution of the main cost components is comparable. This enables the simulation to be used for studying the main trends, but should raise awareness when observing exact cost comparisons.

5.3 Experiment 1: Overlapping arrival and installation schedule

This experiment aims to determine the extent of overlap between supply and demand in the marshalling port system, affecting the total time vessels are docked during load-in or load-out. Barge arrivals are set at three-day intervals to allow timely load-in without disruptions. The installation vessel's schedule is kept similar to its pattern during the construction of Arcadis Ost 1, representing a system constraint. The first schedule variation has no overlap, resulting in a 61-day project duration. The second, "Quarter overlap," has three barge arrivals overlapping 25% with a 52-day total duration. The third variation overlaps schedules by half, lasting 43 days. The fourth, "Three-quarter overlap," has a single barge arrival before installation, yielding a 34-day project duration. A schematic visualisation of how these arrival schedules are overlapping and how these are used in this experiment is presented in figure 20. The exact schedules and related dates for this experiment are included in appendix C.

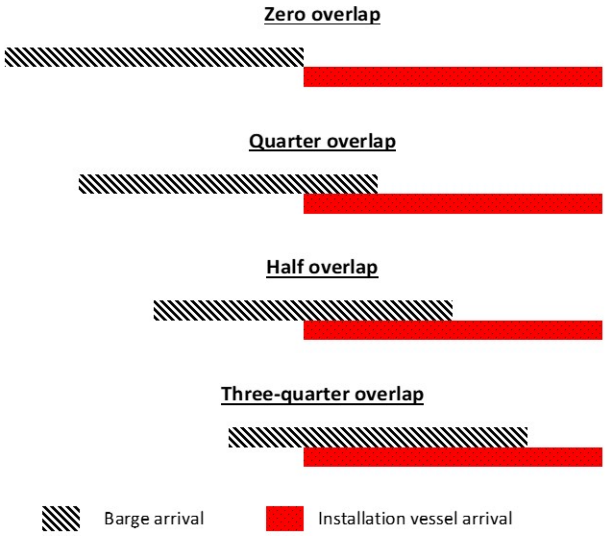


Figure 20: *Schematic visualisation of schedule overlap*

For all scenarios, the total operational costs, including equipment and personnel, the long term storage costs and the costs related to the temporary supports has been summed up. This total can be seen as the basic project costs, which is compared for all schedules from experiment 1 in figure 21.

The first trend that can be observed is that schedule variations show a significant decline in total operational costs the more overlap the barge arrival and installation vessel departure have. The second trend is that for every schedule, the operational costs increase with the amount of equipment. Combining these trends learns that the benefits from shorter schedules

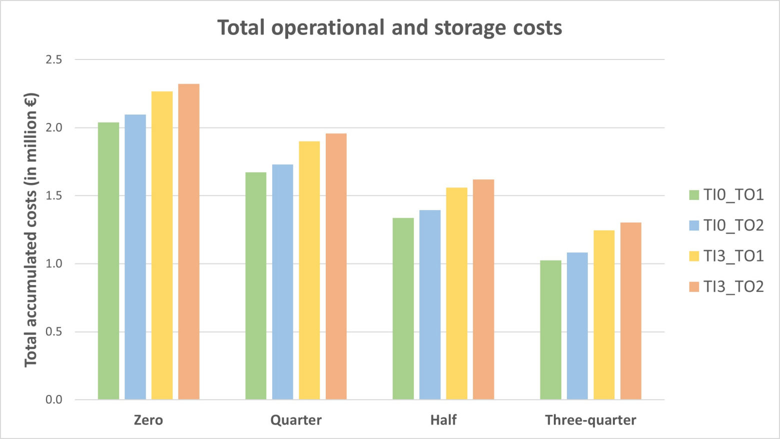
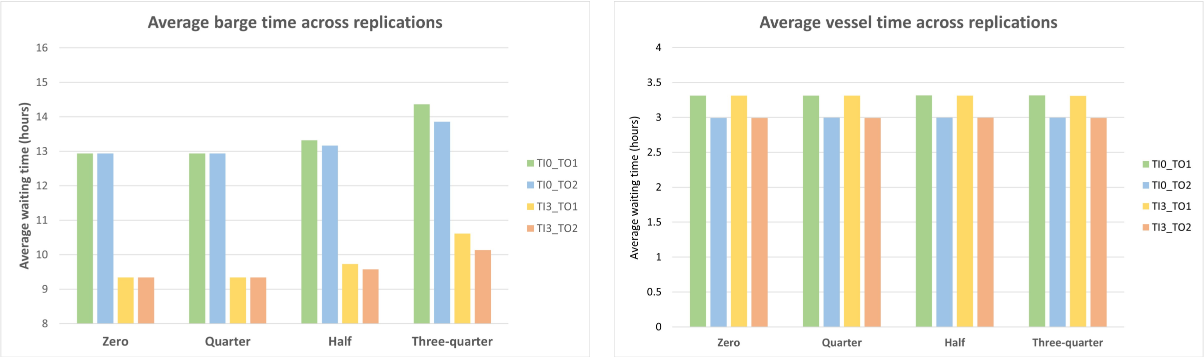


Figure 21: *Operational and storage costs*

have more impact then reducing the usage of equipment. Furthermore, observing this graph tells that scenario TI0-TO1, the scenario without temporary supports for the load-in and with one temporary support for the load out, scores best in terms of cost reduction over all schedules. It can be seen that only half of the costs are required for a schedule with three-quarters overlap compared to a schedule with zero overlap for scenario TI0-TO1, saving approximately one million euros. These results sound promising, but only accounts for the basic project costs and not the costs related to delays or waiting times of the ships.



(a) *Barge time* (b) *Vessel time*

Figure 22: *Average times across replications*

Those are included in figure 22, where the total waiting time of the ships is presented in hours. In figure 22a an increase of about an hour can be detected in average barge time when comparing TI0-TO1 for the "half" schedule and the "three-quarter" schedule. Since this is an additional hour per single load-in, so over the total project an additional ten hours. Another trend that can be seen is that the differentiation between the different scenarios starts to become apparent when the schedule becomes more critical. For the "three-quarter" schedule for example, TI0-TO2 scores slightly better in terms of barge waiting time, while this effect does not appear for the other schedules. However, the main observed trend here is that more equipment leads to shorter waiting times for the barge. In figure 22b, less variation is detected, except from the approximate 20 minute load-out gain from having two supports at the load-out quayside. This can be explained from the fact that in the simulation model, the vessel has been entitled the highest priority, so delays there are not common.

For the barge times, the outcomes presented in figure 22a have been analysed with regard

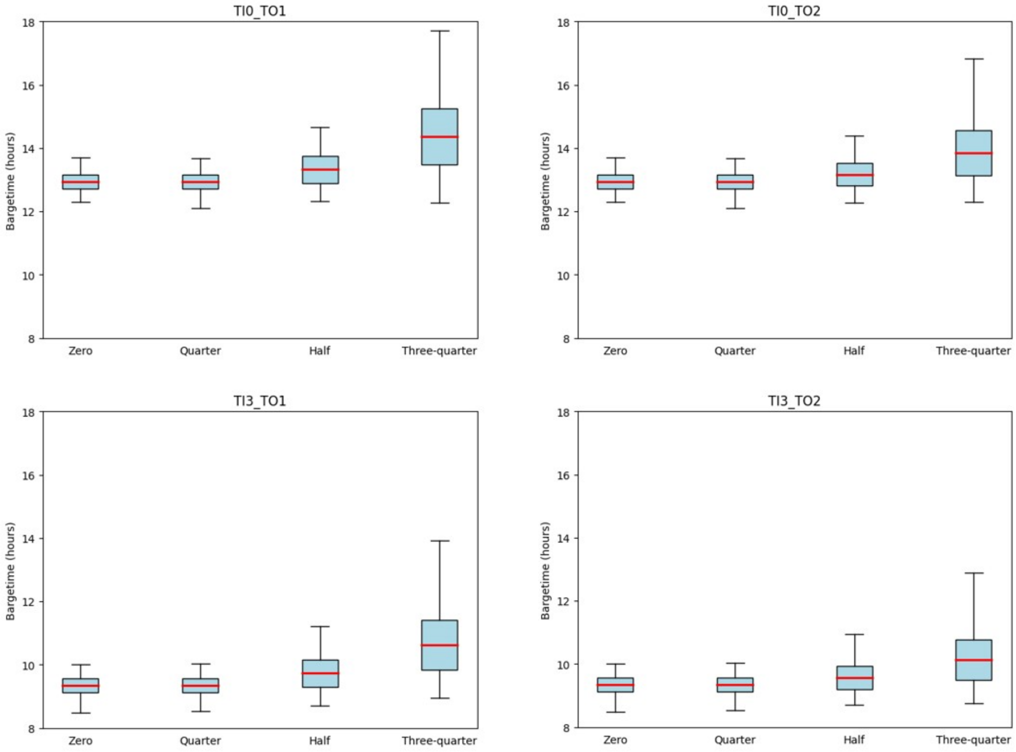


Figure 23: *Mean, standard deviations and extreme values for replication averages of barge times across experiment 1*

to their uncertainties in figure 23. Be aware that both for both graphs the horizontal axis starts at 8 hours to be able to increase visibility of the deviations. The general observed trend from figure 23 is that with the increase in overlap between schedules, the standard deviation of the barge times increases as well. Having two supports for the load-out seems to slightly decrease this uncertainty.

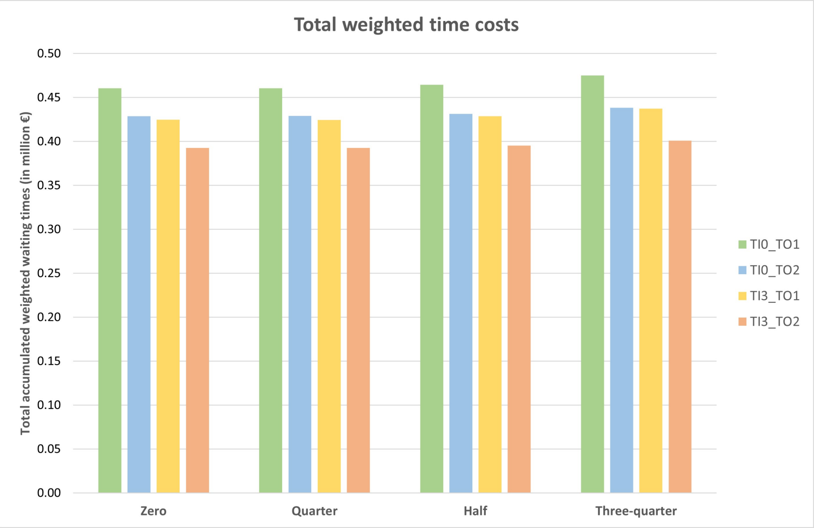


Figure 24: *Accumulated weighted waiting costs from barge and installation vessel*

In order to translate the times from figure 22 into costs, these times have been multiplied with the amount of observations in the simulation and the day rate of the ships, to be accumulated as the total weighted times which is shown in figure 24. A trend can be identified that is the opposite of what is seen from the project costs in figure 21, which means that the delay costs decrease with the amount of supports. An interesting aspect is that for almost every schedule, the delays for TI0-TO2 and TI3-TO1 are almost identical.

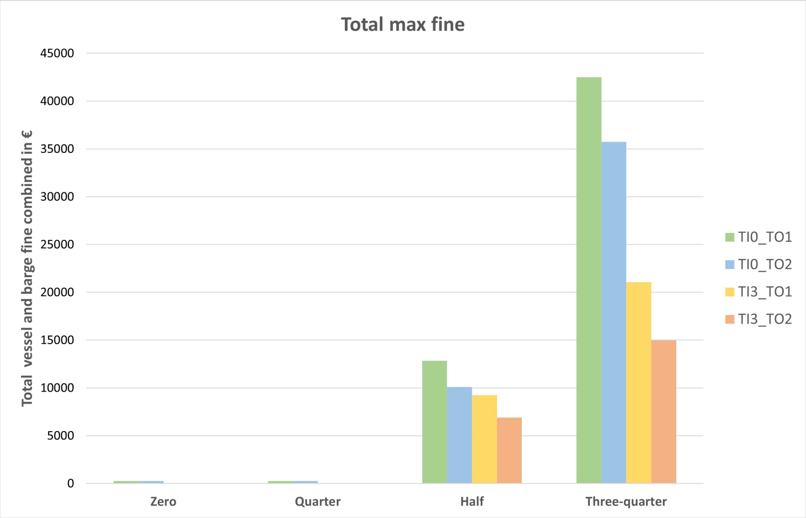


Figure 25: *Total maximum fine across replications*

In figure 25, the total maximum value across replications for both the barge and the installation vessel presented. Here it can be clearly seen that for the "three-quarter" schedule, the TI0-TO1 scenario generates the highest fines. Also the differentiation between scenarios is the largest for that schedule. It should be noted that these results are in particular very dependent on the assumptions and input data regarding the magnitude of the fines. Also the maximum value is taken here to give an indication of the worst case scenario, as the fines are incidental costs.

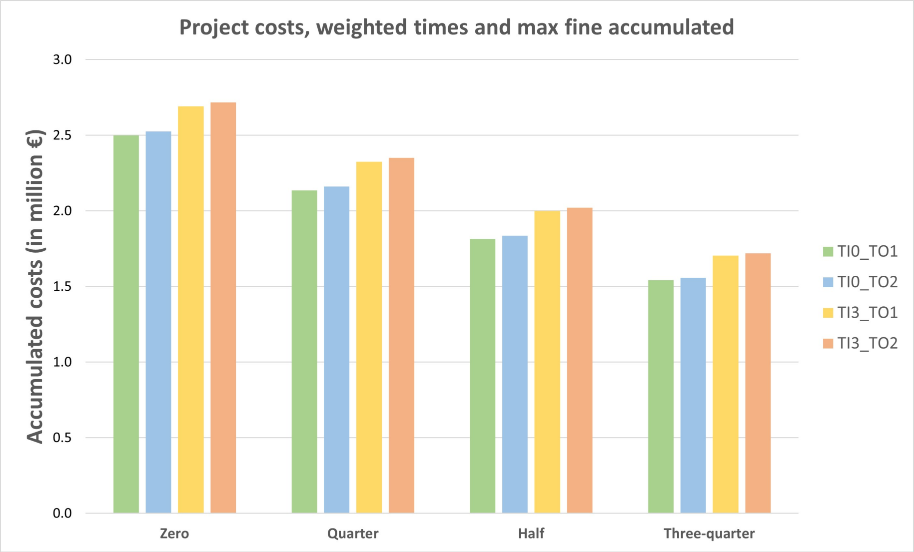


Figure 26: *Accumulated costs experiment 1*

The results from figure 21, figure 24 and figure 25 have been accumulated and merged into one overview, which is presented in figure 26. The total maximum fine has been added here to simulate the worst case scenario in terms of costs. This way, the costs for fines are counted in addition to the total weighted times, since the maximum fine is an outlier, while the weighted times are an average. Based on these conditions, it is found that scenario TI0-TO1 is still the most cost-competitive scenario, in the “three-quarter” schedule. This schedule is overall the most cost-competitive, also for the other scenarios. TI3-TO2 in a “three-quarter” schedule is for example still cheaper then TI0-TO1 in a “half” schedule. The scenarios with zero supports for the load-in and the ones with three supports for the load-in have grown closer to each other compared to figure 21, but still the same schedule/scenario combinations are the cheapest options. Apparently the weighted times and maximum fines do not weigh up against the costs that are made for additional supports.

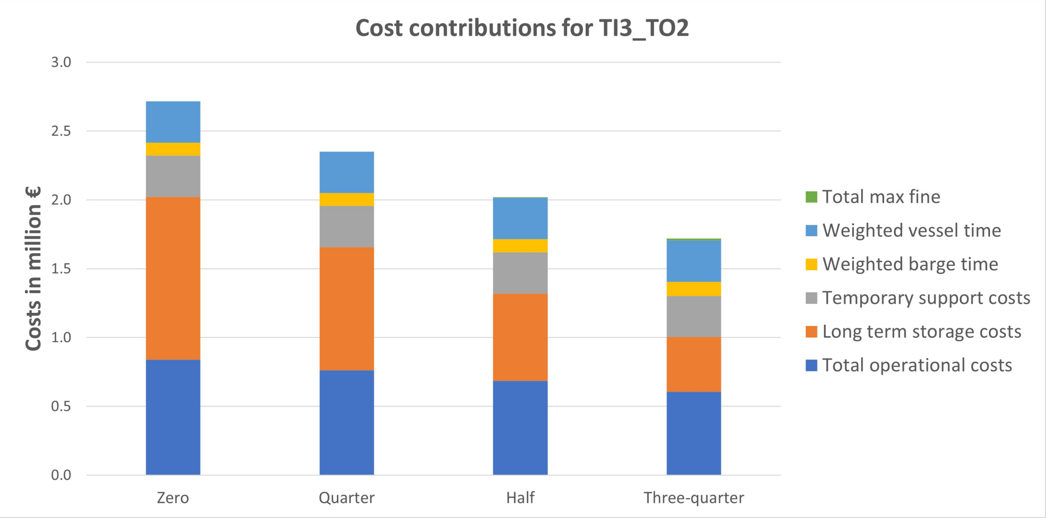


Figure 27: *Cost contributions for scenario TI3-TO2*

The last graph that has been made from the data of experiment 1 is figure 27, were a breakdown from the cost distributions is visualised for scenario TI3-TO2 to get insights in which cost factor contributes the most to the cost reductions as a result of a more compressed schedule. It can be seen that the total operational costs decline quite a lot, but the most noticeable change is the decline in long term storage costs. This can be explained with both the area that has to be rented and the amount of storage bunds decreases with the maximum amount of monopiles that has to be stored in the marshalling port.

The summarised output data that was being used for the generations of the graphs for experiment 1 is included in appendix F.

5.4 Experiment 2: Timing of arrival

To address systematic errors from experiment 1, we analyze different timings of barge arrival relative to the installation vessel. Variations include a barge arrival one day before, on the same day, and one day after the installation vessel's arrival. This helps quantify the impact of timing differences and provides insights for future contract considerations. The schedule used as a source for the input values for this experiment, has been graphically displayed in figure 28. The more detailed specific schedule has been included in appendix C.

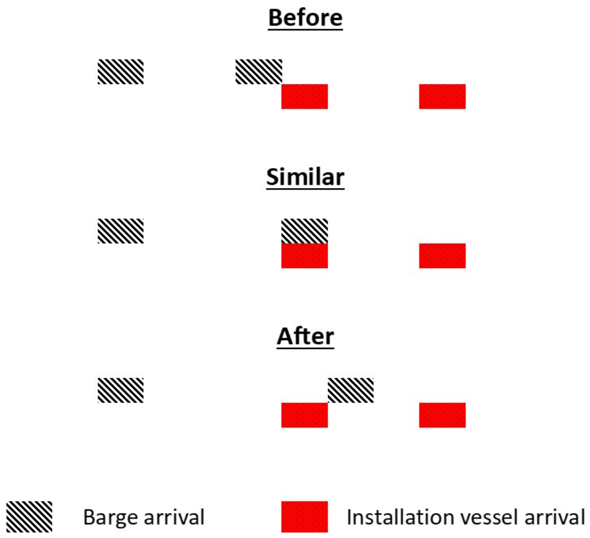


Figure 28: *Schematic visualisation of arrival timing*

For the second experiment, a simplified schedule with two barge arrivals and two installation vessel arrivals has been applied to the scenarios, with the purpose of investigating the influence of the timing of the barge with respect to the installation vessel. Three moments, before, similar and after the installation vessel arrival, have been taken into account, of which total operational and storage costs are presented in figure 29. With the "before" schedule, the total of six monopiles have to be stored simultaneously in the marshalling port, requiring an extra sand dune for the storage of three monopiles. This could be an obvious explanation for the higher costs for this schedule, as all other elements like project duration are kept the same.

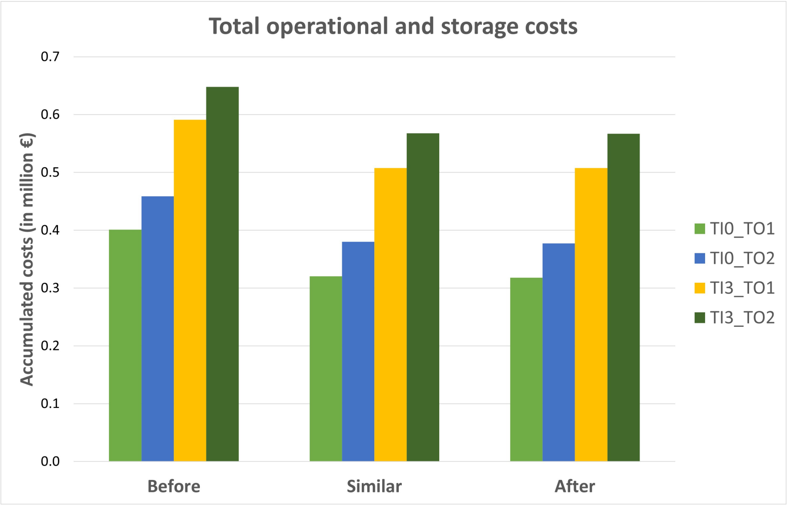


Figure 29: *Operational costs experiment 2*

More importantly in this experiment is the average barge time across replications, to compare which order of arrival is preferred, shown in figure 30. Please note that the horizontal axis starts at 8 hours instead of zero to improve visibility. Here a clear distinction can be made between the critical schedule and the non critical schedule in terms of differentiation between scenarios. For the “similar” schedule, the difference in waiting time for each scenario is unique while for the “after” schedule it is clear that the TI3 scenarios cause a time reduction of approximately 3.5 hours. In the “before” schedule, those scenarios even cause a time reduction of four hours compared to the scenarios without temporary supports for the load-in. Note that purely based on the barge time, the “similar” schedule performs the worst in average throughput time for every single scenario.

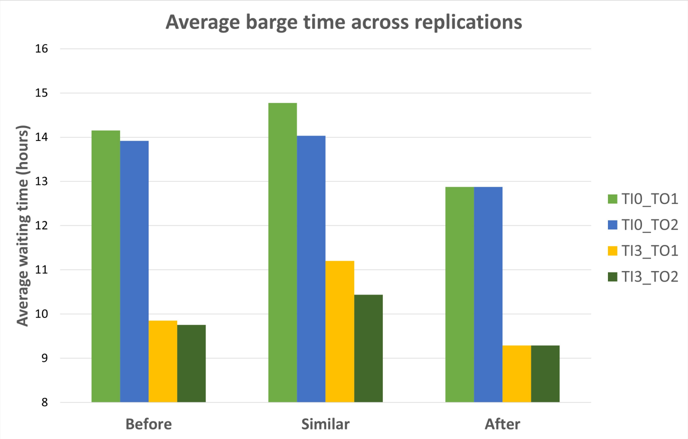


Figure 30: *Average barge time experiment 2*

Again, based on the results presented in figure 30, the standard deviations and extreme values have been analysed in figure 31. It can be seen that the distribution of the barge times for the “after” schedule remains straightforward for all scenarios, as the resources are not conflicting for this schedule. Also for the scenarios with no supports for the load-in, the standard deviations are relatively higher for the “before” schedule then the “similar” schedule.

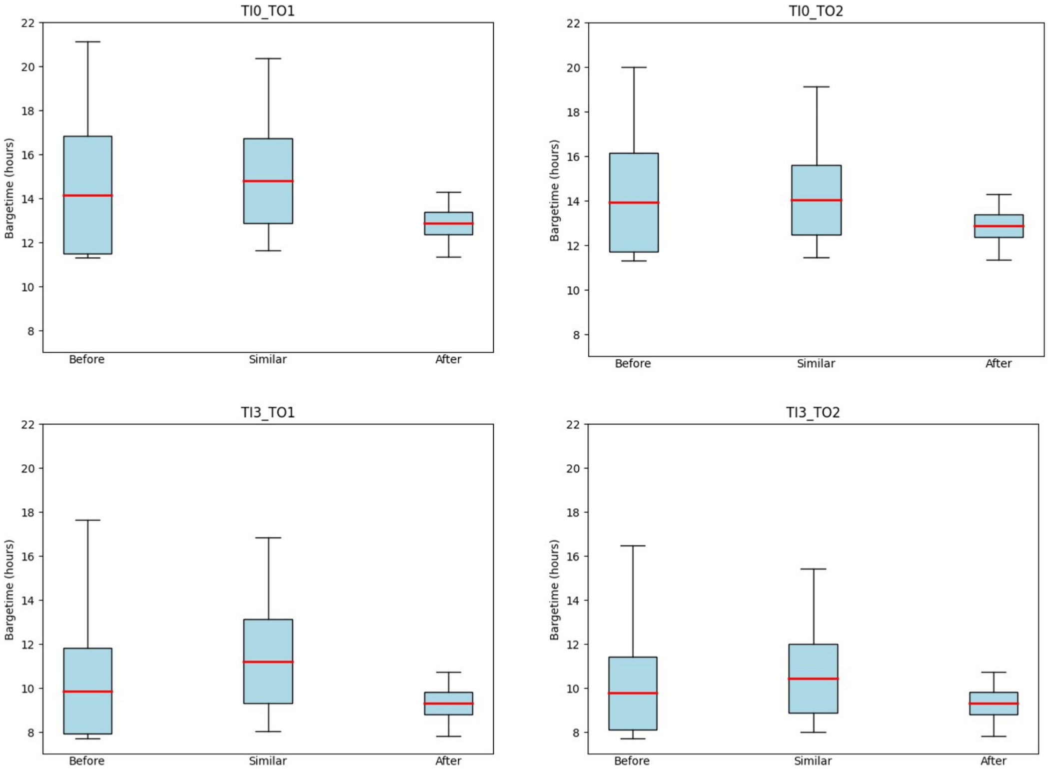


Figure 31: *Mean, standard deviations and extreme values for replication averages of barge times across experiment 2*

The total maximum fines for the second experiment is shown in figure 32. The main observations that stand out from this graph are that more equipment helps to reduce the total maximum fines, and that an arrival of the barge after installation vessel departure helps to almost completely get rid of fines.

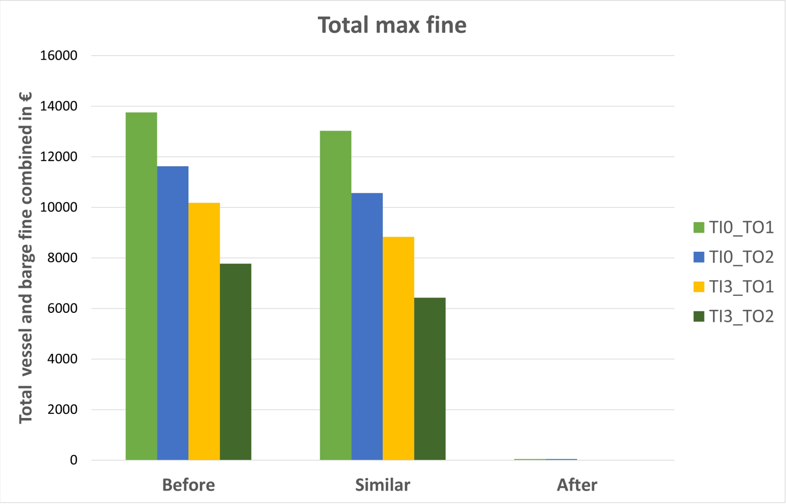


Figure 32: *Total maximum fine across replications*

In figure 33, the operational costs from figure 29, weighted time costs derived from figure 30 and the maximum fines from figure 32 have been accumulated, the same way it has been done for experiment 1 in figure 26.

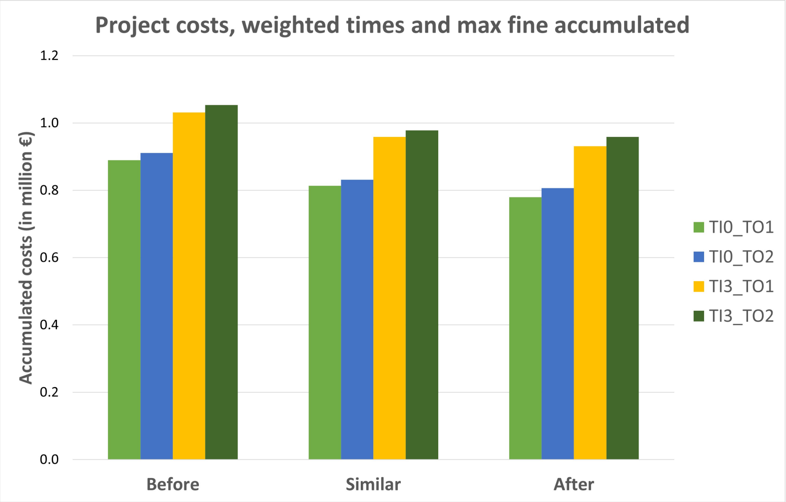


Figure 33: *Accumulated costs experiment 2*

Based on these totals, again scenario TI0-TO1 comes out as the best option, this time in the "after" schedule. However, a comparison based on costs might give a distorted picture here as the fines are in a different order of magnitude then the project costs. Therefore the choice for a certain scenario might be less relevant then the schedule choices. The most important notion here is that when there is a choice for contractors and planners, an arrival of the load-in shipment after the load-out shipment is always preferred. The output data that has been used for the generation of these graphs is provided in appendix G.

6 Discussion

In this chapter, the limitations and generalisability of this study are discussed in section 6.1. Furthermore, the Management of Technology perspective is presented in section 6.2. The managerial relevance follows in section 6.3, to conclude with future research recommendations in section 6.4.

6.1 Limitations and generalisability

Since this study revolves around a case study, the generalisability is bounded by the assumptions and the conditions that the simulation model is build on. These conditions should always be reconsidered when this model is being applied to other cases. An example would be the type of load out, which could be conducted in various ways. A wet-tow for example would also require one or two cranes onshore to be able to lift the monopile in the water. Additional activities would be required onshore to make this type of load out happen, like putting plugs on the sides of the monopile to enable it to float. These devices and the crane rental provides extra costs to the onshore scope, but also reduces the criticality of the load-out durations. Since the monopile now will be transported by a tugboat with an significantly lower day rate then the expensive installation vessel, delays are less costly. Several dynamics of the simulation model would not be the same as for the load-out of an installation vessel anymore, and would require a thorough walk through to make the simulation model applicable to different load-out or load-in methods.

Other limitations are the amount of schedules that have been fed through the model. Having more intermediate steps or various intervals between the barge arrivals instead of only the three day interval for experiment 1, might reveal more insightful correlations than the current experiments. Also the fixed installation vessel arrival days in the schedule is based on a specific schedule from a single case, while a different orientation or including failures or sudden schedule changes might make the model more realistic.

To conclude, the assumptions themselves cause quite some uncertainty in the system as well. Although estimations have been discussed with experts, some assumptions might be of a critical importance to the reliability of the model, and can deviate from the actual value. Also the triangular distribution that has been chosen to include low, most likely and high estimates might have not been the most suitable distribution. Nevertheless, the general trends that have been found from the results such as the benefits from using shorter schedules, can be applied to several types of load out, since it concerns limiting the amount of storage spaces.

6.2 Management of Technology perspective

The focus for this thesis mainly centers around the onshore handling scope, which was the responsibility of Mammoet for the case of Arcadis Ost 1. However, findings and recommendations following from chapter 5 go beyond that scope. For example requesting the barge to arrive only on days following the installation vessel departure day would require extensive collaboration with several stakeholders, such as Steelwind Nordenham as the manufacturer of the monopiles and Muller-Dordrecht as the transporter of the monopile by barge. This is similar for recommendations regarding schedule overlap. Many stakeholders are affected by such a change in the project dynamics, which can cause conflicting interests. The port of Rønne for example, is affected by a shorter demanded area rental period, while Steelwind Nordenham might face inventory overstock at their production facility due to storage limitations, which can lead to a congested supply chain for other projects. In figure 34, such storage limitations can be seen as storage area might also be scarce at manufacturing locations.

Figure 34: *Scarce port area at manufacturing location*

Due to the broad variety of stakeholders whose choices and actions are all interrelated, the decision-making environment can be seen as a network, although there are hierarchical aspects in the organisational structure. DEME is for example the main contractor employed by Parkwind for the installation of the monopiles, who on his turn contracted Muller-Dordrecht for the overseas transportation and Mammoet for the onshore handling. Nevertheless, approaching the involved parties as a network could simplify the adoption of cost reducing strategies, which can be beneficial for all parties involved.

According to de Bruijn and ten Heuvelhof (2018), for actors to participate in collective decision-making, process management is required, in addition to an agenda that is sufficiently appealing, also known as a multi-issue agenda. In a network, specifying a scope is problematic. It implies that there is a party that can impose its scope on other parties. A fixed scope can restrict the decision-making space and, as a result of that, can hamper goal-seeking behaviour and learning processes of the involved actors, and thus reduce the possibilities for package deals (de Bruijn & ten Heuvelhof, 2018).

When an initiator has a problem and formulates a fixed scope, this initiator is not a very attractive partner for the others because they cannot see enough possibilities for solving their own problems (de Bruijn & ten Heuvelhof, 2018). For a heavy lifting contractor such as Mammoet, this can be avoided by getting the involved parties around the table to generate value creation along the whole supply chain with the aim that each party wins more than it loses. Sharing information is crucial here, since the more information actors have, the better they can deal with unexpected opportunities or obstacles. If Mammoet would share the projected gains as a result of a specific schedule, other parties such as DEME can see for themselves whether a different schedule would be feasible, by exploiting weather windows for example.

One of the important aspects from a process-based approach is evaluating whether parties are satisfied, whether the process was fair and maybe most importantly, whether enduring relationships have been created. Building trust in the negotiations and being able to collaborate towards a better outcome then the original plan will leave the other parties with an impression of a cooperative attitude. This positive experience can work in your advantage when contractors are being selected for future projects in this sector.

Since building trust is such an important element for collaboration in the long term, the current system of penalties or punishments for delays might seem odd. Bresnen and Marshall (2000) emphasize that the use of incentives, such as rewards, helps to reinforce collaboration and build trust between clients and contractors in the long term. Punishments and rewards tend to modify stakeholder behaviour differently, which is an important notion for the initial phases of a project, when contracts are established. While incentives encourage and reward positive behaviour, penalties tend to stop undesired behaviour. For the observed project, financial incentives for finishing the whole project in time, evenly distributed among the contractors, could have helped to enhance the level of collaboration, while clauses including punishments for delays might increase suspicion.

Of course, such a process-based decision-making approach is harder to realise in a real life case, especially as subcontractor with limited control over the project development choices. The offshore wind market is a fast changing market, with a fierce competition among contractors and where tasks and responsibilities are fragmented among numerous parties. The competition in the market could pose an obstacle towards a more integrated and collaborative approach, where in general the cheapest and quickest solution for each individual party is the obvious choice. However, if there is an opportunity to sit down with the main contractor, the developer and the manufacturer in the tendering phase, the value creation from discussing the schedule might already provide a competitive advantage for heavy lifting contractors.

The main challenge here is to clearly communicate incremental process innovations to the other involved actors in the system and to show them the mutual benefits that can be achieved.

6.3 Managerial relevance

Cost reductions on the short term would be the most obvious and direct application of this research to managers in the offshore wind industry, especially from heavy lifting contractors. For the specific case of Arcadis Ost 1, this would mean a tighter project schedule as was found in the first experiment in section 5.3, with as much overlap between the arrival of the barge and installation vessel as possible. The second experiment (section 5.4) emphasized the importance of trying to communicate and realise the arrival of barges only the day after the installation vessel has left. However, in the bigger picture this could provide insights on the main costs contributors for comparable projects. These insights might learn that the amount of storage bunds that is required has to be critically examined before agreement to a contract.

Reducing the total time that equipment and personnel has to be rented may seem to be a disadvantage for heavy lifting contractors like Mammoet at first glance, however, this could also tackle the global scarcity of appropriate equipment and skilled people to enable large offshore wind farm construction. When less time is spent on a specific project, those resources could be allocated to other projects quicker, or operate for multiple projects from the same marshalling yard, which would simultaneously save mobilisation costs.

6.4 Future research

For future research, scenario options that have been presented in figure 14 can be implemented in the simulation models. Also a schedule variation where all barge arrivals are after the installation vessel arrival would be interesting to see whether the project duration can be decreased without compromising on average waiting time for the ships. Additionally, scaling up the amount of monopiles in the system might reveal other bottlenecks in the logistical sequence. Except from monopiles, the interaction with topside components can give a more complete picture of whole marshalling port activities for a full wind park construction. To conclude, would the combination of a logistic supply chain problem with a spatial layout optimization be the most complete representation of the reality. A mathematical optimization might enable decision makers to make choices regarding the location and the priority of the placements of wind turbine components, based on the installation variability. This would also enable the researcher to take the dimensions of the ever growing components into account, and make recommendations for future equipment design and new methods of handling.

7 Conclusion and recommendations

The literature review performed in this study revealed that although various studies are dedicated to offshore installation strategies, the literature regarding marshalling ports for supporting offshore wind farm construction is limited. However, several studies do acknowledge that marshalling ports play a crucial role in future projects and the adoption of offshore wind energy in foreign markets, although various challenges are faced in marshalling ports nowadays. The port facilities are impacted by high requirements regarding channel depth and load bearing capacities, which are a result of the ever increasing weight and size of wind turbines and their foundations. Strict time windows and variability in schedules from expensive installation vessels demand a high level of flexibility, which is challenging with a dependency on the supply rate from a production facility. These challenges, together with the extensive demand for cheap renewable energy to reduce foreign dependency and compete with fossil fuels, resulted in the search for a cost-efficient strategy for the onshore handling of offshore wind turbine structures, in specific monopile foundations.

A discrete event simulation (DES) was considered most suitable to perform a quantitative evaluation of strategies which are bounded by numbers such as activity durations and arrival times. For this evaluation, it has been chosen to apply the simulation to the case study Arcadis Ost 1, a 257 MW offshore wind farm that is being developed in the Baltic Sea. Marshalling activities for the monopile foundations were conducted last year in the port of Rønne on the Danish island Bornholm. Insights from Arcadis Ost 1 and comparable projects were used to construct the simulation model in an iterative process. The input values and logistical sequences in the model were discussed with engineering experts for validation and creation of a realistic representation of the project. It has been decided to investigate four main scenarios, that vary in the amount of supports that are being used for the load-in and load-out, facilitating the barge and installation vessel respectively. To test these scenarios and their resilience and performance towards schedule changes, two experiments regarding schedule changes have been conducted, where the input values for arrival times from the supply barge and installation vessel were altered. The first experiment concerned four levels of overlap between the barge arrival and installation schedule. The second experiment was conducted to explore the influence of the timing of the arrival of a supply shipment with respect to a vessel requesting monopiles for installation. The gathered data has been processed into several performance indicators such as the total operational costs, including personnel and equipment, the costs related to the steel supports on the quayside, and the costs related to long term storage on sand dunes or storage bunds. The total time that vessels are occupied during a load-out or load-in has been monitored and weighted based on the day rate, and fines were calculated if those durations exceeded a pre-defined threshold.

From the experiment regarding overlap in schedules, it was found that a significant cost reduction can be achieved at the marshalling port from having a tighter project schedule where supply overlaps for three-quarters the installation schedule. The average time that a barge is docked for a load-in shows an increase when the schedules are more interconnected, where the scenario with only one support for the load out shows the largest deviations. This scenario also performs the poorest in terms of total maximum fine across simulation replications. These fines start occurring significantly from a schedule that is overlapping for half of the time. However, even with the total fine and weighted average times of the vessels accumulated, the scenario with only one support for the load-out performs best in terms of total costs. This is mainly due to the fact that the costs related to the waiting times for the ships, within the assumptions and boundaries of this research, do not weigh up against the costs for additional supports.

From a cost contribution analysis for the specific scenario with three supports for the load-in and two supports for the load-out, it was found that the largest cost reductions are gained in the long term storage costs when tightening the project schedule. This is an important finding, addressing that the reduction in required storage spaces and land area has the biggest impact on the total costs, followed by the reductions in operational costs.

From the experiment regarding the timing of arrivals, it was found that the time a barge has to wait to be unloaded is significantly less if the barge arrives the day after the installation vessel has left. Using more supports, especially three additional supports for the load-in, does help to reduce the waiting time for the barge and the related fines, but a way bigger impact is made with adequate management of the timing of the barge arrival.

Based on the findings, an answer can be formulated to the main research question: *"Which logistic strategy in terms of resource allocation for the onshore handling of monopiles in marshalling ports is the most cost-efficient, considering the arrival rates of shipments?"*

Within the boundaries and assumptions of this research, a strategy where load-in and load-out schedules have approximately three-quarters overlap is considered most cost-efficient. Reducing the total project duration is critical, as it will tackle two of the most important costs: the required amount of storage bunds and the related area rental, and the total time that equipment and personnel has to be rented. Of these costs, the long term storage cost reductions have the largest contribution. Within this tighter project duration, the scenario with only one temporary support at the load-out location is found to be the cheapest option, since the resulting delays do not way up against the additional costs that would come with more supports. To conclude, if an onshore handling contractor would be able to have a say in the project schedule, they should aim to have barge arrivals planned after the installation vessel has left to avoid conflicting resources.

This is consistent with the most important recommendation, which revolves around collaboration among stakeholders in the system. Involving all relevant actors of offshore wind projects in an early stage can result in extensive mutual benefits. The involved parties might be able to complement and assist each other with issues that would not become visible if every individual actor would pursue the cheapest option. With an overarching supply chain management, for example coordinated by the project developer, the overall construction costs can be reduced, without harming any particular party. This could result in a reduction of the unit costs of wind energy for consumers, enabling a stronger competition with fossil fuels. Eventually, when the price of wind energy manages to end up below the price of those traditional energy sources, competitive market forces will act as a catalyst and accelerate the energy transition towards a fully sustainable future.

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Appendices

A Pictures Arcadis Ost 1

Figure 35: *Monopile production*

Figure 36: *Site move at Steelwind*

Figure 37: *Load out at production facility (Dillinger, 2022)*

Figure 38: *Barge arrival side view*

Figure 39: *Barge viewed from quayside*

Figure 40: *Seafastening grillage and RoRo ramps*

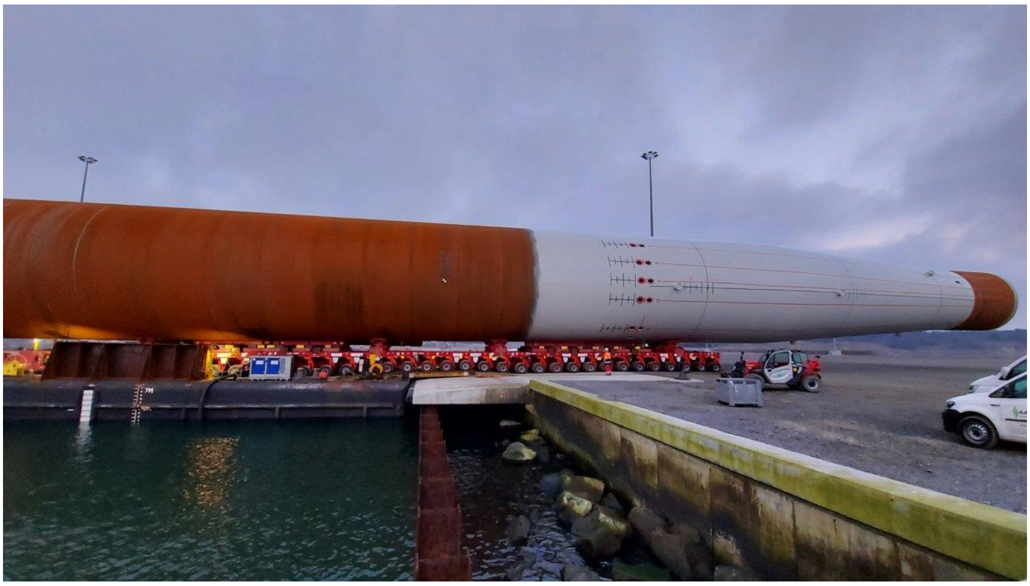
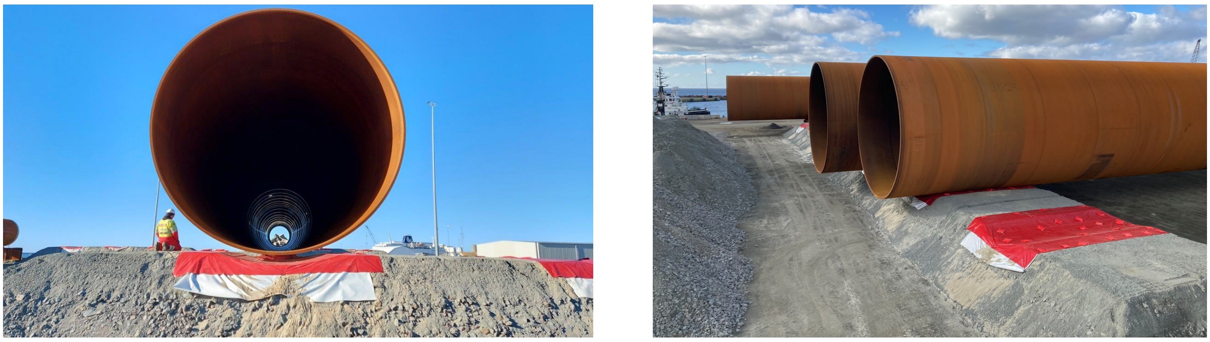


Figure 41: *RoRo operation*

Figure 42: *Monopile transport with SPMT*



(a) *Monopile laydown*

(b) *Monopile on storage bund*

Figure 43: *Storage bunds (also referred to as sand dunes)*

Figure 44: *Supervisor and operators*

Figure 45: *Installation vessel sailing*

B Arena Simulation models

Arena Simulation model TI0-TO1

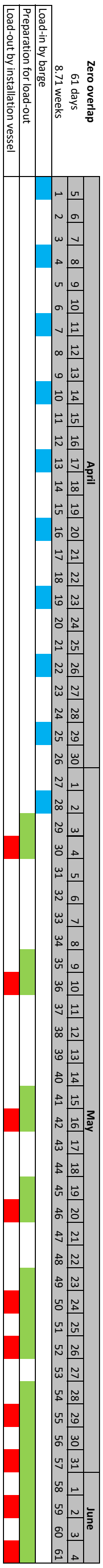
Arena Simulation model TI0-TO2

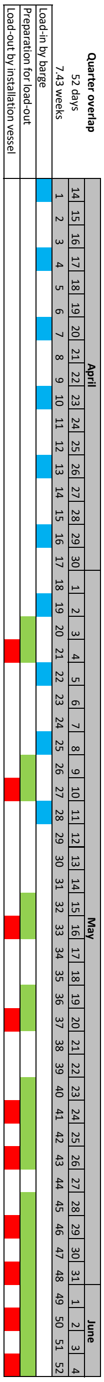
Arena Simulation model TI3-TO1

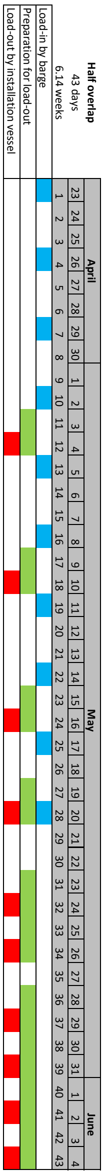
Arena Simulation model TI3-TO2

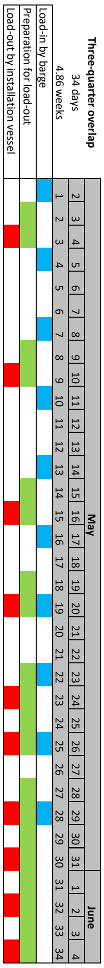
C Schedule variations

Schedule variations Experiment 1

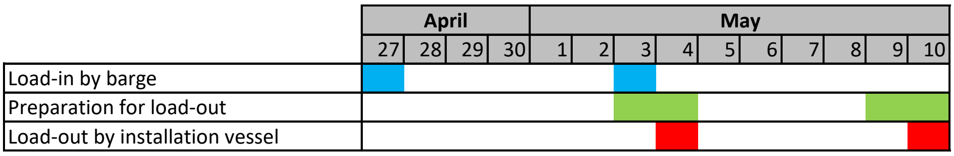




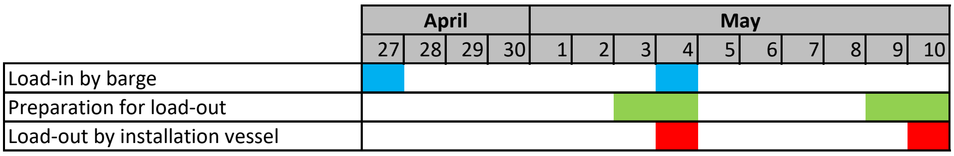




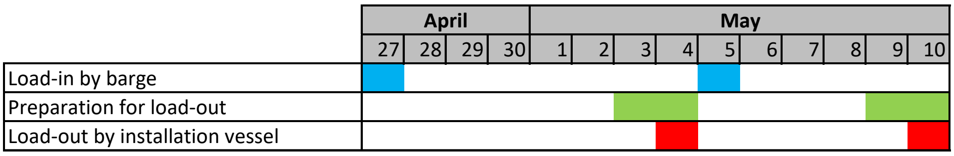
Schedule variations Experiment 2



	April				May									
	27	28	29	30	1	2	3	4	5	6	7	8	9	10
Load-in by barge	🟦						🟦							
Preparation for load-out							🟩	🟩					🟩	🟩
Load-out by installation vessel								🟥						🟥

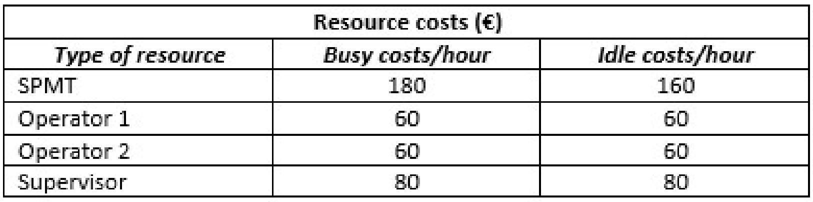


	April				May									
	27	28	29	30	1	2	3	4	5	6	7	8	9	10
Load-in by barge	🟦							🟦						
Preparation for load-out							🟩	🟩					🟩	🟩
Load-out by installation vessel								🟥						🟥

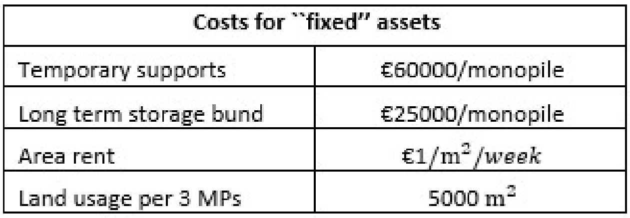


	April				May									
	27	28	29	30	1	2	3	4	5	6	7	8	9	10
Load-in by barge	🟦								🟦					
Preparation for load-out							🟩	🟩					🟩	🟩
Load-out by installation vessel								🟥						🟥

D Assumptions model

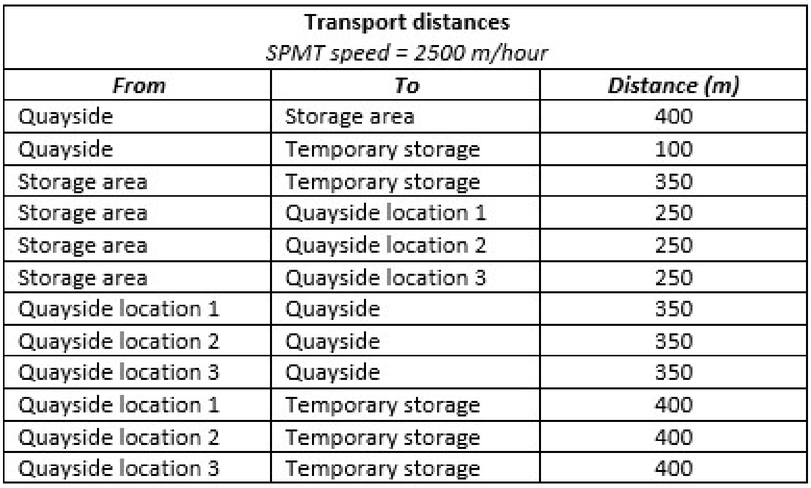


Resource costs (€)		
Type of resource	***Busy costs/hour***	***Idle costs/hour***
SPMT	180	160
Operator 1	60	60
Operator 2	60	60
Supervisor	80	80

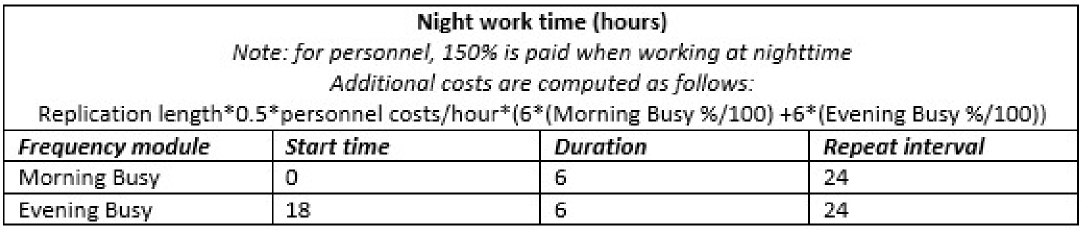


Costs for ``fixed'' assets	
Temporary supports	€60000/monopile
Long term storage bund	€25000/monopile
Area rent	€1/m^2/$week$
Land usage per 3 MPs	5000 m^2

Fines (€/hour)	
Barge	1000
Installation vessel	10000



Transport distances *SPMT speed = 2500 m/hour*		
From	***To***	***Distance (m)***
Quayside	Storage area	400
Quayside	Temporary storage	100
Storage area	Temporary storage	350
Storage area	Quayside location 1	250
Storage area	Quayside location 2	250
Storage area	Quayside location 3	250
Quayside location 1	Quayside	350
Quayside location 2	Quayside	350
Quayside location 3	Quayside	350
Quayside location 1	Temporary storage	400
Quayside location 2	Temporary storage	400
Quayside location 3	Temporary storage	400



Night work time (hours) *Note: for personnel, 150% is paid when working at nighttime* *Additional costs are computed as follows:* Replication length*0.5*personnel costs/hour*(6*(Morning Busy %/100) +6*(Evening Busy %/100))			
Frequency module	***Start time***	***Duration***	***Repeat interval***
Morning Busy	0	6	24
Evening Busy	18	6	24

E Results Validation TI0-TO1

		Validation TI0_TO1
Project duration	Hours	2370.48794
	Days	98.8
	Weeks	14.11
Operational costs	All Resources.BusyCost	70271.76
	All Resources.IdleCost	786802.42
	System.TotalCost	857074.17
	Resource Utilization	0.08
	Evening Busy	0.104
	Morning Busy	0.084
	Additional night time costs	266822.12
	Total operational costs	1123896.29
Long term storage spaces	Overall Max Value	24
	Costs per piece	25000
	Long term storage costs	600000.00
Total temporary supports	Number	1
	Costs per piece	60000
	Temporary support costs	60000
Bargetime	Average of replication averages	13.561
	Weighted barge time	135610.38
Vesseltime	Average of replication averages	3.316
	Weighted vessel time	331591.88
Bargefine	Average of replication averages	663.44
	Overall Max Value	22873.78
Vesselfine	Average of replication averages	0.00
	Overall Max Value	0.00
Total project costs		1783896
Total weighted times		467202
Total max fine		22873.78

F Results experiment 1

TI0-TO1 results

		Zero	Quarter	Half	Three-quarter
Project duration	Hours	1458.5	1242.5	1026.5	810.5
	Days	60.8	51.8	42.8	33.8
	Weeks	8.68	7.40	6.11	4.82
Operational costs	All Resources.BusyCost	70282.79	70276.09	70269.17	70298.99
	All Resources.IdleCost	458471.96	380718.31	302964.87	225176.61
	System.TotalCost	528754.75	450994.40	373234.04	295475.61
	Resource Utilization	0.13	0.16	0.19	0.24
	Evening Busy	0.171	0.202	0.241	0.298
	Morning Busy	0.133	0.156	0.197	0.265
	Additional night time costs	266378.24	266588.21	269576.26	273588.31
	Total operational costs	795132.99	717582.61	642810.30	569063.91
Long term storage spaces	Overall Max Value	30	24	18	12
	Costs per piece	25000	25000	25000	25000
	Number of sand dunes	10	8	6	4
	Area rent per sand dune	43407.38	36978.81	30550.24	24121.66
	Long term storage costs	1184073.79	895830.46	633301.42	396486.66
Total temporary supports	Number	1	1	1	1
	Costs per piece	60000	60000	60000	60000
	Temporary support costs	60000	60000	60000	60000
Bargetime	Average of replication averages	12.940	12.934	13.319	14.362
	Weighted barge time	129398.45	129344.76	133190.14	143617.37
Vesseltime	Average of replication averages	3.311	3.311	3.314	3.314
	Weighted vessel time	331127.27	331077.22	331383.20	331397.75
Bargefine	Average of replication averages	0.41	0.45	258.14	2429.50
	Overall Max Value	264.27	264.27	12842.24	42503.17
Vesselfine	Average of replication averages	0.00	0.00	0.00	0.00
	Overall Max Value	0.00	0.00	0.00	0.00
Total project costs		2039207	1673413	1336112	1025551
Total weighted times		460526	460422	464573	475015
Total max fine		264.27	264.27	12842.24	42503.17

TI0-TO2 results

		Zero	Quarter	Half	Three-quarter
Project duration	Hours	1458.2	1242.2	1026.2	810.2
	Days	60.8	51.8	42.8	33.8
	Weeks	8.68	7.39	6.11	4.82
Operational costs	All Resources.BusyCost	72205.29	72189.86	72180.83	72198.54
	All Resources.IdleCost	456534.61	378789.22	301037.78	223261.00
	System.TotalCost	528739.90	450979.09	373218.61	295459.54
	Resource Utilization	0.14	0.16	0.19	0.24
	Evening Busy	0.155	0.182	0.220	0.276
	Morning Busy	0.147	0.172	0.215	0.281
	Additional night time costs	263869.65	264208.62	267521.37	270611.52
	Total operational costs	792609.55	715187.71	640739.98	566071.06
Long term storage spaces	Overall Max Value	30	24	18	12
	Costs per piece	25000	25000	25000	25000
	Number of sand dunes	10	8	6	4
	Area rent per sand dune	43397.79	36969.21	30540.64	24112.07
	Long term storage costs	1183977.86	895753.72	633243.86	396448.29
Total temporary supports	Number	2	2	2	2
	Costs per piece	60000	60000	60000	60000
	Temporary support costs	120000	120000	120000	120000
Bargetime	Average of replication averages	12.940	12.934	13.167	13.855
	Weighted barge time	129398.45	129344.76	131673.49	138552.19
Vesseltime	Average of replication averages	2.994	2.996	2.997	2.996
	Weighted vessel time	299362.66	299565.70	299704.72	299567.71
Bargefine	Average of replication averages	0.41	0.45	141.02	1477.92
	Overall Max Value	264.27	264.27	10095.45	33721.20
Vesselfine	Average of replication averages	0.00	0.00	0.00	1.20
	Overall Max Value	0.00	0.00	0.00	2003.31
Total project costs		2096587	1730941	1393984	1082519
Total weighted times		428761	428910	431378	438120
Total max fine		264.27	264.27	10095.45	35724.51

TI3-TO1 results

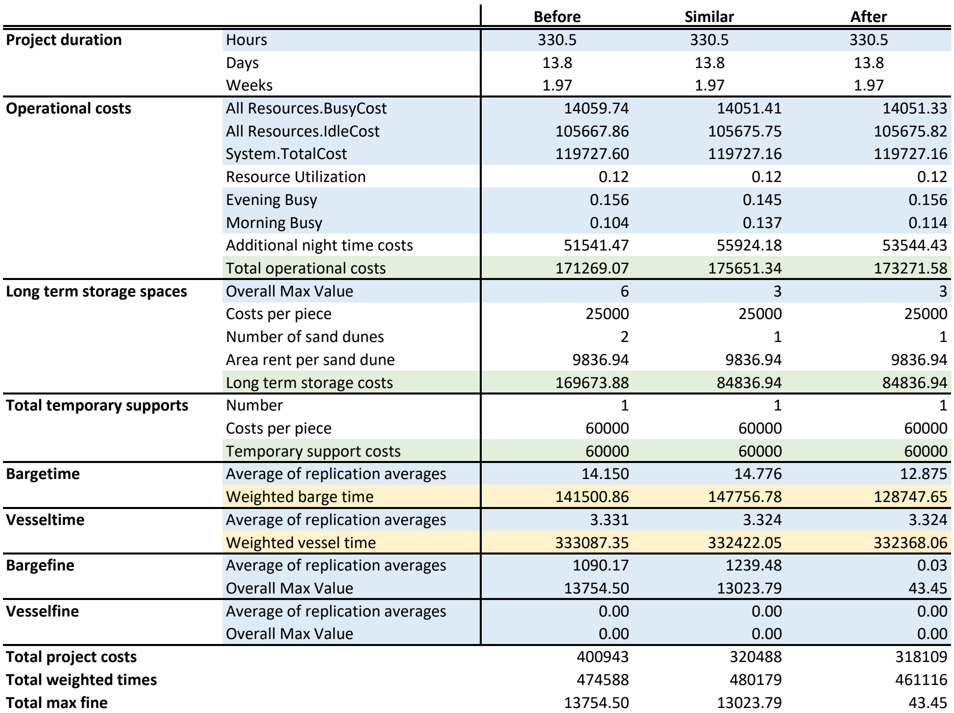
		Zero	Quarter	Half	Three-quarter
Project duration	Hours	1458.5	1242.5	1026.5	810.5
	Days	60.8	51.8	42.8	33.8
	Weeks	8.68	7.40	6.11	4.82
Operational costs	All Resources.BusyCost	81632.52	81630.32	81617.45	81621.07
	All Resources.IdleCost	447720.89	369962.98	292215.17	214451.75
	System.TotalCost	529353.41	451593.30	373832.62	296072.81
	Resource Utilization	0.15	0.18	0.22	0.28
	Evening Busy	0.181	0.213	0.254	0.316
	Morning Busy	0.177	0.208	0.255	0.326
	Additional night time costs	312758.93	313107.88	313367.35	312493.13
	Total operational costs	842112.35	764701.17	687199.97	608565.94
Long term storage spaces	Overall Max Value	30	24	18	12
	Costs per piece	25000	25000	25000	25000
	Number of sand dunes	10	8	6	4
	Area rent per sand dune	43407.49	36978.92	30550.34	24121.77
	Long term storage costs	1184074.87	895831.33	633302.07	396487.09
Total temporary supports	Number	4	4	4	4
	Costs per piece	60000	60000	60000	60000
	Temporary support costs	240000	240000	240000	240000
Bargetime	Average of replication averages	9.344	9.342	9.729	10.617
	Weighted barge time	93437.94	93417.92	97289.00	106165.84
Vesseltime	Average of replication averages	3.311	3.311	3.312	3.310
	Weighted vessel time	331087.68	331075.25	331200.32	330953.26
Bargefine	Average of replication averages	0.00	0.00	93.08	834.16
	Overall Max Value	0.00	0.00	9250.54	21058.12
Vesselfine	Average of replication averages	0.00	0.00	0.00	0.00
	Overall Max Value	0.00	0.00	0.00	0.00
Total project costs		2266187	1900532	1560502	1245053
Total weighted times		424526	424493	428489	437119
Total max fine		0.00	0.00	9250.54	21058.12

TI3-TO2 results

		Zero	Quarter	Half	Three-quarter
Project duration	Hours	1458.2	1242.2	1026.2	810.2
	Days	60.8	51.8	42.8	33.8
	Weeks	8.68	7.39	6.11	4.82
Operational costs	All Resources.BusyCost	83565.58	83568.76	83551.10	83553.00
	All Resources.IdleCost	445774.17	368011.16	290267.89	212506.09
	System.TotalCost	529339.76	451579.92	373818.99	296059.09
	Resource Utilization	0.16	0.19	0.22	0.28
	Evening Busy	0.164	0.193	0.233	0.294
	Morning Busy	0.191	0.224	0.274	0.347
	Additional night time costs	310065.49	310418.54	312038.08	311251.50
	Total operational costs	839405.24	761998.46	685857.08	607310.59
Long term storage spaces	Overall Max Value	30	24	18	12
	Costs per piece	25000	25000	25000	25000
	Number of sand dunes	10	8	6	4
	Area rent per sand dune	43397.95	36969.38	30540.80	24112.23
	Long term storage costs	1183979.47	895755.00	633244.82	396448.93
Total temporary supports	Number	5	5	5	5
	Costs per piece	60000	60000	60000	60000
	Temporary support costs	300000	300000	300000	300000
Bargetime	Average of replication averages	9.344	9.342	9.575	10.137
	Weighted barge time	93437.94	93417.92	95746.98	101369.81
Vesseltime	Average of replication averages	2.992	2.991	2.994	2.994
	Weighted vessel time	299183.90	299142.03	299374.42	299358.56
Bargefine	Average of replication averages	0.00	0.00	35.64	399.83
	Overall Max Value	0.00	0.00	6902.64	14978.65
Vesselfine	Average of replication averages	0.00	0.00	0.00	0.00
	Overall Max Value	0.00	0.00	0.00	0.00
Total project costs		2323385	1957753	1619102	1303760
Total weighted times		392622	392560	395121	400728
Total max fine		0.00	0.00	6902.64	14978.65

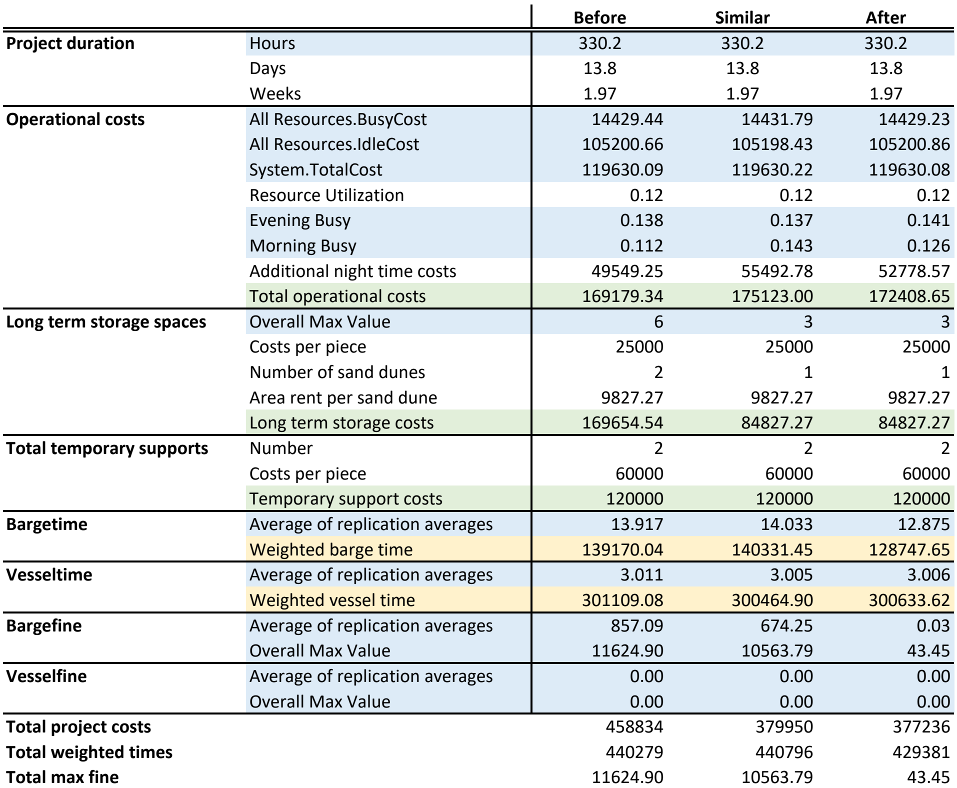
G Results experiment 2

TI0-TO1 results



		Before	Similar	After
Project duration	Hours	330.5	330.5	330.5
	Days	13.8	13.8	13.8
	Weeks	1.97	1.97	1.97
Operational costs	All Resources.BusyCost	14059.74	14051.41	14051.33
	All Resources.IdleCost	105667.86	105675.75	105675.82
	System.TotalCost	119727.60	119727.16	119727.16
	Resource Utilization	0.12	0.12	0.12
	Evening Busy	0.156	0.145	0.156
	Morning Busy	0.104	0.137	0.114
	Additional night time costs	51541.47	55924.18	53544.43
	Total operational costs	171269.07	175651.34	173271.58
Long term storage spaces	Overall Max Value	6	3	3
	Costs per piece	25000	25000	25000
	Number of sand dunes	2	1	1
	Area rent per sand dune	9836.94	9836.94	9836.94
	Long term storage costs	169673.88	84836.94	84836.94
Total temporary supports	Number	1	1	1
	Costs per piece	60000	60000	60000
	Temporary support costs	60000	60000	60000
Bargetime	Average of replication averages	14.150	14.776	12.875
	Weighted barge time	141500.86	147756.78	128747.65
Vesseltime	Average of replication averages	3.331	3.324	3.324
	Weighted vessel time	333087.35	332422.05	332368.06
Bargefine	Average of replication averages	1090.17	1239.48	0.03
	Overall Max Value	13754.50	13023.79	43.45
Vesselfine	Average of replication averages	0.00	0.00	0.00
	Overall Max Value	0.00	0.00	0.00
Total project costs		400943	320488	318109
Total weighted times		474588	480179	461116
Total max fine		13754.50	13023.79	43.45

TI0-TO2 results



		Before	Similar	After
Project duration	Hours	330.2	330.2	330.2
	Days	13.8	13.8	13.8
	Weeks	1.97	1.97	1.97
Operational costs	All Resources.BusyCost	14429.44	14431.79	14429.23
	All Resources.IdleCost	105200.66	105198.43	105200.86
	System.TotalCost	119630.09	119630.22	119630.08
	Resource Utilization	0.12	0.12	0.12
	Evening Busy	0.138	0.137	0.141
	Morning Busy	0.112	0.143	0.126
	Additional night time costs	49549.25	55492.78	52778.57
	Total operational costs	169179.34	175123.00	172408.65
Long term storage spaces	Overall Max Value	6	3	3
	Costs per piece	25000	25000	25000
	Number of sand dunes	2	1	1
	Area rent per sand dune	9827.27	9827.27	9827.27
	Long term storage costs	169654.54	84827.27	84827.27
Total temporary supports	Number	2	2	2
	Costs per piece	60000	60000	60000
	Temporary support costs	120000	120000	120000
Bargetime	Average of replication averages	13.917	14.033	12.875
	Weighted barge time	139170.04	140331.45	128747.65
Vesseltime	Average of replication averages	3.011	3.005	3.006
	Weighted vessel time	301109.08	300464.90	300633.62
Bargefine	Average of replication averages	857.09	674.25	0.03
	Overall Max Value	11624.90	10563.79	43.45
Vesselfine	Average of replication averages	0.00	0.00	0.00
	Overall Max Value	0.00	0.00	0.00
Total project costs		458834	379950	377236
Total weighted times		440279	440796	429381
Total max fine		11624.90	10563.79	43.45

TI3-TO1 results

		Before	Similar	After
Project duration	Hours	330.5	330.5	330.5
	Days	13.8	13.8	13.8
	Weeks	1.97	1.97	1.97
Operational costs	All Resources.BusyCost	16322.83	16332.70	16332.76
	All Resources.IdleCost	103504.55	103495.20	103495.15
	System.TotalCost	119827.38	119827.90	119827.90
	Resource Utilization	0.14	0.14	0.14
	Evening Busy	0.177	0.151	0.164
	Morning Busy	0.134	0.165	0.153
	Additional night time costs	61526.43	62696.28	62973.88
	Total operational costs	181353.81	182524.18	182801.78
Long term storage spaces	Overall Max Value	6	3	3
	Costs per piece	25000	25000	25000
	Number of sand dunes	2	1	1
	Area rent per sand dune	9835.34	9835.34	9835.34
	Long term storage costs	169670.68	84835.34	84835.34
Total temporary supports	Number	4	4	4
	Costs per piece	60000	60000	60000
	Temporary support costs	240000	240000	240000
Bargetime	Average of replication averages	9.853	11.200	9.289
	Weighted barge time	98533.61	112002.94	92888.03
Vesseltime	Average of replication averages	3.313	3.308	3.308
	Weighted vessel time	331345.53	330781.43	330793.44
Bargefine	Average of replication averages	330.69	453.84	0.00
	Overall Max Value	10176.60	8834.33	0.00
Vesselfine	Average of replication averages	0.00	0.00	0.00
	Overall Max Value	0.00	0.00	0.00
Total project costs		591024	507360	507637
Total weighted times		429879	442784	423681
Total max fine		10176.60	8834.33	0.00

TI3-TO2 results

		Before	Similar	After
Project duration	Hours	330.2	330.2	330.2
	Days	13.8	13.8	13.8
	Weeks	1.97	1.97	1.97
Operational costs	All Resources.BusyCost	16700.06	16711.17	16718.68
	All Resources.IdleCost	103035.30	103024.77	103017.66
	System.TotalCost	119735.36	119735.94	119736.34
	Resource Utilization	0.14	0.14	0.14
	Evening Busy	0.154	0.145	0.149
	Morning Busy	0.141	0.175	0.165
	Additional night time costs	58477.35	63191.99	62221.33
	Total operational costs	178212.71	182927.93	181957.67
Long term storage spaces	Overall Max Value	6	3	3
	Costs per piece	25000	25000	25000
	Number of sand dunes	2	1	1
	Area rent per sand dune	9826.09	9826.09	9826.09
	Long term storage costs	169652.18	84826.09	84826.09
Total temporary supports	Number	5	5	5
	Costs per piece	60000	60000	60000
	Temporary support costs	300000	300000	300000
Bargetime	Average of replication averages	9.754	10.437	9.289
	Weighted barge time	97538.22	104367.40	92888.03
Vesseltime	Average of replication averages	3.002	2.995	2.990
	Weighted vessel time	300229.52	299453.17	298959.32
Bargefine	Average of replication averages	231.15	179.33	0.00
	Overall Max Value	7769.94	6427.88	0.00
Vesselfine	Average of replication averages	0.00	0.00	0.00
	Overall Max Value	0.00	0.00	0.00
Total project costs		647865	567754	566784
Total weighted times		397768	403821	391847
Total max fine		7769.94	6427.88	0.00