Supply Chain Simulation of Offshore Wind Farm Monopile Installation

Performance of different supply chain configurations under dynamic weather influences

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Preface

I would like to express my gratitude to my supervisor at Allseas, Boudewijn van Gelder, for the helpful discussions, feedback and guidance during the thesis process. I would also like to thank all the other colleagues at Allseas for their input and enjoyable conversations. Additionally, I would like to thank my supervisors from Delft University of Technology, Alexander Verbraeck and Bilge Atasoy, for their involvement in this project and the time dedicated to coaching, giving feedback and providing me with interesting research directions. Finally, I also want to thank the people around me for their support and insightful discussions.

Roman Schuring
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Executive Summary

The goal of the EU is to have 40% of energy from renewable sources by 2030. Offshore wind farms are seen as an important source of energy in order to reach these goals. Wind farms are actively developed and the number of wind farms planned or developed is expected to grow in the upcoming years. This development can be beneficial for companies operating in the offshore industry as it provides a growing market. In the installation phase of offshore wind farms, large heavy lift vessels or dedicated installation vessels are required in order to install the big monopiles (the most used type of foundation in wind farms) by drilling those into the seabed. A monopile installation project consists of the whole process of loading monopiles to vessels, transporting monopiles to the wind farm and drilling monopiles in the seabed. Each installation project has different characteristics as the weather at the installation location, the distances to the suppliers and the vessels that are available differ between projects. Different project characteristics require different choices to be made when planning a typical installation project in order to optimally plan or reduce the expected cost of a project. One of these choices is determining which supply chain configuration will be used to get the monopiles from the supplier to the offshore wind farm. The choice of configuration is important as it determines the type of vessels that are required and if intermediate storage ports need to be rented, which requires initial investments. Assessing literature, it becomes clear that available literature mainly focuses on planning of offshore wind farm installation projects and does not consider choices made related to the design of the supply chain. Literature focussing on the design of the supply chain does not assess these effects under the influence of weather. However, the total time it takes to install an offshore wind farm and the cost that relate to this installation are dependent on weather conditions and are therefore important to include when modeling offshore operations.

The purpose of the research study is to assess the performance of different supply chain configurations. The performance of these different configurations is assessed on the key performance indicators project cost, project duration, utilization of the vessels and the waiting on weather duration. From the literature, four different supply chain configurations were identified. Based on the knowledge of experts in the field of offshore operations, an additional configuration was added. The five different supply chain configurations considered in the analysis are listed below.

1. *Direct* configuration: The installation vessel sails back and forth between the installation location and the supply port in order to restock monopiles.
2. *Transfer offshore* configuration: The installation vessel stays at the offshore wind farm location and a supply vessel sails back and forth between the supply port and the wind farm. The monopiles are transferred offshore between the two vessels.
3. *Transfer port* configuration: This configuration includes an intermediate port that acts as a sheltered area for the transfer between a supply vessel and an installation vessel. The installation vessel sails between the intermediate port and the installation location while the supply vessel sails between the supply port and the intermediate port. The vessels will wait for each other at the intermediate port to transfer monopiles from the supply vessel to the installation vessel.
4. *Transshipment buffer* configuration: In this configuration, the intermediate port includes a quay and a storage area. The supply vessel and installation vessel do not wait for each other but use the storage area in the intermediate port to load and unload the foundations.
5. *Transfer offshore buffer* configuration: Two supply vessels are used to transport monopiles. The two supply vessels make use of an intermediate port with a quay and storage area to load and unload components. One supply vessel will deliver the monopiles from the supply port to the intermediate port, while the second supply vessel will deliver monopiles from the intermediate port to the installation vessel and transfer the monopiles offshore. The installation vessel will stay at the offshore wind farm location during the complete installation process.

In order to assess the performance of different supply chain configurations, a discrete event simulation model is developed. Integrated within the simulation model is the developed weather module. The weather module is a second order markov chain model that is able to generate synthetic weather realizations based on characteristics of historical weather data. The model improves markov models described in literature by explicitly integrating the persistence of weather phenomena. Validating the improved model shows that the model is able to generate unique weather data that still exhibits a good fit with the statistical properties of the historical weather data both in terms of descriptive statistics and persistence values.

In order to assess the effect of using different supply chain configurations on the key performance indicators, 6 different experiments were performed within the developed simulation model. The first experiment is based on a case study of a typical offshore wind farm project and is used to test the effect of different configurations on the different key performance indicators. The installation of 30 monopiles at a location close to the coast of the UK with the supplier located in the Maasvlakte in Rotterdam is simulated. In this simulated project, a typical offshore wind farm installation vessel and a barge with two tugs are used to compare the different configurations. The other five experiments that are performed use the same parameters assumed in the case study but investigate the moderating effect of varying one parameter on the relation between the supply chain configuration and the duration of the installation project. The experiments and the results of these experiments are listed below.

1. The first experiment is based on the described case study. It is found that the direct configuration is the best performing configuration. The project duration and cost of the *direct* configuration are lower compared to other configurations, and the variance of these key performance indicators is low.
2. The second experiment investigates the effect of changing the speed of the supply vessel or the installation vessel. It is found that using dedicated supply vessels that are able to sail at higher speeds will decrease overall project duration and make all configurations except the *transshipment buffer* configuration perform better compared with the direct configuration. It was also found that changing the installation vessel speed does not impact which configuration performs best, the direct configuration stays the best performing configuration and becomes even more attractive when the installation vessel operates at higher speeds.
3. The third experiment considers the moderated effect of using different weather limitations for transfer operations. Changing the weather limitations, so making offshore transfer possible in worse weather conditions, did not change the fact that the *direct* configuration was found to be the best performing configuration. The *transfer offshore* configuration, however, outperforms the other configurations (except the *direct* one) in the duration of the installation project when offshore transfer can take place in worse weather conditions.
4. The fourth experiment tests a different number of monopiles stored at the intermediate port in advance, in this experiment also the effect on cost is included. The duration that an installation vessel needs to be operational can be reduced by using intermediate ports with a storage area with enough capacity. When the goal is to minimize the duration the installation vessel is being used, it is recommended to make use of the *transshipment buffer* configuration. With enough storage space, the total cost of an installation project when using an intermediate port (with a capacity of 15 monopiles) is around 18% higher compared with the direct configuration, but the duration the installation vessel is required reduces by around 15%.
5. In the fifth experiment, the moderating effect of different weather conditions is analyzed by changing the start date of the installation project and by manually scaling the weather data to become more calm or worse. Manually scaling weather data with 120%, in order to simulate worse weather conditions, results in the *transfer offshore* configuration to be twice as expensive, which is an increase of 14 million euros. Worse weather does not impact which configuration performs best, but the variance in duration and cost of the installation project differs a lot between different supply chain configurations when the weather gets worse. The configurations that need to transfer offshore exhibit more variance when weather is worse compared to other configurations. This is due to the lower offshore transfer limits and the increase in the number of operations that are dependent on calm weather. The same increase of around 15 million euros is found when a project would start in November compared to starting in May due to the presence of worse

weather conditions in winter. It can be concluded that weather is found to be very important in the performance of different supply chain configurations.

6. In the sixth experiment, the moderating effect of the distance between the supply port and the wind farm is analyzed. It was found that at lower distances between the supply port and the installation location, the differences in project durations become smaller. Experimenting with a distance of 200 kilometers using the *transfer offshore* configuration will result in a 25% increase in project duration, but this is almost an increase of 99% when the wind farm is assumed to be located 800 kilometers from shore. The direct configuration is, however, still the best performing configuration regardless of the distance between the supply port and the installation location.

The results describe how different supply chain configurations influence the duration of an installation project or project cost. Under the assumptions of the case study, it was found that the best performing configuration is the *direct* configuration. In the other performed experiments, this configuration was often still the best performing configuration. Only when high-speed supply vessels are used, the *direct* configuration is not preferred. When the goal is to minimize the usage of the installation vessel, it is recommended to use the *transshipment buffer* configuration. Planners can use these qualitative insights as a starting point for the choice of the preferred supply chain configuration when planning an offshore wind farm installation project. This will enable planners to make educated choices in the planning phase and give these planners insight into the different factors that are important in the supply chain of offshore wind farm installation projects. From a theoretical point of view, this report contributes to the sparse literature on the supply chain and logistical decisions in the field of offshore wind farm installation. Next to these insights, the weather module used to generate synthetic weather data improves markov models discussed in literature and provides a solution to the problem of persistence that is present in conventional markov models.

Contents

1
Introduction

Climate change is threatening the world as we know it. It is not only impacting nature and wildlife, but also human life and entire economies are threatened. Events like these can have a large economical and societal impact on countries. This is why the European Union (EU) set the objective to make the whole EU climate neutral before 2050, which requires that actions should be taken in the coming years (European Council, 2022, 2023b). The goal of the European green deal is to accelerate industry transition to sustainability. The laws that will be implemented to reach these objectives contain proposals for renewable energy and state that the EU binding target is to have at least 40% of energy from renewable sources by 2030 (European Council, 2023a). From a governmental perspective, this binding target requires setting climate goals and implementing programs in order to become more sustainable and reach the green deal goals. Offshore wind farm energy is seen as an important factor contributing to reaching the sustainability goals, according to the Dutch government. This is why the Netherlands is actively developing wind farms on the north sea and allocating new locations to build wind farms. The government expects that wind energy will need to grow significantly after 2030 in order to reach the climate goals and the required demand of sustainable energy (Ministerie van Economische Zaken en Klimaat, 2020). From a company perspective, these developments can be beneficial as new markets become available to enter which were previously not part of the company's product or service offerings.

One of such companies exploring these offerings is Allseas. Allseas is a contractor in the offshore energy market specialized in offshore pipeline installation, heavy lift, deep-ocean nodule collection and river waste collection. With their versatile fleet and the largest construction vessel in the world, the Pioneering Spirit, Allseas can deliver a range of services in different locations. Due to the developments of the growing wind farm market, the available versatile fleet and available in-house knowledge, the installation of offshore wind farms can be a promising market to explore.

An important aspect in the installation of offshore wind farms is the placement of monopiles. A monopile is the type of foundation most used in the installation of offshore wind (Sánchez et al., 2019). The monopile is a structure that is drilled into the ground in order to support the tower with the turbine that will be placed on top of the monopile.

Within Allseas different vessels are available that could transport these foundations, allowing them to offer the service of lifting and installing these monopiles. But related to the supply chain, some questions remain unanswered, due to the complex interaction of these installation processes with environmental conditions. The preferred way of transporting monopiles from the supplier to the wind farm remains unanswered for Allseas. This question can be categorized as a supply chain configuration decision as the decision involves choosing processes and transportation modes in order to design a preferred monopile installation process. These questions cannot be answered by simple calculations due to the complexity of the offshore wind farm processes and supply chain. This complexity can be attributed to the size of the components that need to be transported throughout the supply chain but also to the external environment which impacts the supply chain extensively due to weather limitations. Bad weather can interrupt installation processes leading to stock build up in the supply chain, which means that the impact of upstream delays will impact the whole planning more downstream in the supply chain (Hrouga & Bostel, 2020).

1.1. Research Gap

There is not a lot of research investigating offshore wind farm installation from a supply chain configuration (the way a supply chain is designed) or logistics perspective (Vis & Ursavas, 2016). A lot of research is done on planning and scheduling offshore wind farm projects, but these assume a certain network to be in place in order to plan operations (Hrouga & Bostel, 2020; Rippel et al., 2019). These papers do not investigate different supply chain configurations. This is interesting as the supply chain configurations and the logistical decisions made are important in the installation of offshore wind farms. Especially, vessel availability and the effect of weather conditions play an important role in the efficiency of the installation process. This qualitative insight is discussed in literature, but no method is recommended to assess the discussed effects. (Vojdani & Lootz, 2012) Another qualitative insight is stated by Drunsic et al. (2016) as they propose different methods of organizing the supply chain of offshore monopile installation. The authors state that it is required to test these proposed methods in a quantitative way in order to assess the performance of using different configurations.

The papers that do investigate logistics of offshore wind farm installation do not take the stochastic influence of weather into account (Irawan et al., 2018) or do only account for historical realizations of weather (Tjaberings et al., 2022). Only taking into account historical weather realizations results in assessing only a subset of the weather conditions that can occur as often only a limited amount of historical data is available. The influences of weather can be integrated by using a stochastic weather model that is able to generate synthetic weather data based on historical data. Using stochastic markov chain models is an appropriate method to simulate such synthetic weather data (Eberle et al., 2022). Persistence of weather phenomena is important when modeling offshore activities as this determines the possible weather windows where offshore operations can take place. The described markov chain models in literature are, however, only able to reasonably replicate the persistence of weather phenomena in the synthetic weather data (Masi et al., 2015; Scheu et al., 2012). The synthetic weather data is often too conservative and tends to overestimate the occurrence of short weather windows (Scheu et al., 2012). Integrating the markov chain models as these are proposed in literature would therefore lead to unrealistic results.

In order to assess the effect of using different supply chain configurations, it is important to consider environmental factors, the location of the wind farm and ports and the design of the vessel. Assessing differences in configurations is important as this insight would allow reducing logistic cost and installation time. It would also help to assess the profitability of candidate projects, solutions, and the effect of using different vessels.

The available models and research into different supply chain models do not provide insight into the effect of choosing different supply chain configurations. The reviewed literature that relates to the supply chain does either not include the stochastic effects of weather or focuses on other areas of interest assuming a certain supply chain configuration is already in place. Therefore, this report will investigate multiple supply chain configurations while accounting for weather uncertainties to give insight into the effect of using different configurations. This leads to research questions discussed in the next section.

1.2. Research Question

The main research question and corresponding sub questions are listed below.

"What is the effect of using different supply chain configurations on the performance of offshore wind farm monopile installation under dynamic weather influences?"

1. What are the supply chain configurations to consider?
2. What are the key performance indicators to consider?
3. What is the effect of using different supply chain configurations on the key performance indicators under dynamic weather influences?
4. How do the above effects differ with regard to the moderating variables vessel speed, offshore transfer weather limit, stock at the buffer location, weather conditions and the distance between the supply port and the wind farm?

The first sub-research question focuses on the question of which supply chain configurations to take into account. The second sub-research question focuses on which key performance indicators to investigate. The third sub-research questions investigate the effect of using different configurations in a given case. This case will give insight into the effect of using different supply chain configurations. The fourth sub-research question elaborates on the third sub-research question by assessing the effect of changing the case parameters. An analysis is performed on multiple parameters like the impact of different environmental conditions, the influence of wind farm location and vessel characteristics in order to assess what happens if one parameter is defined differently.

Answering all these sub-research questions makes it possible to reflect on the effect of different supply chain configuration on the performance of offshore wind farm monopile installation under dynamic weather influences.

1.3. Research Methodology

The first and second sub-research questions will be answered by performing a literature review. The third and fourth sub-research question will be answered by experimenting with a developed computer model. This supply chain simulation model with an integrated weather module simulates a typical offshore wind farm installation project. It consists of a discrete event simulation model and a multivariate markov chain model as integrated weather module. The markov chain model that is used will be an improved version of the models described in literature in order to avoid overestimating short weather windows. The simulated installation project is a wind farm installation project 300 kilometers from the coast of the UK. This case study reflects a real offshore wind farm that will be built in the near future and provides an appropriate case to test different supply chain configurations. The developed supply chain model simulates the process of delivering monopiles to the installation location according to different supply chain configurations and installing the monopiles constrained by weather conditions.

1.4. Contribution

Investigating the supply chain configurations from a strategic perspective is a contribution to the field of wind farm monopile installation literature as it provides insight into the different configurations that are available and their applicability in different wind farm projects. The weather model developed is another theoretical contribution to the field. The weather model integrates explicitly the duration of certain weather events in a Markov model and provides the possibility to generate new realizations of synthetic weather which statistically still represent the conditions at the wind farm installation location. Within literature, there is no previous research found that incorporated weather event durations in order to generate synthetic weather realizations. Both the developed weather model and its integration with a simulation model therefore do not only provide practical insights but also add theoretical knowledge to the literature available.

1.5. Outline

Chapter two offers a literature review describing previous modeling attempts of the offshore wind supply chain. It also describes important supply chain configurations and key performance indicators used in the offshore wind industry. The chapter will conclude with the research gap specification and the conceptual model used within this research. In chapter three, the simulation model is presented. The fourth chapter describes the developed weather module in more detail and reflects on the shortcomings of weather models described and proposed in literature. Chapter five shows the design of the experiments that will be used to answer the main research question. The results of these experiments are discussed and visualized in chapter six. The last chapter, chapter seven, will summarize the main findings and provide practical and theoretical recommendations.

2
Literature Review

First, the reviewed literature on the installation phase of offshore wind farms is investigated. Secondly, the different supply chain configurations and the key performance indicators to consider are investigated. Lastly, the research gap is specified.

In the literature review, only journal articles are discussed as the conference papers that are available differ a lot in quality and sometimes lack background information on the used methods, the conference papers however are read to see if important information is missed by excluding these papers. The exceptions are the conference paper of Hrouga and Bostel (2020), as it provides a good overview of the available literature, and the paper of Drunsic et al. (2016) which is the only literature available that provides insight into different supply chain configurations. The search terms listed in Table 2.1 are the terms used to search on the scopus citation database for the literature review. Only articles that include installation of foundations for offshore wind are included, other structures like floating wind are not included in the literature review as these structures will lead to different transportation requirements. After the structured search, papers with a lot of references (like the paper of Hrouga and Bostel (2020)) are analyzed for “connected papers” in order to create a graph of all the related work which leads to identification of papers not captured in the search terms.

Keywords	offshore wind, offshore wind farm, supply chain, logistics, installation , model, modelling, optimization, simulation
Search Query	“offshore wind” AND installation AND “supply chain” “offshore wind” AND installation AND logistics offshore AND wind AND farm AND logistics offshore AND wind AND installation AND “supply chain” “OWF” AND installation AND (logistics OR “supply chain”)

Table 2.1: Keywords and search queries literature review

2.1. Wind Farm Installation Research

The four main activities of the supply chain in offshore wind farms are visualized in Figure 2.1 (Poulsen & Lema, 2017).

The installation & commissioning phase is of particular interest as this phase is complex and uncertain. This uncertainty mainly stems from the weather limitations present

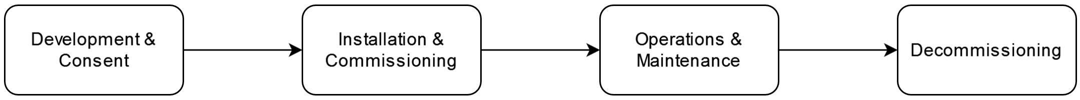


Figure 2.1: Main activities offshore wind farm supply chain

in the installation process. Wind farms are built on locations where high winds are common (as these are good wind farm locations), but installation vessels have operational limits during installation. These limits are dependent on the type of vessel, the operation that is performed and the environmental conditions. Bad weather leads to delays and weather windows in which installation is not possible, therefore, when the weather allows installation, stock is required quickly to benefit from this window (Hrouga & Bostel, 2020). Unplanned bad weather and downtime will lead to stock build up back in the supply chain. (Vis & Ursavas, 2016)

Offshore wind turbines require strong foundations connected to the seabed when installing them offshore. Although new structures like jacket systems are used, monopiles are currently the most common foundation and are expected to remain the most preferred option. The quick installation of this foundation type and the simple design are making it the most suitable choice for most installation projects. Although wind farms are planned in deeper water, the size of monopiles is also increasing, currently XL monopiles are installed in deep water, which allows depths of 36 meters without any other supporting systems installed to this monopile. An important factor is therefore the transport, storage and installation challenges that arise from the increase in size of these foundations. (LEANWIND consortium, 2018)

Although the installation phase is complex and important, not a lot of research focuses on this phase. Most research is focused on the operation and maintenance, not the installation of offshore wind farms. Research on logistics in the installation phase is sparse, as pointed out by Vis and Ursavas (2016). Vis and Ursavas (2016) test different supply chain configurations regarding pre-assembly of components. The paper does not assess any vessel usage configurations as the process of offshore wind farm installation is assumed to be performed by a single vessel that sails back and forth to one specific port location. Although the paper mentions that an important aspect of the installation phase consists of the shore to site distance, the paper does not test any configurations regarding the logistical network of transporting pre-assembled components to the installation site. The paper, however, does reflect on which supply chain strategies are possible, the all-in-one and the feeder strategy. The feeder strategy describes smaller supply vessels (for example a barge) bringing components from port to the site, and the all-in-one describes the installation vessel as transporter of components. (Vis & Ursavas, 2016)

Hrouga and Bostel (2020) performed an extensive review on logistic planning for offshore wind farm operations. The authors researched available literature and categorized the logistics into the strategic, tactical and operational level. Where on strategic level, the location of offshore wind farms is considered. On the tactical level the planning of operations for offshore wind farm installation. The operational level considers vessel routing on a daily basis, weather factors in fuel consumption or operational scheduling. On the strategic level, the distance between installation sites and the supplier location is important when determining the optimal location of offshore wind farms. On the tactical level, the review distinguishes between optimization and simulation models. Multiple papers investigate optimal installation planning on this tactical level (Barlow et al., 2018; Irawan et al., 2017; Sarker & Faiz, 2017; Scholz-Reiter et al., 2011). The research of Barlow et al. (2018) also focuses on installation scheduling but uses discrete event simulation to test the effect of using different start dates.

The review performed by Rippel et al. (2019) gives an overview on the research that relates to planning offshore wind farm installations. It discusses how the different planning tasks relate to each other and relates the planning tasks to different levels. The paper states that discrete event simulation is a good method to evaluate different configurations in offshore wind farm installation as it enables to model detailed processes while integrating uncertainty and weather dynamics. The importance of integrating uncertainty related to weather dynamics is also emphasized by Ursavas (2017) who state that simple deterministic approaches to modeling installation processes is not sufficient. The authors developed a stochastic program taking into account disruptions arising from different weather conditions in order to develop a robust schedule.

The paper of Vojdani and Lootz (2012) provides qualitative insights into approaches on how to design supply chain networks for the installation of offshore wind farms. The paper recommended that simulation of network structures is needed to investigate the behavior of the system under uncertainty and stochasticity. The paper further points out that the maritime logistical process should be seen as the bottleneck of the supply chain due to the influence of vessel availability and weather conditions. (Vojdani & Lootz, 2012). The paper of Irawan et al. (2018) takes a different focus compared with other research in the field and focuses on the strategic phase of selecting the best installation port and creates a schedule for the transport of components from suppliers towards the chosen best installation port. The paper considers multiple suppliers, plants, secondary ports if required and the transport to the final installation port which is the port served by the installation vessel. The model developed tries to determine optimal movements in order to minimize cost. The authors recommend future research to integrate offshore processes into the model to create a fully integrated supply chain decision support tool. Another shortcoming that can be identified is the fact that the model is developed to meet the demand of the installation port without including the influences of weather. Rippel, Lütjen, et al. (2021) focus on the resupply of components to a supply port by combining simulation and optimization. The paper finds that by choosing specific resupply cycles onshore capacity can be reduced.

In other research, simulation is also used to analyze offshore logistic processes while taking into account the effect of weather. Chartron (2019) focuses on evaluating the usage of crew support vessels, material supply vessels and towage vessels. By varying the combination of vessels used and simulating these sets of vessels, the logistic costs are analyzed under influence of historical weather. The main focus is on the usage of vessel combinations, so no different supply chain configurations are tested or analyzed.

Another area of focus within the field of offshore wind farm installation is the focus of sharing resources and information. The review of Hrouga and Bostel (2020) emphasizes the importance of investigating resource and information sharing activities in the offshore supply chain. The review also emphasizes the lack of focus on the global supply chain where the different phases are considered all at once. The paper of Beinke et al. (2017) look into sharing resources used within installation processes by performing a simulation study mainly focussing on material flows and onshore processes. It found that weather plays a very important role in usage durations and utilization of vessels. Quandt et al. (2017) investigate which information needs to be shared in order to efficiently install offshore wind farms. Another study looks at the effect of sharing information about weather forecast, port capacity and the supply of vessels (Beinke et al., 2020).

Other focuses in the field are vessel routing and crew scheduling. In order to route vessels efficiently, research is done on speed optimized trips based on average fuel consumption (Norlund & Gribkovskaia, 2017). Crew scheduling is also investigated in order to reduce personnel cost (Rippel, Foroushani, et al., 2021).

A paper that closely relates to the research goal of this report is the paper of Tjaberings et al. (2022). In this paper different strategies of installing and transporting monopiles and transition pieces are tested with the use of discrete event simulation. It considers the impact of weather while simulating different supply chain strategies like direct sailing, offshore transfer and wet towing monopiles combined with piling strategies. In the context of supply chain configurations, the paper only compares the direct sailing strategy with the offshore transfer strategy but does not consider other supply chain configurations. Also, the weather uncertainty is based only on historical weather data and is therefore a subset of the possible weather conditions that can occur, the variability related to weather is therefore not fully assessed.

2.2. Supply Chain Configurations and Key Performance Indicators

An important aspect to consider is the delivery method for a project. The main methods that can be distinguished according to Drunsic et al. (2016) to deliver monopile foundations are listed in Figure 2.2. These methods will be called supply chain configurations in this report as they provide different configurations of organizing the transportation within the supply chain.

1. Loading at supply port and transporting to a staging port for storage (an intermediate storage port)
2. Loading of components on a vessel at supply port and offloading on floating barge in sheltered harbor near the wind farm.
3. Supply vessel that loads at supply port and unloads at offshore wind farm
4. Loading of components directly on installation vessel at supply port.

Figure 2.2: Identified supply chain configurations (Drunsic et al., 2016)

One of these methods is the direct loading of components on the installation vessel. According to Drunsic et al. (2016) this direct loading method is preferred, but in reality, this is not always feasible due to the distances to the manufacturer's facility. The authors of this paper also state that generally voyage duration for the main installation vessel should be minimized, and the chosen approach depends on the distances between locations, vessel availability and capabilities of port facilities. The authors state that during planning, a cost benefit analysis is required to assess the supply chain configuration that fits the given project. The analysis should include risk of damage, delays and cost of double handling. However, how to perform such an analysis is not provided in the paper.

In this report, the researched configurations are in line with the most important scenarios listed by Drunsic et al. (2016), but investigate these at a more detailed level by including realistic limitations of weather and simulating synchronization levels. The main supply chain configurations analyzed are either the direct sailing of the installation vessel back and forth to supply itself at the main source point, the usage of supply vessels and transshipment offshore, and the usage of supply vessels to do transshipment at an intermediate port. This intermediate port is either used as just a sheltered area to provide ship-to-ship transfer (where the supply vessel acts as a buffer) or as a storage location with cranes to unload and load vessels. Based on conversations with experts an additional configuration is added. This configuration describes using supply vessels for both transporting from the supply port to an intermediate port and a feeder vessel transporting from an intermediate port to the wind farm (scenario 5) is researched.

The four supply chain configurations based on the paper of Drunsic et al. (2016) and the additional configuration are listed and visualized below in Figure 2.3.

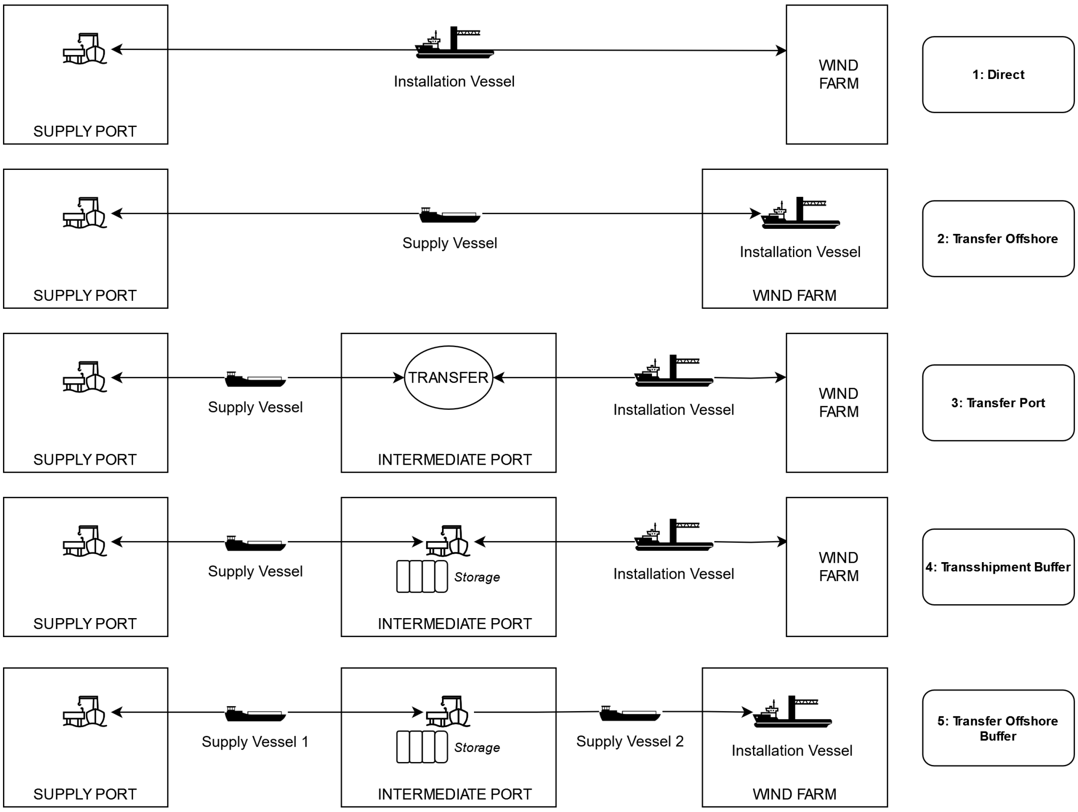


Figure 2.3: Different supply chain configurations to be tested

In order to assess the effect of using different supply chain configurations the key performance indicators of offshore wind farm installation processes need to be identified The identified most important project performance indicators are project duration and corresponding project cost (Barlow et al., 2015; Tekle Muhabie et al., 2018; Vis & Ursavas, 2016).

2.3. Research Gap Specification

Based on the literature review, the identified gaps are listed in Figure 2.4 and described below.

- Supply chain decisions offshore are not investigated
- Complex logistics networks are not considered
- Stochastic influence of weather is often not included
- No quantitative method to analyze different supply chain configurations

Figure 2.4: Identified research gaps in literature review

Several gaps can be identified based on the reviewed literature. Firstly, the research question considered focuses on supply chain decisions in the installation of offshore wind. However, most of the reviewed papers focus on developing short or medium term installation schedules for the installation of offshore wind farms, not decisions related to the design of the supply chain (Barlow et al., 2018; Irawan et al., 2017; Sarker & Faiz, 2017; Scholz-Reiter et al., 2011). It can be concluded that the performance of different supply chain configurations like intermediate hubs and the effect of vessel design or weather is not researched yet. Secondly, the research integrating part of the supply chain only consider vessels that directly sail between a location at shore and the wind farm installation location (Vis & Ursavas, 2016). The supplier location is often considered to be given, and more complex logistical networks that are present in the supply chain are not considered. Thirdly, the papers that do investigate logistics (although not specifically offshore) tend to not fully take into account the stochastic influence of weather (Irawan et al., 2018; Tjaberings et al., 2022). Although weather restrictions are likely to play a big role in determining the performance of supply chain configurations. Weather influences should therefore be included in the analysis of strategic decisions in order to make correct and informed decisions on the supply chain configuration and vessels used (Ursavas, 2017). Lastly, the paper that describes different configurations to transport foundations offshore does not provide a method of assessing the performance of these configurations (Drunsic et al., 2016).

2.4. Terminology

Within literature, terms are sometimes used interchangeably. Therefore, the table below describes the main terms used within the two models. The term fully written out is stated together with the shorter term used in the remainder of this thesis and in the models. Also, a description of each term is presented.

Term	Referred As	Description
Supply Port	Supply Port	The port where the supply, in this case foundations, are stored and expected to be picked-up by the installation company. Often the pre-assembly site and main suppliers operate in this port.
Transshipment Port	Transshipment Port	Port that is designated to do transshipment for the supply chain process under consideration. Transshipment takes place when at a port cargo is unloaded from a feeder vessel to the shore and later on loaded again to a main line vessel or the other way around. Transshipment cargo therefore goes over the quay twice, for unloading and loading to another ship. (Ligteringen, 2022)
Ship-to-ship Transfer	Transfer	Ship-to-ship transfer describes transfer of cargo between two vessels without including any onshore operations or dwell time of cargo ashore. The transfer is assumed to take place directly from one vessel to the other. Can happen in a sheltered location where the vessels are anchored or offshore. (Wikipedia, 2022)
Port Transshipment	Transshipment	Port transshipment describes ship-to-ship transshipment where transshipment takes place at a port to unload cargo from a vessel and load this cargo again on another vessel.
Intermediate port	Intermediate port	A port that is visited in between the supply location and the destination location. At this point direct ship-to-ship transfer or port transshipment can take place.
Installation Vessel	Installation Vessel	The vessel that is responsible for the installation of the wind farm foundations and includes specialized equipment to perform these installation operations.
Feeder Barge	Barge	Seagoing barges with the main goal of feeding the main installation vessel with cargo or transporting cargo from the supply port to the transshipment port. These barges are supported by tugs in order to manouvre and operate.
Offshore Supply Vessel	Supply Vessel	An offshore supply vessel, also called an offshore support vessel, has the main purpose of transporting goods or persons to support offshore processes. In this case, a general definition is used as a multitude of vessels can be used to supply these goods, for example, a dedicated supply vessel built for transporting monopiles, barges or even other installation vessels can act as a supply vessel.

Table 2.2: Table with main terms used

3
Supply Chain Model

In order to investigate the effect of using different supply chain configurations, a way of experimenting with those configurations is required. Also, the effect of different weather conditions should be included in these experiments. In order to run multiple tests and assess conditions like distance to shore and weather influences, a lot of different experiment runs are required. Manually tracking the weather while experimenting with different configurations is not possible as this would require multiple years of running before inferences can be made. It is therefore better to model the system in a way that allows fast experimentation and testing without costly investments and long experiment duration. This is possible by making use of computer simulation. In order to model real life installation projects, the supply chain will be modeled with the help of discrete event computer simulation, which will be further explained and described in section 3.3. This simulation model of the processes that occur in the supply chain will be called the supply chain model. The supply chain model will simulate the operational processes, the interactions between the vessels, and the stochastic behavior of operations in order to accurately reflect real life operations

3.1. Conceptual Model

In the literature review, Section 2.2, the different supply chain configurations and key performance indicators are identified. This answers sub-research questions 1 and 2. In order to answer sub-research questions 3 and 4 and the main research question, the relation between the configurations and the key performance indicators need to be investigated. This section will introduce the conceptual model used in order to answer the research question.

The main independent variable in this research is the strategic choice of a supply chain configuration that determines how the monopiles are delivered from the supplier to the wind farm installation location, as shown in Figure 2.3. The dependent variables are the described key performance indicators of offshore wind farm installation processes.

Regarding the key performance indicators installation vessel usage is interesting to include as it describes the duration the most expensive vessel, the installation vessel, needs to be operational and cannot be used for other projects. As sailing is the main contributor to fuel usage and therefore, the project cost will be split into the overall total cost and the fuel cost in some experiments. As it is expected that stochastic influences like weather will influence project duration, the waiting time due to weather will also be taken into account in the main case study experiment. The used dependent variables are summarized in Figure 3.1.

- Project cost
    - Total cost
    - Fuel cost
- Project duration
- Vessel usage duration
- Waiting on weather duration

Figure 3.1: Dependent Variables - Key Performance Indicators

Next to the main independent and dependent variables also some additional parameters will be experimented with by varying their values. These varying parameters are called moderators as the effect of changing these parameters on the relation between the supply chain configurations and key performance indicators is researched. The goal of including these moderators is to assess the effect of changing the variables and to investigate the importance of the different variables. One of these parameters that will be varied is the effect of distance from shore as it is expected to influence the performance of the supply chain configurations (Vis & Ursavas, 2016). As the supply vessels are expected to be cheaper to operate than the installation vessels, it is expected that making use of a buffer, so storing monopiles at an intermediate location, will impact overall project cost and project durations. Therefore, the number of monopiles that are stocked before the installation vessel starts operating is varied to test the impact of these choices. The vessel characteristics like operating and sailing limits are also likely to influence the dependent variables as these determine the weather window durations. The weather itself plays a big role in determining the weather window durations and is therefore varied by applying a simple increase/decrease factor to the available weather data. The start month of the project is also expected to influence the dependent variables due to seasonal variance in weather conditions and is therefore also varied.

The conceptual model in Figure 3.2 shows the relation between the independent and dependent variables. Investigating this relation and the effect of the moderators will allow answering sub-research questions 3 and 4 and therefore the main research question. The main dependent variables will be referred to as key performance indicators (KPI) in the remainder of this report.

3.2. Integrated Framework

This section introduces the structure of the supply chain model and the integration of a separate weather module, which is discussed in more detail in Chapter 4.

A model that is able to generate random weather should be integrated with the supply chain simulation model in order to include the effect of dynamic weather influences. The development of a weather model is required as there are no methods available to incorporate random weather realizations within the simulation process that both reflect the characteristics of the weather at a certain location and at the same time reflect a realization that is unique (i.e., has not happened before).

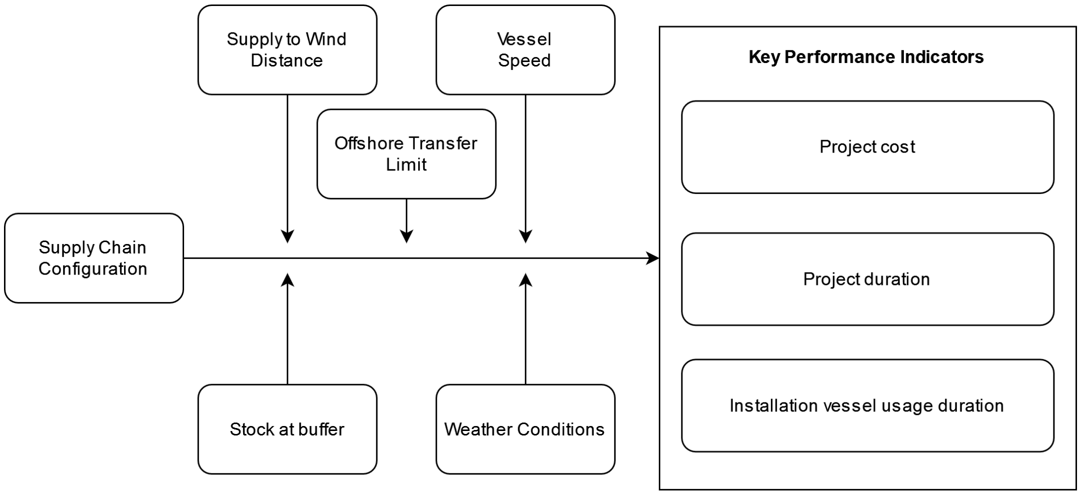


Figure 3.2: Conceptual model with independent and dependent variables

The development of the weather module and the used modeling technique are described in chapter 4. The developed supply chain computer model, abbreviated as LOGSIM (logistic simulation), is presented as a package with multiple modules each responsible for different parts of the simulation. These modules can also be used independently of each other which allows, for example, to use the weather model for other purposes. The description of the developed package and code for the developed simulation model used in this paper is described in Appendix B.

The integration of the different modules is visualized in Figure 3.3. At the start of a simulation run, the weather model is instantiated with a synthetic weather sample. During the processes of sailing, transfer or installation, the supply chain model can request a weather window from the weather model. It gives the current simulation clock time and the limits that are considered to the weather model which returns the first possible hour the requested operation can take place. This search function is bundled in the weather model to reduce the amount of information that needs to be communicated between modules as the function uses information about the current weather realization.

To summarize, in order to assess the performance of the different supply chain configurations a supply chain model needs to be developed consisting integrating a separate weather module. In the following section, the supply chain model will be described. As the weather model development required iterations and multiple validations, a separate chapter will describe the developed weather model, chapter 4.

3.3. Discrete Event Simulation Methodology

The discrete event system specification formalism, is very useful to simulate mesoscopic processes within Port and Waterway networks. This is due to the fact that the level of detail allows studying large areas of interest but still includes detailed sub-models including engineering knowledge. (Koningsveld et al., 2023). Within this formalism, events are modeled in a discrete way jumping from state to state. The state variables remain constant for a certain number of times before a jump to another state happens again. (Hill, 2002). Using a discrete event simulation allows including stochastic processes that govern the duration of states or the probabilities of certain events. This

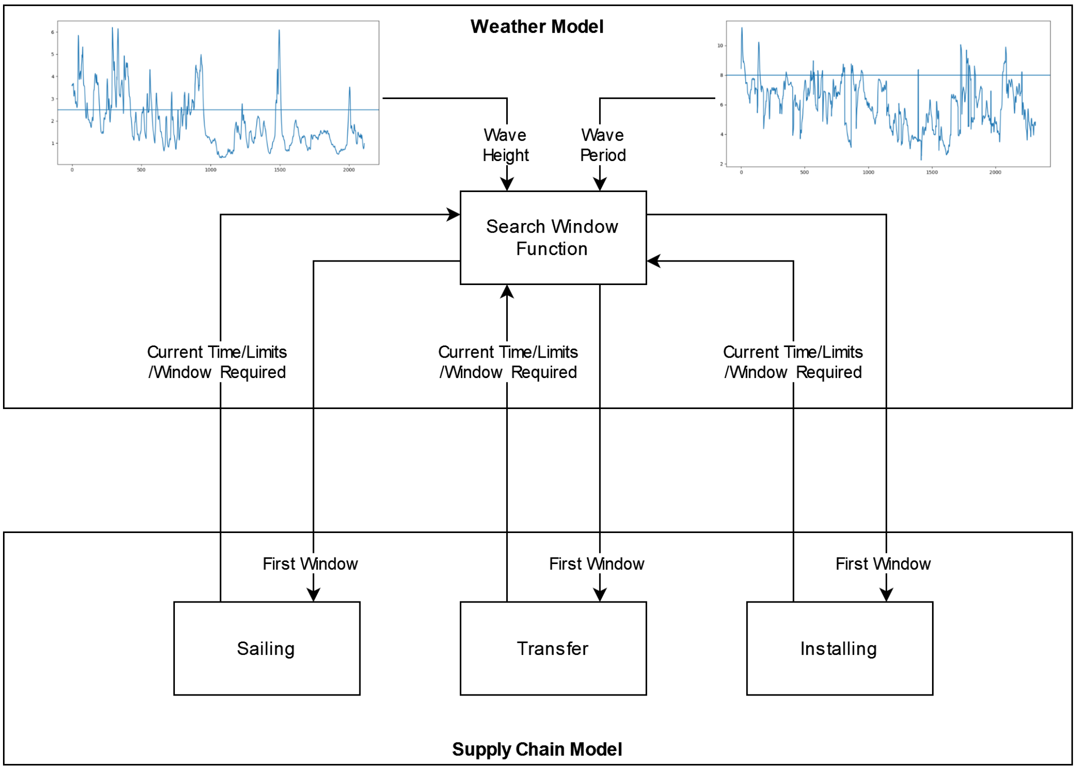


Figure 3.3: Weather and Supply Chain Model Interaction

seems particularly useful for this report as the duration of operational activities and downtime is governed by the stochastic weather processes. By integrating the random weather realizations, these realizations can be used to govern the order and duration of events. Discrete event simulation is useful to model this dependence, especially as the current system involves sequential and repetitive operations (i.e., the installation process) (Vis & Ursavas, 2016). Using computer simulation is appropriate as the goal of this report is to experiment with a model of a real system to evaluate various operation strategies, which is in line with the definition of a simulation study (Shannon, 1977). Simulation is often used within the field of operation research and is therefore a well-established technique(Shannon, 1977).

A discrete event simulation model can be described from three different perspectives, also called worldviews. Each simulation language uses one of these world views. It is important to investigate which world view is appropriate in order to choose the correct language for implementation of the simulation model. The three world views are the event scheduling-, activity scanning-, and process interaction world view. The event scheduling view provides locality of time, it describes how system state changes take place. The activity scanning view focuses on locality of state, it describes all actions that occur at the moment a particular state is reached. The last worldview, the process interaction view, provides locality of object, each process describes actions of a particular object. The process under consideration is that of multiple vessels that need to operate within a certain network according to specified conditions. Each of these vessels has their own parameters and specific goals/behaviors. In order to easily separate the behavior of these vessels with their corresponding processes, it is easiest to create separate objects of vessel types with corresponding parameters and processes. This allows instantiating multiple instances of the same object and easily change the number of vessels within the simulation. This object-oriented way of simulating follows the process-interaction world view. Following this worldview fits best with the modularity that is preferred within the simulation model development. The main difficulty will be the interaction between the different objects as at certain points their processes need to interact, despite the fact that they are defined as separate objects.

The supply chain model is developed to answer the main research questions. In order to provide the functionality of experimenting with the supply chain model, the computer model is preferably developed with open source and well-known software.

One of the most popular programming languages of 2023 is Python (TIOBE, 2023). Python is a widely used programming language that is interactive, interpreted and allows object-oriented programming. The python language is open source, easy to understand, and includes a lot of extensions that ease programming. Therefore, Python is the preferred language for developing a modern modular simulation model in an object-oriented way. Next to this, multiple Python extension packages are available that ease the creation of simulation models. (Python Software Foundation, 2023) A well-known Python package for discrete event simulation is SimPy (Team SimPy, 2023). Although SimPy provides a lot of functionality to simulate in a process-oriented way, it is hard to model more complex interactions between different processes due to the lack of more advanced process interaction functionalities. The package Salabim was developed to overcome this issue by providing essential process interaction methods like the ability to passivate, interact and hold other objects. Salabim enables modeling complex interactions and overcomes the difficulties that are present when modeling in an object-oriented way. (van der Ham, 2018) It was therefore chosen to develop the supply chain model in Python (3.10) with the package Salabim (23.1.4) (Python Software Foundation, 2023; van der Ham, 2018).

3.3.1. Process Flow

From a methodological perspective, the main problem for the development of the conceptual supply chain model is, "How to model the supply chain processes of a wind farm installation process in a realistic way"? Literature was used to sketch the first iteration of the supply chain processes (Barlow et al., 2015; Sarker & Faiz, 2017; Tjaberings et al., 2022; Vis & Ursavas, 2016). Based on expert knowledge (the different experts are described below) and validation of the visualized process model with experts the supply chain process model was iteratively improved.

In order to visualize the supply chain process, the business process model notation (BPMN) is used to visualize the process flow of the simulated process and allows to see the logic of tasks and activities in a process oriented way. These process flows give a clear overview of the different processes and allowed validating the processes with experts in a visual way. Configurations will differ in their corresponding process flow as the supply chain configuration to be used is one of the parameters that will be analyzed. Sub models are used extensively as at these points the model can be extended and specified in more detail during the development of the simulation process. The development process starts from an overview of the processes, and during development the interactions and processes that require more detail are extended. The main process flow describing the installation vessel is presented in Figure 3.4. The supply vessel process flow is visualized in Figure 3.5. The process of synchronization between the vessels at intermediate locations is visualized in Figure 3.6.

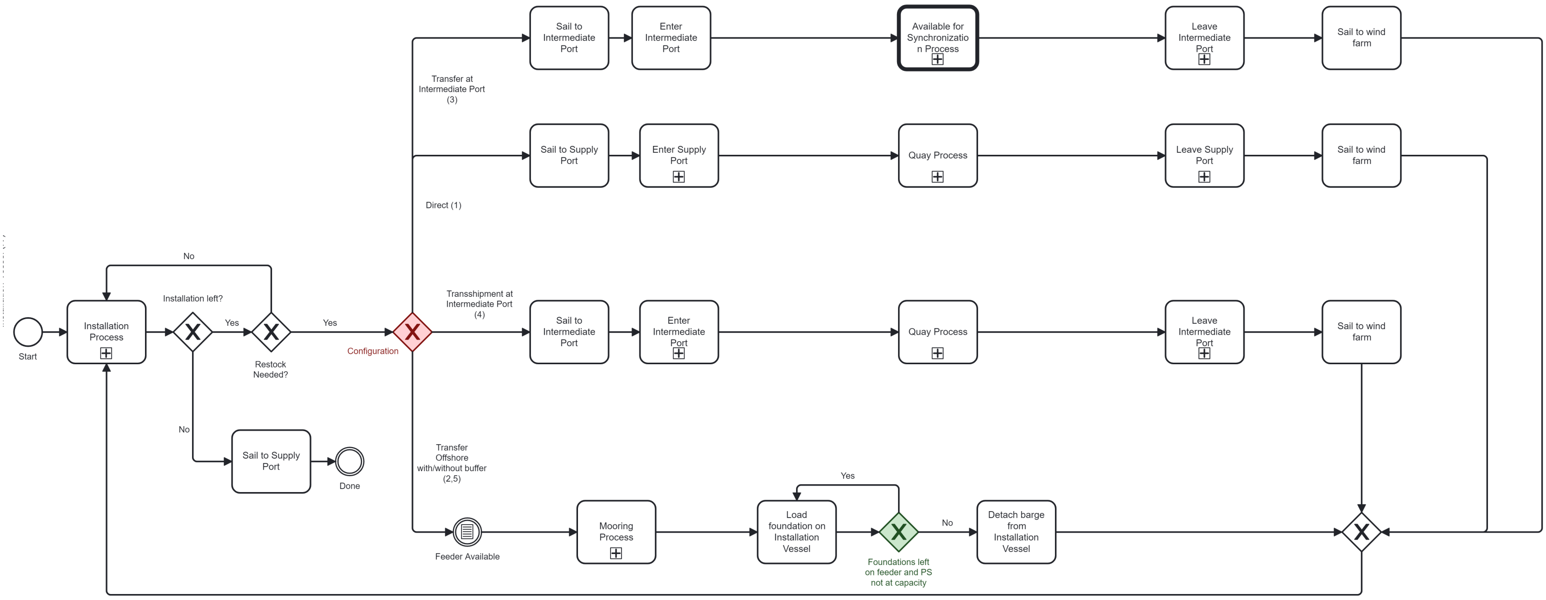


Figure 3.4: Installation vessel Process Flow

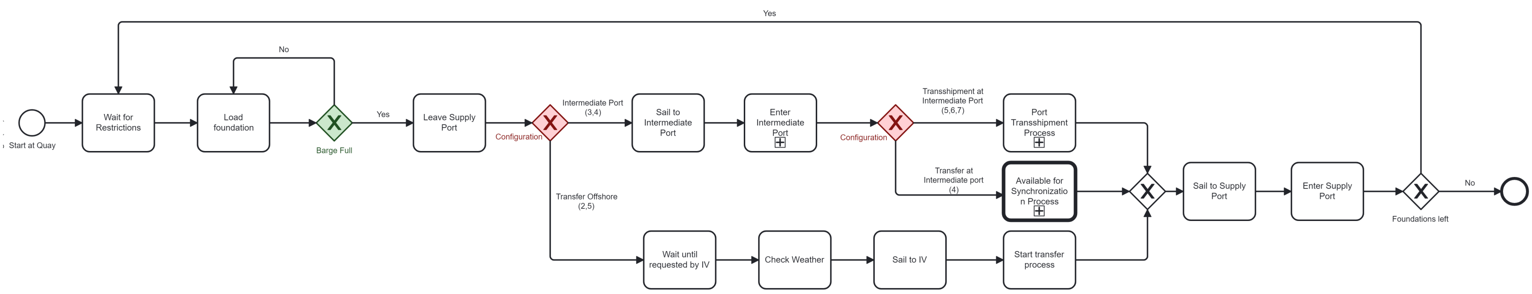


Figure 3.5: Supply Vessel Process Flow

Three different experts provided input in the iterative improvement process of the supply chain model, one working on weather forecasting and reporting for offshore operations, another with experience in designing offshore wind farm installation and support vessels, and the third expert had experience with the wind farm industry as a whole and gave insight into the dimensions, types and processes of foundation installation. These three experts were all asked the same questions, listed below, and the answers were combined in process flows. The interview was semi-structured following the structure of the listed questions but allowing to let the conversation develop to more detailed information if this was considered to be interesting or important. With the expert on weather forecasting and the expert with wind farm industry experience, two different meetings were scheduled to validate and develop the installation schedule. The expert on vessel design was only consulted once in order to validate the limits and process flow related to vessel operations mentioned by the other experts. This was an interactive approach as some processes required more detailed modeling than others. No problems occurred during this process as the experts were aligned in their answers.

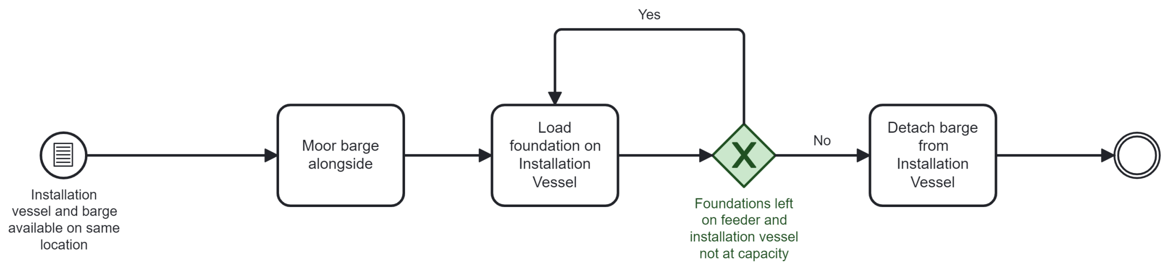


Figure 3.6: Synchronization Process Flow

1. How does the installation process of a monopile look like?
2. How does this differ between ports and installation locations?
3. How would this differ if a supply vessel will be used to deliver monopiles to the installation vessel?
4. How does this differ between types of installation vessels?
5. Which steps are critical in terms of project duration and cost?
6. Which decision rules are important in determining if sailing/installation takes place?
7. How is weather interpreted to decide if operations can take place?
8. Are there further things to consider when modeling the supply chain of offshore monopile installation?
9. After first iteration: Is this model a realistic representation of real offshore operations?

Some of these the processes identified require modelling assumptions or parameter estimations, which are described in the assumption section, subsection 3.3.3.

3.3.2. Parameters

The tables below show the main variables with the corresponding units that are used within the supply chain model and are required to model the process flows discussed. The variables that can be set for the installation vessel are given in Table 3.1 and those for the supply vessel in Table 3.2. Parameters related to the experiment, weather and distances are given in Table 3.3. The parameters considered as distribution in the developed simulation are labeled with TRUE in the table. The main dependent variables are given in the conceptual model Figure 3.2 and the different supply chain configurations (so the possible values of the main independent variable) are defined in section 2.2.

3.3.3. Assumptions

The assumptions within the supply chain model are categorized per sub-process below.

Parameter	Unit	Distribution
Foundation Capacity	-	
Sailing Speed Offshore	knots	TRUE
Sailing Speed Port	knots	TRUE
Day Rate	euro/day	
Mobilization Rate	euro	
Sailing Cost	euro/hour	
Installation Time	hour/monopile	TRUE
Installation limit wave	meter	
Installation limit period	seconds	
Sailing limit wave	meter	
Sailing limit period	seconds	
Alongside limit wave	meter	
Alongside limit period	seconds	
Load time	hour	TRUE
Mooring time	hour	TRUE
Unmooring time	hour	TRUE
Alongside mooring time	hour	TRUE
Alongside unmooring time	hour	TRUE
Alongside transfer time	hour/monopile	TRUE

Table 3.1: Installation Vessel Parameters

Parameter	Unit	Distribution
Foundation Capacity	-	
Sailing Speed Offshore	knots	TRUE
Sailing Speed Port	knots	TRUE
Day Rate	euro/day	
Mobilization Rate	euro	
Sailing Cost	euro/hour	
Sailing limit wave	meter	
Sailing limit period	meter	
Load time	hour/monopile	TRUE
Mooring time	hour	TRUE
Unmooring time	hour	TRUE

Table 3.2: Supply Vessel Parameters

Ports

1. Entering the port, and the whole process of tug assistance within the port is not included in the model as this is a standardized process outside the scope of the installation company, rather the duration of entering/leaving can be set. This duration will cover the complexity of the entering/leaving process without introducing to much parameters.
2. The intermediate port has x allowable storage, quay(s) and cranes available which are not used by any other vessels outside the scope of the supply chain model. This assumption is made as the conditions of operating from an intermediate port can differ per project, in most cases however the port is rented privately with own equipment and storage locations, so no other vessels will make use of the same resources.
3. The loading vessel waits until there is enough capacity at the intermediate port to load completely (or the maximum available items at the end). This avoids the

Type	Parameter	Unit
Weather	Start day	-
Weather	Start month	-
Weather	Synthetic	-
Weather	Samples	-
Weather	Scale factor	-
Configuration	Type	-
Distances	Supply to wind farm	km
Distances	Supply to intermediate	km
Distances	Intermediate to wind farm	km
Experiment	Intermediate location capacity	monopiles
Experiment	Intermediate location quays	-
Experiment	Intermediate location stock minimum	monopiles
Experiment	To Install	monopiles

Table 3.3: Experiment Parameters

scenario that a vessel docks multiple times to unload or load just a few monopiles at the time, which in reality would not happen.

4. Capacity at the intermediate port should always be bigger than capacity that a vessel can have (so at least 3 if a supply vessel has a capacity of 3). As the vessel needs to unload completely there should be enough space at port in order to perform this operation.
5. According to experts supply port quays are reserved for the installing company and are almost never used at the same time by other company, therefore the assumption is made that a quay is always available at the supply port and there are enough foundations on the side to immediately satisfy all the requested demand of the vessels, no additional waiting time or probabilistic stock shortages are simulated.
6. In the supply port the supply vessel always loads fully to its capacity before sailing of (except ofcourse if the last monopiles need to be transported).
7. Entering and exiting the ports is governed by the same sailing limits as offshore. This is because every port will look differently and will shield vessels from environmental conditions to different degrees. Assuming that the exiting and entering time of ports is governed by offshore weather seems to be the best way to compare the key performance indicators in a fair way. The time of entering and exiting is small compared to the sailing time, so this assumption will not make a big difference in the final results.
8. According to experts, if an intermediate location is used it makes sense to first build up some stock in this port before starting to operate the installation vessel. The number of required monopiles that need to be stocked before starting is a parameter.

Offshore

1. The supply vessel always loads fully to its capacity before sailing of to the installation vessel except when there are no monopiles at shore anymore to be transported to the vessel.
2. The supply vessel capacity will always be equal to that of the installation vessel to allow full transfer of goods. This is to avoid the possibility that a supply

vessel docks/undocks multiple times offshore requiring large weather windows. According to the experts this aligning of stock levels makes the most sense from a logistical perspective

3. Before sailing from a port, the first window is searched where at least 2 monopiles can be installed and sailing to the wind farm is possible.
4. Before starting the installation of a monopile the installation vessel will communicate the time that it expects to take to finish installation of all monopiles. Based on this information, the supply vessel will sail at the last moment possible and at the first moment a full window is available to be on the water.

Sailing

1. The fuel costs are based on fuel usage at average conditions, the relationship between environmental conditions in the simulation model and the drawn sailing speeds are not considered in the calculation of the fuel usage.
2. Random draws from the sailing speed distribution determine sailing speed . It is assumed this speed is the average speed during the duration of the trip.
3. Sailing is governed by the current weather at the installation location.

Routing Assumption

The offshore wind farm location is considered to be the most critical in terms of weather influences. In the case of the north sea, the assumption can be made that if the offshore wind farm locations weather characteristics allow sailing and operating of supply vessels for the required period of time (sailing and transferring with the supply vessel) the weather characteristics on the route also allow safe sailing of the supply vessel. It is possible to include routing weather characteristics as restrictions in the simulation window based on historical data sets. Data can be based on the North Sea Wave Database for example. But it is now chosen to not implement this due to the mentioned reasons. In discussions with experts, it becomes clear this is not the most important factor to take into account when modeling the supply chain configurations and this assumption is valid, especially when operating in the area of interest. Both the installation restrictions and sailing restrictions are therefore based on historical data of the offshore wind farm location.

Decision Rules

In the process model some more advanced decision rules should be taken into account within the simulation model according to experts to create a realistic model. In the first iteration of the model, all decisions were made one operation ahead and no communication between vessels was implemented. In real life, however, according to experts some decision rules are in place. For example, sailing to the installation location with the installation vessel does not make sense if installation limits will be exceeded once the vessel arrives at the wind farm. The three main decisions that are discovered and implemented in the supply chain model are listed below.

1. The installation vessel should only sail out if sailing to the wind farm is possible with the current weather, and after sailing, it can at least install two monopiles. A vessel will often sail out when a storm is fading away even though installing would not be possible at that moment, but this allows to be at the installation

location as soon as installing is possible. In order to be able to perform operations offshore, the guideline used is that at least a few (in this case 2) monopiles should be installed without any limitations.

2. A supply vessel will only sail if it is possible to sail to the wind farm, load all the monopiles and sail back again within all the required weather limits.
3. At the moment the installation vessel starts installing it will communicate continuously the expected time of being out of stock. The supply vessel will start the check of sailing out only at the moment it will be able to arrive at the installation vessel exactly at the time the installation at board of the vessel is finished, and the onboard storage of monopiles is empty.

3.3.4. Implementation of Computer Model

After developing the conceptual supply chain model the conceptual model is implemented as computer model in Python and Salabim, as discussed at the start of this section. More details about the implementation of the computer model are given in Appendix B. The weather model described in chapter 4 is integrated as Python module in this computer model. The validation of the computer model is described in section 6.2.

4 Weather Model

Currently for offshore wind farm locations historical weather data is available, sometimes for only a limited number of years. In order to test the different supply chain configurations, it would be preferable to use more random samples within the simulation. This can only be done by creating synthetic weather data that is not the same as the realized historical weather but consists of the same statistical properties like averages, variations and weather windows. It is better to use these generated data samples instead of historical data as it allows testing the effect of using different configurations in weather realizations that did not occur yet, and it allows testing configurations with as many realizations as is preferred. This makes it possible to increase the sample size of the runs and see the effect of a configuration in 1000 different weather realizations, giving insight into the distribution of the key performance indicator results. The weather model that will be developed should be able to generate synthetic data based on historical training data which allows to test supply chain configurations in different weather realizations.

Synthetic weather data can be generated with multivariate simulation trained on historical weather time series. One recent article compares weather models using Markov chains, autoregressive and long short-term memory models. The results of using Markov chains were considered to be the best (especially related to correlation metrics). The paper also concludes that using first-order or second-order Markov chains seems to be sufficient in order to generate realistic data. (Eberle et al., 2022). By following the approach in this paper and the citations used in this paper, a synthetic weather model was developed. The model, as implemented in the paper, was, however, not able to replicate the persistence of weather windows sufficiently in this report. Only taking into account historical weather realizations results in assessing only a subset of the weather conditions that can occur as often only a limited amount of historical data is available. When investigating offshore operations it is important to correctly model the persistence of weather phenomena as this determines the possible weather windows when operations can be performed . Also other markov chain models described in literature are, not able to correctly replicate persistence of weather windows. The number of short weather windows are overestimated, making the windows that operations can take place too conservative compared with historical weather data (Masi et al., 2015; Scheu et al., 2012). Integrating the markov chain models as these are proposed in literature would therefore lead to unrealistic results.

Therefore, efforts were made to improve the stated Markov models by explicitly incorporating the duration of weather states and using second-order Markov chains. This improvement resulted in a good fitting Markov model that can be used to realistically simulate weather effects on offshore operations.

In this chapter, the weather model is formalized and described. Below in Table 4.1 the main assumptions of the weather module are stated. These assumptions are explained in the sections describing the weather model.

Assumption	**Argument Validity**
Wind direction not included.	You can position the vessel to create a lee-side.
Wind speed not included	Not governing in vessel limits. The model becomes overly complicated when unnecessary variables are included

Table 4.1: Weather Model Assumptions

In order to test the development of the model an example training data set is used with historic weather data of the offshore wind farm location East Anglia (latitude: 52.670, longitude: 2.901), which is 43 kilometers from the shore of England. The hourly training data is generated with the SWAN model. The SWAN model is a validated wave generation model developed by the TU Delft (Zijlema et al., 2010). The input data is hourly weather data from the 3th of January 1979 until the 31th of December 2018. So this is around 40 years of historical data resulting in 350611 data points (each hour). For each date and time the wind speed in meter per second, the significant wave height in meter and the peak wave period in seconds is stated. No missing values are present. The descriptive statistics of the used dataset are reported in Table 4.2.

Statistic	**U**	**Hs**	**Tp**
count	350,592	350,592	350,592
mean	8.31	1.47	6.12
std	3.98	0.85	1.52
min	0.02	0.10	1.74
25%	5.40	0.86	5.03
50%	7.95	1.25	6.12
75%	10.80	1.85	7.08
max	29.13	7.93	19.97

Table 4.2: Descriptives of Dataset

4.1. Parameters

Before training the weather model the required parameters should be identified. For the purpose of the simulation, it is important to include the variables that accurately represent the weather windows that are available. The main variables that limit the operations can be identified as the significant wave height [m], the peak wave period [s] and the wind speed [m/s]. These variables are referred to as $H_s, T_p \& U$ respectively. These variables are also included in research that investigates Markov models for synthetic weather generation (Eberle et al., 2022; Hagen et al., 2013; Scheu et al., 2012). It is assumed that although the wind direction is important in offshore wind operations, it is possible to use the installation vessel to create a lee side for the vessel alongside which avoids needing to integrate this variable within the weather model.

The significant wave height describes the average measurement of the largest 33% of waves. Large waves are measured as these are the ones impacting the operations. Especially when offshore transshipment takes place, the wave height is important as loading and offloading monopiles with a crane can only happen until certain wave heights (to avoid having the load bounce back on the vessel, for example). Peak wave period is also called a spectral peak period and describes the wave period associated with the most energetic waves (Meteomatics, 2023). The wind speed describes the speed of the wind during a period at a certain height.

Firstly, an analysis is made on these variables to investigate if these should all be included. Adding more variables reduces the training data that is available as there are fewer observations of state transitions, it also increases the computational effort required. Care must be taken when including too many variables as this would require the bins to be more coarse in order to reduce model complexity (and overfitting) which will result in worse fitting models. The goal of the Markov model, as described before, is to generate synthetic weather data that follows the general statistics of the observed weather data but constitutes new realizations of similar weather. Overfitting the model and increasing the complexity will lead to a lot of state transitions with probability of 1, so following patterns of weather data within the observed dataset, resulting in synthetic weather data that are not new realizations. This was also noted in the paper of Scheu et al. (2012) which states that within their model including extra variables will result in larger bias due to having insufficient data points in the training data set. After testing the exclusion of the wind speed parameter, it can be concluded that excluding this parameter would not impact the results in a significant way. The description of this analysis can be found in Appendix A.4.

4.2. Including Seasonality

There are two different ways to include seasonality effects in the generation of synthetic weather. The first possibility is to train a separate weather model for each month. The second possibility is to standardize the training data before training the weather model. Training a separate model reduces the available training data and creates discontinuous steps at points where data transitions to another month. Standardizing the training data is another way of including seasonality effects in the markov model while still training the model on the complete dataset (Eberle et al., 2022). After loading in 40 years of historical weather data, capturing the weather at a location in the North Sea, a moving average and moving standard deviation is calculated for each possible day-month combination by taking into account the last 15 and the next 15 days (so years are disregarded in this calculation). As the data has a frequency of 1 hour, this means the average and variation are calculated over 24 (hours) * 40 (years) * 31 (days) = 29.760 observations for each day-month combination. This calculated value allows standardizing each parameter. This is required to take out the seasonal variations that are present in the parameters. By storing these standardization values, it is easy to reverse the standardization after synthetic data is generated. The parameters are standardized following the formula of Eberle et al. (2022) and is presented in Equation 4.1.

The first steps are training of the Markov model and generation of synthetic weather samples that include drawn standardized values for both the significant wave height and peak wave period parameters. In combination with a given start date, the samples that are generated can be transformed back to data that includes seasonal influences using the reversed standardization formula presented in Equation 4.1.

$$\tilde{X}_t = \frac{X_t - \bar{X}_{mov,t}}{\hat{\sigma}_{mov,t}} \tag{4.1}$$

4.3. Basic Markov Model

The first model that was tested was the model that was only trained on the state combinations of the binned significant wave height parameter (H_s) and the peak wave period (T_p), the basic markov model. The following sections will describe how the model is trained and synthetic weather data is generated.

4.3.1. Training

The data was standardized using Equation 4.1 with a moving window of 15 days. Afterward, the standardized values of the variables (H_s and T_p) are binned in 15 bins. The set of states (each state describing the weather at a certain moment in time) exists of all possible combinations of these bins as given in Equation 4.2. This results in set S with 225 unique combinations), each of these combinations is defined as a state $s_1, s_2, \ldots, s_n \in S$. For example, the state $(3, 5)$ in set S describes a wave height with a value in bin 3 and a peak wave period with a value in bin 5.

$$S = \{(H_{bin}, T_{bin}) \mid H_{bin} \in \{1, 2, \ldots, 15\}, T_{bin} \in \{1, 2, \ldots, 15\}\} \tag{4.2}$$

The Markov model applied is a second-order markov chain. This means that the next state depends on the previous two states. The probability of the state k depends on the previous states j and i as shown in Equation 4.4. In order to make visualization and handling of the previous states easier, all possible previous state combinations are combined as shown in Equation 4.3 where i represents X_{t-2} and j represents X_{t-1}. Set S, the set of individual states, and set S', the set of combined states, allows to present the transition probability as implemented in the weather model in Equation 4.5. The variable, $p_{i,j,k}$, represents the probability of transitioning from the combined previous states (i,j) to state k. After determining k and proceeding one step further in time k will become the previous state in which the new combination (i, j) will equal (j, k).

$$S' = \{(i, j) \mid i, j \in S\} \tag{4.3}$$

$$p_{i,j,k} = P(X_t = k | X_{t-1} = j, X_{t-2} = i)) \tag{4.4}$$

$$p_{i,j,k} = P(X_t = k | X_{t-1} = (i, j)) \tag{4.5}$$

The probabilities of these state transitions are determined by analyzing historical weather data. The probabilities are estimated by counting the number of observed transitions from (i, j) to k and dividing this value by the total number of observed transitions from the state combination (i, j) to any state as shown in Equation 4.6 with N representing the count of observations. This allows creating the transition matrix P

with as rows the (i, j) combinations and as columns the possible next states k. The values in this matrix are the transition probabilities observed in the training data. Also, a separate list P_{start} is generated that stores the overall number of observations containing each state combination in the training data. This list will be used in the synthetic data generation process to draw a random start combination.

$$p_{(i,j),k} = \frac{N_{(i,j),k}}{\sum_{l \in S} N_{(i,j),l}} \quad \forall (i, j) \in S', \forall k \in S \tag{4.6}$$

4.3.2. Generating Data

With the probability matrix P random weather data can be generated. This is done by firstly selecting a random state combination (i, j) from the P_{start} list according to the probabilities given in this list. These most occurring weather combinations will have the highest probability of being chosen as a start state combination in the random weather generation process. From this start state combination the correct row is selected in matrix P and the next state k is randomly chosen according to the probabilities given in the matrix. The newly drawn state k takes the place of j as this is becomes now a previous state from the perspective of the next draw which results in state combination (j, k). From this state combination the correct row is again selected in probability matrix P and the process repeats. As the training data is hourly data, each newly generated state k, consisting of variables (H_{bin}, T_{bin}) represents the weather at a certain hour. After generating the required number of hours, a list of generated states is available. As each state represents a combination of the variables H_{bin} and T_{bin} random draws are taken from these bins to get a standardized random value of the wave height and peak wave period (H_s, T_p). The standardization needs to be reversed again with Equation 4.1, resulting in a dataset of synthetically generated weather.

4.3.3. Validation

In this chapter the first iteration of the synthetic weather data model is validated. The synthetic data is randomly generated data, but the probabilities of certain weather characteristics should be close to the real historical data.

The main statistics of this model and the input data are presented in Table 4.3. The mean value is modeled almost perfectly compared with observed weather statistics. This is also the case for the quantile values of the model. Only the standard deviation, minimum and maximum differ due to the filtering that is done in the pre-processing of the data (to avoid additional outlier states in the Markov model for the most extreme values). It can be concluded that the descriptive statistics are replicated well using this synthetic Markov model.

Next to the validation of these distributions and general descriptive analysis it is also important to look at storm persistence. As weather windows determine if operations take place, the Markov model should replicate the persistence behavior of the 'real' weather. In order to analyze this behavior, the weather window duration given certain limits is plotted in empirical distribution functions. A weather window is defined as a window in which operations can take place without exceeding the limits defined for this operation. Given the limits of wave height below 2.5 and a peak period below 8 seconds (normal value for installation procedures) the cumulative distribution

Statistic	Hs Observed	Hs Basic Model	Tp Observed	Tp Basic Model
count	350,592	438,000	350,592	438,000
mean	1.47	1.47	6.12	6.13
std	0.85	0.80	1.52	1.42
min	0.1	0.30	1.74	3.10
25%	0.86	0.87	5.03	5.07
50%	1.25	1.29	6.12	6.12
75%	1.85	1.89	7.08	7.13
max	7.93	4.52	19.97	9.81

Table 4.3: Statistics of Basic Markov Model

function in Figure 4.1 is plotted showing the durations of weather windows that allow operations. The cumulative distribution function of a wave height below 1.5 and peak period below 8 seconds is presented in Figure 4.2. As can be observed, the Markov model tends to overestimate the occurrences of shorter weather windows. This is in line with past research (Scheu et al., 2012).

This will make the model run with synthetic weather more conservative as more often weather will be deemed inappropriate for operations. This is confirmed in research as it is difficult to realize agreement in persistence values when analyzing different scales in time (Scheu et al., 2012). These persistence values are although important as they provide the duration of which an operation is feasible. As the impact of weather is assumed to play an important role in the downtime and results of the simulation, it is preferred to work with a model that captures the persistence of the weather windows in a better way.

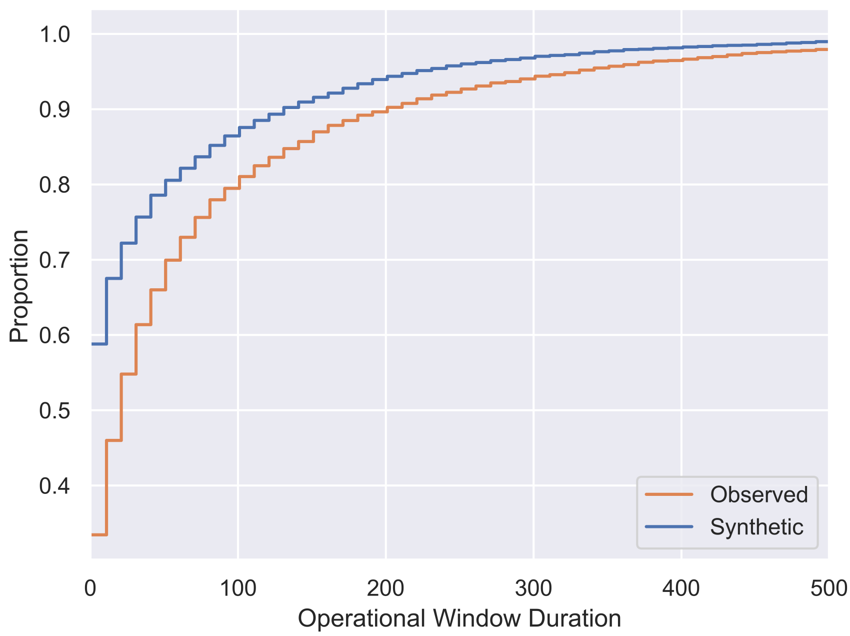


Figure 4.1: Window Duration Limit 2.5/8

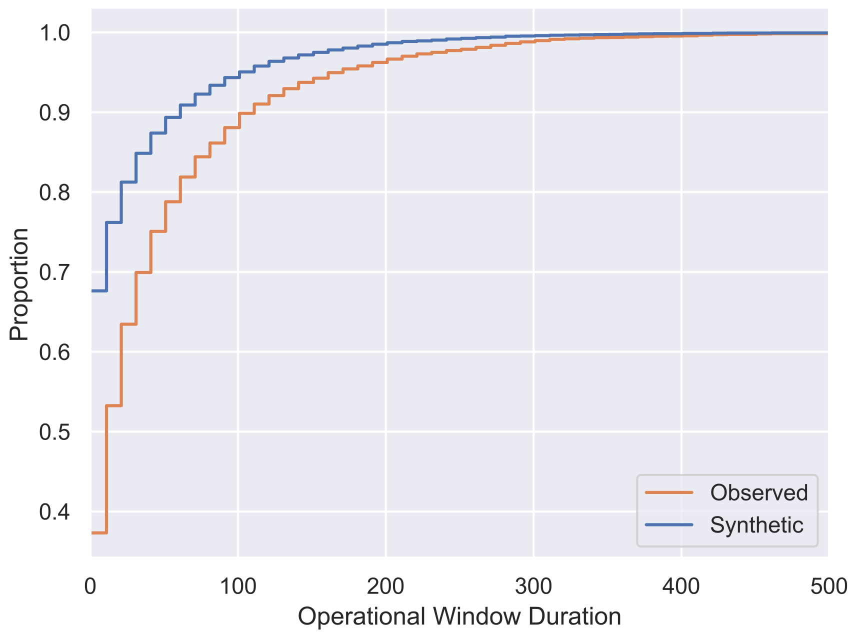


Figure 4.2: Window Duration Limit 1.5/8

4.4. Improved Markov Model

The main shortcoming of the first created model is the fact that it is not able to capture the persistence of weather windows sufficiently while these are very important in determining operational windows within simulation runs. This shortcoming is validated by the previous analyzes of weather window persistence. The developed model currently implicitly incorporates the persistence of weather windows by the probabilities that the Markov model transitions to either the same bin or a bin with "better" weather when within an operational weather window. As long as this happens and the model does not escape towards a bin with values above operational limits, a weather window is present. After validation, it seems like the Markov model is not able to persist the weather windows as present in the training data implicitly. The model overestimates the occurrences of small operational windows as it escapes the weather window bins that are within the operational limits to quickly and often. The idea of explicitly incorporating the duration of staying within a certain bin was therefore tested. This is not yet done within research that investigates generating synthetic weather data for offshore operations. The following sections will describe how the model is trained and synthetic weather data is generated.

4.4.1. Training

In order to include these durations the durations first need to be generated based on the training data. The process of generating this synthetic weather is visualized in Figure 4.3 and will be described in more detail below.

After standardization and binning the variables H_s and T_p in 15 equal bins the training data consists of the variables H_{bin} and T_{bin} describing the bins the observed values belong to. For each of the observations in the training data the number of times a

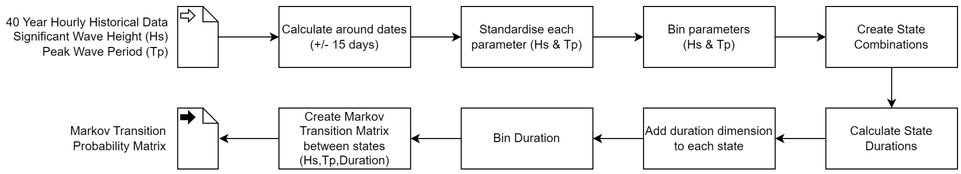


Figure 4.3: Training Process of Weather Model

certain bin combination (H_{bin}, T_{bin}) is repeated after each other is recorded. Afterward, the training data is reduced to the form (H_{bin}, T_{bin}, Dur) describing the observed bins and its duration. As the durations in these observations follow a continuous scale, the values are made discrete by also binning the durations in 23 different bins, resulting in a $(H_{bin}, T_{bin}, Dur_{bin})$ combination for each observation.

The set of states, set S, exists of all possible bin combinations an observation can have. The set S can be defined as given in Equation 4.7. All possible states are combined in the same way as described in the training section of the basic markov model, subsection 4.3.1. The only difference is that each state $s_1, s_2, \ldots, s_n \in S$ now describes a combination f $(H_{bin}, T_{bin}, Dur_{bin})$ instead of only the variables (H_{bin}, T_{bin}). Each state combination (i, j) as defined in Equation 4.3 is now related to state i and state j where each state includes the duration information. In this way the duration of the combinations are taken into account explicitly in the improved model. The transition probabilities and the next states are determined in the same way as given in Equation 4.5 and Equation 4.6. The results of the estimated transition probabilities are stored in matrix P and the occurrences of start states in list P_{start}.

$$\begin{aligned} S = \{(H_{bin}, T_{bin}, Dur_{bin}) \mid & H_{bin} \in \{1, 2, \ldots, 15\}, \\ & T_{bin} \in \{1, 2, \ldots, 15\}, \\ & Dur_{bin} \in \{1, 2, \ldots, 23\}\} \end{aligned} \tag{4.7}$$

4.4.2. Generating Data

The data is generated in the same way as described in the previous model subsection 4.3.2 and is visualized in Figure 4.4. But in this case each newly generated state k consists of a state with the variables $(H_{bin}, T_{bin}, Dur_{bin})$. So not only for the variables H_{bin} and T_{bin} random draws from the bins should be taken but also for the Dur_{bin} variable. This results in standardized random values for the H_{bin} and T_{bin} variables and a random drawn duration Dur. This duration is the hours these random drawn values will persist before moving to the next drawn values. The standardization needs to be reversed again with Equation 4.1 and the found value is duplicated in the synthetic dataset according to the duration parameter. In this way, the persistence of weather observations is included in the markov model in an explicit way.

4.4.3. Validation

The box plots showing the monthly values for both the observed data and the Markov model are presented in Figure 4.6. Table 4.4 shows the descriptive statistics of this model. Figure 4.5 shows in yellow the synthetic generated peak wave periods and significant wave heights and in blue the original observed data.

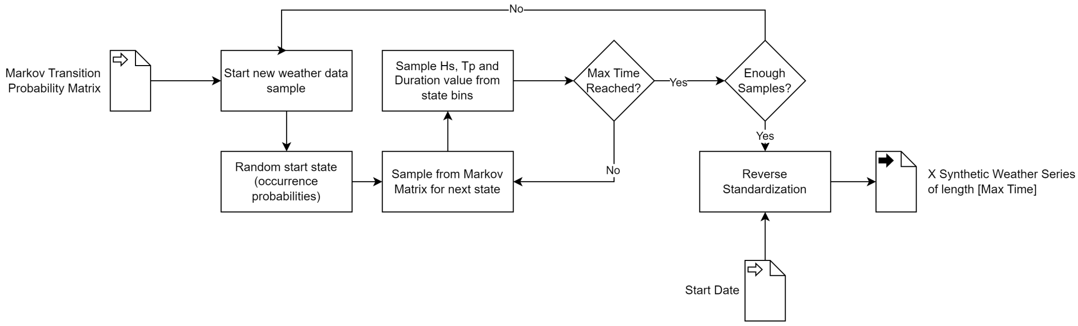


Figure 4.4: Generating process of synthetic weather

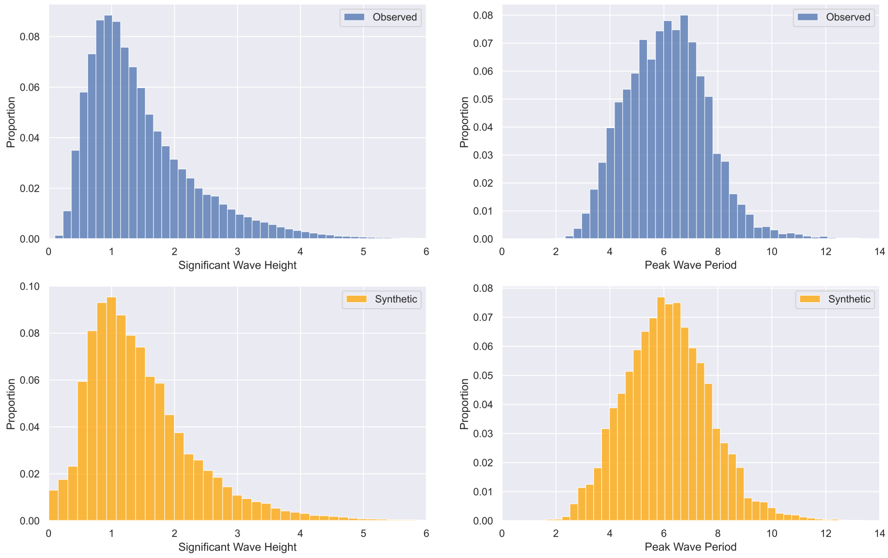


Figure 4.5: Histograms of wave height and wave period of model and observed

Overall, the model seems to be a good fit based on the descriptive statistics of the synthetic weather data. Most important is to assess the weather windows durations that occur. The main question to be answered is if the duration of operational weather windows that are generated with the model is close to the durations that occur in the observed (the input) data set. In order to assess the distribution of durations fit of the model, a Kolmogorov–Smirnov test was performed (Massey, 1951). Such a test can be used to compare two samples to answer how much these would overlap if they are both considered to be a sample drawn from a distribution. It is assumed that the real distribution is not known and both the observed data is a sample of a distribution (the SWAN model draws from the "real" weather data) and the developed weather model is a sample of weather data. The duration of operational weather windows is tested at $Hs = 2.5$ and $Tp = 8$. By testing these samples, the null hypothesis states that the two independent samples are identical. With the improved Markov model a Ktest statistic of 0.028 was found, resulting in a p value of 0.053. As this p value is not considered significant at the p=0.05 level, the null hypothesis is accepted, and it can be stated that the two weather window duration distributions are likely to

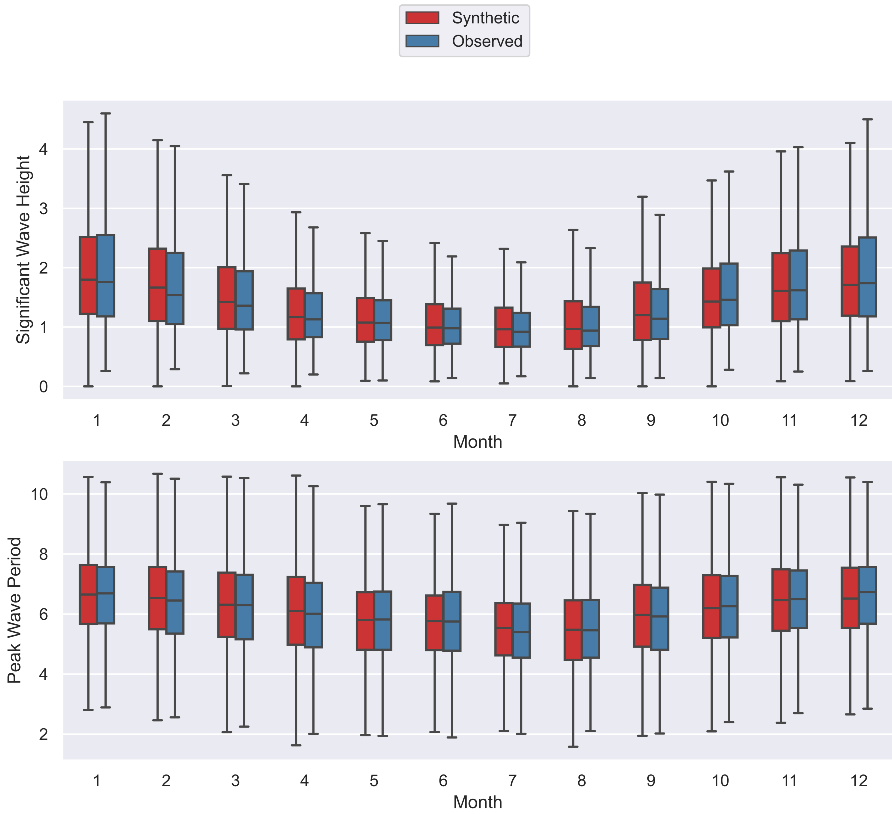


Figure 4.6: Box plots of model outcomes versus observed values by month

be considered identical. The corresponding cumulative distribution function of the operational weather window durations is visualized in Figure 4.8 and Figure 4.7.

Visually the step distribution function of the operational window duration seems to be a good fit as strengthened by the reported Kolmogorov–Smirnov test statistic. Comparing this figure with the earlier presented cumulative distribution functions of the durations generated by the basic markov model shows a large improvement in model quality with regard to the persistence of weather characteristics. The differences between the observed and modeled distributions increase slightly when the significant wave height limit is set to 1.5 meters instead of 2.5 meters. Figure 4.9 and Figure 4.10 show the wave height persistence cumulative distribution functions separately at the 1.5 and 2.5 meter setting to show this difference.

The differences, however, are not that big and do not impact the simulation runs significantly as the overall effect on the duration of operational weather windows is small. It can be concluded that the improved markov model is able to accurately generate synthetic weather data that fits well in terms of descriptive and persistence with the observed/input data.

It is also important to assess the 'uniqueness' of the newly generated data. As the goal of the synthetic weather is to test performance of supply chain configurations in different conditions, the newly generated weather data should differ enough from the historical data in order to avoid generating the same patterns in multiple weather realizations.

Statistic	Hs Observed	Hs Improved Model	Tp Observed	Tp Improved Model
count	350,592	438,000	350,592	438,000
mean	1.47	1.45	6.12	6.11
std	0.85	0.87	1.52	1.58
min	0.10	0.00	1.74	1.26
25%	0.86	0.85	5.03	5.00
50%	1.25	1.26	6.12	6.06
75%	1.85	1.84	7.08	7.12
max	7.93	9.12	19.97	19.92

Table 4.4: Statistics of Improved Markov Model

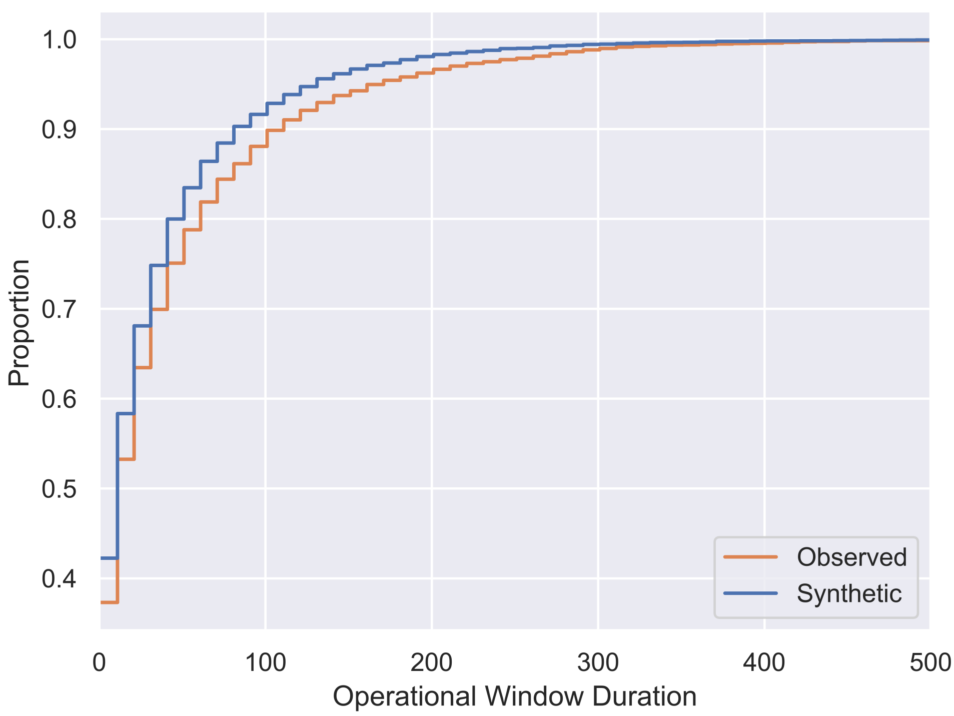


Figure 4.7: CDF of improved markov model (with durations) for limit 1.5/8

The uniqueness of the data can be assessed by comparing individual blocks in the generated time series with the training data and to assess how much these differ from each other. If the data is unique, it is expected that almost no exact matches are found within the training data set. One way of comparing two time series is based on using matrix profiles to compute the distances between two blocks of different time series (Zhu et al., 2016). By shifting the defined blocks, all possible combinations between the two time series (the synthetic and training data) can be compared and the most similar sequences can be retrieved. These sequences can then be analyzed and visualized in order to assess the uniqueness of the data. The analysis is performed with the STUMPY package (Law, 2019) in Python (Python Software Foundation, 2023).

The STUMPY package allows efficient calculation of the distance matrix and distance profile between the synthetic time series and the observed (training) time series. The window length used in the comparison of the time series is $m = 72$, so blocks of

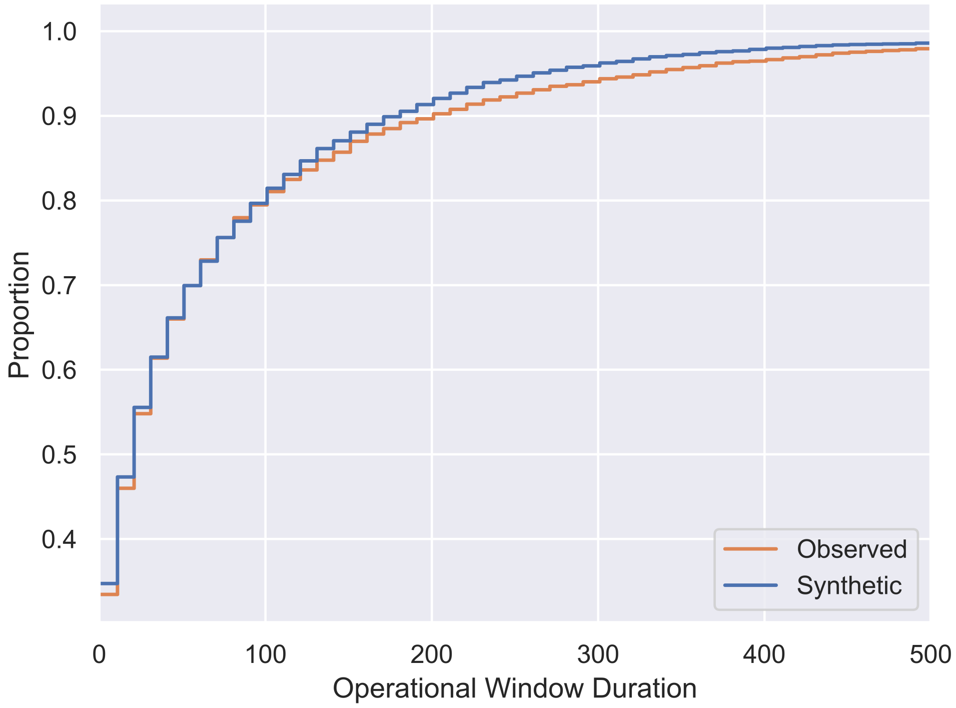


Figure 4.8: CDF of improved markov model (with durations) for limit 2.5/8

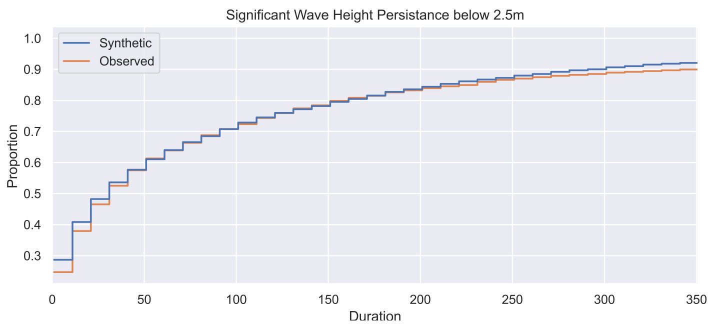


Figure 4.9: CDF of Wave Height 2.5 (Improved Markov Model)

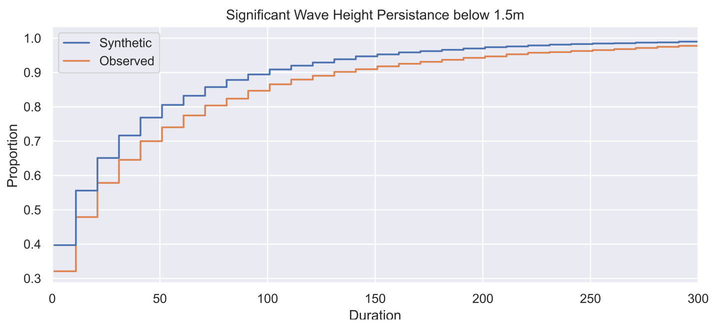


Figure 4.10: CDF of Wave Height 1.5 (Improved Markov Model)

72 hours are compared. This window is large enough to avoid finding reoccurring patterns by chance and represents a realistic duration used within the simulation model. The distribution of the distances between the two time series is visualized in Figure 4.11.

There are no observations with a distance of 0, so no exact matches are found. Visual inspection of the most similar sequences show that the data indeed seems to be unique and no patterns of the training data are exactly replicated in the synthetic data.

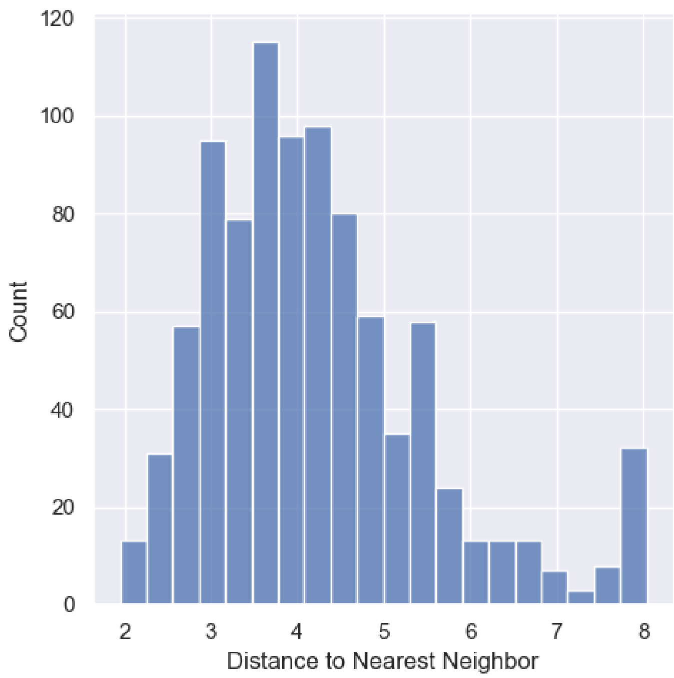


Figure 4.11: Distribution of found distances to nearest neighbor

To summarize, it can be concluded that the randomly generated weather data consists of unique time series with descriptive statistics close to the observed weather data. The weather model can therefore be used in the simulation to assess performance under the influence of different weather conditions.

5
Experimental Design

In this chapter, the experimental design is explained. First the case study experiment is described, this experiment will also be the starting point for the moderator experiments. After the case study experiment, five different moderator experiments will be performed. In each moderator experiment all parameters will be fixed to the parameters used in the case study experiment and only the moderating variable will be varied.

5.1. Overview

By talking with experts and conducting online research the case study experiment parameters used in the model were determined. The following questions were asked to two different experts in a semi-structured way to get insight into typical wind farm installation vessels and corresponding values.

1. What is a typical offshore installation vessel and what are the characteristics of such a vessel?
2. What are typical supply vessels?
3. When transferring from this supply vessel to this installation vessel what are the weather limitations to consider?
4. When sailing with the installation vessel, what are the weather limitation values to consider?
5. When sailing with the supply vessel, what are the weather limitation values to consider?
6. What other limitations should be taken into account?
7. What are the day rate and mobilization cost that are expected?

The resulting parameters act as a starting point for the comparison of the supply chain configurations and for the moderator experiments. In order to replicate real life scenarios, a typical installation vessel is used. By consulting experts and people who worked with these vessels, the parameters can be determined and used within the simulator. The installation vessel that will be used is able to transport up to 3 monopiles, with weights of around 1000 tons, at the same time and operate with transit speeds of around 12 knots. The vessel is able to position and install monopiles while using dynamic positioning (DP). This vessel will provide a realistic representation of a standard installation vessel with a modern installation system aboard (dynamic positioning instead of jack-up) allowing installation in deeper locations.

To simulate a supply vessel, a barge with a capacity of 3 monopiles is chosen. Some barges will allow carrying less or more monopiles, but as this does not align with the capacity of the vessel, it is more efficient to choose a barge that carries the same amount of monopiles. The feeder barge is expected to need at least two tugs in order to navigate it offshore and orient it next to the installation vessel or to navigate within ports. The example barge used allows carrying 3 monopiles of around 1500 tons within each voyage. The type of barge that is used as a supply chain vessel in this experimental design is called a towed flat top pontoon as it requires towage by supporting tugs and provides a flat deck in order to store the monopiles. Within the supply chain model, the tugs themselves are not modelled as the appropriate durations and operations are already captured in the parameters of the supplying vessel (the barge in this case). The barge limitations will always be more constraining than the limits of tugs (as tugs can operate in more heavy weather than the barges with foundations on board) the parameters of barges will therefore be used for the weather limitations. The cost, however, includes renting the two tugs. The corresponding operation durations of the barges relate to the assumption that it is operated with two tugs.

An example picture of a typical barge and installation vessel used in this experimental design are provided in Figure 5.1. A picture of a typical offshore tug is shown in Figure 5.2

(a) Typical Installation Vessel - Seaway Strashnov by Kees Torn, CC BY-SA 2.0 (cropped)

(b) Barge to transport monopiles

Figure 5.1: Vessels used in experimental design

The weather limitations assumed for the installation vessel are shown in Table 5.1. The limitations for the barge are shown in Table 5.2. The parameters assumed for each vessel are given in Table 5.3. The day rate and the mobilization rate of the vessels are based on numbers found in literature (Ioannou et al., 2020; Jalili et al., 2022) and are verified with experts with the questions listed at the start of section 5.1. The parameters that are not shown in this table are based on observed data and fitted distributions as described in the next section.

Operation	Hs [m]	Tp [s]
Installation	2.5	8
Sailing	3.5	8

Table 5.1: Operational Limitations Installation Vessel

Figure 5.2: Offshore tug

Operation	Hs [m]	Tp [s]
Transshipment Alongside of Installation Vessel	1.5	8
Sailing	3	8

Table 5.2: Operational Limitations Barge

In the example scenario the installation of monopiles in Dogger Bank Wind Farm is considered. Dogger bank is an offshore wind farm developed North East of England. Monopile supplier SIF will be the main supplier and manufacturer of the monopiles for the development of Dogger Bank Location C. (Sif Group, 2021) SIF is located at the Maasvlakte 2 in Rotterdam, see Figure 5.3, and will be the supplier of all foundations that are required. The location of SIF in the Maasvlakte is visualized in Figure 5.4a. In this case study experiment, a subset of 30 monopiles is considered to be installed, this provides enough operations in order to simulate real scenarios realistically. Installation of the turbines is expected to start in 2025, and the overall development of Dogger Bank C is expected to be finished in 2026. (Cummins (2020) and Dogger Bank (2022)) The foundations are installed in water depth between 18 and 36 meters at a location around 300 kilometers away from the UK shore. This is a bit further away than most of the previous installed wind farms at the shore of the UK, but provides an interesting case study as it allows to experiment with more complex supply chain configurations. If the shore was only a few kilometers away from a wind farm it is most likely that more simple scenario's would be preferred as sailing distances and the influence of weather are less likely to influence operations due to calmer weather conditions close to shore. The simulation model incorporates this case to provide a realistic installation scenario. This will allow incorporating a realistic project size, sailing distances and project characteristics.

SIF is able to deliver monopiles at quay side for direct transportation to offshore wind farms. It places its production facility next to its quay and provides buffers, so enough

Vessel	Parameter	Value
Installation Vessel	Capacity	3 monopiles
	Day Rate	200,000 euro/day
	Mobilization Rate	600,000 euro
	Sailing Fuel Cost	800 euro/hour
	DP Fuel Cost	360 euro/hour
Barge	Capacity	3 monopiles
	Speed	5–7 knots
	Day Rate	25,000 euro/day
	Mobilization Rate	200,000 euro
	Sailing Fuel Cost	530 euro/hour

Table 5.3: Vessel Parameters Used

Figure 5.3: SIF as Supplier at the Maasvlakte in Rotterdam
by Kees Torn, CC BY-SA 2.0

monopiles are available when required. SIF has a deep sea quay wall of 600 meters long and crawler cranes to load foundations to the installation vessels (Sif Group, 2022). As an intermediate port, the Teesport Port is chosen (PD Ports, 2023). As this is a port close to the wind farm location, provides sheltered locations and provides quays and storage facilities that can be rented to operate from (Knight Frank, 2023). The rented location is visualized in Figure 5.4b. The rental cost assumed for this intermediate port is around 250,000 euro (see Appendix A.3 for the calculation). This cost is only taken into account when monopiles are stored in the intermediate port as it is expected that for ship-to-ship transfer no additional costs will be incurred. The assumption for this case is that it is possible to store 9 monopiles at this intermediate location, allowing enough buffers but without needing a lot of space. The minimum number of monopiles at the intermediate port, before the installation process starts, is also set to 9, this means that 9 monopiles will be loaded to the intermediate port before the installation vessel or other supply vessels start operating. The value of 9 is chosen as the supply and installation vessel in this experiment both have a capacity of 3 monopiles, as 9 is a multiple of 3 this simplifies the logistical operations. As explained in the subsection 3.3.3, a berth is expected to only be used by the vessels simulated in the supply chain model. Therefore, no utilization percentages of these berths need to be taken into account. Only when a vessel included within the supply chain model is occupying the berth, the other vessel has to wait for the location to free up.

(a) Supply Port Location - SIF **(b)** Intermediate Port Location - Teesport

Figure 5.4: Supply Port and Rented Port Locations

The parameters used for the ports that are considered are given in Table 5.4, the location of the wind farm follows from The Wind Power (n.d.). A map of the different locations used in the experimental design is shown in Figure 5.5 The distances derived from these locations can be found in Table 5.5. The distances for the wind farm are calculated from the middle point of the wind farm location as the sailing distances and operations within the wind farm are not simulated in the supply chain model. The distances for the ports are calculated from the entrance location of each port. As sailing within ports will look different based on the port characteristics. The distance within the ports is a parameter in the supply chain model.

Port	Parameter	Value
Supply Port	Coordinate	Lat: 51.966408, Lon: 4.003272
	Berths Available	2
Intermediate Port	Coordinate	Lat: 54.604178, Lon: -1.155431
	Berths Available	1
	Minimum stock build up	9
	Capacity	9
	Rental Cost	250,000 euro/month
Wind Farm	Coordinate	Lat: 55.039972; Lon: 2.819972

Table 5.4: Parameters of Ports Used

Location 1	Location 2	Distance
Supply Port	Wind Farm	355km
Supply Port	Intermediate Port	460km
Intermediate Port	Wind Farm	260km

Table 5.5: Distances between Locations

5.2. Data Collection

Parameters that are hard to determine by experts are the installation duration per monopile, the loading duration at the supply port and the speed of the installation vessel within ports or offshore. These values are dependent on the type of installation vessel used and the specific supply port the installation vessel operates from. In order to make an educated estimation of these parameters, automatic identification system

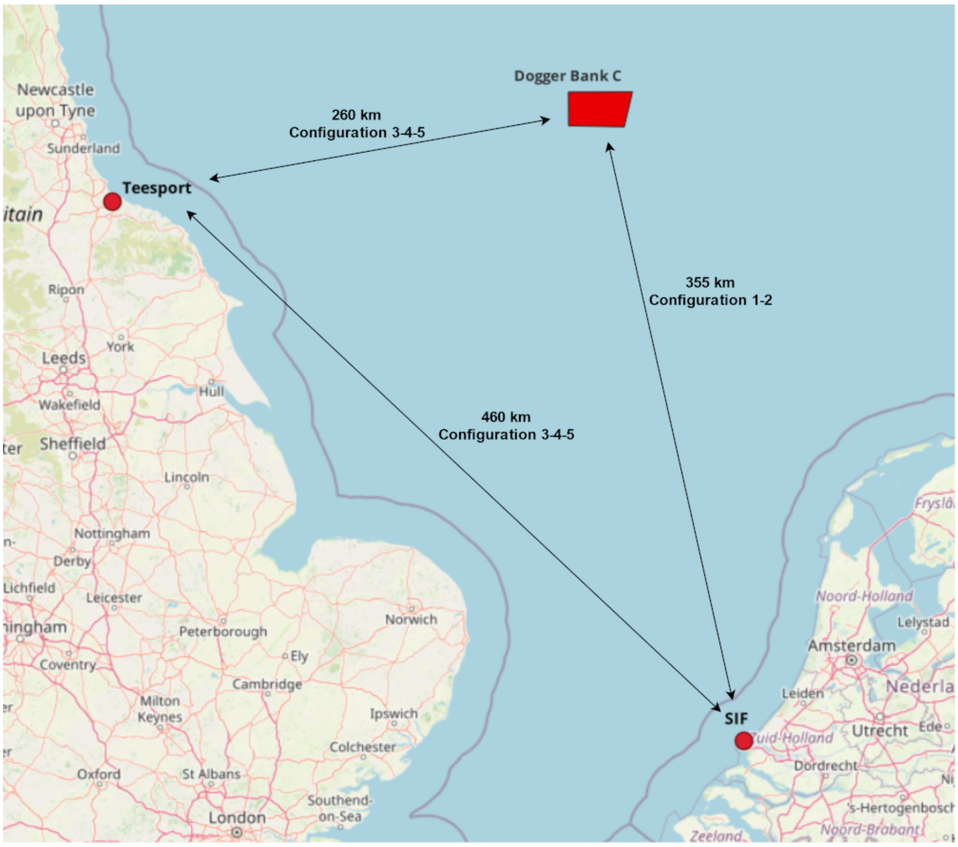


Figure 5.5: Overview of different locations

(AIS) data will be analyzed of a wind farm installation project that is performed with a typical installation vessel. The data provides timestamped location data with the current speed and sailing direction of a specific vessel. In this case AIS data of the vessel the Seaway Strashnov vessel is analyzed. This is an appropriate vessel as the AIS data provided also used SIF as supplier port and the capacity of the vessel aligns with the capacity in the case study. For example the loading cycles at the quay wall of SIF are estimated based on 12 historical loading cycles that are observed in the AIS data of the Seaway Strashnov. As an example, five of these historical loading cycles are visualized in Figure 5.6. As in the case study experiment, the same vessel and supply port are used, this would give insight into the parameter distributions to use in the simulation model. Data is retrieved from online AIS sources and analyzed with the open source QGIS software (QGIS Association, 2023). In Figure 5.6 an example of the AIS data used is shown for five different loading cycles at the quay of the supply port The process of retrieving different samples for each parameter based on AIS data is described in Appendix A.1.

Next to these operational parameters, the cost parameters used within the simulation model need to be determined. The day cost of the installation vessel and the supply vessel are provided by experts and easily validated online. But the fuel cost and fuel usage of the vessels are not provided by experts and therefore need to be approximated based on online sources. It is found that tugs will cost approximate 530 $euro/hour$ and the installation vessel 800 $euro/hour$ when sailing offshore. The use of dynamic positioning for the installation vessel will cost around 360 $euro/hour$.

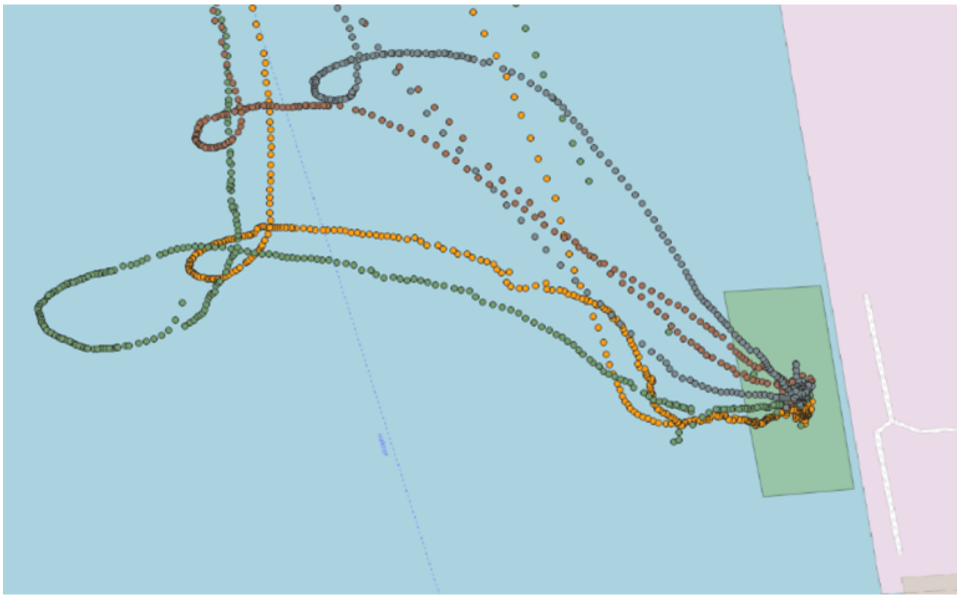


Figure 5.6: AIS Paths to SIF Berth

These approximations are based on the installed thrusters and the estimated fuel usage of the engines. The calculations can be found in Appendix A.2. Important to take into account is that the fuel costs are based on fuel usage at average conditions, the relationship between environmental conditions in the simulation model and the drawn sailing speeds are not considered in the calculation of the fuel usage.

5.3. Fitting Duration Distributions

As explained before, AIS data is used to gather information about the operational durations and required vessel parameters. How these samples are collected based on AIS data is described in Appendix A.1. The speed of the Seaway Strashnov when sailing offshore, the installation duration, the loading time at the supply port and the time of sailing within the supply port are analyzed. The sample size of the observations for each duration parameter is given in Table 5.6. The speed parameters are given in Table 5.7

Parameter	**Sample Size**	**Mean Duration [min]**	**STD Duration [min]**	**Minimum Duration [min]**	**Maximum Duration [min]**
Installation Duration	24	494.13	133.33	332	778
Loading at SIF Duration	12	666	162.43	430	891

Table 5.6: Observations AIS Data Durations

In order to draw random values a distribution needs to be fitted. Due to the small sample size, it is best to fit a simple function that relies on a small number of parameters to create a distribution. An often-used distribution only based on the minimum, maximum and mode value are the triangular distribution and the PERT distribution. Due to the more natural form and less sharp edges, it is chosen to take random draws

Parameter	Sample Size	Mean Speed [knots]	STD Speed [knots]	Minimum Speed [knots]	Maximum Speed [knots]
Speed offshore	19	7.67	0.97	5.02	8.99
Speed port	24	5.89	0.92	4.51	8.13

Table 5.7: Observations AIS Data Speed

following a PERT distribution. PERT is based on the beta distribution requiring only the three points discussed before to estimate the alpha and beta shape parameter of the beta distribution.

To estimate a PERT distribution, the mode of the data is needed as parameter. As it cannot be assumed the data is symmetrically distributed, the mode cannot be assumed to be equal to the mean values, the mode therefore needs to be estimated. This can be done with the help of uni-variate kernel density estimation (KDE). KDE can be used to estimate the probability density function of a random variable. This density derivative can then be used to get the estimated mode of the data. The small sample sizes here are sufficient in size to perform a KDE. Two examples of the kernel density estimation output are given in Figure 5.7. In Figure 5.8 an example pert density plot is given for the installation duration per monopile. Table 5.8 shows the minimum, maximum and mode defining the fitted distributions. The mooring and unmooring duration distribution is based on expert knowledge. As stated before, the most frequent mooring duration is around an hour, but sometimes takes somewhat longer or shorter than exactly one hour. The PERT distribution of the mooring and unmooring time is based on this statement. Using assumed minimum and maximum values is expected to work better than simply assuming a discrete value.

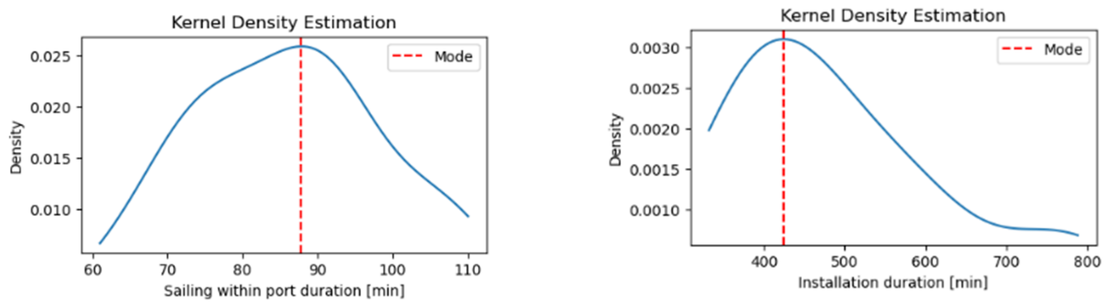
5.4. Assumptions

The following assumptions are made for parameters that are not determined by gathered data.

1. The speed of barges is according to experts between 4 and 6 knots, therefore the assumption is made that the sailing speed of a trip takes on a uniform distribution with 4 knots as minimum and 6 knots as maximum.
2. No data is available on the loading duration distribution that happens offshore. Although expert states that loading one monopile offshore takes around 2.5 hours. As this mode equals the mode of the loading time distribution estimated at SIF it is assumed loading durations offshore follow the same distribution as the loading time at SIF .
3. It is assumed that the loading time at the intermediate port is the same as the loading time distribution at SIF.

5.5. Experimental Settings

The determined and assumed parameters are used in the developed simulation package in order to test the different supply chain configurations. In order to assess the performance of the different configurations, these need to be tested in different



(a) Sailing within port speed

(b) Installation duration

Figure 5.7: Kernel Density Estimation to determine Mode

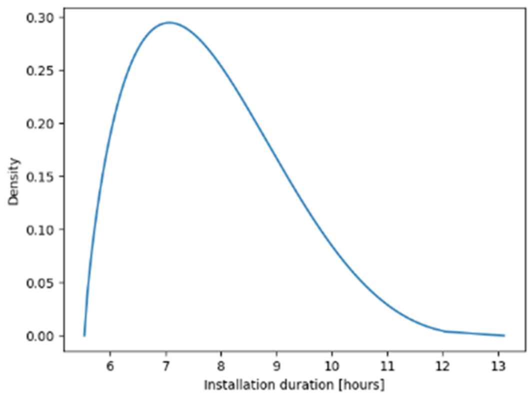


Figure 5.8: PERT Distribution of Installation Duration

weather realizations. The weather samples are based on starting the first of May, as this is a typical month to perform offshore operations as storms are less frequent during these periods and less waiting on weather takes place. It is chosen to run each supply chain configuration with 100 different weather samples, this would provide enough insights into the distribution of the key performance indicators without too much computational effort. This results in the fact that in the end, each found key performance indicator its mean value is based on operating with the given parameters in 100 different weather situations. It is also chosen to use only one barge in the configurations that require barges, adding multiple barges in different configurations would make it hard to compare them with each other which is therefore avoided in the performed experiments. The described experimental settings are given in Table 5.9.

5.6. Moderator Experiments

After running the case study experiment, an analysis is performed for a number of different moderators. These parameters will be changed one by one while keeping the other parameters fixed to the case study experiment. This will allow investigating the effect of changing parameters like distance to shore and vessel operating limits as it is expected that these will impact the key performance indicators. It is also interesting to investigate if certain supply chain configurations become more attractive in different projects or when working with different vessels. This insight will allow reflecting on

Operation	Unit	Minimum	Maximum	Mode
Sailing Offshore	Knots	5.02	8.99	8.11
Sailing Port	Knots	4.51	8.13	5.53
Installation	Hour	5.53	13.13	7.07
Loading	Hour	1.72	4.28	2.45
Mooring/Unmooring	Hour	0.75	1.25	1

Table 5.8: PERT Distribution Parameters

Run Configurations	All five
Start Month	May
Samples per configuration	100
Seed used at start	1000

Table 5.9: Experimental Settings

the impact of using different vessels and working on different projects. It is, however, difficult to get all the required parameters for these imaginary vessels, for example, the costs are hard to determine as there is no clear relation between parameters like speed, weather limits and the corresponding cost increases. The key performance indicators related to cost will therefore not be included in most of these moderator experiments, but merely the project duration and installation vessel usage will be reported. As the cost of the intermediate port is estimated based on the capacity and minimum stock value, it is possible to also present the cost differences for this parameter, therefore, the costs are shown only for the minimum stock parameter. It is assumed that the capacity will equal the minimum stock value to enable this cost approximation. The costs used for the moderator experiments of the intermediate minimum stock parameter are given in Table 5.11. The project durations, however, can be compared and analyzed when changing parameters. The main focus will therefore be on the key performance indicators related to duration. If it is possible to estimate the cost for a moderator experiment, both the resulting cost and durations will be presented.

Not all variables will be tested in the moderator experiments as not all of these are interesting to investigate. The most important variable that was identified in cooperation with experts are the operational weather limits of the vessel. Therefore, the sailing limit of the supply vessel (as this is low in the case study experiment due to the vessel being a barge) and the transfer limits offshore are experimented with. Also, the distance to shore, which is considered to be important according to previous research, is varied. This is done by combining the supply to wind farm distance and the intermediate port to wind farm distance at the same time. Assuming that the intermediate port to wind farm distance is perpendicular to the distance line between the supply port and the wind farm, this allows calculating the distance between the supply and intermediate port with the Pythagorean theorem. The chosen distance will start at 200km as it does not make sense to compare a scenario close to shore, due to the fact that in reality, an intermediate port will not be placed in a triangular fashion when the wind farm is close to shore. Next to this the start month (seasonal influences of weather) and the sailing speeds are varied for both the supply and installation vessels. Indirectly, the impact of weather at installation locations is taken into account by varying the weather limits for the different vessels. According to experts, the limit of 8 seconds for the peak wave period is considered to be a standard value for the maximum operation of a vessel. The wave limits, however, are dependent on the design and type of the vessel and are therefore are varying more often. Therefore, it is chosen to only vary the wave limits of the vessels in the analysis. It is, however, interesting to also investigate the direct effect of operating in worse or better weather conditions as this impacts the operation of all vessels at the same time. As only the training data used in the case study experiment is available in the correct format, a simple multiplication factor is used to approximate better/worse weather conditions. After generating synthetic weather, the values within these samples will be multiplied with a scale factor. A scale factor below 1 will decrease the sampled weather values and make the differences between hours denser. This approximates better weather conditions. Scale factors above 1 will, however, increase the values of the sample and increase differences between time steps and therefore approximate worse weather conditions.

The main values in the moderator analyzes are the same as the values discussed in the previous chapter (section 5.1). Each of these parameters will be changed one by one while keeping the other parameters set to the case study experiment. This will allow analyzing the impact of a certain parameter.

A summary of the parameters that are experimented with in the moderator experiments are given in Table 5.10, in the table the installation vessel is abbreviated as IV. The values in between brackets describe the distribution parameters used. A complete overview of all the different values that are tested are given in Table 5.12.

Parameter	**Unit**	**Main**	**Low**	**High**
Alongside Limit Wave	meter	1.5	1	2.5
IV: Sailing Speed	knots (PERT)	(5.0, 9.0, 8.1)	(2.9, 6.9, 6.0)	(10.9, 14.9, 14.0)
Supply: Sailing Limit Wave	meter	3	2	4
Supply: Sailing Speed	knots (uniform)	(4,6)	(2,4)	(12,14)
Distance Supply to Wind	kilometer	355	200	1000
Distance Intermediate to Wind	kilometer	260	50	450
Start Month	-	1	1	11
Weather Scale Factor	-	1	0.8	1.2
Intermediate Minimum Stock	monopiles	9	6	15

Table 5.10: Summary of Experimented Parameters

Stock/Capacity	**Cost in euros/month**
6	201,600
9	250,000
12	285,600
15	336,000

Table 5.11: Cost of intermediate port rental based on the minimum stock parameter value

Parameter	Unit	Base	Variants				
Alongside Limit Wave	meter	1.5	1	2	2.5	-	-
IV: Sailing Speed	knots (PERT)	(5.02, 8.99, 8.11)	(2.91, 6.88, 6)	(6.91, 10.88, 10)	(8.91, 12.88, 12)	(10.91, 14.88, 14)	-
Supply: Sailing Limit Wave	meter	3	2	2.5	3.5	4	-
Supply: Sailing Speed	knots (uniform)	(4,6)	(2,4)	(6,8)	(8,10)	(10,12)	(12,14)
Distance Supply to Wind	kilometer	355	200	500	650	800	1000
Distance Intermediate to Wind	kilometer	260	50	150	350	450	-
Start Month	-	1	3	5	7	9	11
Weather Scale Factor	-	1	0.8	0.9	1.1	1.2	-
Intermediate Minimum Stock	monopiles	9	12	15	6	-	-

Table 5.12: Moderator Experiment Overview

6 Experimental Results

In this chapter first the experimental results are presented for the case study. Descriptive tables and visualizations show the effect of using different supply chain configurations on the different key performance indicators. Secondly, the results of the five different moderator analysis are presented with accompanying discussion of these results. The five different moderators experiments are the vessel speeds, the offshore transfer limit, the stock at the intermediate port, the weather conditions and the supply to wind farm distances. The chapter ends by validating the cost and duration key performance indicators order of magnitude in order to validate the results.

6.1. Performance of Different Supply Chain Configurations

The project key performance indicator descriptive statistics are shown in Table 6.1. The waiting on weather indicator is calculated as the total time a vessel is waiting on weather divided by the time these vessels were operating and is given in Table 6.2. The presented waiting on weather percentage mean is the mean of the weather percentages of all the vessels that are operating in a particular supply chain configuration. The indicators that are vessel-specific are given in Table 6.5 for the installation vessel, Table 6.3 for the first supply vessel and Table 6.4 for the second supply vessel used in the fifth configuration. The used percentage indicator describes the percentage of time the vessel was used during the total project duration. Within some figures, the installation vessel will be abbreviated to IV in order to decrease the space required for the text. The whiskers show the 1.5 interquartile range; the block size describes the first until the third quantile; the point where the colors of the block change show the median value and the small circle the mean value of the sample distribution. The names of the supply chain configurations refer to the supply chain configurations visualized in Figure 2.3.

It is found that the total cost, shown in a boxplot in Figure 6.1, is the lowest when using the *direct* configuration. Also, in terms of project duration, this configuration takes the least amount of time as shown in Figure 6.2. The most expensive configurations are the *transfer offshore*, *transfer port* and *transfer offshore buffer* configuration. The most variation is present in the *transfer offshore* configuration and the *transfer offshore buffer* configuration. This is likely due to the fact that in these configurations, waiting on weather occurs for the supply vessel (the barge) due to the lower sailing and offshore

Supply Chain Configuration	Project Cost in M euros mean (std)	Fuel Cost in M euros mean (std)	Project Duration in hours mean (std)
1. Direct	9.4 (0.7)	0.42 (0.01)	992.3 (80.5)
2. Transfer Offshore	14.4 (1.7)	0.47 (0.01)	1388.2 (183.6)
3. Transfer Port	15.1 (1.0)	0.87 (0.01)	1430.5 (106.5)
4. Transshipment Buffer	12.6 (1.0)	0.87 (0.01)	1437.5 (110.0)
5. Transfer Offshore Buffer	14.6 (1.3)	0.92 (0.02)	1492.2 (129.3)

Table 6.1: Descriptive statistics of supply chain configuration results

Supply Chain Configuration	IV	Supply	Supply 2
1. Direct	12.4%	-	-
2. Transfer Offshore	1.6%	23.2%	-
3. Transfer Port	6.4%	14.3%	-
4. Transshipment Buffer	7.7%	14.2%	-
5. Transfer Offshore Buffer	1.1%	14.1%	18.9%

Table 6.2: Waiting on weather as percentage of vessel usage time

Supply Chain Configuration	Supply Usage Duration mean (std)	Used % mean (std)
2. Transfer Offshore	1377.8 (181.7)	99.3% (0.5)
3. Transfer Port	1411.0 (111.0)	98.6% (0.9)
4. Transshipment Buffer	1404.8 (113.1)	97.7% (1.2)
5. Transfer Offshore Buffer	1404.7 (114.2)	94.3% (4.0)

Table 6.3: Descriptive statistics of supply vessel usage

Supply Chain Configuration	Supply Usage Duration mean (std)	Used % mean (std)
5. Transfer Offshore Buffer	1107.3 (116.9)	74.2% (4.1)

Table 6.4: Descriptive statistics of second supply vessel usage

transfer limits. This waiting will increase project durations which due to the day rate of vessels increase overall cost.

An important cost component is the fuel cost that is incurred for the different configurations. Fuel cost is directly related to fuel usage and therefore emissions. The fuel cost does not differ between samples as both the standard deviation and interquartile range is small. The fuel cost is, however, notably different between configurations as shown in Figure 6.3. The configurations *transfer port*,*transshipment buffer* and *transfer offshore buffer* require almost double the amount of fuel in comparison with the *direct* and *transfer offshore* configuration. This makes sense due to the fact that using an intermediate port as in configuration the *transfer port*,*transshipment buffer* and *transfer offshore buffer* configurations requires sailing longer distances and sailing with more vessels at the same time in order to perform the transfer or transshipment process at the port. This increase in vessel movements will lead to more fuel usage and therefore

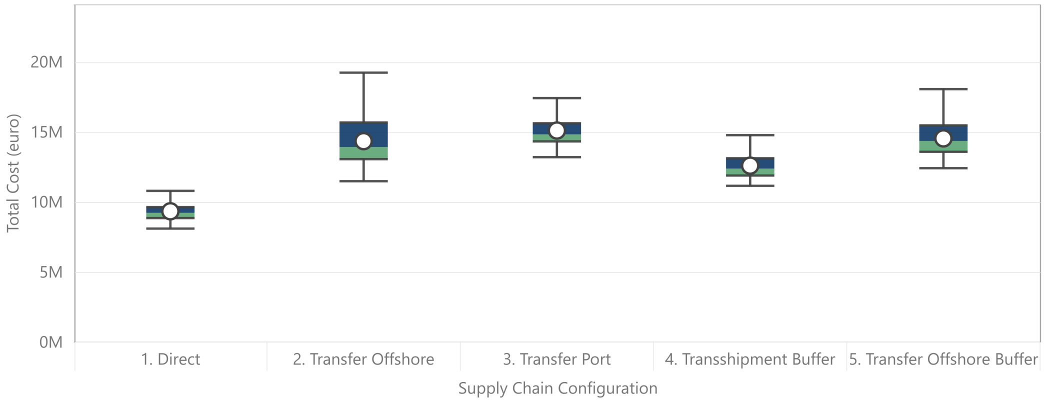


Figure 6.1: Total cost per supply chain configuration

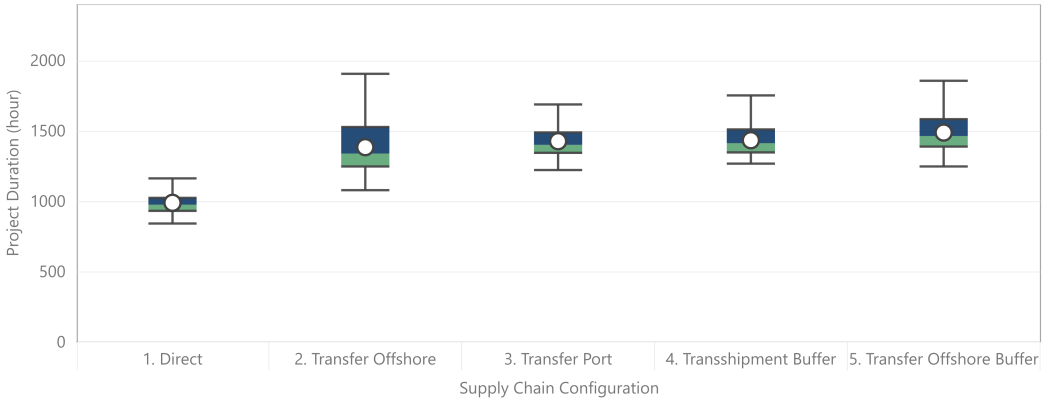


Figure 6.2: Total project duration per supply chain configuration

more fuel cost.

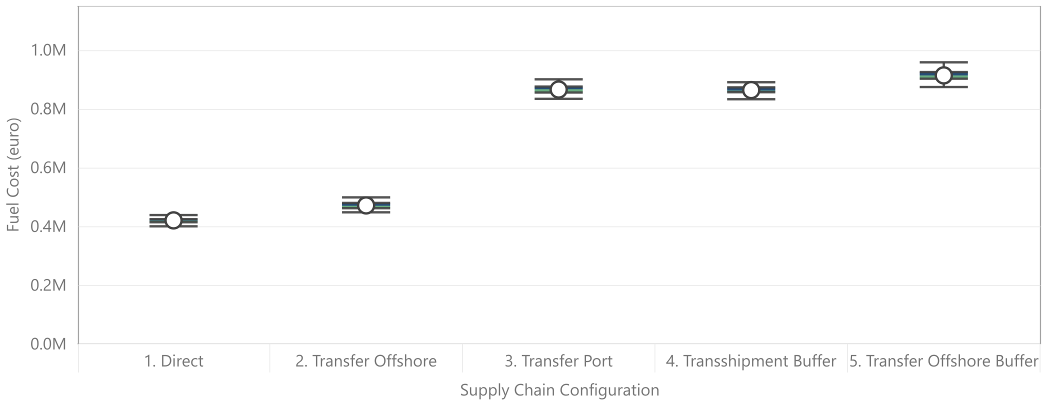


Figure 6.3: Fuel cost per supply chain configuration

The usage of the installation vessel differs significantly between different configurations (see Table 6.5 and Figure 6.4). In the both configurations where first a buffer is built at the intermediate ports, so the *transshipment buffer* and *transfer offshore buffer* configuration, the installation vessel operates less than 75% of the complete project duration. Making the total time the installation vessel is used in configuration *transshipment buffer* almost equal to the project duration of the *direct* configuration. The *transshipment buffer* configuration has the lowest duration waiting for other vessels compared to the other configurations. It is also the second most cheap and fast configuration, which is an effect of the low installation vessel usage duration (therefore reducing the total cost). The cost of using barges for a longer duration and renting the intermediate port seems to be less important than the day rate of the installation vessel. Project duration and therefore cost seem to not have a direct relation, the total cost is mostly governed by the duration of the installation vessel is operated. This relation will further be explored in the moderator analysis of the minimum stock at intermediate port parameter.

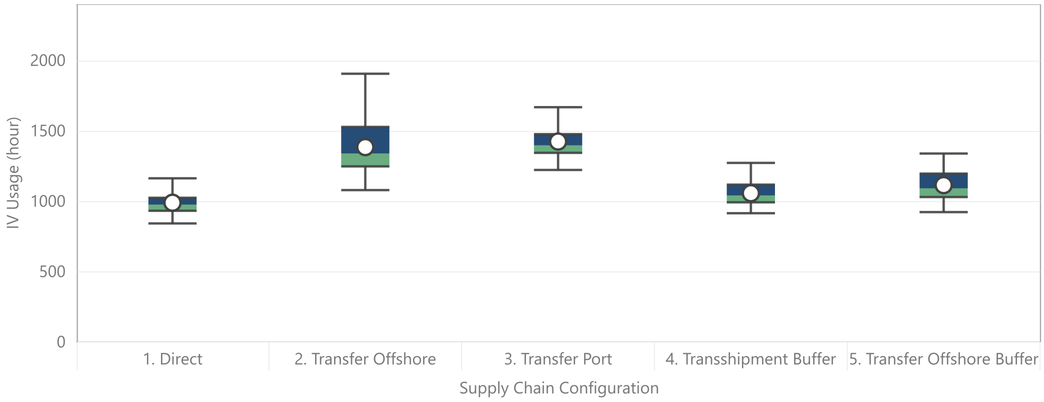


Figure 6.4: Installation vessel duration per supply chain configuration

Supply Chain Configuration	Installation Vessel Usage Duration mean (std)	Vessel Cost in M euros mean (std)	Used % mean (std)
1. Direct	992.3 (80.5)	36.1 (5.9)	100.0% (0.0)
2. Transfer Offshore	1388.2 (183.6)	63.9 (10.8)	100.0% (0.0)
3. Transfer Port	1427.9 (105.5)	52.7 (6.7)	99.8% (1.1)
4. Transshipment Buffer	1060.2 (95.3)	38.4 (6.1)	73.8% (4.2)
5. Transfer Offshore Buffer	1117.6 (117.1)	46.3 (8.1)	74.9% (4.2)

Table 6.5: Descriptive statistics of installation vessel usage

As the installation vessel is used in all different configurations and is the most expensive vessel to operate, it is interesting to show a comparison of the installation vessel's average usage duration. The boxplot in Figure 6.5 shows how much of the time the installation vessel was either sailing, operating (so installing, mooring, transferring), waiting on weather or waiting for other vessels. These different categories are listed and described below.

1. Sailing: The vessel is either sailing offshore or within a port
2. Operating: The vessel is installing, loading/unloading, transfering, mooring or unmooring
3. Waiting Weather: The vessel is waiting on a weather window to install, sail or transfer
4. Waiting Other: The vessel is waiting for other vessels to transfer, waiting for a quay to be available, waiting for the availability of monopiles at an intermediate

port or waiting to be requested by other vessels (the supply vessel waiting before it is required by the installation vessel).

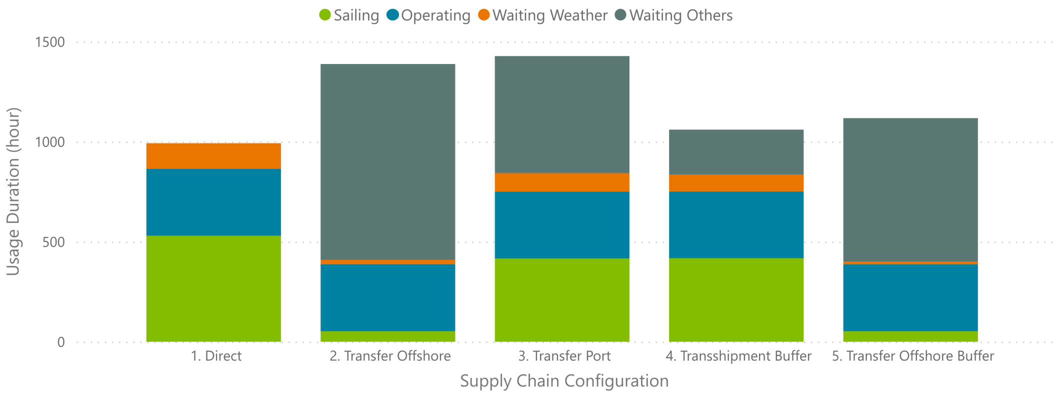


Figure 6.5: Average installation vessel usage duration

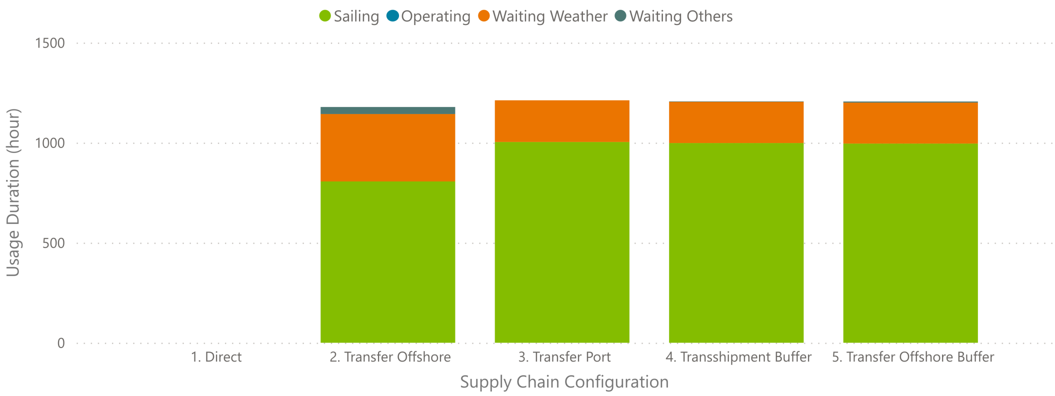


Figure 6.6: Average supply vessel usage duration

It becomes clear that in all other configurations than the *direct* one, a significant amount of time is spent waiting on other vessels. Within the *transfer offshore* configuration, around 71% of the total installation vessel usage time the vessel is waiting for the barge to transfer its components offshore. Also for the *transfer offshore buffer* configuration, the installation vessel waits for long durations on the other barges (around 64% of the time). This finding can be explained by the fact that the supply vessels that need to deliver monopiles to the installation vessel are slow vessels (compared to the installation vessel). This will lead to sailing durations exceeding some of the installation cycle durations, leaving the installation vessel waiting for restock by the supply vessels. The other explanation is that the weather limits of transferring offshore are low, and the barge will only sail out from the supply port if it is possible to both sail, transfer and sail back within the required weather limits. Therefore, longer weather windows with lower limit are required in order to transfer the monopiles offshore. This results in the fact that the supply vessel often has to wait on weather windows. This effect can also be clearly observed in the supply vessel usage boxplot shown in Figure 6.6. In the configuration *transfer offshore* the supply vessel is waiting around 29% of its time on weather in order to start operations, this in turn impacts the project duration and therefore also the total cost.

As explained above, it becomes clear that the key performance indicator results related to vessel speed, weather limits, and the corresponding waiting on weather durations. The impact of weather is large and will lead to waiting times and low utilization of vessels when operations are performed that require calm weather (transferring offshore, for example).

In this experiment it can be concluded that when cost and project durations are favored, it is preferred to use the *direct sailing* configuration, where the installation vessel sails back and forth between the supply port and the wind farm. The alternative of having an intermediate port that is used as a buffer, so the *transshipment buffer* configuration, is the second best performing alternative based on cost. In regard to minimizing the usage of the installation vessel in terms of duration, the *direct* and *transshipment buffer* configurations are preferred. When the goal is to minimize the movement of the installation vessel and at the same time using it for the shortest time possible, the *transshipment buffer* configuration seems to be the best performing alternative. Using such a buffer allows the installation vessel to be used as late as possible, minimizing its sailing distances and therefore optimizing the hours the installation vessel is used. The *transfer offshore* configuration seems to be in this experiment the worst performing, both the interquartile ranges and the mean values for both the total cost, project duration and installation vessel usage are found to be among the worst compared with other configurations. The *transfer offshore* configuration performance is highly dependent on weather conditions which can lead to big deviations in project duration and cost when bad weather occurs. It seems like this configuration, so transferring offshore, can only be an option in good weather conditions, which will be further explored in the moderator analysis section.

6.2. High-level Validation

Validation of the computer model is performed by creating multiple state plots that show the state a certain vessel is in. The validation is performed based on the parameters used in the case study, described in the previous section. States are set when a vessel is held for a certain duration. An example state plot for the installation vessel is given in Figure 6.7. Also the number of monopiles on the different vessels are plotted to validate the computer model, an example for the installation vessel is given in Figure 6.8. For each simulation run also the locations of the vessel are stored. This allows assessing the location and state combinations to see if the right processes happen at the right locations.

Next to the generated plots, animations are developed that show the stock levels at the locations and vessels, the locations of the vessels themselves and the current state they are in. As these visually provide insight in the model, these allow validating the model in a correct manner. A example of such an animation is given as screenshot in Figure 6.9. By constantly assessing the animations and state outputs, the model was developed iteratively. Logical errors or programming bugs were removed by observing this output, and experts were given the opportunity to provide feedback based on the visualized supply chain model. This iterative process results in a validated model that was run according to many checks and different configurations. It also resulted in stating some additional assumptions that were present in the underlying behavior of the model. This allows strengthening the argument that the model is implemented correctly and accurately reflects real world behavior.

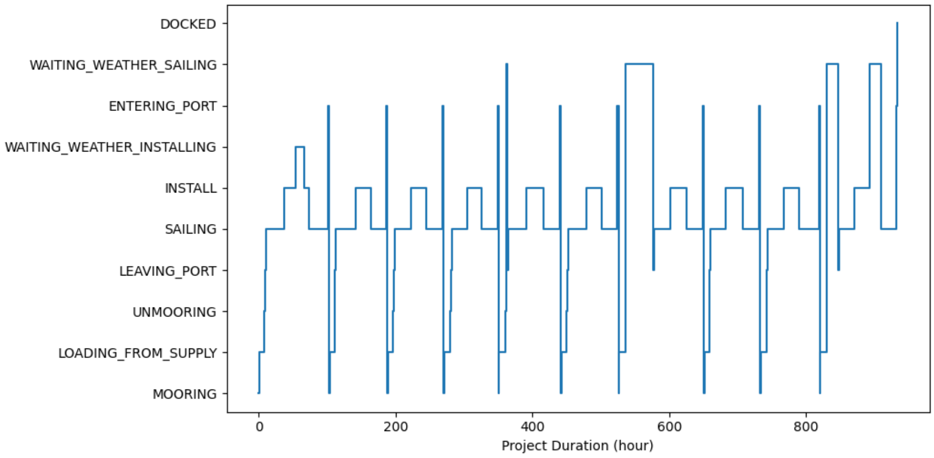


Figure 6.7: State plot of installation vessel (*direct* configuration)

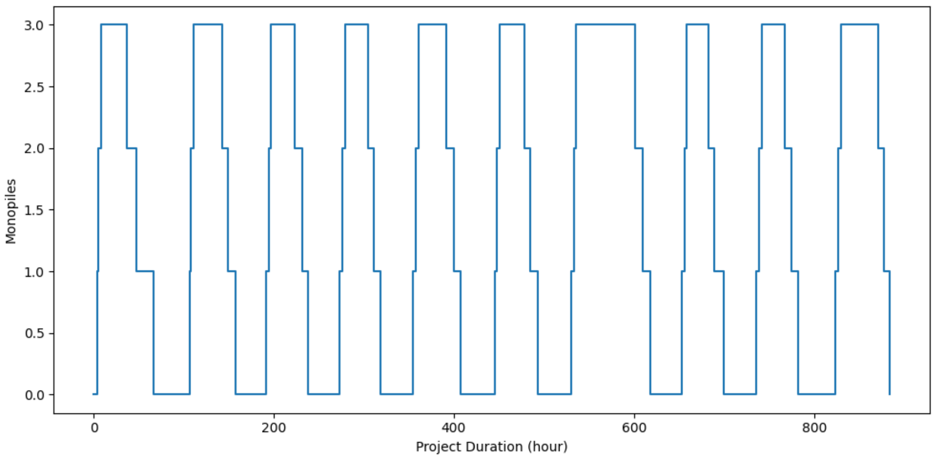


Figure 6.8: Monopiles on board of installation vessel (*direct* configuration)

It is also required to validate the key performance indicators order of magnitude for the main experiment. Therefore the project cost and project duration resulting from the experiment performed in the previous chapter will be compared with the order of magnitude of similar installation projects. Data from the similar installation projects is used to estimate the expected project duration and project cost. This can then be compared with the experimental results, which will give insight into how realistic the simulation is found to be. For a typical UK wind farm project, it is expected that foundation installation will cost around 116 thousand euros per turbine megawatt.. The offshore logistics related to the installation process adds another 4000 euros in additional cost, which brings the expected total at 120 thousand euros per MW. These numbers are based on the installation of 100 wind turbines with a capacity of 10MW per turbine and a project 60 km from shore. (BVG Associates, 2019) With the 30 monopiles for the simulated project, this will result in an expected cost of around 36 million euros. The direct sailing configuration is currently the most used in wind farm projects.

Figure 6.9: Screenshot of animation (*transshipment buffer* configuration)

Therefore, this simulation configuration setting is chosen to compare the expected cost with. For the base experiment, the average direct sailing cost is found to be around 9.4 million euros. The cost, however, is highly dependent on the day rates, and each parameter can vary a lot between projects, as is also pointed out within the report that includes these cost calculations, it is therefore expected that the cost can differ quite some amount between different projects. It can be concluded that the order of magnitude found is correct and realistic compared to the expected cost of wind farm foundation installation.

The expected project duration can be compared in the same way. The full cycle time of foundation installation is expected to be around 2 to 3 days per monopile, including waiting on weather, loading and the installation itself. This means that it would take between 1440 and 2160 hours to install 30 monopiles. (BVG Associates, 2019) Within the simulation results, the project duration of the direct sailing configuration is around 1000 hours. The mean of the duration results is a bit lower than the expected installation duration. The differences are likely explained by the assumed installation duration and the fact that in the simulation model, a dynamic positioning vessel is assumed which requires less positioning and orientation time than a jack-up vessel. The values found are close to the expected durations, and therefore it can be concluded that the model realistically represents the project durations of real UK wind farm projects.

These simple validation steps strengthen the comparisons made between the different supply chain configurations and their real world validity.

6.3. Moderator Analysis

In this section the results of varying the moderators are presented and discussed. In the graphs used to describe the analysis of the speed parameters (that are defined according to a distribution) are described with a category number. This number refers to a certain speed distribution used in the simulation. The used categories and corresponding values within these plots are summarized in Table 6.6. The names of the supply chain configurations refer to the supply chain configurations visualized in Figure 2.3.

Parameter	Category	Value	Unit
Supply Speed (knots)	1	Uniform(2,4)	knots
	2	Uniform(4,6)	knots
	3	Uniform(6,8)	knots
	4	Uniform(8,10)	knots
	5	Uniform(10,12)	knots
	6	Uniform(12,14)	knots
Installation Vessel Speed (knots)	1	PERT(2.91, 6.88, 6)	knots
	2	PERT(5.0, 9.0, 8.1)	knots
	3	PERT(6.9, 10.9, 10.0)	knots
	4	PERT(8.9, 12.9, 12.0)	knots
	5	PERT(10.9, 14.9, 14.0)	knots

Table 6.6: Overview of categories used in plots and corresponding values

6.3.1. Vessel Speed Parameters

Regarding the speed distribution of the installation vessel only significance differences in the mean project duration are found for the *direct* configuration. Within the other configurations, no duration differences are found. As the speed of the installation vessel increases, also logically, the overall project duration decreases. Interesting is the fact that only for the *direct* configuration an effect is found. This is likely due to the fact that within the other configurations the installation vessel is not the most constraining and the project duration is dependent on the speed of the supply vessels. The sailing speeds of the installation vessel and the corresponding boxplot for the project duration are given in Figure 6.10. The line plot in Figure 6.11 shows the effect of this change and allows to compare the change with other configurations in terms of project duration. The plot shows that with increasing sailing speeds, the difference between the project duration of the 1st and the other configurations becomes larger.

Varying the speed distribution of the supply vessel impacted all configurations except the *direct* configuration (as supply vessels are not used in this configuration). The corresponding boxplots are given in Figure 6.12 and Figure 6.13. The plots clearly show that when the speed of the supply vessel increases, the project duration and usage duration of the installation vessel (the most costly vessel) decreases significantly converging to a value that is close to or below the project duration of the best performing configuration, the *direct* configuration.

In Figure 6.14 the mean project durations are overlapped in one plot to show the differences between configurations more clearly. When the supply vessel has a speed between 8 and 10 knots (category 4), all configurations except the *transshipment buffer* configuration outperform the *direct* configuration in project duration. When the supply vessel has speeds between 10 and 12 knots (category 5) and the *transfer offshore* configuration is used the average project duration is around 17% lower compared with the *direct* configuration. Using supply vessels with a speed distribution between the 10 and 12 knots compared to speeds between the 4 and 6 knots reduces project duration significantly with 40% in the *transfer offshore* configuration. Supply vessels with such speed would likely be dedicated supply vessels as barges will not be able to sail that fast offshore. Also, for all configurations the variance in project duration and installation vessel usage duration is reduced, especially for the *transfer offshore* and *transfer offshore buffer* configuration the variance reduces quickly at higher supply vessel speeds. As the weather window required is reduced due to the higher vessel speeds, the waiting on weather percentages decrease and the overall project is finished in a shorter amount of time. In the *transfer port* configuration the supply vessel will be ready and waiting at the intermediate port most of the time, so it can be used directly when the installation vessel requires restocking at this intermediate port.

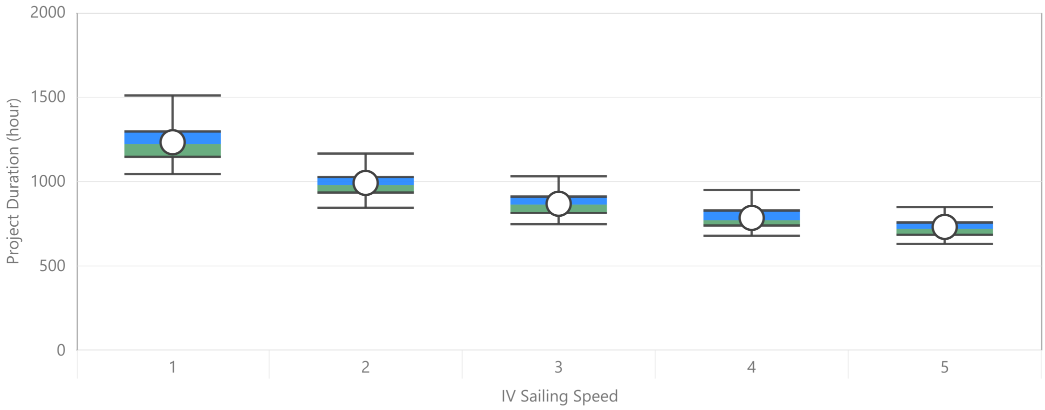


Figure 6.10: Project duration at different installation vessel sailing speed categories (Table 6.6)

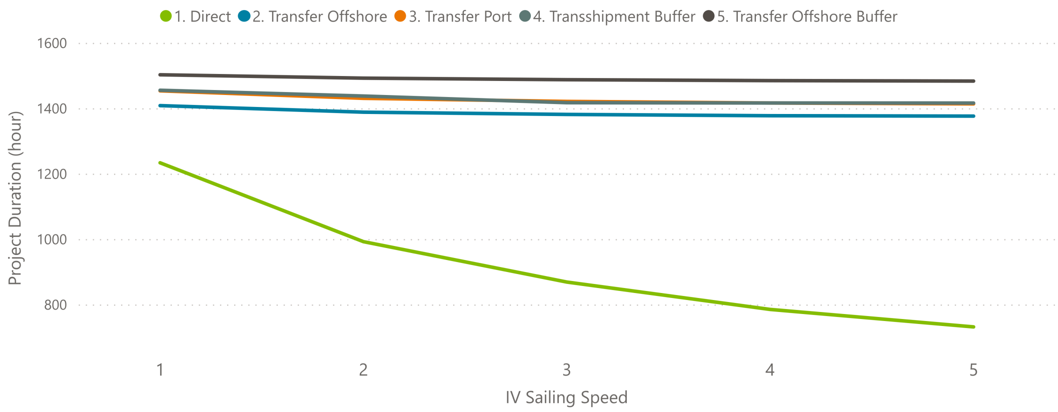


Figure 6.11: Project duration comparison at different installation vessel sailing speed categories (Table 6.6)

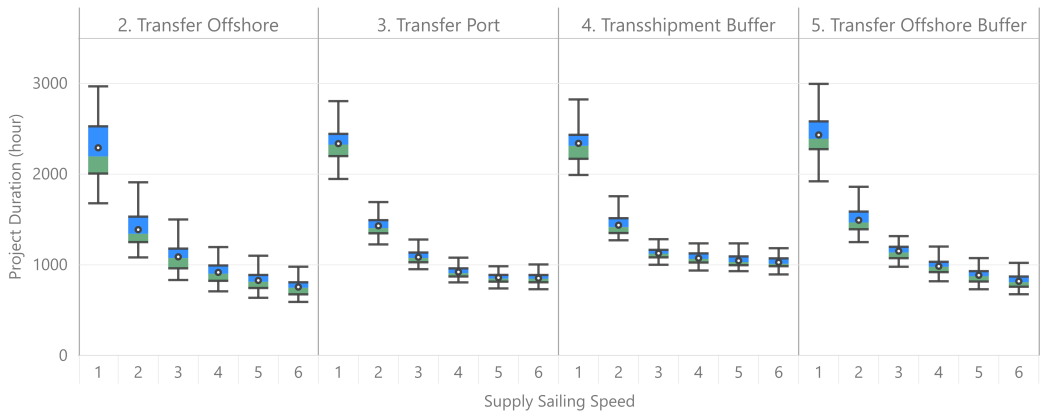


Figure 6.12: Project duration at different supply vessel sailing speed categories (Table 6.6)

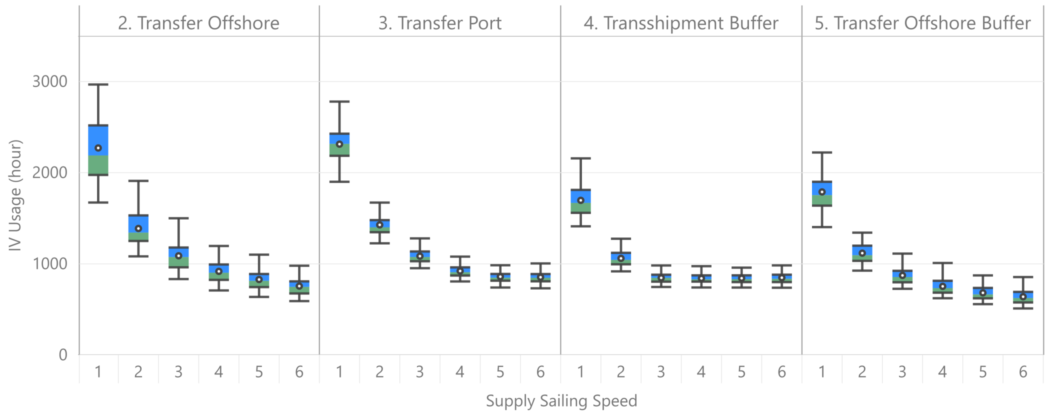


Figure 6.13: Installation vessel usage duration at different supply vessel sailing speed categories (Table 6.6)

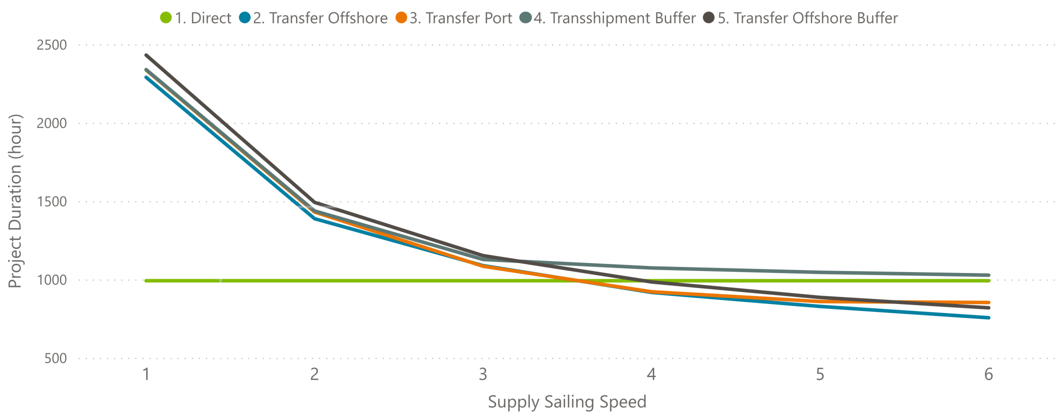


Figure 6.14: Project duration at different supply vessel sailing speed categories (Table 6.6)

6.3.2. Offshore Transfer Weather Limitation

Next to varying the speed of the installation vessel and the supply vessels also the alongside wave limit is varied. This is the significant wave height limit allowed to moor alongside the installation vessel and transfer monopiles offshore. This limit is found to be only important in the configurations that take into account offshore transfer (configuration *transfer offshore* and *transfer offshore buffer*), which makes sense as in other operations this limit is not used. The boxplot for the project duration as well as the installation vessel usage duration and lineplot are given in Figure 6.15 Figure 6.16 and Figure 6.17 respectively. Both the project duration and installation vessel usage duration decrease when the alongside transfer limits increase. This is due to the fact that there are more appropriate weather windows available to transfer offshore when the allowed limit increases. The decrease in durations however seem to be steeper between 1.0 and 1.5 meter than it is at higher wave limits. Even when considering higher wave limits the project duration is still significantly higher for the two offshore transfer configurations compared with the *direct* configuration. At an alongside limit of 1.5 meter the *transfer offshore* configuration, however, outperforms the *transfer port*, *transshipment buffer* and *transfer offshore buffer* configuration in terms of project duration. It seems the improvement in project duration approaches a limit (see Figure 6.17) when the alongside limit is increased, this is due to the fact that also a sailing limit of

2.5 meter is taken into account in these configurations. Therefore, only changing the alongside limit does not lead to a continuous decrease in project durations.

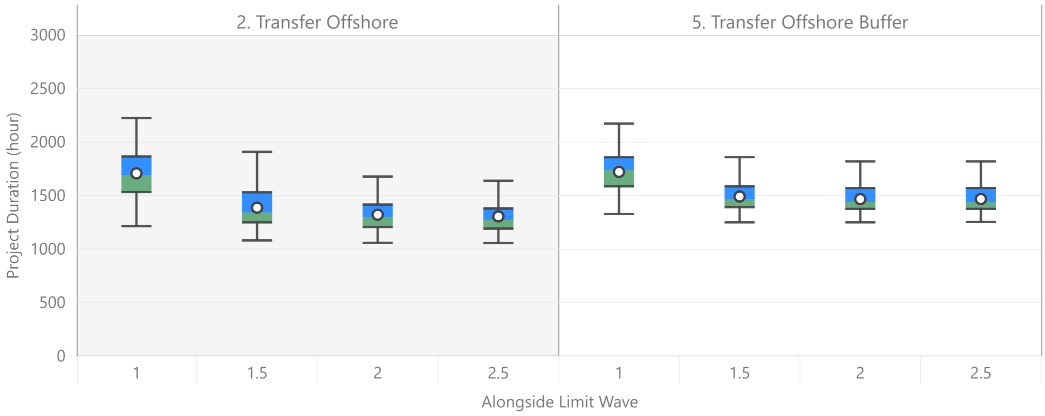


Figure 6.15: Project duration at different alongside wave limits

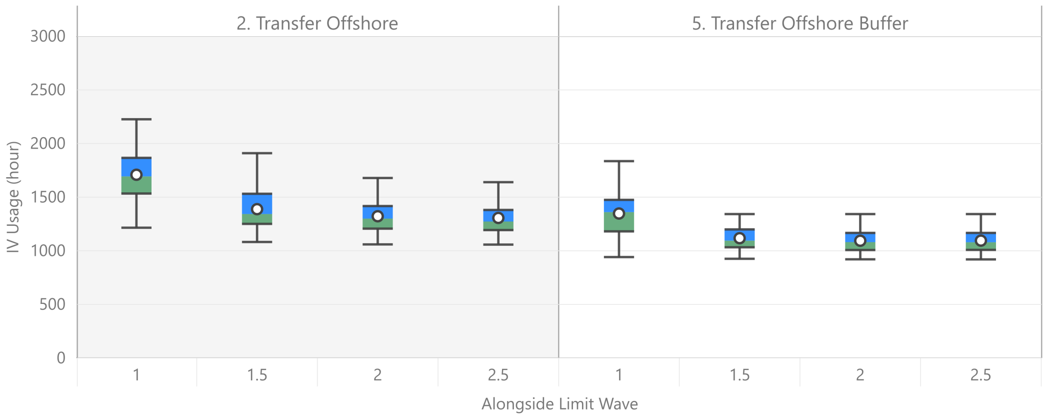


Figure 6.16: Installation vessel usage duration at different alongside wave limits

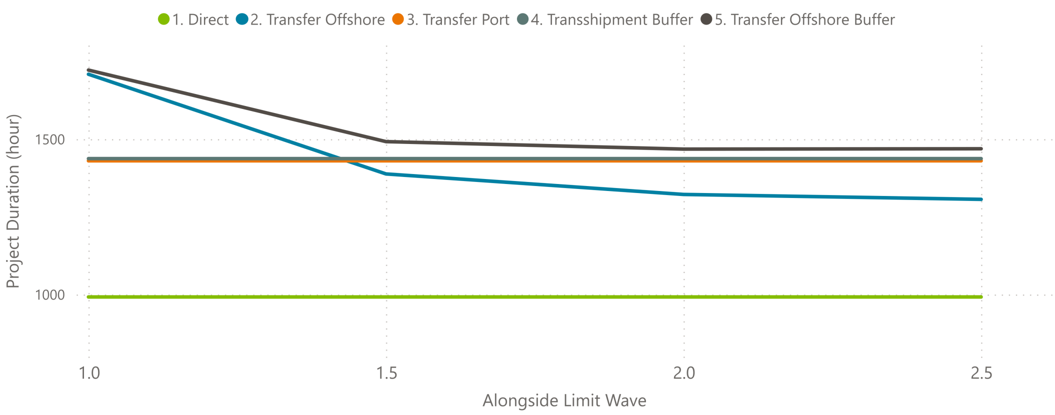


Figure 6.17: Project duration comparison at different alongside wave limits

6.3.3. Stock at buffer

The minimum stock that was stored in the intermediate port before starting operations with the installation vessel was also tested as this impacts the overall project duration, installation vessel usage and cost. The following plots show the results of using different minimum stock requirements, Figure 6.18, Figure 6.19 and Figure 6.20. In this case the cost can be presented as discussed in section 5.6. This change impacts only the *transshipment buffer* and *transfer offshore buffer* configurations since these are the only configurations utilizing a buffer at the intermediate port. In the *transshipment buffer* configuration the overall project duration stays at around the same level but the installation vessel usage decreases when increasing the minimum stock level. Initially storing 15 monopiles instead of 6 monopiles in the *transshipment buffer* configuration reduces the installation vessel usage duration from 1205 hours to 840 hours, which is a reduction of 30%. This can be attributed to the weather impact at lower minimum stock levels. When lower minimum stock levels are used the installation vessel will in some weather realizations empty the intermediate port in a few installation cycles. In these cases on average more monopiles are taken from the intermediate port than are refilled by the supply vessels during the installation process due to the fact that the supply vessels are sometimes waiting on weather before sailing from the wind farm to the intermediate port and have a lower sailing speed. Increasing the stock at the intermediate port will allow the installation vessel to work longer without any interruption which leads to a decrease in installation vessel usage durations

The overall cost of the *transshipment buffer* configuration also decreases significantly when increasing the intermediate minimum stock level (as shown in Figure 6.20). Storing 15 monopiles instead of 6 in advance reduces the total cost from around 13.7 million to 11.1 million euros, a reduction of 19%. This can be explained by the fact that the reduction in installation vessel usage durations and the corresponding decrease in operating cost offset the cost of renting a bigger intermediate port for a longer period of time (as project durations get longer). When initially storing 15 monopiles the costs are still 18% higher compared with the *direct* configuration, but the duration the installation vessel is required reduces by around 15%.

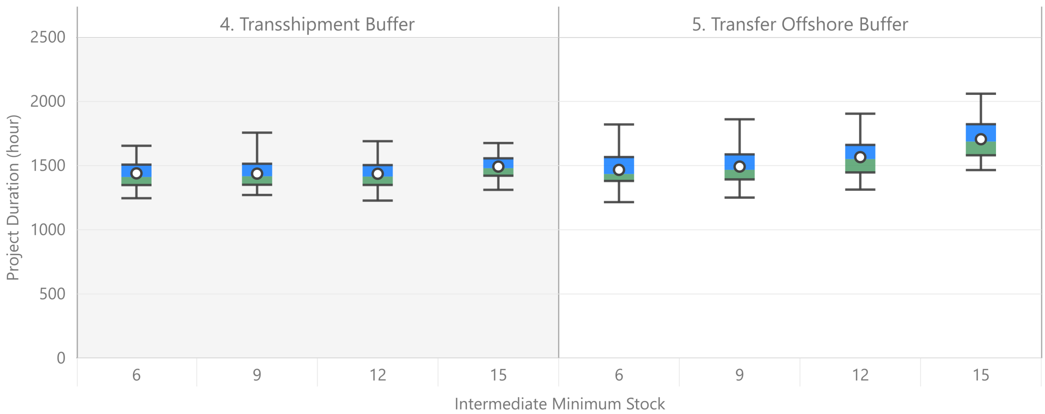


Figure 6.18: Project duration with different minimum stock levels

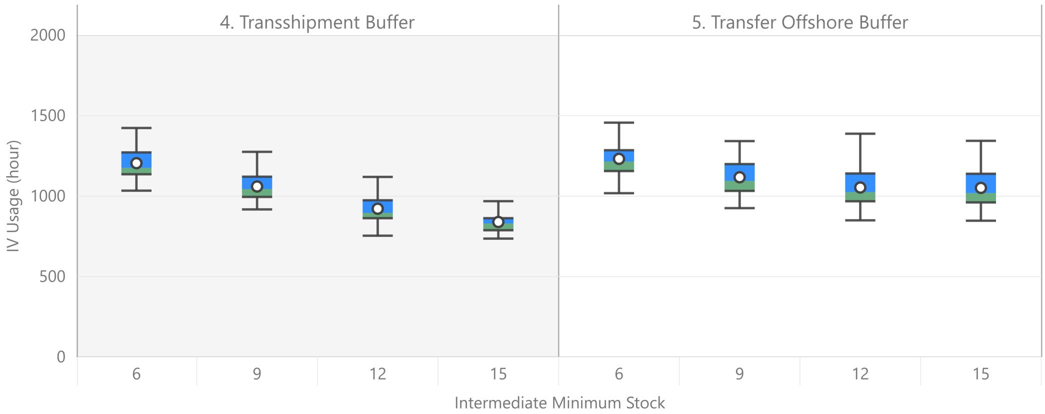


Figure 6.19: Installation vessel usage duration with different minimum stock levels

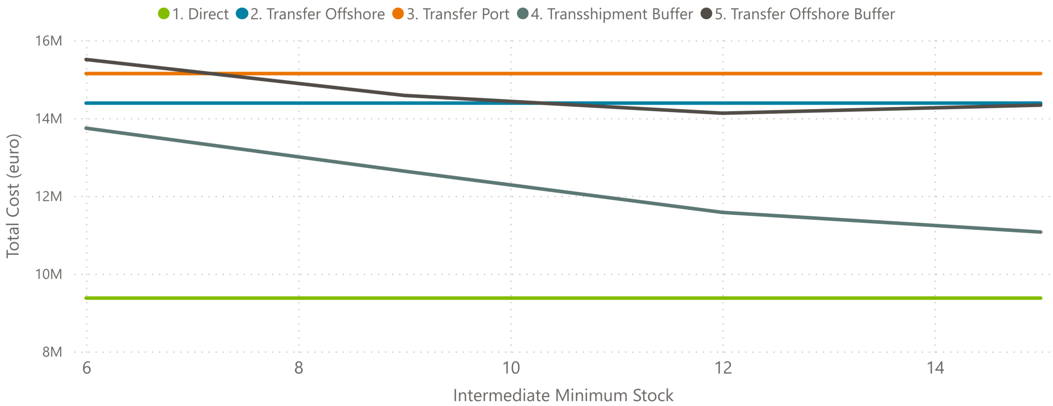


Figure 6.20: Total cost with different minimum stock levels

6.3.4. Weather Conditions

It is expected that the results will be different when the project starts in different months due to the seasonality in the weather data. If weather changes due to this seasonality also the waiting on weather durations are expected to differ and therefore also the project duration and project cost. The boxplot is presented in Figure 6.21 and the comparison of the average total cost in Figure 6.22. Both the variation and mean project duration and cost decrease for all configurations towards the summer period and seem to increase again during the winter/fall periods. This is expected as storms are more frequent in the fall and winter than they are in spring and early summer. When no storms are present, less waiting on weather is required and the project can be performed in a shorter amount of time, resulting in lower cost. The differences can be significant as can be observed from Figure 6.22. Configuration *transfer offshore* is even reduced in cost by 16 million if the installation process starts in May instead of November.

The weather conditions are varied by applying a simple multiplication factor as described in section 5.6. As the costs are not influenced by the weather itself but are a result of the vessel operating, the cost can be presented for this parameter. The results are presented in Figure 6.23 and Figure 6.24. These show that as the weather becomes worse also the overall project costs and durations increase. This is expected as the most important costs within the model are related to vessel usage cost which on its turn is influenced by the duration a vessel is used. When weather gets worse, more waiting on weather will occur and in this way increasing project durations and operating cost. Another important observation from these results is the fact that the variance of the *transfer offshore* configuration increases significantly when weather becomes worse due to the strict weather limits that are required when transferring offshore. Also, the average costs increases significantly, the *transfer offshore* configuration becomes twice as expensive, which is an increase of 14 million euros.

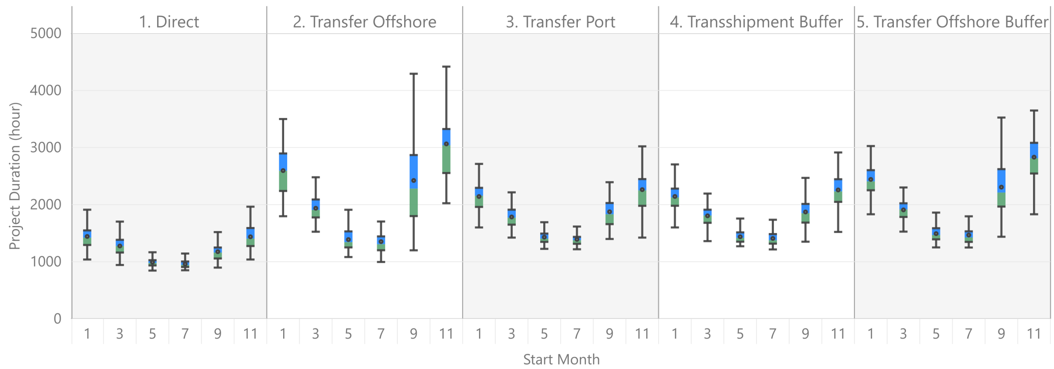


Figure 6.21: Project duration with different start months

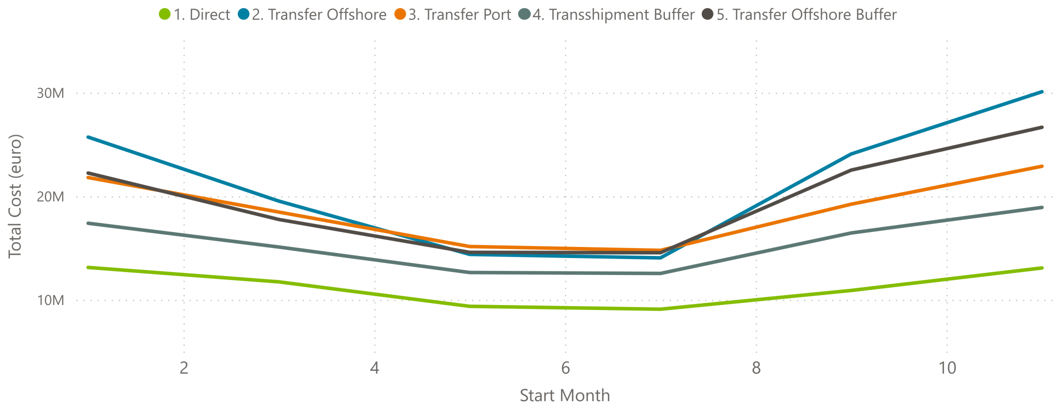


Figure 6.22: Total cost with different start months

6.3.5. Supply to Wind Farm Distance

In Figure 6.25 and Figure 6.26 the results of varying the distance between the supply port and wind farm are shown. It was found that when the distance of the intermediate port to the wind farm was varied while keeping the same distance of supply port to wind farm, no significant differences were found. Therefore, only the results are shown where the distance of the intermediate port to the wind farm is 150 km. Overall, all configurations seem to increase in project duration when the distance to shore is increased. In this case also, the *transfer offshore* configuration will increase in variation at increasing distances. This is due to the fact that longer distances need to be traveled which increases the weather window required to operate the supply vessel. As the supply vessel has, lower limits than the installation vessel this will lead to an increase in

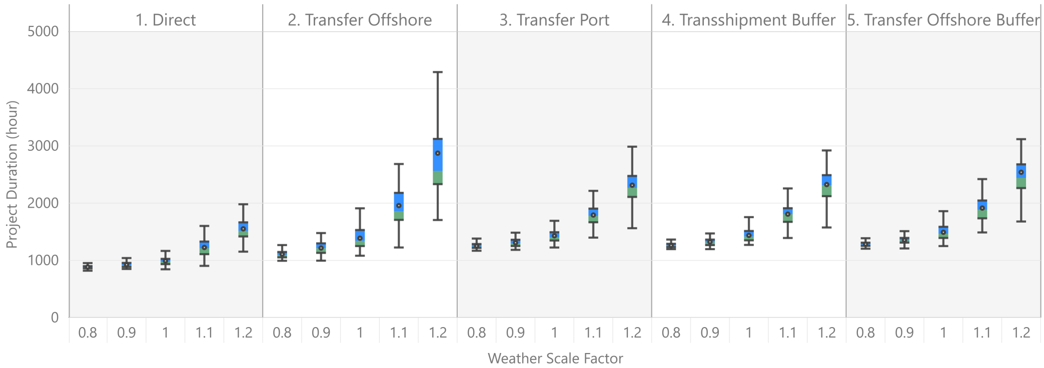


Figure 6.23: Project duration with different weather conditions

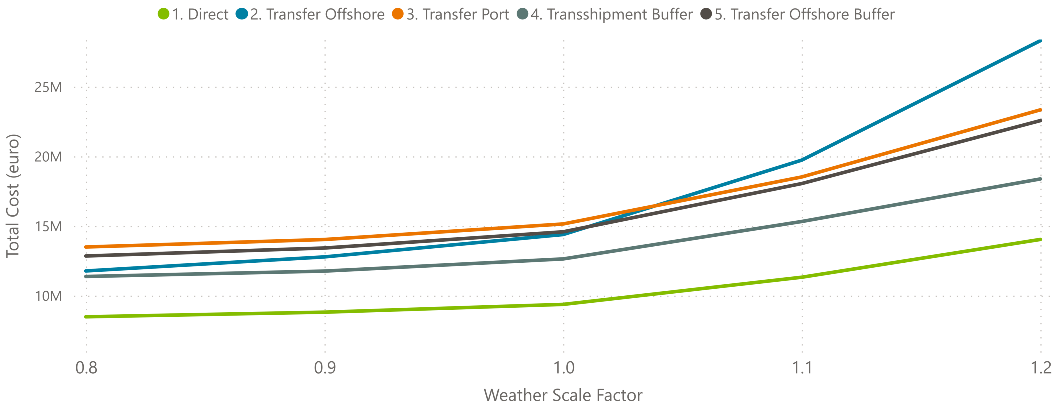


Figure 6.24: Total cost with different weather conditions

waiting on weather durations for the supply vessel and therefore an increase in project duration. It would be expected that with increased distances the *transshipment buffer* and *transfer offshore buffer* configuration become more attractive. This is, however, not the case as the supply vessels in these configurations also need to sail longer distances which will increase project durations. The *transfer offshore buffer* configuration does not exhibit the same big variance found in the *transfer offshore* configuration. When it is preferred to keep the installation vessel at the wind farm and the wind farm is located far from the supply port choosing the *transfer offshore buffer* configuration will not lead to the big variances that are present in the project duration results of the *transfer offshore* configuration. The usage of the intermediate port and the buffer will mitigate the effect of big weather windows required to restock the installation vessel.

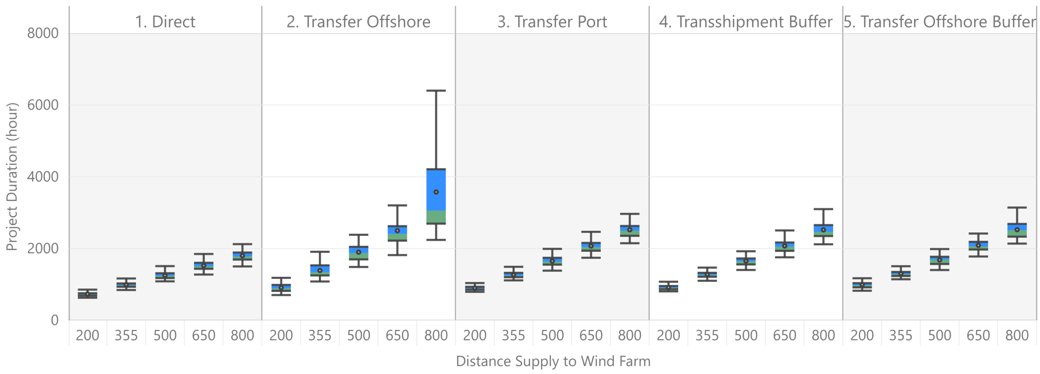


Figure 6.25: Project duration with different distances supply to wind farm

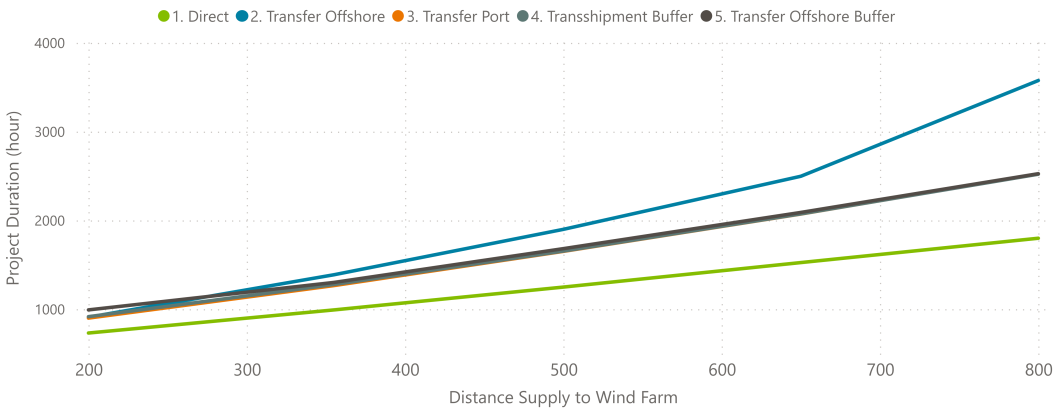


Figure 6.26: Project duration with different distances supply to wind farm (cropped)

7 Conclusion and Recommendations

In order to investigate the effect of using different supply chain configurations in offshore wind farm monopile installation, five different configurations are analyzed and assessed according to different key performance indicators. The performance of these configurations is evaluated based on numerical experiments. These experiments are performed in a computer simulation model which simulates the supply chain processes and the influence of weather. The investigated supply chain configurations are listed below.

1. *Direct* configuration: The installation vessel sails back and forth between the installation location and the supply port in order to restock monopiles.
2. *Transfer offshore* configuration: The installation vessel stays at the offshore wind farm location and a supply vessel sails back and forth between the supply port and the wind farm. The monopiles are transferred offshore between the two vessels.
3. *Transfer port* configuration: This configuration includes an intermediate port that acts as a sheltered area for the transfer between a supply vessel and an installation vessel. The installation vessel sails between the intermediate port and the installation location while the supply vessel sails between the supply port and the intermediate port. The vessels will wait for each other at the intermediate port to transfer monopiles from the supply vessel to the installation vessel.
4. *Transshipment buffer* configuration: In this configuration he intermediate port includes a quay and a storage area. The supply vessel and installation vessel do not wait for each other but use the storage area in the intermediate port to load and unload the foundations.
5. *Transfer offshore buffer* configuration: Two supply vessels are used to transport monopiles. The two supply vessels make use of an intermediate port with a quay and storage area to load and unload components. One supply vessel will deliver the monopiles from the supply port to the intermediate port, while the second supply vessel will deliver monopiles from the intermediate port to the installation vessel and transfer the monopiles offshore. The installation vessel will stay at the offshore wind farm location during the complete installation process.

The main research question focuses on the effect of using the different supply chain configurations on the performance of offshore wind farm monopile installation under dynamic weather influences. In order to answer this research question and sub research question 3, the first experiment performed is a case with a typical offshore wind farm installation. Next to this case study also five other experiments are performed in order to research the effect of varying moderating variables and therefore answering sub research question 4. The moderator variables examined are the speed of the vessels, the offshore transfer weather limit, the stock at the buffer location, the weather conditions and the distance between the supply port and the wind farm. The effect of changing one of the moderator variables on the relation between the supply chain configurations and the key performance indicators is investigated in these experiments by keeping all parameters fixed to the case considered in the first experiment and changing only the moderator that is investigated.

In this report, a quantitative method is used to test complex logistical networks and supply chain decisions offshore while taking into account the stochastic influence of weather. Part of this is the developed weather model that is able to generate synthetic weather data. The weather model developed in this report improves earlier models that try to generate synthetic weather data with Markov Models and is therefore an important theoretical contribution to literature. A limitation in this report is the way the synthetic weather data is used in the supply chain model. The synthetic weather data generated in this report is only focussed on the wind farm location itself. A recommendation for future research is to use the developed weather model and generate weather data for the complete sailing routes of the vessels. Using the developed model for multiple locations can give more insight into the differences between configurations and can show the effect of distance to shore in a more detailed manner. The developed supply chain model, the weather module and the analysis of the different supply chain configurations address the identified research gaps in literature and contribute to the sparse literature available.

7.1. Experimental Findings

The findings of the first case study experiment show that the *direct* configuration in the main experiment is the best performing configuration in terms of project duration and cost. Also, the fuel usage of this configuration is the lowest compared to other configurations. There seem to be no additional benefits in using more advanced configurations in the tested case study experiment. Important to consider is the variation that is present in some more advanced configurations. This is attributed to the differences in weather between the run samples, the effect of weather impacts the performance of offshore transfer configurations to a larger degree.

The second experiment shows that when dedicated supply vessels are used, the project duration can be decreased to the point that the *transfer port*, *transshipment buffer* and *transfer offshore buffer* become the preferred configurations and outperform the direct configuration. Also, the variance of these configurations becomes smaller at higher supply vessel speeds making the configuration easier to plan and control compared to the four other configurations. Changing the speed of the installation vessel does make improvements to the project duration, but does not impact the differences between the different supply chain configurations. Future research should try to quantify the effect of reducing variance in offshore wind monopile installation in order to give insight into the cost reduction that follows from choosing configurations with low variance.

From the third experiment it is found that designing vessels to increase offshore transfer limitations does not make a significant impact on the project durations as still big windows are required to both sail and transfer in one trip.

In the fourth experiment the results show that with intermediate ports, the *transshipment buffer* and *transfer offshore buffer* configuration, it is possible to decrease the usage duration of the installation vessel below that of the direct configuration by adding enough stock in the ports. The usage duration of the installation vessel can be reduced by 15% with a increase in cost of 18% when storing 15 monopiles instead of 6 at the intermediate port. This is an interesting finding as it shows that having such a port can provide benefits even though no significant effect on project durations is found. It would be interesting for future research to investigate different safety stock holding strategies in order to test if these strategies further improve the benefits of using intermediate ports. When the goal is to minimize the installation vessel usage duration it is recommended to use such an intermediate port with buffer and allow enough monopiles to be stored at these locations. It is possible that cost benefits can be obtained when the used installation vessel is expensive to operate. The reduction in installation vessel usage cost is then expected to outweigh the extra cost required to store monopiles in the intermediate port. Whether the cost of using dedicated supply vessels will outperform the reduction in project duration and installation vessel usage duration should be further explored in future research.

In experiment five one of the most impactful parameters both in terms of cost and project duration is found to be the environmental conditions the vessels operate in. Changing the weather by applying a scale factor or just by starting operations in a different month impacts cost drastically. Weather and its impact are therefore considered to be one of the main drivers of project cost and performance of the different configurations. Using the *transfer offshore* configuration in bad weather increased cost by 14 million euros which is twice as expensive as in normal weather conditions. Changing the weather does not significantly change the best performing configuration, the *direct* configuration, but does decrease the variances found in the results of other configurations and makes the differences between different configurations smaller.

From the sixth experiment it can be concluded that when distances are lower the differences in project durations between configurations becomes smaller. At each distance tested however the direct configuration is still the best performing configuration.

An important result that follows from this report is the insight that approximating the expected project cost and project duration without taking into account the variance of these parameters is oversimplified. Some configurations do not differ that much based on their mean value, but the variance of some key performance indicators differs a lot. The *direct* configuration or the usage of intermediate ports as transfer/transshipment location are less influenced by weather variations and are therefore easier to plan and control.

As the direct sailing configuration performs best on all key performance indicators, it is recommended to use this configuration if the alternative consists of using barges instead of dedicated supply vessels and if it is not possible to make a more detailed assessment of the specific project. If it is the goal to minimize the usage of the installation vessel it is recommended to make use of the *transshipment buffer* configuration with enough storage area. When dedicated supply vessels are available with high sailing speeds the *transfer offshore* configuration becomes attractive as it leads to a decrease in average project durations, decrease in project duration variation and a decrease in the usage duration of the installation vessel. As weather plays an important role, the results will differ significantly between installation locations and fleet composition, it is therefore recommended to test specific project characteristics and the effects of using different vessels, stock levels and supply chain configurations.

7.2. Practical Contribution

In addition to the theoretical contributions this report also contributes to practice. This report contributes by informing offshore wind farm planners about the different factors that play a role in the supply chain of offshore wind farm monopile installation. It also enables planners to better argue about the different supply chain configurations at hand and to make an educated choice on the preferred supply chain configuration for a specific installation project.

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A Calculations

A.1. AIS Analysis

As typical installation vessel it is chosen to examine the publically available location data of the Seaway Strashnov. With the help of 12 historical loading cycles, performed by the Seaway Strashnov, the loading time distribution of the vessel at SIF can be estimated. This is done by retrieving full loading cycles and analyzing the duration the vessel is moored at berth at the SIF location. The drawn block is the assumed area where the berthing takes place, the loading cycle time (of the 3 monopiles) can be estimated from the entrance and leave points to this block. It is known that at this location three monopiles are loaded. According to expert estimations, the estimated mooring and unmooring time is around an hour. This allows estimating the loading time per monopile. If, for example, the observed duration is 11 hours, it is estimated that the loading time per monopile is (11-2)/3=3 hours. By calculating this expected loading time for each observation, the distribution of the loading times can be estimated.

The sailing time within the port is estimated in the same way, observing the entering/leaving time from the berth and the time the vessel enters/leaves the port area. The measured distance from the entrance of the Port of Rotterdam to SIF is found to be 15.31 kilometer, which allows to estimate the distribution of the expected sailing speed within ports.

This speed can then be assumed to be equal among ports and can be applied to the intermediate location used within this experiment. The path used to calculate this distance within the intermediate port is visualized in Figure A.1.

When the barge is expected to load and sail some modifications to the operation durations are required. As the cranes at the supply port stay the same, it is expected that loading the barge will take around the same time as loading the installation vessel. However, due to the simplicity of the barges and the already connected barges it is expected that mooring and unmooring time will take only half an hour for the barge. The speed of the barge is around 6 knots. But the maximum speed of the installation vessel within ports was only 5.9 knots. Therefore, it is expected that the barge will also slow down and the barge sailing durations within the ports will equal the values of the installation vessel.

To validate the installation duration that is stated by experts, 9 installation cycles of the Seaway Strashnov were observed with AIS data. The installation cycles are determined

Figure A.1: Distance in Intermediate Port

by observing the AIS data and finding the 3 spots the vessel was around the same location.

Visually, the three installation clusters were identified (see an example in Figure A.2). By investigating the incoming AIS data points and outgoing datapoints of this cluster, the duration of installation can be estimated.

That the installation of a monopile takes around 5–6 hours as stated by experts is indeed valid, according to the observed data. Important, however, is the fact that this also shows sailing times within the farm can be significant. This is because other activities are also done by these installation vessels before installing the pile itself. For example, the placement of noise mitigation screens needs to happen before installation is possible. Also, anchoring is often used by this vessel as it uses dynamic positioning as support. In the simulation model, no distinction between these activities is made, the distribution used within the simulation will be fitted on the observed data.

A.2. Fuel Cost

In order to calculate the sailing cost an estimation needs to be made on the energy usage of the vessel and the corresponding fuel cost. As the parameter duration data was fitted based on data of the seaway strashnov it is chosen to also use this vessel for the fuel cost calculation. The Seaway Strashnov has 6 main engines of the Wartsila 9L32 type (Seaway 7, 2022). The main thrusters used for sailing are 2 thrusters with a power output of 5000 kW. According to documentation of Wartsila the specific fuel oil consumption is 178.8 g/kWh (Wärtsilä, 2019). It is expected that the vessel will not sail with a full power output as this is not economical. Therefore, the assumption is made that only 85% of the full power will be used to sail, which is in line with assumptions made within other papers (Hulskotte et al., 2003). The energy required equals power multiplied by time. The power is assumed to equal $5000 * 2 * 0.85 = 8500kW$ when

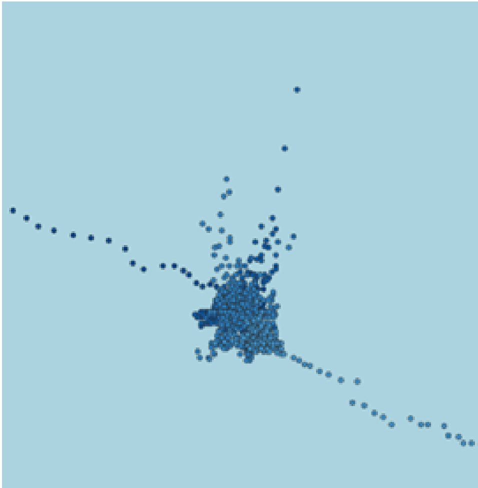

Figure A.2: Example of AIS data while Installing

sailing offshore. The fuel consumption in kilograms per hour can be calculated by multiplying the power consumption in kW by the fuel oil consumption in grams per kWh, which gives 1519.8 $kg/hour$, so 1.52 $tons/hour$. As this report looks into the installation of monopiles using dynamic positioning, also the cost of operating the dynamic positioning should be taken into account. With internal data of Allseas the expected fuel usage while using dynamic positioning systems is around 45% of the fuel usage of a vessel in transit. The expected consumption is estimated as 0.684 $tons/hour$.

This value was compared with internal data at Allseas and was found to realistically represent the average consumption of an offshore vessel sailing at cruising speed. The assumption of the fuel cost for the tugs is based on the tug rastar 3800 series. The fuel usage at cruising speed is around 0.6 $tons/hour$. In the experimental setup of this report, two tugs are used, therefore, the total fuel usage is 1.2 $tons/hour$.

The most used fuel type for four-stroke engines like the engines in the Seaway Strashnov and tugs is marine diesel oil, also referred to as very-low sulphur fuel (0.5%S) (Hsieh & Felby, 2017). The average price of very-low sulphur fuel in the harbor of Rotterdam was around 523.76 $euro/metric$ ton between January and May 2023 (Ship and Bunker, 2023)). This allows calculating the expected fuel cost per hour for both vessels. The tugs will cost 534.23 $euro/hour$ and the installation vessel 796.12 euro/hour of sailing offshore. The use of dynamic positioning for the installation vessel will cost around 358.25 $euro/hour$. These values can be used in the simulation to provide a cost estimation of all sailing operations, the specific calculated values will be used in the simulation but will be rounded in the report (as the values are a rough approximation).

A.3. Intermediate Port

The cost of renting an intermediate port should also be taken into account in order to present a fair comparison in costs between supply chain configurations. Based on the fact that in the base experiment, the capacity of the intermediate port is around 10 monopiles, and each of these monopiles is expected to have a maximum dimension of 120 meters long and 9 meters in diameter (Sif Group, 2023) the required area to store these monopiles can be approximated. Within the port additional space is required for transporting, moving and load-out of the monopiles. In order to provide some manoeuvring space, the routes around the monopile storage locations should be around 100 meters wide. Combining this information in a rough sketch allows approximating the expected area that is required in the intermediate port as visualized in Figure A.3. The total area can be estimated to be around 72,000 square meters to store 10 monopiles.

The cost per square meter is hard to determine as these sources are often private and subject to supply, current prices in the market and demand. Some data is, however, available for the port prices in Rotterdam. A yard with quay can be rented in this area for around 3.5 $euro/m^2$ a month (Franklin Offshore Europe, 2014). The expected cost of using an intermediate port is therefore around 250,000 euro/month.

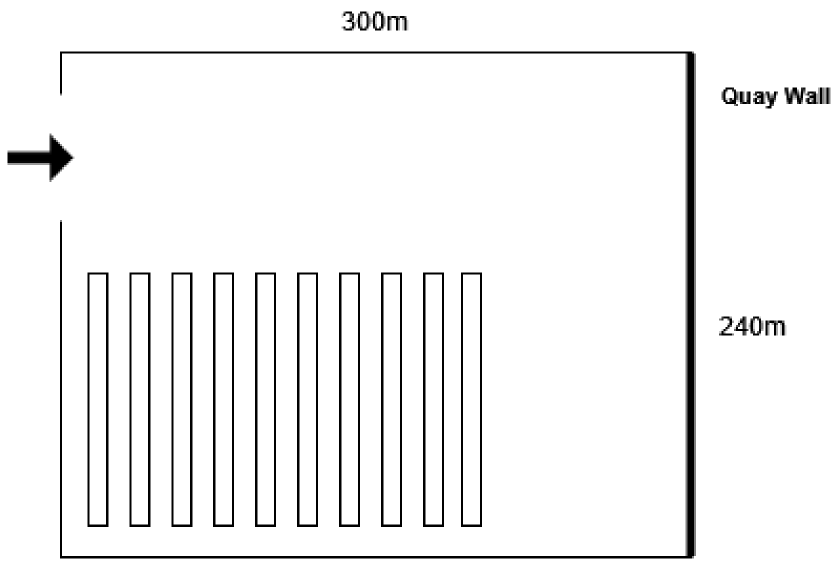

Figure A.3: Approximate Area Calculation Intermediate Port

A.4. Excluding Parameters

For the analysis of the used variables, the limits as presented in Table A.1 are assumed. This follows from the limits often used when performing offshore operations related to wind farm installation practices. The wind speed limit is hard to determine upfront due to the fact that on the vessel the super intended will determine if operations can continue based on the observed wind speed and the expected risk of the operation. Experts state that it is expected that the wind speed is not governing the weather limits during most operations, therefore the input data is analyzed to assess the need of including the wind speed.

Type	Variable	Limit
Wave height	H_s	1.5/2.5 meter
Peak wave period	T_p	8
Wind Speed	U	12 – 15 m/s

Table A.1: Parameter Overview

Within the simulation model operations cannot be performed when at least one of the stated limits is reached or exceeded. It is therefore analyzed how much of the data points in the train dataset exceed the limit of wind speed but still are within the limits of the wave height and peak wave periods. Given that wind speed as variable is excluded this describes the data points that would have resulted in downtime if it would have not been excluded. The results obtained are stated in Table A.2

Scenario	Percentage Limit Excluded %	Limit
$H_s = 1.5; U = 12; T_p = 8$	0.04	1.5/2.5 meter
$H_s = 2.5; U = 12; T_p = 8$	6.78	8
$H_s = 1.5; U = 15; T_p = 8$	0.00	12 – 15 m/s

Table A.2: Scenario for exclusion based on window duration

The largest data exclusion happens when the operational limit is set to 2.5 and the wind speed to the lowest value. It is therefore analyzed how much data is excluded between the wind speed limits of 12 and 15 (when assuming a wave height of 2.5 meters. The plot and corresponding data are shown in Figure A.4 and Table A.3.

Wind Speed	Percentage Limit Exceeded Excluded %
12.0	6.78
12.5	4.70
13.0	3.04
13.5	1.78
14.0	0.94
14.5	0.43
15.0	0.17

Table A.3: Wind and Percentage Excluded

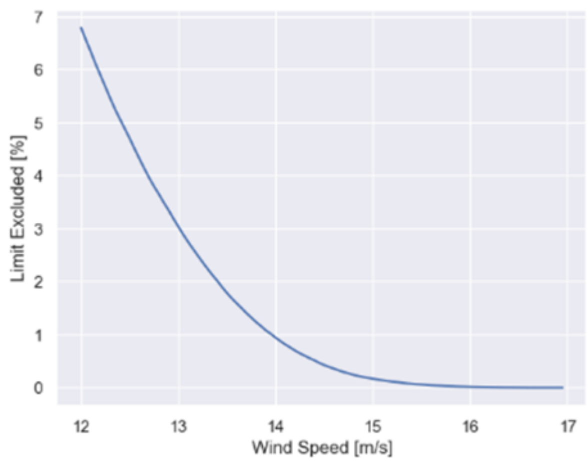

Figure A.4: Limit exceed percentage for different wind speeds

As can be observed the wind percentage of limit excluded reduces quickly when choosing a value closer to 15. As only in a conservative case (considering low winds) and while using the limit of 2.5 meters more than 5% of limits are excluded it is chosen to exclude the wind speed parameter. The final synthetic model will fit better on the observed data due to the increase in data to train on which weights up to the impact of excluding these limits, which only happens when the most conservative case is considered.

B

Software Documentation

As discussed in the methodology section the model is implemented in Python with the Salabim package. The simulation package is called "LOGSIM". The complete documentation and code is published together with this report. The code and documentation are also published at https://github.com/scurom/LOGSIM under the MIT license. The following sections will give a brief overview of the package and its structure.

B.1. Installation and Usage

The simulation package requires Python 3.10.4 or higher and the python packages listed in requirements.txt to be installed in order to run the simulation. If results need to be saved instead of only plotting or animating the results, it is preferred to have a MongoDB database installed and running. A local MongoDB database can be installed by following the instructions on the MongoDB website. It is also possible to use the free shared MongoDB database provided by MongoDB Atlas as this provides sufficient storage for the results of the simulation. The results can also be saved to JSON files, but this is not recommended as it is not as efficient as using a database, and it relies on the user to manually provide unique id's for each run to prevent overwriting previous results.

The package can be used by importing the logsim package and creating an instance of the Experiment class. After the experiment class is initialized with the required parameters the run_experiment() method can be called to run the simulation. A working example can be found in the "main.py" file in the root directory of the package and is described in the documentation. Make sure to load a weather data file in the correct format as described in the documentation in order to run the simulation (as the simulation cannot run without taking into account weather).

B.2. Structure

Each file in the developed python package contains different classes with different functionalities. Some modules use methods or structures of other classes. The dependencies between these modules are visualized in Figure B.1, the arrow means that a module depends on another module. The most central module is the "classes" module, this contains the Experiment class. This class uses almost all modules in order to correctly set up, run and store the results of the simulation. The weather, database and enumeration module to not depend on any other module of the logsim package. An outline of the overall implementation and how the most important classes interact is visualized in Figure B.2. Each module is shortly discussed in the subsections below.

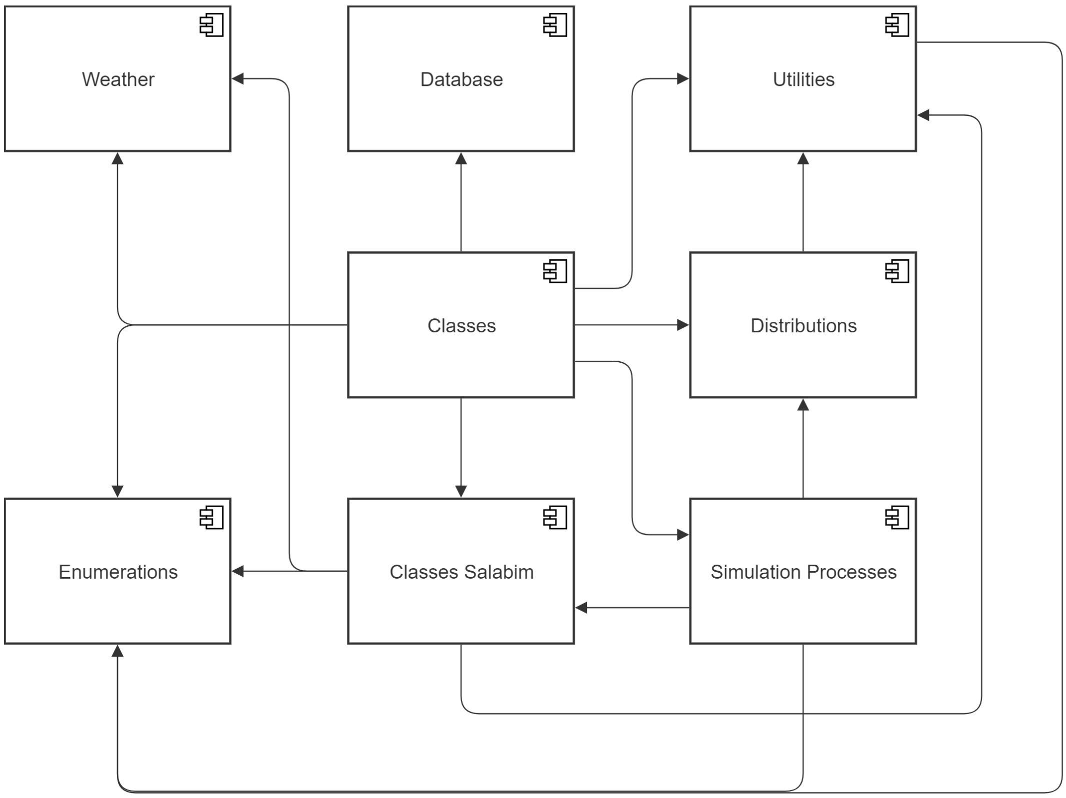

Figure B.1: Package Content Diagram

B.2.1. Classes Module

This are overwritten salabim classes and self created classes mainly used to run the simulation and set correct parameters for the simulation.

The classes Vessel, InstallationVessel and SupplyVessel have the goal of providing a structured way to store and enter parameters for the vessels. The most important class is the Experiment class as it provides the main simulation run and contains methods to transform and clean the results of the runs before storing it to the database. The main method used is the logsim.classes.Experiment.run_experiment() method. This method will go over each of the weather samples and create a seperate salabim environment for each sample. It will generate the vessel components and run the appropriate supply chain configuration. It will then save the sample in the experiment class with the logsim.classes.Experiment.save_sample_result() method. After each sample is run it will call the logsim.classes.Experiment.calculate_kpis() method to clean the results, calculate the overall KPI's and store it in the database by calling the logsim.db.Database.insert() method. Each entry in the database will be one run with the corresponding configuration and parameters, it contains the durations of each sample and the overall KPI's. It is also possible to write the

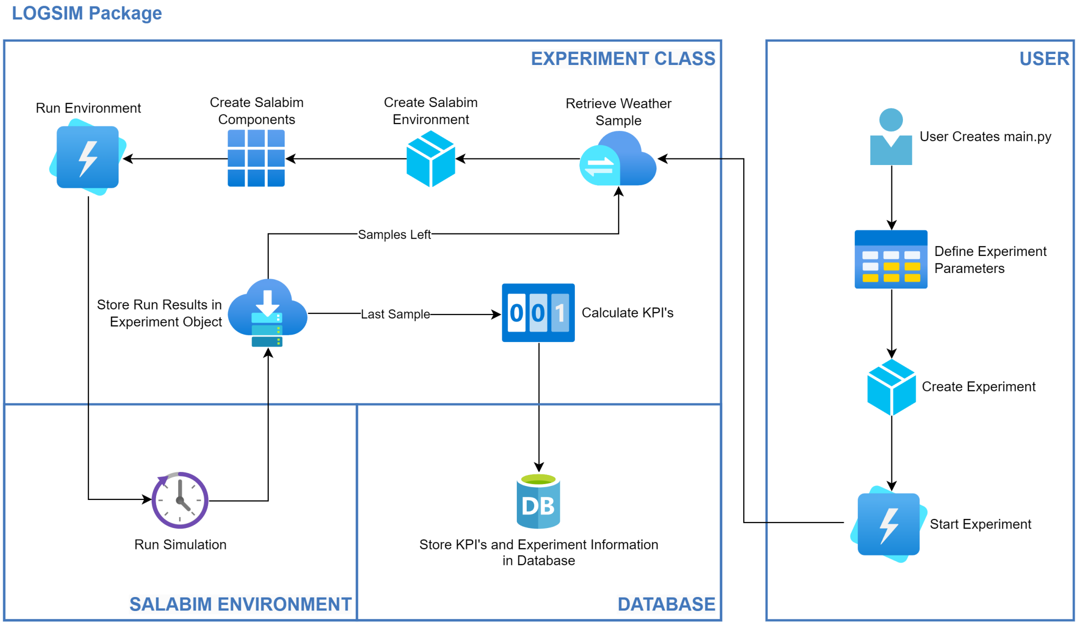

Figure B.2: Software Architecture Overview

results to a JSON file instead of a database by setting the save_json parameter to True in the logsim.classes.Experiment.run_experiment() method, although this is not recommended and can result in overwriting previous results if the method is called incorrectly.

B.2.2. Salabim Classes Module

This are overwritten salabim classes and self created classes mainly used to run the simulation and set correct parameters for the simulation. The salabim environment class is based on the sim.Environment class and is used to run the simulation. It contains the required stores and data storage for each simulation run. It also provides methods that can be used to let the simulation interact with the weather module. The Component class adds some additional monitoring functionality in order to store results correctly. The SimulationEnvironment class is used to store the current run experiment, it contains a salabim environment which is overwritten at each run (to reset all resources and the clock to 0).

B.2.3. Simulation Process Module

This module contains the process flow that is used by the simulation environment to simulate the installation and supply process. The flows contain the operational durations, random draws from distributions and the logic that is used to determine next activities. Each component is a class and contains the main process flow of that component in the process method. According to the vessel parameters and the supply chain configuration that is considered in the experiment the correct flows are called. This module also enables interaction and communication between the different components.

B.2.4. Weather Module

The weather module contains two classes, the logsim.weather.MarkovChain class and the logsim.weather.WeatherData class. The WeatherData class is designed to train, use and save a Markov model that is able to generate random weather data. The weather data class takes different setting parameters as the number of bins, the number of hours to generate and the number of samples to generate. When the weather module class is initialized, it will look into the cache to retrieve previously trained models (checks it based on the input file name). The columns name should match the following names exactly: [date_time,Hm0, Tp] in order for the WeatherData class to work properly, respectively the date time in hours, the critical wave height and the peak period. The date_time column should be in the ISO8601 format, for example: 2003-01-03T11:00. The data should be in hourly intervals. When new data is present and no models are present in the cache, the WeatherData class will train a new model and save it in the cache.

The WeatherData class uses the MarkovChain class to fit a Markov model to the data and to store the transition matrix. The MarkovChain class is also used to generate a random new state based on the current state and the corresponding probabilities stored in the transition matrix. This is done by using the logsim.weather.MarkovChain.find_next_state() method of the MarkovChain class.

B.2.5. Enumerations Module

This module contains all enumerations used in the project. This enables a structured set of options and values for the user to choose from. The module contains enumerations for the different modes that are tracked, the key performance indicators that are calculated, the tracked locations and the supply chain configurations (LogisticType). Also, custom exceptions are defined to handle errors in the simulation.

B.2.6. Distributions Module

This are implemented distributions used for sampling. The Distribution class is an abstract base class that defines the interface for all distributions and states the required methods. It is preferred that new distribution implementations inherit from this class and use the frozen distribution to store the distribution type from the scipy.stats module. These distributions are implemented manually in this module in order to provide additional functionality that enables the distributions to be stored in the database and to be used in the simulation.

B.2.7. Database Module

The database module contains the classes that are used to interact with a MongoDB database. The connection string should be saved in the environment variable LOGSIM_URI. The connection is performed with the package pymongo. The DB class is used in the other modules when data should be written to the database, like run results.

B.2.8. Utilities Module

The utilities module contains a collection of functions that are used in different parts of the project. Some basic plotting functions for the simulation results are included, as well as a function that enables synchronized animation of the simulation. The utilities module is not required for the simulation to run, but is used to generate plots or additional functionality if needed.

C
Attributions

- Document Template - TU Delft Thesis Template by Daan Zwaneveld (CC BY-NC 4.0).
- Maps used to visualize locations and calculate distances - Base map and data from OpenStreetMap and OpenStreetMap Foundation, CC-BY-SA.
- Figure 5.1a - Seaway Strashnov by Kees Torn, CC BY-SA 2.0
- Figure 5.3 - SIF as Supplier at the Maasvlakte in Rotterdam by Kees Torn, CC BY-SA 2.0