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Simulation Model for the Installation of Semi-submersible Foundations for Floating Offshore Wind Turbines

Simulationsmodell für die Installation von Halbtauchergründungen für Offshore-Windturbinen

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Abstract: The transportation and installation phase of floating platforms plays a critical role in setting up a floating offshore wind park. The main reason being the installation strategies are not the same for all types of floating platforms as they essentially vary depending upon various factors such as the draft, assembly location and met ocean requirements. Moreover they are prone to improvements in terms of effective time and cost perspective. The main aim of this paper is to model and simulate the logistics of the installation strategies deployed for semi-submersible platforms considering a fictitious floating offshore wind farm in the North Sea consisting of 36 turbines.

1 Introduction and Problem Definition

The costs of offshore wind energy are still very high, compared to other methods of energy production. Currently the levelised cost of energy (LCOE) of offshore wind in Europe is determined to be at 129EUR/MWh in Denmark to 155EUR/MWh in Germany (Noonan et al. 2018). Kost et al. (2018) give a range from 75EUR/MWh to 138EUR/MWh for German offshore wind projects in 2018 whereas the costs of other types of energy production are in the range of 46EUR/MWh to 80EUR/MWh for lignite or 63EUR/MWh to 99EUR/MWh for black coal or 38EUR/MWh to 115EUR/MWh for photovoltaics. LCOE are the cost during the whole lifetime using discounted present value and a levelised annual energy production (Jensen et al. 2017). The willingness to invest is closely linked to the economic success and public acceptance of the projects. LCOE must be taken into account in order to establish competitiveness with other methods of power generation. As offshore wind turbines are installed further from the coast in greater water depths, floating foundations will become more important in the future (Ferreño González and Diaz-Casas 2016). Due to different processes in the production and installation of floating offshore wind turbines, there are large differences in the supply chain compared to the supply chain of fixed offshore wind turbines which affect the share and amount of logistics costs. For floating offshore wind turbines, a study by The Carbon Trust came to the conclusion that improving the installation processes has the second highest potential in terms of cost reduction of the considered influencing factors (James and Ross 2015). This paper aims to provide a way to lower the installation costs by using an agent-based simulation model using AnyLogic.

The structure of a supply chain for floating offshore wind turbines differs from the supply chain for fixed offshore wind turbines. The possibility to carry out more steps of the installation on land (in the port / in the shipyard) results in further cost reduction potentials and the dependency on the weather is lower. The possibility of portside major repairs is an advantage too. The processes in the supply chain for floating offshore wind turbines are complex, interdependent and characterised by stochastic influences. Tests on a real system are not possible as these would be too costly and there are not enough installed projects at this time.

The installation of the semi-submersible platform in deep water is restricted to certain wind speed and wave height ranges. The delays incurred due to these restrictions cause a considerable impact on the project timelines resulting in unforeseen costs. Therefore managing the logistics operation such that the turbines and vessels are in the right place at the right time is a major challenge. With the development of a simulation model the processes are analysed to evaluate the weather dependency. This provides the possibility of improving the efficiency of the planning of logistic operations leading to optimisation of the available weather window. This paper aims to evaluate the weather dependency and costs associated with respective offshore operations.

2 State of the Art

The following section provides an insight into the floating platform technology and the installation processes. It also addresses the current state of research and provides the reasoning for using agent-based simulation.

2.1 Floating Offshore Wind Turbines

There are three different types of floating offshore wind systems: spar-buoy, tension leg platform (TLP) and semi-submersible systems (Pérez-Collazo et al. 2015). The systems are characterised by different techniques regarding the way they are stabilised in the water. The spar-buoy is ballast stabilised, the TLP is moorings stabilised and the semi-submersible is buoyance stabilised (Henderson, Collu and Masciola 2016). In the following paragraph only the semi-submersible system will be explained in more detail. This type of floating offshore systems floats semi-submerged in the water and is anchored to the seabed with catenary mooring lines and the structure is stabilised by the distributed buoyance. Advantages of this system are that they can be used in shallow waters (>40 meters) and that no specialised vessels have to be used. Standard tugboats are sufficient for the transport. Another advantage is the assembly of the turbines onshore and that major repairs can be done in port by transporting the semi-submersibles back to port. The disadvantages are the following: The semi-submersible structure needs a high volume to provide the needed stability and buoyance. Additionally a great amount of welding joints complicates the production and thus extends production time. Because of the high mass of the structures there is a tendency for wave-induced motions (Castro-Santos 2016; Cruz and Atcheson 2016).

2.2 Transport and Installation

The following gives an overview over the transport and installation process for a semi-submersible floating offshore wind structure. This process is based on the installation process of the WindFloat project (a prototype semi-sub turbine) installed off the coast of Portugal. Parallel to the production of the main components, the pre-lay of the mooring was done by an anchor handling and tug supply vessel (AHTSV) (Cruz and Atcheson, 2016). Then the columns were pre-assembled outside the dock and later moved to the dry dock for assembling. The commissioned turbine was towed to the final location by the AHTSV and hooked up to the mooring system (Edp, 2015). This process is represented in Figure 1.

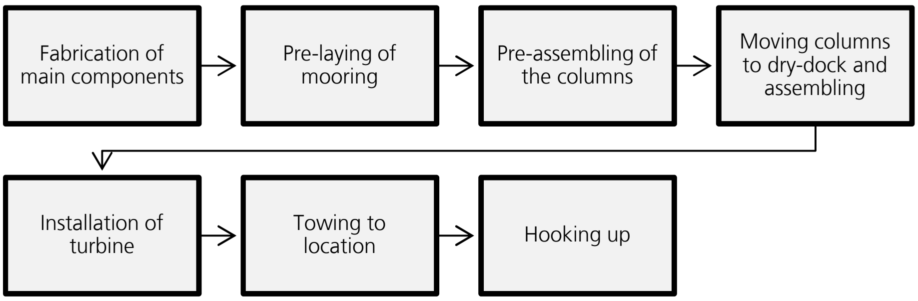

Figure 1: *Transport and Installation of Windfloat, see Edp (2015)*

2.3 State of Research for the Simulation of Offshore Wind Logistics

Previous research has focused on the operation and maintenance phase using a discrete-event simulation model for the simulation of offshore wind logistics (Münsterberg 2017) and on risk management for the installation of fixed foundation structures of offshore wind energy farms using an event-oriented simulation model (Gabriel 2007). Oelker et al. (2017) did a multi agent-based discrete-event simulation for maintenance processes of offshore windfarms. Fraunhofer IFF and ISL (2010) have examined the supply chain of an offshore wind farm with fixed foundations within the framework of a research project. Ait-Alla et al. (2013) did a mathematical simulation model on the installation of fixed offshore wind turbines. Quandt et al. (2017) did a paper on information sharing on the offshore wind park installation process using a mathematical simulation model.

2.4 Research Gap

The research gap for this paper is thus the agent-based simulation of logistics processes for the transport and installation of floating offshore wind parks. None of the above mentioned models deal with the simulation of a floating offshore wind installation supply chain using an agent-based model. To the knowledge of the authors there is currently not a published model for transport and installation of floating offshore windfarms using an agent-based simulation in AnyLogic. Agent-based simulation was used for this paper because of the properties described by Espinasse et al. (2000): an agent can represent one entity of the supply chain, agents are autonomous (agents can be added / removed without interference in the model and without restructuring the whole model), and agents are solving problems by collaboration and thus show the behaviour of real supply chains. These properties make agent-based simulation very useful in explaining processes of supply chains for floating offshore wind turbines since these processes are complex, interdependent and characterised by stochastic influences. Furthermore tests on a real system are not possible as these would be too costly and there are not yet enough installed floating offshore projects.

3 Simulation Framework

In this paper the floating offshore wind farm consists of 36 wind turbines. The capacity of the farm results in a total of 180MW for the given turbine size of 5MW each. The farm is located at 58.404°N, 0.733°W, which is at a distance of 200km from the shoreline with a water depth of 200m. Parameters such as significant wave height, wind speed and water depth range required for the installation of a semi-submersible platform are taken into account. Furthermore taking into consideration the distance to the shore and port facilities such as dry dock and quay side depth, the port of Nigg in Scotland is selected as the base port for the offshore operations. The wind farm is set up in a square formation (6x6) with 1km distance between each turbine.

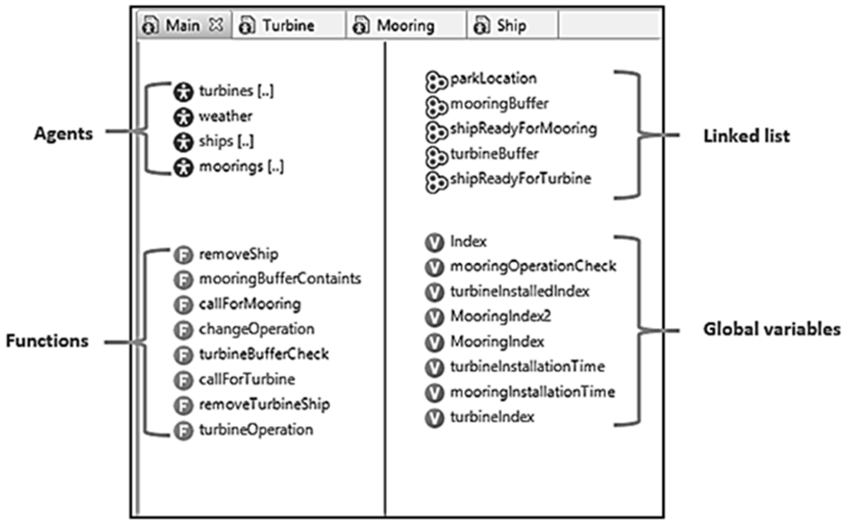

Figure 2: *Overview of the agents and objects created in AnyLogic*

3.1 Model Development

AnyLogic is used to model the actors and their functionalities into respective agents and statecharts. This section describes the development of the agent-based simulation model for the installation of the semi-submersible platform. The entities which have an effect on the simulation environment are clustered and assigned to agents. These include the semi-submersible turbine, ships, weather and mooring systems. These agents are made to interact with each other by developing a statechart as described in the following sections. The overview of the agents, their interactive functions, variables and objects created for this simulation model are displayed in Figure 2.

3.1.1 Mooring Agent

The mooring agent represents the catenary mooring system used for the installation of a semi-submersible platform. The population of this agent is considered as 36, same as the number of turbines to be installed. The mooring agent starts with its location at the storage area of the port. When this agent receives a notification from the ship, it transits to *CraneHandling*. In this process, the *AssignMooringBuffer* function is called. This function is used for loading of the mooring system onto the ship by an onshore crane. After loading the agent waits for transit. The statechart of this agent is described in Figure 3.

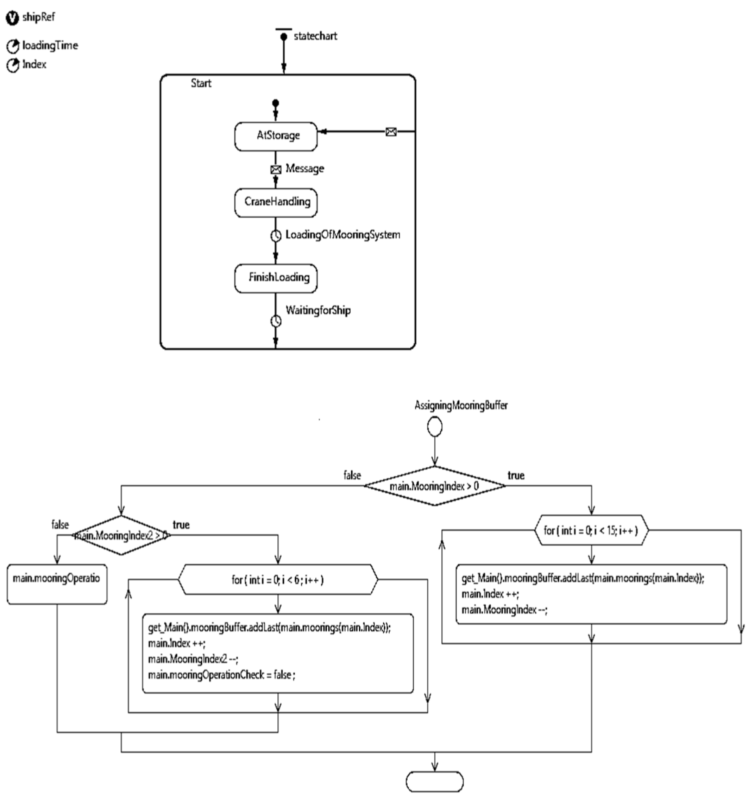

Figure 3: *Anylogic statechart for mooring agent*

3.1.2 Ship Agent

The ship agent represents the anchor handling tug supply (AHTS) vessel, which is used for the installation of the mooring system and the 36 turbines. The population of this agent is 1, as the same AHTS is responsible for mooring and turbine installation. The statechart of this agent is described in Figure 4.

After loading of the mooring agent, the vessel transports the systems to the installation site by checking the sea state conditions. At the location, the AHTS waits for suitable weather conditions for the installation. Installation starts with the lowering of mooring lines onto the seabed. The vessel ensures that the anchor lands correctly and is embedded in the seabed. The mooring lines fastened to the anchors are hooked up to the floating buoys. This process is repeated until all the remaining anchors are installed. Once the installation is complete it checks for weather conditions suitable for transport and continues with installation of remaining mooring systems on board (Vryhof 2015).

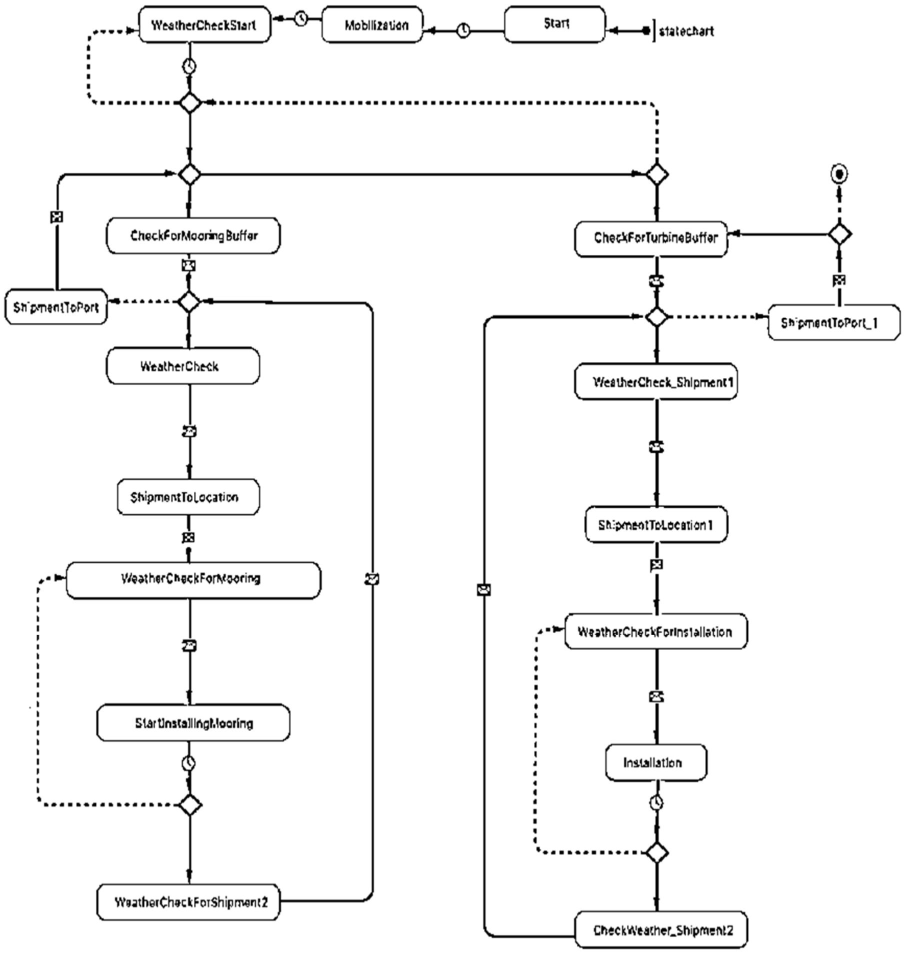

Figure 4: *Anylogic statechart of AHTS for installation of semi-submersible platform*

For low draft platforms such as the semi-submersible the following installation strategy is deployed as described in the statechart presented in Figure 4. The process begins with the ship agent checking for the availability of the turbine agent. In the presence of the later, the turbine and rotor nacelle assembly are fully mounted on the platform located at the dry dock of the port. The floating platform is hooked to the AHTS vessel, which is then floated out. After launching, ballasting is carried out by the crane vessel. Until this process is completed, the agent remains in the *CheckForTurbines* state. In *WeatherCheck_Shipment* state, the agent checks for suitable sea state condition for transportation. In suitable sea state, the agent transits to *ShipmentToLocation1* state where the floating platform is towed to the open sea at the identified location and the platform is positioned by the AHTS. With suitable weather condition for installation the agent then transits in *Installation* state where the AHTS pulls in the mooring lines and hooks it to the platform. After hooking the tension in the mooring lines is adjusted for stabilisation. These are then locked with chain stoppers. The agent checks the state of the sea regularly with attaching mooring lines to the platform. At suitable weather conditions for the shipment, the agent transits to *ShipmentToPort_1* state where the AHTS sails back to the port to install the remaining semi-submersible platforms.

3.1.3 Weather Agent

The weather agent simulates the average daily weather at the windfarm location. There is no population and location allocated for this agent. Table 1 describes the weather-related limits for the respective processes associated with turbine installation (James and Ross 2015).

Table 1: *Weather-related limits for transportation and installation*

Equipment/Platforms	Significant wave height limits [m]	
	Transportation	Installation
Mooring Systems	4	2.5
Semi-Submersible platform	2	2

3.1.4 Turbine Agent

The turbine agent represents the respective semi-submersible platform, and the assembled turbine tower and rotor nacelle assembly. The population of this agent is 36, mirroring the size of the proposed wind farm. They are located at storage area of the port.

3.2 Validation and Verification

Verification of the model is carried out by recording and analysing the process runtimes for the installation of a single turbine. The developed model is validated by comparing the installation time of the model with the time defined in literature. The validation result of the model is shown in Table 2. It can be seen that there exists a difference of 1 hour and 0.08 million EUR. However, this difference lies under the error range specified in the literature (James and Ross 2015).

Table 2: *Validation of the developed model*

Source	Installation [hours]	Cost [mEUR]
Model	21	1.63 mEUR
Literature	22	1.71 mEUR

4 Results

The results are obtained by running the simulation until all turbines are installed and the agents are back at their initial location. The cost and time breakdown for transportation and installation of a single semi-submersible platform is shown in Figure 5. The weather delay signifies the delay incurred due to weather restrictions during transportation, mooring installation and platform installation. The resulting delay for all the processes adds up to 6.45 days and the cost incurred due to weather down time amounts to 710,643EUR. Transportation involves shipment between the port and the wind farm location for mooring and turbine installation. Time and costs associated with this process amounts to 1.33 days and 158,000EUR respectively. The mooring process involves installation of anchors and mooring lines, and results in 1.34 days and 120,474EUR. Installation involves hooking of mooring lines, which results in a duration of 0.75 days and costs 93,031EUR. Miscellaneous processes involve ballasting and loading of mooring equipment and the turbine. This amounts to a duration of 1.88 days and costs estimate to 543,399EUR.

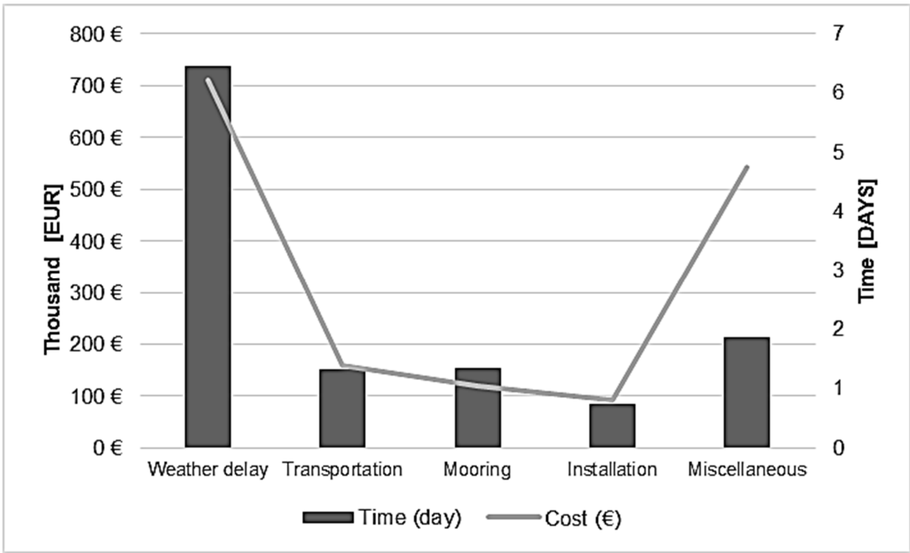

Figure 5: *Cost and time analysis of transportation and installation of semisubmersible platform*

Capital expenditure (CAPEX) represents the initial investment costs which are taken into consideration only once during the lifetime of the project. These costs include the turbine cost, platform manufacturing costs, costs for anchors and the total costs incurred during transportation and installation. After analysis, the total CAPEX value is evaluated to be 16,361,557EUR.

5 Conclusion

The installation phase of the offshore wind farm is considerably complex in planning and execution. It is highly dependent on weather and constraints imposed by oversized components during transportation and installation. Additionally due to the underestimation of weather dependency of time windows suitable for installation many wind power projects were considerably delayed. Hence, the motivation to develop a tool to analyse the logistical approaches for installation of floating offshore wind turbines was identified. It is observed that the semi-submersible platform has a prominent structure with the highest production cost. This is mainly due to its active ballast concept. However due to its minimal water depth allowance it can be deployed in relatively shallow waters ranging from 40 to 280 meters. Furthermore, the feasibility of onshore assembly for the semi-submersible concept due to its structure makes it less dependent from the use of crane and supply vessels. Hence, this results in lower installation costs amounting to 1.62 millionEUR. Additionally the CAPEX cost for the semi-submersible platform concept amounts to 3.31millionEUR/MW. This is mostly due to the costs associated with the production of the platform. However it is anticipated that the mass production of these platforms can have a major impact on the reduction of the CAPEX.

Summarising all of the above, the model developed for the floating platform meets the requirements it has been designed for and can be used to evaluate the cost required for transportation and installation at different locations.

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