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DISCRETE EVENTS SIMULATION OF A MANUFACTURING LINE FOR FLOATING WIND TURBINES

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ABSTRACT

This paper presents the simulation model developed for designing and optimizing a mass manufacturing plant of floating offshore wind units. The floating wind technology used for the analysis is CROWN FW®, a competitive solution made of concrete and steel deck. To respond to the huge demand of the industry, mass production is necessary and the optimization of the construction sites and the logistic procedures highly valuable. The manufacturing line involves three workstations that produce floaters, two turbine assembly workstations and in land workstations for preassemblies. The simulation model has been implemented in Flexsim. The model has been parameterized to allow testing different procurement scenarios, task durations and planning of a 50 units program. It includes the effect of meteorological conditions like the windspeed or the tides height which can cause interruptions of some workstations. The results obtained in a first optimization run are discussed.

1 INTRODUCTION

Offshore wind is generally regarded as one of the key renewable energy sources that will contribute to decarbonize the economy. It offers benefits in terms of higher capacity units than onshore wind and more constant and reliable wind conditions. The production capacity factors that it achieves can be up to 70%, higher than onshore windfarms.

Within offshore wind, there are two alternative technologies: floating and fixed turbines. So far, fixed turbines have been the preferred option for most farms. The floating technology has not yet achieved a full technological readiness level, but it offers a great potential because it allows to install farms at depths where fixed units are not viable, therefore increasing the potential spots for energy production. However, it poses several challenges in the design and manufacturing of these units.

Portwind is a project lead by the Spanish engineering company Seaplace and funded by the Red.es program in Spain, which is part of the EU NextGeneration funding. Portwind addresses the industry challenge regarding the great demand of construction of offshore wind units for the coming years. To achieve these goals, the project focuses on the optimization of the manufacturing process and the supply chain. The project team has envisioned a manufacturing and assembly line for the mass production of floating turbines that would be installed in a port. To analyze and optimize the manufacturing and logistics involved, a digital model of the process has been developed in Flexsim and used to optimize some aspects of the supply chain.

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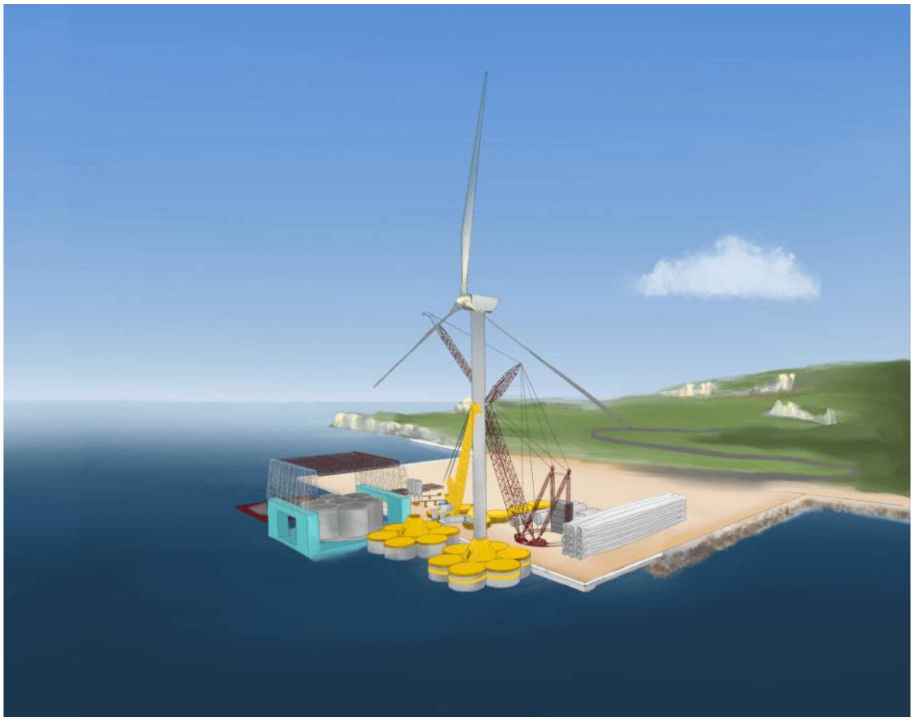

Figure 1: Proposed manufacturing line in a port.

Although this project is still in progress, this paper describes the main elements of the simulation model and the results obtained in a first optimization run. Section 2 of the paper presents some previous work done on simulation for offshore wind applications. Section 3 of the paper describes the manufacturing process. Section 4 discusses the simulation model developed, the hypothesis assumed and the validation of the model. Section 5 shows the initial results obtained in a simulation experiment aimed at understanding the capacity of the proposed manufacturing line and to ensure that the procurement process satisfies the demand requirements. Finally, section 6 discusses the conclusions drawn from this work.

2 BIBLIOGRAPHIC REVIEW

Most papers discussing the logistics and the manufacturing process of offshore windfarms (OWF) have focused on the installation phase and on fixed technologies. Rippel et al. (2019) define and identify the requirements for planning installation of OWF. In their paper, they review the literature concerning the installation of offshore windfarms and describe the main stages and tasks involved in the construction of a OWF. One of the critical aspects in planning these activities are the weather conditions, which can cause significant delays in the duration of the project. Windspeed and wave height set constraints for when to carry out activities like sailing to transport the components to the site and for the turbines' assembly. The paper does not discuss in detail the manufacturing of all the components (the support like a jacket or the turbine elements), but they are obviously pointed out as key inputs for the installation process.

Discrete events simulation (DES) is an extensively used methodology to simulate the operations for any kind of manufacturing or logistics process (Robinson 2004; Banks et al. 2010). All the processes involved in the supply chain of a OWF are subject to a high level of uncertainty in their durations (increased by the influence of the weather conditions in many activities) and feature a high level of complexity due to the need of coordinating multiple processes in parallel, supply of numerous components and transports by sea that make it one of the problems in planning best approached by discrete events simulation. We might say that it complies with all the basic rules set by Banks for when to use DES. Hence, several papers that discuss the planning and operational optimization of windfarms manufacturing and installation have adopted DES as a methodology.

Byon et al. (2011) present one of the first studies on how to develop a DES model for the operational planning and maintenance of a windfarm, although in this case it is still an onshore one. Their work shows the advantages of developing such a model in DES and they report results on how to increase the power generation through an improved maintenance policy. Other authors like Pérez et al. (2015) have also applied DES to manage maintenance resources for a windfarm. In this case, their results show cost savings in maintenance while reducing the number of turbine failures thanks to better planning.

The most extensively problem studied through DES for OWFs is the installation process. One of the first papers that we have found presenting a DES application to solve a problem related to the OWF installation is the work by Lütjen and Karimi (2012). These authors use simulation to control the inventory of components at the port from where the items are supplied to the windfarm site. Their model simulates the impact of weather conditions on the inventory levels and they develop a heuristic for coordinating the installation vessels.

Muhabie et al. (2015) developed a DES model to support planning the logistics involved in the installation of a offshore windfarm. Their model considers the windspeeds and wave heights to simulate the interruptions of the activities. The same authors further explored the impact of ocean weather conditions in (Tekle Muhabie et al. 2018). Their work points out the high risks to the time and cost of installation caused by these stochastic effects. Then Beinke et al. (2017) explored the benefits from sharing resources in the installation of multiple OWFs using a simulation approach. Their results highlighted the cost savings and reductions in makespan that could be achieved by adopting this strategy. Barlow et al. (2018) present a discrete events simulation model for the logistics and installation process for a OWF. They combine the simulation model with an optimization algorithm to obtain an installation schedule that accounts for the seasonal uncertainties in weather and oceanic conditions. Another methodology based on simulation applied to the scheduling of a OWF installation is described by Peng et al. (2020) based on Petri nets. Finally, Tjaberings et al. (2022) discuss and simulate different strategies to install OWFs using either jacket of monopile foundations.

While these papers have focused on the installation phase, other authors have explored the manufacturing of the jackets used in fixed offshore turbines via simulation. Lamas-Rodriguez et al. (2016) developed several DES models to simulate the jacket manufacturing process in a shipyard in order to minimize the flowtime per jacket, to reduce the workstations utilization and to decrease the buffer content. Then, Álvarez et al. (2018) applied DES to assess jacket manufacturing project risks. They combined the simulation with a genetic algorithm to define a strategy to mitigate the risks and to optimize the layout design. Finally, Rodríguez et al. (2021) developed a methodology based on simulation to evaluate the profitability of investing in a manufacturing process for jackets for OWFs. Their model integrates the discrete simulation of the manufacturing line adding the costs and the revenues such that each model run provides an estimate of the operational performance of the production line as well as the expected cash flows.

Floating technologies for OWFs have not been as widely studied in the literature as fixed ones. The work by Díaz and Guedes Soares (2022) describes the methodology for planning and the challenges involved in the installation of floating OWFs. Their research emphasizes the logistical complexities involved in transporting components, highlighting that the greater distance from the coast significantly complicates these operations. Smith et al. (2023) employ DES to simulate the process of installing floating OWFs. They study the assembly process of floating turbines assuming that the total workload is distributed among several ports, some of which would be specialized in the construction of the floating foundations and others in the marshalling and assembling of turbines. They illustrate this through three case studies and conclude that their methodology can guide the definition of the construction strategy in the early stages of the project.

The only work that we have identified that discusses the planning and construction of floating foundations for OWFs is the last one mentioned (Smith et al. 2023). We have not identified other works that focus on the production process for floating OWFs. Therefore, this paper presents the simulation-based methodology that we adopted to optimize the serial line for producing floating foundations as well as the turbine assembly in one single manufacturing line.

3 PROCESS DESCRIPTION

Seaplace, in cooperation with the University of A Coruña, have developed a simulation model for the construction of a 1GW windfarm that would implement the CROWN FW® technology for floating wind turbines developed by Brezo Energy. Each unit will have a power of 20MW and there will be a total of 50 units. Adopting this technology, the foundation for the turbine will be a concrete caisson that will be finished with steel lids and a transition piece (TP) where the turbine will be assembled. The construction strategy implemented in the model involves a total of 5 main workstations for producing the floaters and assembling the turbines. It also includes the inland processes that will supply preassemblies and other components to the manufacturing line. This mass production approach aims to reduce the overall time required for manufacturing and assembly, optimize resource utilization, and minimize production costs.

3.1 The Manufacturing Line

The 5 workstations of the manufacturing line are divided in two parts: the floaters production and the turbine assembly and pre-commissioning. The steps of the floaters production line are:

- Workstation 1 “Rebar”. In this first workstation the rebar for the slab (the bottom side of the floater) is assembled.
- Workstation 2 “Caisson”. The caisson is extruded in a floating dock. All the concreting activities are performed in this workstation, as well as the wall rebar and other activities. Once the caisson is ready, the dock is immersed. To launch the dock, the tide height needs to be checked to ensure that there is enough depth.
- Workstation 3 “Floater assembly”. The floater foundation is finished in this step. The main activities carried out in this workstation are the assembly of the lids and the transition piece. It requires a crawler crane to lift and hold the elements for assembly.

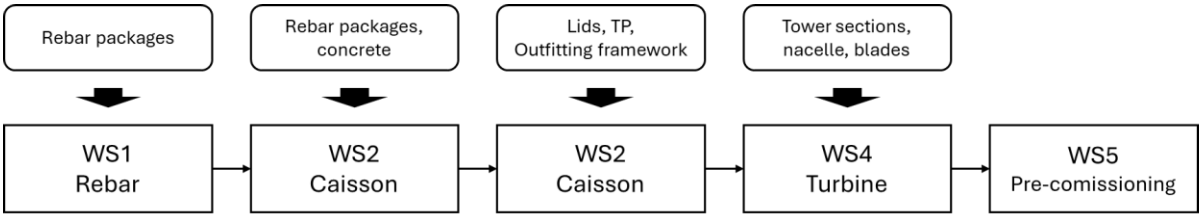

Figure 2: Process diagram of the workstations.

Then, the workstations in charge of the turbine assembly are:

- Workstation 4 “Turbine assembly”. In this workstation a ring crane would assemble the tower on top of the transition piece, the nacelle and the blades.
- Workstation 5 “Pre-comissioning”. The last workstation is responsible for the pre-commissioning activities.

Some preassembly works will also be carried out in the same port, but in onshore workstations. These workstations will assemble some outfitting elements, will prepare the rebar packages and will join pairs of tower sections before the assembly on the floater.

Both the crawler crane and the ring crane in the workstations 3 and 4 can only operate if the windspeed does not exceed a maximum value.

3.2 Procurement

Seven main types of components will be sourced from external manufacturers: the transition piece, lids (regular, mooring, and triangular), tower sections, nacelle, and blades. These suppliers are likely to be situated at or near other ports, necessitating maritime transport. Procuring these components is a critical aspect of the process, as stockouts could lead to significant delays and issues. However, storing these large elements requires substantial port space and represents a significant cost factor.

A simplified logistics model was adopted for the simulation. The components will be transported in vessels from the supplier port They will be grouped in three types of shipments. The first one will be used for lids and transition pieces. The second type of transport will be used for turbine sections. The third type will be used for the blades and the nacelles. The vessels operate in a loop in which they follow the next steps:

1. The departure from the supplier port. There is a delay for loading the components on the vessel (the load time).
2. Then the vessel travels to the port where the floaters will be manufactured. To unload the cargo two conditions must be met:
   (a) The berthing area should have available space for the ship.
   (b) The buffers of components must have enough capacity to store all the unloaded cargo. If this the buffer is full, a simulation model generates a delay until some space becomes free.
3. The components carried in the vessel are unloaded by means of two crawler cranes.
4. After finishing unloading the vessel returns to the supplier port to load more components.

4 THE SIMULATION MODEL

The simulation model for this system was implemented in Flexsim. The simulation model required to develop a set of customized workstations, the process flows that simulate the procurement process, the internal transport systems at the port, customized kinematics for the cranes and interruptions caused by wind conditions, the tide height, and the work shifts. 3D models for all the main assets (like the floating dock, the cranes or the components of the floating turbine) were designed by the team and simplified to

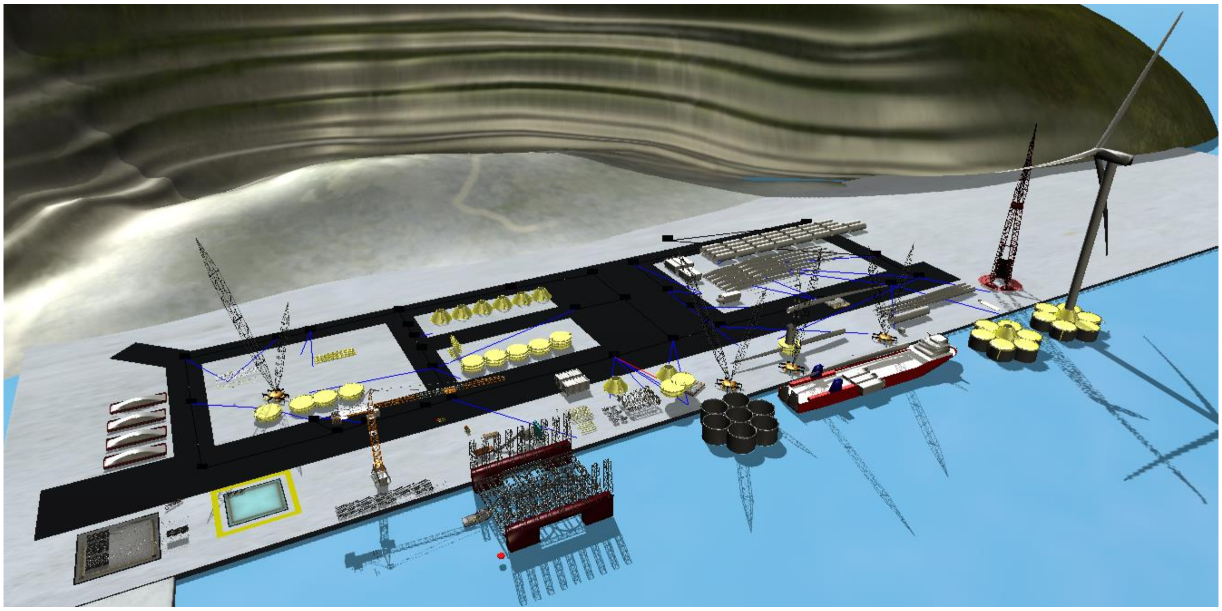

Figure 3: 3D view of the simulation model with the manufacturing line, the berthing dock and the storage areas.

show a good visual while limiting the number of polygons to prevent lags in the 3D visualization. Once built, the model was demonstrated in various events using virtual reality googles.

4.1 3D Model

As with any other Flexsim model, the 3D world of the model is where the layout and the 3D shapes of all the resources are defined. This model features a 3D landscape and port facilities as a background, along with a blue plane representing the sea. It includes customized fixed resources for the workstations, task executors corresponding to cranes and other transport means, and buffers for temporary storage of supplies and floaters between workstations 2-3 and 3-4.

Due to the significantly lower cycle times of workstations 4 and 5 compared to workstations 1-3, and the high cost of the ring crane, the decision was made to initially keep workstations 4 and 5 inactive. Floaters will be stored in a temporary buffer in the port, referred to as "wet storage." Workstations 4 and 5 will be activated at a strategic point to ensure timely turbine assembly, project completion, and optimized resource utilization.

4.2 Workstations

We developed a set of customized workstations using Flexsim's object process flows. The logic implemented at each workstation was as follows:

- Upon the arrival of a unit at the workstation, tasks are executed in the required sequence. Some tasks are performed in parallel, while others follow a fixed order. Each activity is represented by a "Delay" object, with its duration determined by an object label indicating the task's duration in hours.
- Before the "Delay" of each activity the workers needed are acquired as process flow resources.
- In the case of assembly operations, the required component is demanded and transported from the previous buffer where these units will wait for assembly. The assembled components, once received, are placed and rotated to appear visually where they should be.
- Interruptions from wind, tide conditions and workshifts are also managed in the workstations using Flexsim's preemption.

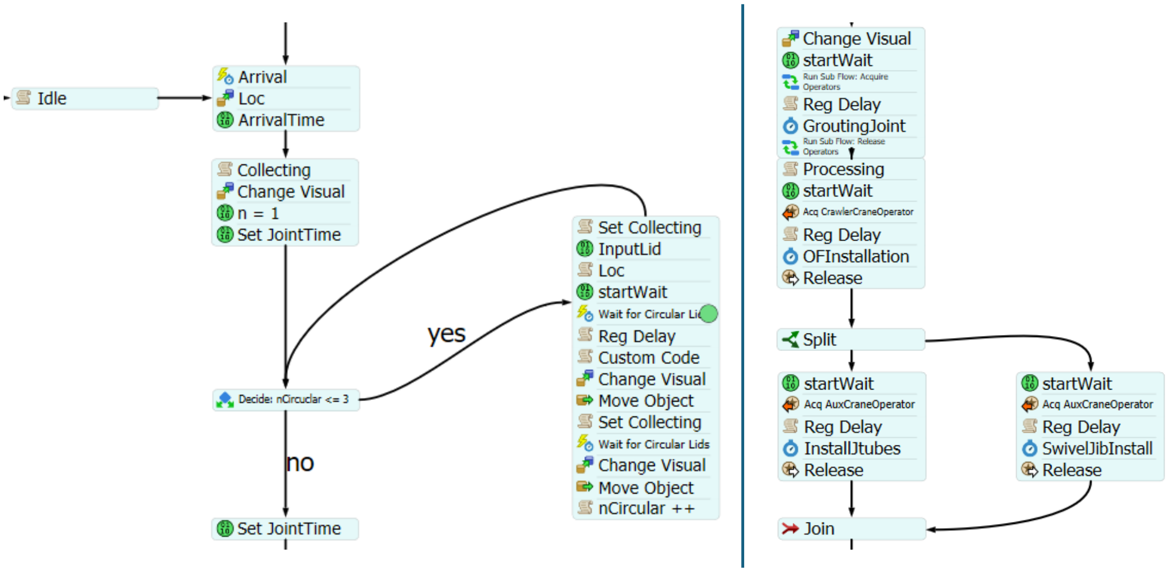

Figure 4: Screenshot of the process flow for workstation 3 where we can see an example of the collection of the lids components on the left and some tasks in parallel on the right (installation of outfitting components).

4.3 Procurement and Resources

To simulate the procurement process we developed a general process flow that generates the arrivals of components to the berthing dock as explained in section 3.2. The vessels that carry the cargo are only displayed during the unload activity as a sort of decoration, but the duration of the trip, the operations at the supplier port and a random delay to account for possible delays during the voyage by sea are simulated as steps of the process flow without a 3D representation.

The workforce resources are also not simulated using the 3D Flexsim operators but by numeric resources in a process flow which are then acquired by each process.

4.4 Wind and Tide Interruptions

To generate wind and tide interruptions, both are defined as tracked variables in Flexsim and updated within a general process flow. Tide conditions are set according to the calendar, while wind speed is generated from historical records obtained from local weather stations, with simulations of wind speed variations conducted in hourly steps. At workstations 3 and 4, interruptions occur if the wind speed exceeds the set limit, with work resuming once the wind speed drops below this threshold. Additionally, the shift status is checked because the workstation may be off-shift by the time the wind speed decreases, delaying work until the next shift. Tide-related delays are managed by a custom script that calculates the remaining time until the next permissible window for immersing the caisson.

4.5 Verification and Validation

Since this project is still in the engineering phase and there is no actual implementation of this concept, we could not make a formal validation with real data. Instead, once we had a working model, we made multiple experiments to check the results from the model and to discuss them with the team project members. To better understand the total duration of the project in the simulation, several KPIs were obtained. One result that was very important to validate the model was a table of "delays" that occur at each workstation that was filled by adding a script each time that a delay may happen in the model (like acquiring a worker or waiting for a component arrival) and registering the duration of the delay and the cause. We could therefore understand if the delay made sense in a real situation. After several attempts, the team came to a consensus that the simulation model was valid for the experimentation phase.

5 FIRST OPTIMIZATION RUN

The Portwind project is still ongoing when writing this paper. This section describes the simulation experiments conducted so far aimed at ensuring that the 50 units program could be finished in time.

5.1 Parameters

The simulation model is fully parameterized and all the relevant parameters for each workstation or any other resource can be defined in two parameters tables: one table for the resource parameters and one for the procurement process. The main variables include:

- The task duration for each task carried out in the workstations.
- The crane speeds for each degree of freedom.
- The tugboat and the SPMTs speeds.
- Number of workers of each type.
- Capacity of the component storage buffers.
- The parameters for the procurement process:
  - Load time.
  - Travel distance.
  - Vessel average speed.
  - Unload time.

- Random delay.
- Number of vessels.
- Number of unloading positions in the dock.

5.2 KPIs

Although the model collects many statistics during the execution, the main ones used to analyze the results and make decisions where:

- The total duration of the project (makespan).
- Utilization rate of the workstations and the cranes.
- Content of the storage buffers, particularly the wet storage.
- The staytimes in each workstation.
- The dock utilization.
- The number and duration of the delays at each workstation.

In this paper we are only presenting the results concerning the variations in makespan, because they are the most critical ones.

5.3 Scenarios

An initial scenario was defined for the unload time of the vessels, the number of vessels, the number of positions for unloading in the dock and the capacity of the component buffers. Since in the base scenario the total duration exceeded the goal, a new set of experiments was designed to adjust these parameters to meet the goals. In the first experiment we explored different conditions for the procurement process:

- The unload time was reduced from in steps of 1 day.
- 1 or 2 unload positions were tested.
- The number of vessels was increased by up to 2 vessels.

In the second experiment we tested increases in the storage capacity for turbine units.

- The unload time tested was reduced in steps of 1.
- The capacity of the buffers increased by 3 and 6 units.

In the third and last experiment in this run, we tested reductions in the storage capacity for lids and transition pieces. The goal was to compensate the increase in cost that the additional storage capacity for turbines would cause.

- The unload time tested was reduced in steps of 1.
- The capacity of the buffers was reduced in steps of 1 for the lids and the TPs.

5.4 Simulation Results

This first table shows the reduction in the total project duration in the first experiment.

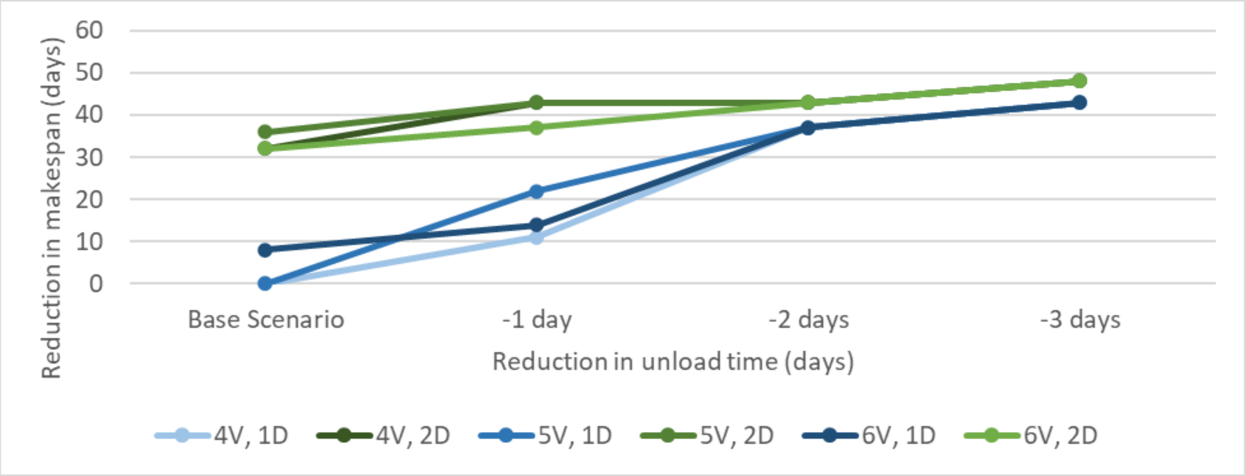

Figure 5: Results from the first experiment. Reduction in the makespan for different reductions in the unload time and for each scenario of number of vessels (V) and dock unload positions (D)

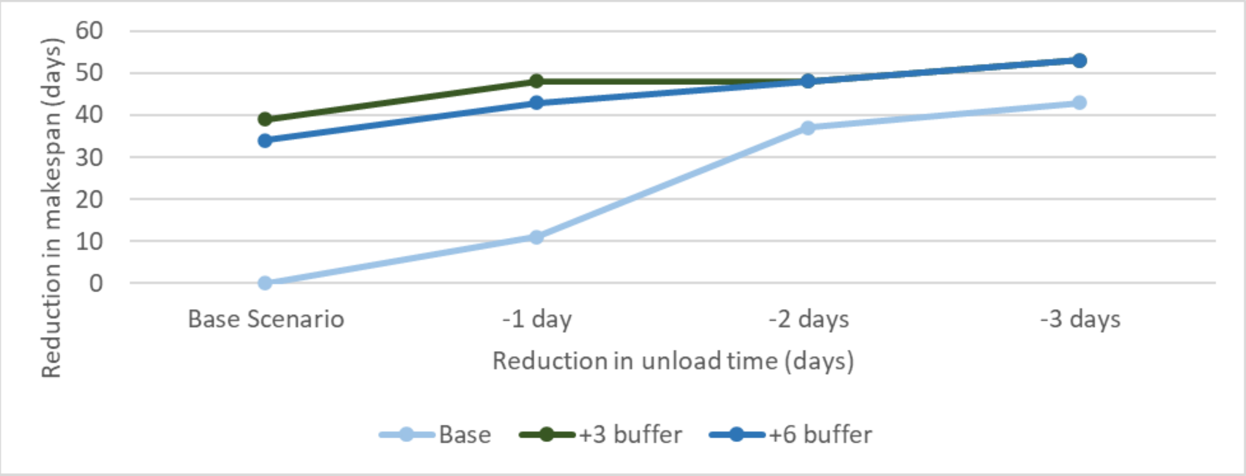

Figure 6: Results from the second experiment. Reduction in the makespan for different reductions in the unload time and for each scenario of turbines buffer capacity.

Figures 5 and 6 show the reduction in days in the duration of the project achieved modifying these parameters The most significant reduction is observed when the turbine buffer capacity is increased in the second experiment. Unload time is also a critical factor; ideally, components should be unloaded three days faster than the base scenario. However, even if this is not feasible, ensuring a capacity for at least three additional units could reduce the project duration by approximately 40 days. The number of vessels did not significantly impact the project duration. Although having two unloading docks would be beneficial, it would increase costs due to the need for additional cranes and port space. The potential gains from this setup can be realized more cost-effectively by simply increasing buffer capacity.

In the third experiment, we tested if the capacity in lids and TPs storage could affect the delivery date. These parameters, however, had a negligible impact on the total duration (Figure 7). Therefore, we could

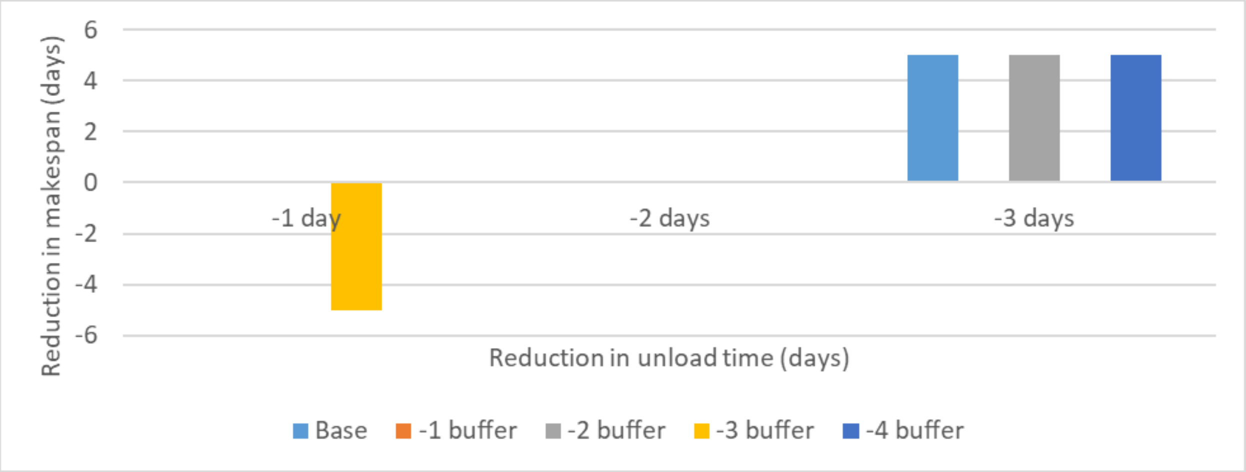

Figure 7: Results from the third experiment. Reduction in the makespan for different reductions in the unload time and for each scenario of lids buffer capacity.

say that the increase in storage area for turbines can be compensated by reducing the storage area for lids and TPs.

6 CONCLUSIONS

A discrete events simulation model of an innovative manufacturing process for floating offshore wind turbines has been presented and used to optimize the procurement process and the buffer capacity in a first experimentation run. The model has shown to be useful for understanding better the behavior and the performance of the proposed manufacturing process. While the project is ongoing, discrete event simulation has already facilitated improved planning of component shipments and storage areas, resulting in significant reductions in the expected project duration. Initial simulation outcomes indicate a need to increase buffer capacity for turbine components, while reducing capacity for lids. Also, the simulation results showed a big impact from reducing the unload time of the vessels but were insensitive to an increase in the number of vessels. More experiments to further optimize the production line will be carried out in the future.

The simulation model has improved the design of the proposed manufacturing process for the CROWN FN® units. This, in turn, may lead to a commercially viable solution that will contribute to the development and installation of floating offshore windfarms.

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