SIMULATION-BASED SCHEDULING FOR OFFSHORE WIND FARM INSTALLATION USING TIMED PETRI NETS APPROACH

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ABSTRACT

Despite the success in developments of wind energy technology, there remain challenges, for example, in offshore wind energy installation. Due to changeable and unstable offshore weather conditions, it is hard to effectively schedule the installation logistics. In this work, we propose a simulation-based scheduling strategy to help the operators and the project managers, to make the main decisions during the installation to increase efficiency, e.g. how many offshore wind turbines should be loaded onto the installation vessel. The offshore logistic concept is modeled using timed Petri nets (TPN) approach. The timed transitions in the TPN model are assigned with operation times estimated by means of discrete-time Markov chain (DTMC) approach, which uses historical weather data. Besides, *operability* is introduced in this work as an indicator to evaluate schedules of a certain time period.

Keywords: offshore wind installation, data-driven scheduling, discrete-time Markov chain, Timed Petri nets

1 INTRODUCTION

Environmental problems have deteriorated due to the utilisation of non-renewable energy sources, such as diesel. The growing awareness, that those non-renewable energy sources should be replaced by renewable ones, has become the motivation for researches of renewable energy. In the recent decade, wind power has been investigated and developed rapidly owing to the global requirements of clean and renewable energy sources. It has contributed a large percentage of the electrical power worldwide and, undeniably, the requirement of wind energy is still growing. Since 2011, Germany's federal government has been working on a new plan for increasing renewable energy commercialisation, with an aim of 100% renewable electricity supply by 2050 (BMUB (2016)). In 2018, wind energy has represented again the second largest share of German

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electricity production according to BWE (2020). In general, up to 80 OWTs (Offshore Wind Turbines) can be installed in an OWF (Offshore Wind Farm) (Schweizer et al. (2011)). Among all the restrictions during the OWF installation, e.g. lack of supplies, manpower and etc., the severest one is given by the weather condition in the location of planned OWF, since the OWF are meant to be built in regions that have as much profitable wind resources as possible. However, this fact also leads to poor reachability of the OWF. Thus, effective OWF installation scheduling is necessary. This can not only reduce the cost in the wind energy installation phase but also decrease the risk during the process, for example component damages. Besides, this will ensure the electricity production of the OWF as early as possible. Thereby, we propose a simulation-based strategy to help operators to make the main decisions during the offshore installation process. While various models have been invented and investigated for offshore operation and maintenance, the effort made in the offshore installation is relative low. However, the models considering the operation and maintenance of offshore wind farms are based on the same common strategy: discrete-event simulation (DES), which fundamentally models the operation of a real system under consideration of reasonable system assumptions. Thereby, in this work, a timed Petri nets approach is applied to model the offshore logistic process. In order to deal with weather disturbances, we adopt the strategy proposed in Rippel et al. (2019), in which operation times are estimated using discrete-time Markov chain(DTMC) under the consideration of historical weather data from German North Sea from 1958 to 2007.

2 OFFSHORE INSTALLATION PROCESS

The offshore installation process has been investigated and summarised in various literature, such as Ait-Alla et al. (2013), Vis and Ursavas (2016). Herein, the offshore installation logistics is briefly introduced in subsection 2.1. The states of the systems are discussed in subsection 2.2. Besides, the main decisions mentioned before are elaborated in subsection 2.3. The weather restrictions are given in subsection 2.4 at the end of this section.

2.1 Logistics

In the literature, several logistic concepts exist for the offshore wind farm installation (Scholz-Reiter et al. 2010, Muhabie et al. 2015, Ait-Alla et al. 2017). Nonetheless, the conventional concept is the strategy widely used in the OWF installation. Basically, it means that the installation vessel possesses two functions: transportation and installation. According to the literature, the installation vessel can be loaded with a maximal number of components for four OWTs. The load operation is performed in the base port, in which wind turbine components are stored. After receiving a signal of permission, the loaded installation vessel sails from the base port to the construction site, i.e., the designed OWF. The construction of an OWT starts if the ensemble offshore weather condition is stable. The construction operation is followed by two possible operations: reposition or sailing back to base port. *Reposition* means that the installation vessel sails to the next location and builds another OWT if there are enough components and weather condition is stable. Sailing back to base port means that the operator has decided to terminate the construction for the current cycle due to material insufficiency or unstable weather condition. In this work, the conventional concept is considered. The greatest advantage of this concept is the existence of the base port, which not only gives flexibility to the installation process but also provides a stable environment for the loading operations for wind turbine components. The main drawback of this concept is the cost originated by renting the base port (Rippel et al. 2019).

Indeed, other logistic concepts exist in the literature. For example, Oelker et al. (2017) have proposed the feeder ship concept to optimise the cost in offshore wind energy installation by removing the base port. The components are transported by feeder ships directly from the manufacturers to the construction site. Ait-Alla et al. (2017) have compared conventional concept and feeder ship concepts, regarding the total cost of offshore wind energy installation. The results show that the feeder ship concept slightly improves the offshore wind energy installation under the consideration of weather disturbances for project with a large number of OWTs.

2.2 States of the System

By adopting the conventional logistic concept, the offshore installation process can be summarised into the following five operations: ① Loading components onto the installation vessel; ② Sailing forward (from base port to construction site); ③ OWT construction; ④ Reposition of installation vessel; ⑤ Sailing back (from construction site to base port). Moreover, the five operations are performed in sequential order. This sequential relation between these five operations is shown graphically in Figure 1. Fundamentally, each operation can be seen as a unique state of the real system.

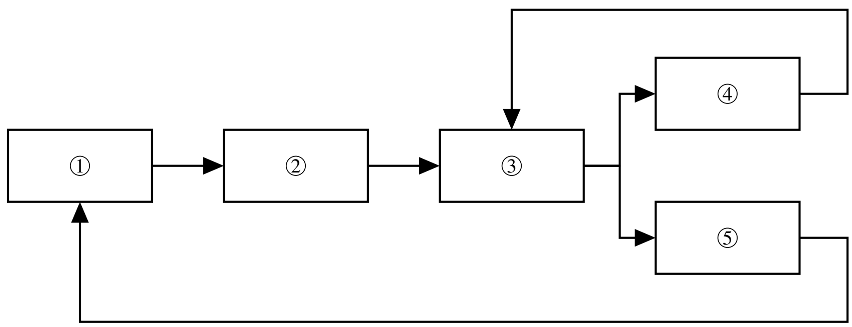


Figure 1: Offshore installation logistics: conventional concept

2.3 Decisions in Scheduling

In the process depicted in Figure 1, three different decisions have to be made. To be specific, two decisions (Decision I and Decision II) need to be made in state ① and one decision (Decision III) is made in state ③.

Decision I The first question that needs to be answered in state ① is *"How many OWTs should be loaded onto the installation vessel?"*. In other words, the operator needs to decide how many OWT components should be loaded for the following installation process. We denote the number of OWTs loaded onto the installation vessel as n_L^{OWT} and, as it has been mentioned before, it possesses with the domain $\mathscr{D}_L^{OWT} = [1,4]$. This decision is non-trivial, since the loading of one OWT costs around 12 hours, i.e., it takes at least two days to fully load an installation vessel without any delays and breaks. This could lead to waste of operable weather condition on the construction site.

Decision II The other decision needs to be made in state ① by the operator is *"When should the vessel sail forward?"*. Basically, the installation vessel needs to wait in the base port for stable weather conditions on the sea to ensure a safe installation condition.

Decision III Depending on the number of OWTs loaded on the installation vessel, there are two options after the construction operation (state ③). If zero OWT remains on the installation vessel, $n_r = 0$, then there will be only one option after the construction, which is sailing back to the base port and loading new components onto the installation vessel. If $n_r \geq 1$, then there will be two options in this case. The first choice is sailing back to base port with all the remaining components. This happens when the offshore weather is unstable for a long period of time. The other option would be repositioning the vessel and installing another OWT, if the offshore weather condition is stable.

2.4 Weather Restrictions

Fundamentally, the restrictions in the offshore installation are given by limits on weather conditions, since the offshore operations require stable weather conditions. For example, in Vis and Ursavas (2016), the authors have used the offshore wind velocity, v, as the indicator to classify the weather restrictions roughly into three levels: 1) lifting operations if $v \leq 10\text{m/s}$; 2) shipments if $v \leq 16\text{m/s}$; and 3) no actions if $v \geq 16\text{m/s}$. Ait-Alla et al. (2013) and Ait-Alla et al. (2017) have not only classified the weather conditions into more categories but also taken the significant wave height into account. A similar weather classification for operations in the offshore installation can be found in Quandt et al. (2017). Rippel et al. (2019) have summarised the weather restrictions in the literature, which is simply adopted in this work.

3 METHODOLOGY

In this section, the methodologies applied in this work are elaborated. First of all, we use timed Petri nets (TPN) approach to construct the offshore installation logistic model. Secondly, we use the discrete-time Markov chain (DTMC) to determine the weather integrated operation time based on historical weather data.

3.1 Timed Petri Nets

Petri nets and their extensions are widely used in the literature to describe systems, which are characterised as being concurrent, asynchronous, distributed, parallel, nondeterministic and/or stochastic. Fundamentals and developments of PN theory are summarised in Murata (1989). Graphically, a PN model is a bipartite graph, which possesses three different elements: places, transitions, and arcs. It is mathematically defined as a 6-tuple (Marsan et al. 2007):

$$\mathscr{P}\mathscr{N} = \{P,T,A,K,D,M_K\}\,, \tag{1}$$

where P is the set of places; T is the set of transitions with $P \cap T = \emptyset$; $A \subseteq (P \times T) \cup (P \times T)$ is the set of arcs. Specifically, A can be dived into three sub-classes: i) input arcs, I, pointing from a place to a transition; ii) output arcs, O, pointing from a transition to a place; and iii) inhibitor arcs, H, pointing from a place to a transition. An input arc formulates the firing rule for a transition, that there must be at least m tokens in the input place, where m is the multiplicity of the arc defining how many tokens should be removed from the input place once the transition fires. The inhibitor arc formulates a firing condition that the number of tokens in input place must be strictly less than the multiplicity of the arc. Besides, the firing of the transition does not remove tokens from the input place. Generally, the arcs show in which direction the thresholds are transported. K is a set of parameters; D contains the domains of parameters in K; and $M_K : P \to \mathbb{N}^+ \cup K$ is the parametric initial marking.

A state of a PN is given by marking, which reveals the number of tokens in each place element. We denote the number of tokens in place p_i as $M(p_i)$, then the state of a PN can be written formally as a vector with $|P|$ components

$$S = (M(P_1), \ldots, M(P_i), \ldots, M(P_{|P|})). \tag{2}$$

Furthermore, the dynamic evolution of a PN model is controlled by the transitions. A transition, T, is called to be enabled if and only if i) the number of tokens in each input place of T is greater equal than the given threshold, which is defined by the associating arc multiplicity; ii) the number of tokens in each inhibitor place of T is strictly less than the given threshold. When transition T fires, it removes the required threshold from the input places and add a given threshold to the output places.

Originally, the PN approach is constructed without the notion of time, which has been later on added into the PN theory as an extension. In difference to the conventional PN theory, there are two types of transitions in the timed Petri nets: immediate and timed transitions (Popova-Zeugmann 2013). An immediate transition fires immediately when it is enabled and has the highest priority. Timed transitions are assigned with time units, which define the time distances between the enabling and the firing of timed transitions.

3.2 Weather Integrated Operation Time Estimation

As it has been mentioned in subsection 2.4, the offshore operations are strongly influenced by the weather condition. Rippel et al. (2019) have proposed an approach to estimate the weather integrated operation time based on historical offshore weather data measured in German North sea. The goal of this approach is to determine the duration of an offshore installation operation, e.g. loading, sailing, etc. It considers the offshore installation as a directed graph, in which operations are represented by nodes and connected by weighted edges. This can be seen as a discrete-time Markov chain since the probability of node, n_i, reaching it adjacent node, n_{i+1}, depends only on the weather condition at time step t

$$P^t_{n_i,n_{i+1}} = P(X^{t+1} = n_{i+1} | X^t = n_i)\,. \tag{3}$$

The probabilities of each state are calculated by applying the transition matrices, $P^0,\ldots,P^n$, onto the initial state, s_0, which indicates the start of the installation. A transition matrix P^t contains entries obtained by means of (3). Besides, the ever-changing weather condition ensures this Markov chain to be timely inhomogeneous, thus $P^t \neq P^{t+1}$. A cardinality of a state, $|s|$, is equal to the number of states. The state at the time step t_i is given by

$$s_i = s_0 \cdot \prod_{k=0}^{i} P^i\,, \tag{4}$$

of which the last entry represents the probability of being at the final state at the corresponding time step. By means of weighted sum

$$d_q = \sum_{i=1}^{\infty} i \cdot (s_i(q) - s_{i-1}(q))\,, \tag{5}$$

the average duration, d_q, needed to reach the q-th state can be evaluated. It simply returns the average time needed to reach the end state if q is equal to the number of all states. Moreover, the approach considers the weather restrictions introduced in subsection 2.4 to estimate the duration of weather dependent operations.

3.3 Log Wind Profile

Since the offshore wind velocities are measured at height 10m above the sea, the *log wind profile* is used here to estimate the mean wind speed at 100m height, at which the lifting operations are performed. The mean wind speed u_z at height z meters above the ground line is defined under neutral stability as follows

$$u_z = \frac{u_*}{\kappa}\left[\ln\left(\frac{z-d}{z_0}\right)\right], \tag{6}$$

where u_* is the friction velocity with unit m/s, κ is the Von Kármán constant (~ 0.41), d is the zero plane displacement in meters, which is the height above the ground where wind speed is zero as a result of flow obstacles, z_0 is the surface roughness in meters. The rearrangement provided by Holmes (2015) makes it possible to calculate the wind speed at a height z_2 based on the measurements at height z_1

$$u(z_2) = u(z_1)\frac{\ln(\frac{z_2-d}{z_0})}{\ln(\frac{z_1-d}{z_0})}\,. \tag{7}$$

In this case, the zero plane displacement, d, is assumed to be zero, since there is no obstacle on the open sea which stops the flow. The (World Meteorological Organization 2014) has published the surface roughness, z_0, for different classes. For an open sea, $z_0 = 0.0002$m.

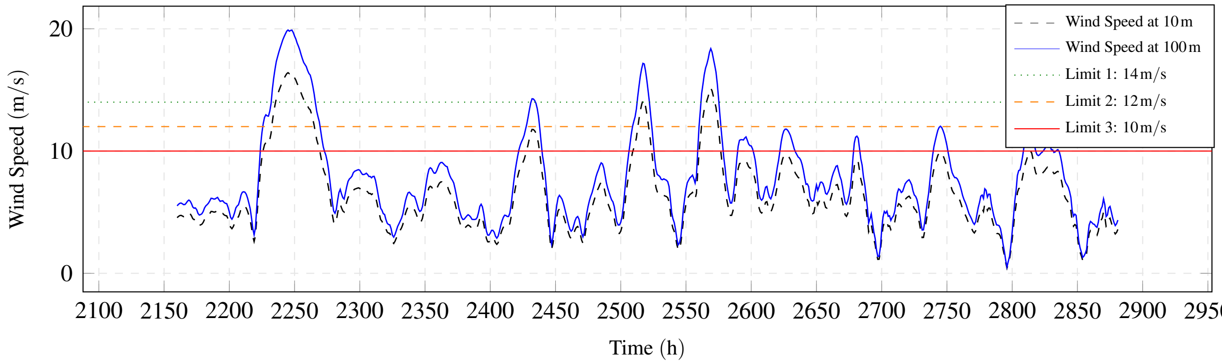
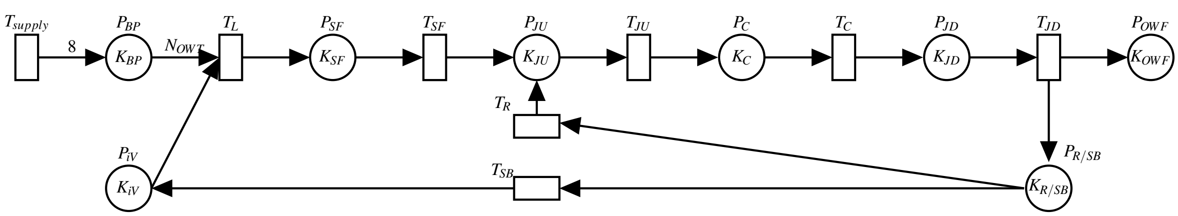


Figure 2: Wind Speed: April 1st 2000 - April 30th 2000

4 OFFSHORE INSTALLATION SCHEDULING

4.1 Model Description

The timed Petri nets (TPN) model shown in Figure 3 represents the offshore wind energy installation process described in section 2, where P, T, K are used to identify *places*, *transitions*, *parameters* respectively. The meaning of the subscripts are given in the section 2 as well.



BP: base port; **iV**: idle vessel; **SF**: sail forward; **JU**: jack-up; **C**: construction; **JD**: jack-down; **OWF**: offshore wind farm; **R**: reposition; **SB**: sail back

Figure 3: TPN Model: Offshore Logistic

The structure of the TPN model shares similarities with the offshore installation logistics depicted in Figure 1. The transitions are representing the five states of the system, while the places are either physical locations, e.g. P_{OWF} represents the offshore wind farm, or boolean conditions. Here we separate the parameters into two major groups. The first group owns parameters, which belong to the global system, such as the start point and endpoint of the process. These are summarised in Table 1. Parameters originated in the TPN model are given in Table 2.

Thus, the state of the TPN model can be given with the help of (2) as follows

$$S = \left[M(P_{BP}), M(P_{iV}), M(P_{SF}), M(P_{JU}), M(P_C), M(P_{JD}), M(P_{R/SB}), M(P_{OWF})\right]. \tag{8}$$

Since the process is linear and sequential, only one of the places $P_{iV}, P_{SF}, P_{JU} P_C, P_{JD}, P_{R/SB}$ can have non-null number of tokens in a state. Thus, the system state ① is described by the set of model states, where

Table 1: Global Parameters

Par.	Type	Domain	Description
t_{start}	integer	$[0,+\infty)$	starting point of the process
t_{span}	integer	$[0,+\infty)$	scheduling time period, $t_{end} = t_{start} + t_{span}$
Δt	integer	$[1,+\infty)$	time increment in hour
$t_{w,max}$	integer	$[0,+\infty)$	maximal waiting time between state ① and ②
N_p	integer	$[1,+\infty]$	planing size in OWTs

Table 2: TPN Model Parameters

Par.	Type	Domain	Description
K_{BP}	integer	$[0,32]$	inventory in base port
K_{iV}	boolean	$0/1$	number of idle installation vessel
K_{SF}	boolean	$0/1$	number of installation vessel ready for sailing forward
K_C	boolean	$0/1$	number of installation vessel ready for construction
$K_{R/SB}$	boolean	$0/1$	number of installation vessel ready for reposition or sailing back
K_{OWF}	integer	$[0,80]$	number of constructed OWTs
N_{OWT}	integer	$[1,4]$	multiplicity of input arc $I(P_{BP} \to T_L)$

$M(P_{iV}) = 1$. We denote

$$① = [M(P_{BP}), 1, 0, 0, 0, 0, 0, M(P_{OWF})]\,. \tag{9}$$

Analogue, we can derive the description for other system states

$$\begin{aligned} ② &= [M(P_{BP}), 0, 1, 0, 0, 0, 0, M(P_{OWF})]\,, \\ ③ &= [M(P_{BP}), 0, 0, 1, 0, 0, 0, M(P_{OWF})] \\ &\quad \wedge [M(P_{BP}), 0, 0, 0, 1, 0, 0, M(P_{OWF})] \\ &\quad \wedge [M(P_{BP}), 0, 0, 0, 0, 1, 0, M(P_{OWF})]\,, \\ ④\&⑤ &= [M(P_{BP}), 0, 0, 0, 0, 0, 1, M(P_{OWF})]\,. \end{aligned} \tag{10}$$

Indeed, system state ④ and ⑤ share the same set of model states.

4.2 Offshore Installation Scheduling

First of all, an installation circle starts with state ① and ends with state ⑤. Besides, the end of state ⑤ is literally the start of the next installation circle. In such an installation circle, the system can go through states ③ and ④ several times depending the number of OWTs loaded on the installation vessel N_{OWT}, while only once through states ①, ② and ⑤. For example, if $N_{OWT} = 3$, then the system has three alternatives: 1) construct one OWT and sail back to base port with two OWTs $(① \to ② \to ③ \to ⑤)$; 2) construct two OWTs and sail back with one OWT $(① \to ② \to ③ \to ④ \to ③ \to ⑤)$; 3) construct all the OWTs then sail back to base port $(① \to ② \to ③ \to ④ \to ③ \to ④ \to ③ \to ⑤)$. Assuming the process has just started at the global time step 0, all possible plans for zero waiting time, $t_w = 0$, between state ① and ② with a different number of loaded OWTs, N_{OWT}, are depicted in Figure 4. Even though all four setups in Figure 4 share the Plan I, but the execution of the plan is different. First of all, higher N_{OWT} value will increase the duration of state ①, which means the start of state ② will be postponed. Secondly, the weather condition may also be different when state ② begins.

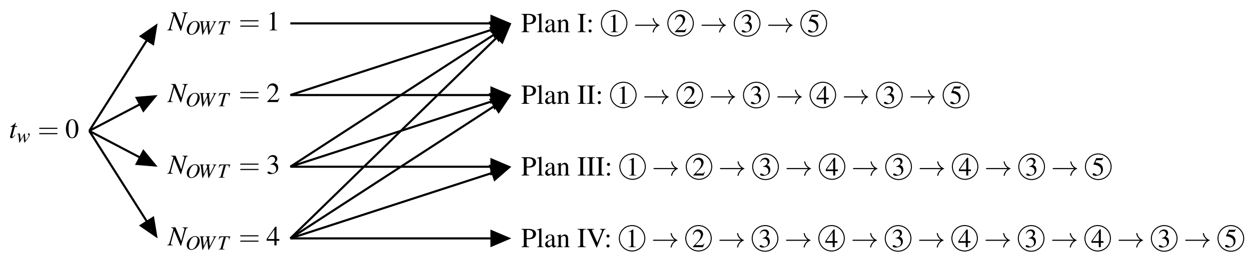


Figure 4: Plans with $t_w = 0$ and different N_{OWT}

Naturally, the decisions made in the actual installation circle have an impact on the decisions for the successive installation circle. For example, an installation vessel is loaded with 3 OWTs and the operator chooses to install only one and go back to base port due to unstable weather condition. Then it gives a restriction to the domain of N_{OWT} for the successive installation circle $\mathscr{D}^{i+1}_{N_{OWT}} = [1,2]$, since there are still two OWTs on the installation vessel. Besides, the operator can choose a different waiting time again.

4.3 Indicator

In IEC TS Standard 61400-26-1 (2010) the time-based availability is defined as follows

$$Availability = 1 - \frac{Unavailable\,Time}{Total\,Time} = 1 - \frac{Unavailable\,Time}{Available\,Time + Unavailable\,Time}. \tag{11}$$

Technically, the *availability* defined above is used to estimate the percentage of time that an OWT is generating electricity, which has been used as an indicator in investigating simulation models for operation and maintenance of the OWF (Dinwoodie et al. 2015). Following this idea, we define the *operability* of an individual offshore installation schedule as follows

$$Operability = 1 - \frac{Non\text{-}operation\,Time}{Operating\,Time + Non\text{-}operating\,Time}, \tag{12}$$

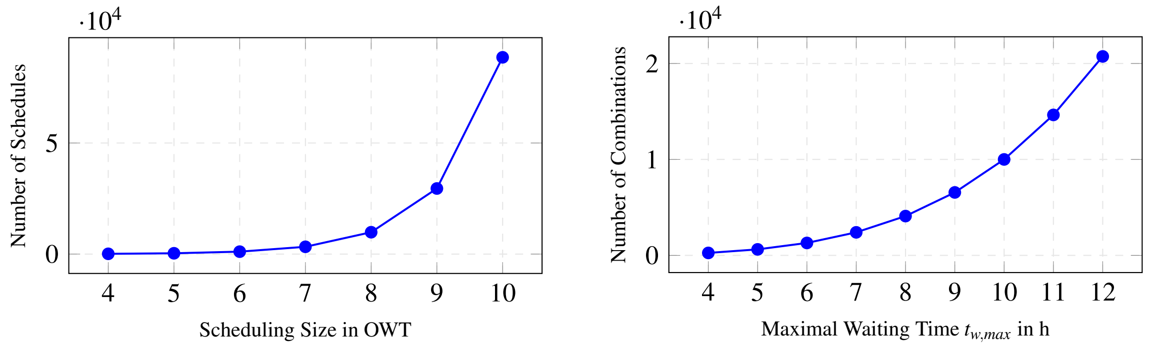
where the *non-operating time* is the difference between the *weather integrated operation time* and the *reference operation time*. For example, the reference operation time of construction is 20h, and the weather integrated operation time by means of DTMC is 30h. Then, the non-operating time, in this case, is 10h. The reference operation times are given in Table 3

Table 3: Reference Operation Time

Operation	Duration (h)	Description
Loading	12	Loading time of one OWT
Sailing	4	Sailing from base port to construction site or other way around
Jack-Up/-Down	2	Jack-Up and Jack-Down of the installation vessel
Construction	14	Time required to install a complete OWT
Reposition	2	Reposition of the installation vessel at the construction site

4.3.1 Simulation Based Decision Support Strategy

The basic idea of helping the operator to make the decisions elaborated in subsection 2.3 is to schedule offshore installation recursively with a moderate scheduling size, N_p, at a time. For example, the construction of an OWF with 40 OWTs can be divided into 10 steps or segments with 4 OWTs each ($10 \times 4\,\text{OWT} = 40\,\text{OWT}$). Schedules for a scheduling size, N_p can contain maximal N_p cycles. For example, it requires at least one cycle ($N_{OWT} = 4$ with Plan IV in Figure 4) and at most four cycles ($N_{OWT} = 1$ with Plan I in Figure 4) for scheduling size $N_p = 4\,\text{OWTs}$. Through investigating all possible schedules for a certain scheduling size, N_p, it helps the operator to make the decision I and III introduced in subsection 2.3, since it finds the best schedule with number of OWTs that should be loaded and constructed in each cycle.Besides, each cycle can have a waiting time up to $t_{w,max}$. For a schedule with N_{cycle}, it results in $t_{w,max}^{N_{cycle}}$ number of combinations. For example, there are $12^4 = 20736$ different waiting time combination for a schedule with 4 cycles with a maximal waiting time $t_{w,max} = 12$. Thus, it is important to choose a moderate scheduling size and a reasonable maximal waiting time to avoid the exponential growth of the search space Figure 5. To mitigate this exponential growth, the proposed approach separates the overall scheduling problem in smaller segments, as noted above. All possible plans existing in the actual step will be evaluated via simulation according to (12). Indeed, the plan with the best *operability* will be taken as the starting point of the simulation for the next time period and the other plans will be discarded.



(a) Number of Schedules with different scheduling size **(b)** Number of Combinations of Waiting Time, $N_{cycle} = 4$

Figure 5: Growth of the search space

5 NUMERICAL SIMULATION

This offshore weather data set contains an hourly resolution of 10 m wind velocity and significant wave height in 50 years (from 1958 to 2007) measured in German North Sea. The measured wind speeds in this data set is amplified with the approach introduced in subsection 3.3 to represent the condition at 100m height. In order to take advantage of the stable offshore weather condition, April 1st 2000 is chosen as the start point for the construction of the designed OWF in the German North Sea, in which 40 OWTs should be installed. Thus, the historical measurements from year 1958 to 1999 are used in the approach introduced in subsection 3.2 to estimate the weather influences during the operation. The weather conditions in year 2000 are considered as unknown. Besides, the initial inventory in base port is set to 12 OWTs and the installation vessel is loaded with zero OWT. To avoid the exponential expansion of search space (see Figure 5a), a planing size of 4 OWTs is used to schedule the installation of the designed OWF. Examples of schedules are given in Table 4. For the chosen planing size (4 OWTs), a schedule can have maximal 4 cycles. Take schedule No. 2 as an example, the vessel should be loaded one OWT, $N_L = 1$, and sail back after the OWT is installed, $N_C = 1$. Thus, the remaining OWTs on the installation is zero $N_{cap} = 0$. In the second cycle, three OWTs should be loaded and installed. The installation vessel sails back to the base port again with zero remaining OWTs.

Table 4: Examples: schedules for planing size 4 OWTs

No.	Cycle 1			Cycle 2			Cycle 3			Cycle 4		
	N_L	N_C	N_{cap}	N_L	N_C	N_{cap}	N_L	N_C	N_{cap}	N_L	N_C	N_{cap}
1	4	4	0									
2	1	1	0	3	3	0						
3	3	1	2	1	2	1	3	1	3			
4	2	1	1	3	1	3	1	1	3	1	1	3

$\boldsymbol{N_L}$: number of OWTs loaded onto the vessel; $\boldsymbol{N_C}$: number of OWTs constructed in the current cycle; $\boldsymbol{N_{cap}}$: number of OWTs remaining on the vessel

Furthermore, we consider a moderate maximal waiting time $t_w = 5\,\text{h}$ to reduce the computational cost shown in Figure 5b. Thus, schedules with 4 cycles have to be simulated 625 times. In total 30930 simulations need to be run to schedule the installation of the 4 OWTs. Using the indicator introduced in subsection 4.3, each schedule combined with different waiting times in cycles are evaluated. Figure 6 shows the operability of each schedule under the consideration of the waiting time combination.

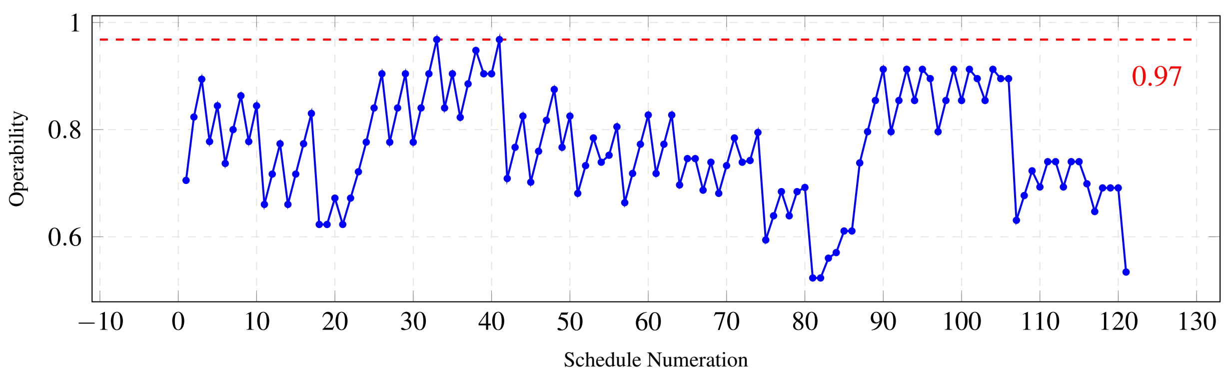


Figure 6: Operability of schedules with planing size of 4 OWTs

Table 5: Schedules with best operability

No.	Cycle 1			Cycle 2			Cycle 3			Wating Time		
	N_L	N_C	N_{cap}	N_L	N_C	N_{cap}	N_L	N_C	N_{cap}	N_L	N_C	N_{cap}
33	1	1	0	2	2	0	4	1	3		-	
41	1	1	0	4	2	2	2	1	3		-	

In this case there exist two schedules with the maximal operability 0.97, which are given in Table 5. It is important to mention, that the similarity in these two selected schedules is given by the usage of the weather integrated operation time and the unitary indicator. The scheduling of the next 4 OWTs needs to consider both of these two schedules as initial condition and simulate them separately. This increases the computational cost as well.

6 CONCLUSION

This contribution introduces a simulation-based scheduling strategy for offshore wind farm installation, which recursively plans the offshore installation with a moderate scheduling size. It always considers the optimal solution in the current phase as the starting point for the next. Combined with DTMC approach, the duration of installation operations are evaluated under the consideration of the weather restrictions, where historical weather data is used for the forecast. This approach provides an agile solution to schedule the offshore installation, and finds the segmental optimums. However, it requires a moderate scheduling size and maximal waiting time to avoid the explosion of the search space. Thus, future works are required to investigate the influence of the scheduling size on the quality of the global solution, since a small scheduling size leads directly to a reduction of the search space. Besides, application of other reduction methods is necessary, when large scheduling sizes and long waiting time are considered in the simulation. Last but not least, comparison between the presented model and other models in the literature for OWF installation is required for the purpose of improving the performance of the current approach.

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