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Original article

Resource Sharing in the Logistics of the Offshore Wind Farm Installation Process based on a Simulation Study

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Abstract

This present contribution examines by means of a discrete event and agent-based simulation the potential of a joint use of resources in the installation phase of offshore wind energy. To this end, wind farm projects to be installed simultaneously are being examined, the impact of weather restrictions on the processes of loading, transport and installation are also taken into consideration, and both the wind farm specific resource allocation and the approach of a resource pool or resource sharing, respectively, are being implemented. This study is motivated by the large number of wind farms that will be installed in the future and by the potential savings that might be realized through resource sharing. While, so far, the main driver of the resource sharing approach has been the end consumer market, it has been applied in more and more areas, even in relatively conservative industries such as logistics. After the presentation of the backgrounds and of the underlying methodology, and the description of the prior art in this context, the network of the offshore wind energy installation phase will be described. This is the basis for the subsequent determination of the savings potential of a shared resource utilization, which is determined by the performance indicators such as the total installation time and degree of utilization of the resources. The results of the simulation show that weather restrictions have a significant effect on the installation times and the usage times of the resources as well as on their degree of utilization. In addition, the resource sharing approach, has been identified to have significant savings potential for the offshore wind energy installation.

Keywords: Resource sharing, offshore wind energy, installation phase, logistics, simulation

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☆ This is a revised version presented at the 4th Ai-MAST held at Mokpo, Korea, December 12-14, 2016.

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1. Introduction

This contribution examines the benefits of the resource sharing approach for the installation-logistics of offshore wind energy (OWE). To this end, the introduction first of all describes the status of OWE in Germany. Furthermore, the subject matter of resource sharing will be introduced and first considerations regarding the implementation in the OWE installation logistics will be made. This first chapter concludes with the description of the research approach the present contribution is based on. A presentation of previous scientific studies in the area of planning and control of OWE installations as well as in the area of resource sharing in logistics is presented in chapter 2. Chapter 3 specifies the area of application in more detail and further describes the logistics network of the OWE installation phase. The key aspects of this contribution are presented in chapter 4. The benefits of resource sharing in installation-logistics are examined by means of an agent-based simulation. For this purpose, the structure of the simulation will be explained, the scenarios, parameters, variables, restrictions and performance indicators will be described and, finally, the simulation of the results will be presented. This contribution concludes with a discussion of the results as well as with an outlook on the subject matter for subsequent research (chapter 5).

1.1 Offshore wind energy and its logistics

In the context of the German energy transition, OWE is a key technology (Federal Ministry for Economic Affairs and Energy 2015, Hau 2014). The reason for this is the high potential availability of wind, which results in a high number of full load hours and the good power plant characteristics of OWE (Burton et al., Hau 2014). Due to the planned exit from nuclear energy in Germany, OWE, as a form of energy generation that is able to provide a base load, is an important component of the future energy mix. Both, the specific challenges of OWE and the competition with conventional and other renewable energy sources, lead to a need for optimization and the lowering of costs in all areas of the value chain in this young industry (Federal Ministry for Economic Affairs and Energy 2015).

Along the entire value chain, logistics is what connects the different OWE players. The most important challenge of OWE logistics is the need to manage dynamic influences, especially the weather conditions and sea state. Thus, a standardization of procedures, equipment and turbine components as well as the creation of logistical processes in accordance with the OWE framework conditions is necessary (Schweizer et al. 2014). Since logistics serve as a connecting element, this requires that the optimization of logistics is considered as a cross-system matter (Beinke et al. 2015). In the context of the OWE installation phase, this does not only include considering the supply chain of one offshore wind farm (OWF) but also taking into account all the OWFs that are to be installed at the same time. Thus, a consideration that extends across different supply chains and projects is necessary due to the supply chain structure of an OWF as well as its project-based nature.

1.2 Resource sharing and its framework conditions in offshore wind energy installation logistics

The subject of the shared use of resources (hereinafter referred to as resource sharing) is described as a virtually unlimited use of resources with negligibly low transaction costs and an increase in resource efficiency (Schönberger et al. 2014). The resource allocation aims at a distribution of the limited resources that is as effective and efficient as possible.

For logistics, resource sharing means new opportunities and challenges. According to Schönberger et al. (2014) and Freitag et al. (2016), the reason for this that performance is no longer based on the possession of resources but on their use. Therefore, due to the high level of standardization of the processes and the logistic objects, in the area of logistics, no competitive advantage can be achieved t exclusively through use of resources.

A transfer of the approach to a specific industry requires defining the potential object of resource sharing. In the context of the logistics of the OWE installation phase, the said object is the means of transport, the storage and port areas as well as the equipment for the installation (Beinke et al. 2015). Due to the fact that the involved stakeholders vary from wind farm project to wind farm project and that, at the same time, are involved simultaneously in different projects, there are always points where the individual supply chains overlaps. Since the number of deployed resources is limited, that leads to a need for a parallel use of publicly provided resources at the same value chain level. Due to the high charter rate of the installation vessels (IV) and the resulting need for a fast and uninterrupted loading and unloading of the vessels,

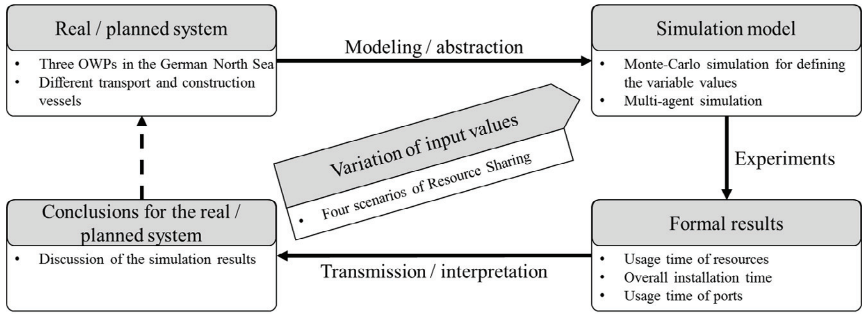


Figure 1: Research approach and process of simulation

the dock sections, for example, are currently used exclusively. This leads to a reduction in the degree to which these resources are used and also to an increase in costs.

Beinke et al. (2015) describe that the current creation of port infrastructure by means of public-private partnerships is a first step towards the implementation of resource sharing. The provision of privately funded resources, such as transport vehicles for transporting the very heavy and large semi-finished products and turbine components between the field warehouse and production, between component suppliers and manufacturers, or between the manufacturer and the port as well as within production, in the form of a groupage cargo system or a resource pool for local businesses is another potential starting point for resource sharing in OWE logistics. This is due to the low cycle times in the production of the individual components as well as the currently low degree of utilization of the transport means (Beinke et al. 2015).

1.3 Research approach

In terms of methodology, the present publication is based on a multi-agent simulation of the OWE logistics and installation processes. A definition of the term simulation that is well known and has often been quoted is provided by VDI 3633. According to said definition, simulation is a method, which, by means of the replication of a real system, makes it possible to obtain insights into said system including its dynamic processes on the basis of models, which can be experimented with (VDI 3633). In this context, a system does not only mean a number of elements, but, in particular, also the mutual relationship between said elements (Hall and Fragen 1956).

Figure 1 illustrates the process of a simulation. The specific elements in the context of this contribution have been added. The illustrated system comprises three OWFs in the German North Sea, which are being installed at the same time. In addition, the real loading scenarios for the IVs and heavy-lift vessels (HLV) to be used as well as the real process times for loading, transport and installation constitute the basis of this simulation model. At the beginning, the respective value assignment of variables is defined by means of a Monte Carlo simulation. The simulation is executed as a multi-agent simulation by the simulation software AnyLogic. The conducted experiments comprise several runs of the simulation for each scenario, respectively. This ensures the comparability of the scenarios. The results of the simulation experiments include the installation time for all three OWFs as well as the degree of resource utilization of the HLVs and IVs. Finally, the simulation results are discussed.

2. Literature review

Due to the subject matter of this contribution, the analysis and presentation of the underlying literature is divided into the area of OWE installation planning and its logistics and the area of resource sharing in the project business.

2.1 Planning of offshore wind energy installation logistics

Contrary to what is the case in traditional logistics chains, the creation of a logistics network for the installation of an OWF requires comprehensive resource planning, the consideration of applicable restrictions and meteorological and oceanographic factors that can influence the specific OWF project. These dynamic disturbances, such as weather impact, make it harder to transfer planning and control concepts from other areas.

Therefore, efficient planning and controlling of the logistics chain are expected to be an important contribution to saving costs (Weise et al. 2014). In this context, a number of previous scientific studies on the planning of installation-logistics, which will be presented hereinafter, were be identified.

Scholz-Reiter et al. (2010) propose a mathematical model using mixed integer linear programming. It calculates the optimum installation schedule for OWFs, taking into consideration different weather conditions. To this end, different weather conditions, installation methods and layouts for the loading of the vessel are taken into account. Since the mathematical problem is NP hard (the time for resolving the problem increased exponentially with the number of problem´s parameters, so they cannot be solved in polynomial time), the authors claim that the proposed mathematical model is only applicable to small scenarios. Therefore, in Scholz-Reiter et al. (2011), the authors present a heuristic that is able to solve larger problems by taking into account longer periods of time, several vessels and a wider range of weather conditions. Muhabie et al. (2015) present a discrete event simulation for the transportation and the installation of OWTs. They take into consideration the actual historical wind speeds and wave heights as well as the probabilistic approach for the analysis of the logistics chain in the offshore wind industry. In Ait-Alla et al. (2013), the authors address the problem of the aggregated installation planning of OWFs. They present a mathematical model that takes into account different operating conditions, such as weather conditions and vessel availability. Vis et al. (2016) address the coherence between logistic methods and the project performance, taking into consideration the external impact of the weather. Their study also takes into account the most important factors of the pre-assembly and vessel loading phase as well as the distance to the mainland. The authors propose a pre-assembly strategy which requires a minimum number of components for the on-site installation and a maximum number of turbines to be loaded on a vessel. The result is a decision-making tool on the basis of simulation. It includes all the logistic processes necessary for the offshore wind turbine (OWT).

2.2 Resource sharing in the project business

Apart from the contribution of Beinke et al (2015), which discusses the resource sharing approach in the OWE installation phase, the authors were not able to identify any other work regarding this topic in the relevant literature. Based on the project character of the OWE installation phase and its logistics, further fields of application which, in the past, were the subject matter of previous scientific studies in the context of resource sharing can be identified. Kriegel (2012) presents a 10-item plan in the context of hospital logistics, which uses innovative procurement and logistics concepts such as resource sharing in order to improve the value added in hospitals. The study presented by Pinheiro et al. (2016) empirically examines the role of social-capitalist dimensions on the way to resource sharing and shows that shared visions and commitments contribute positively to resource sharing.

Zavadskas et al. (2013) examine methods for comparing the performance of projects in the context of the project business in the construction industry. The study analyses project management problems and success factors of construction projects, and illustrates how the efficiency of a project is rated, taking into account the aggregated indicators of a company. The result of said contribution shows the benefit of aggregated indicators for project performance comparisons, which provide useful information for the allocation of resources or for strategic planning.

Both works of Caballini et al. (2015) and Kaiafa and Chassiakos (2015) present optimization methods for the object of resource sharing. In their study, Kaiafa and Chassiakos (2015) develop an optimization method for multi-objective, limited resource planning, which takes into account that resources are only available for a limited period of time. The goal is to minimize the costs which consist of the cost functions of surplus resources, project deadline violations and daily resource fluctuations. The developed approach has been tested multiple times and, taking into consideration the defined targets, provides adequate and well-balanced solutions.

Based on this presentation of previous scientific studies, it is evident that an analysis and consideration of the benefits of a resource sharing approach in the project business has not been performed yet. The present contribution seeks to close this gap in the relevant research.

3. Installation logistics network

Just as in other industries, the logistics chain in production and installation is characterized by a targeted downward flow of material from source (manufacturer) to sink (offshore installation site). Schweizer et al. (2014) outline the supply chain of the OWE installation phase as follows:

The raw material and semi-finished product suppliers mark the starting point of the supply chain. Next, the component manufacturers manufacture the four main components of an OWT. The transportation of the finished components to the port as well as the supply of the component manufacturers with semi-finished products and raw material are usually realized by a logistics services provider. At the port, the turbine components are made available and taken over by the installer, transported to the OWF and installed. In this context, the installer is the customer at the end of the supply chain (Schweizer et al. 2014). The supply chain system of an OWF is summarized in Figure 2.

A closer look reveals that the presented generic model does not illustrate the subject matter comprehensively. The connections between the raw material and the partial system suppliers and the component manufacturers are not, as shown, exclusive and do not only extend from one supply chain level to the next. In addition, there are, for example, sub-supplier relationships or partial order assignments between the component manufacturers (Beinke and Görges 2012). The port also fulfils different tasks and is not only responsible for the provision of the components, it is a central hub which also constitutes as an interface for the delivery of semi-finished products and partial systems to the manufacturers, since, due to weights and dimensions, it is not possible to use only land based transportation (Görges et al. 2014, Weise et al. 2014).

A close look at the port types in the network reveals the mutual relationships in the network in more detail. Görges et al. (2014) characterize in this context the production port by its pure character as a supplier for the component manufacturers and the outward flow of the both, the function of supplying the component manufactures and consolidating the components. In addition, the value adding activities take place on the premises of the port and/or adjacent to production sites (Görges et al. 2014). Proceeding on the basis of this illustration, Figure 3 above shows that OWE production and installation is not a chain, but a network.

By extending the illustrated objective and, thus, by extending the system from a single OWF to a network of several projects, which, in a limited period of time are installed simultaneously or offset from each other, additional mutual effects arise. At the level of the partial system suppliers and the component manufacturers, several players are simultaneously active in different project scenarios. A joint use of port capacities and installation resources can also be considered an option (Beinke et al. 2015, Görges et al. 2014).

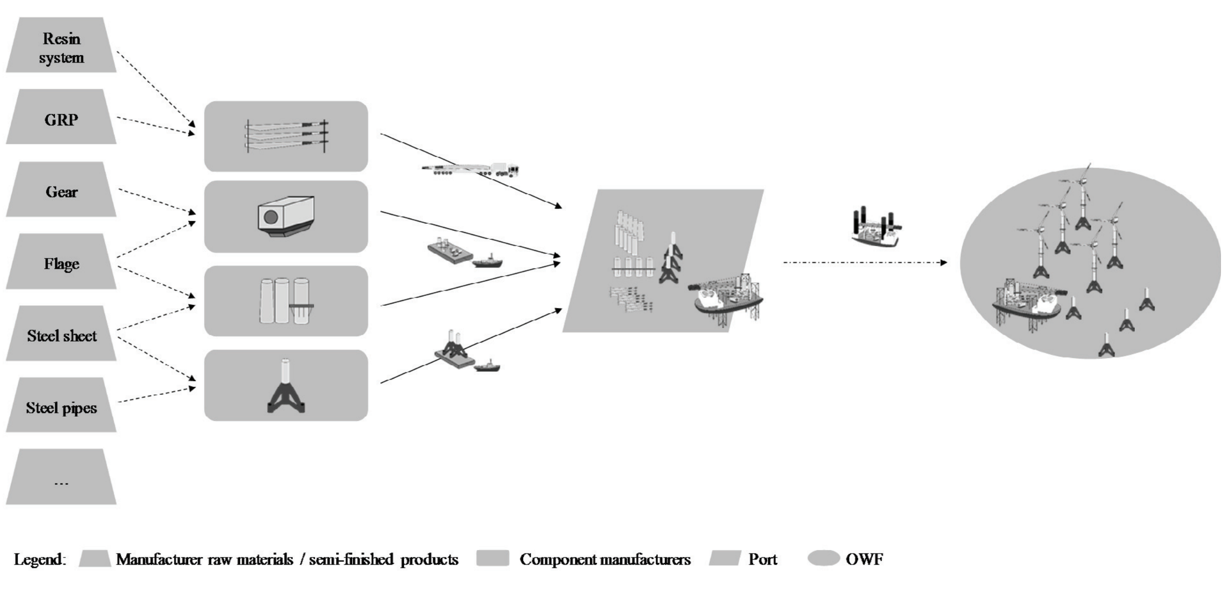


Figure 2: Generic model of the offshore logistics chain of the material flow during the production and installation phase

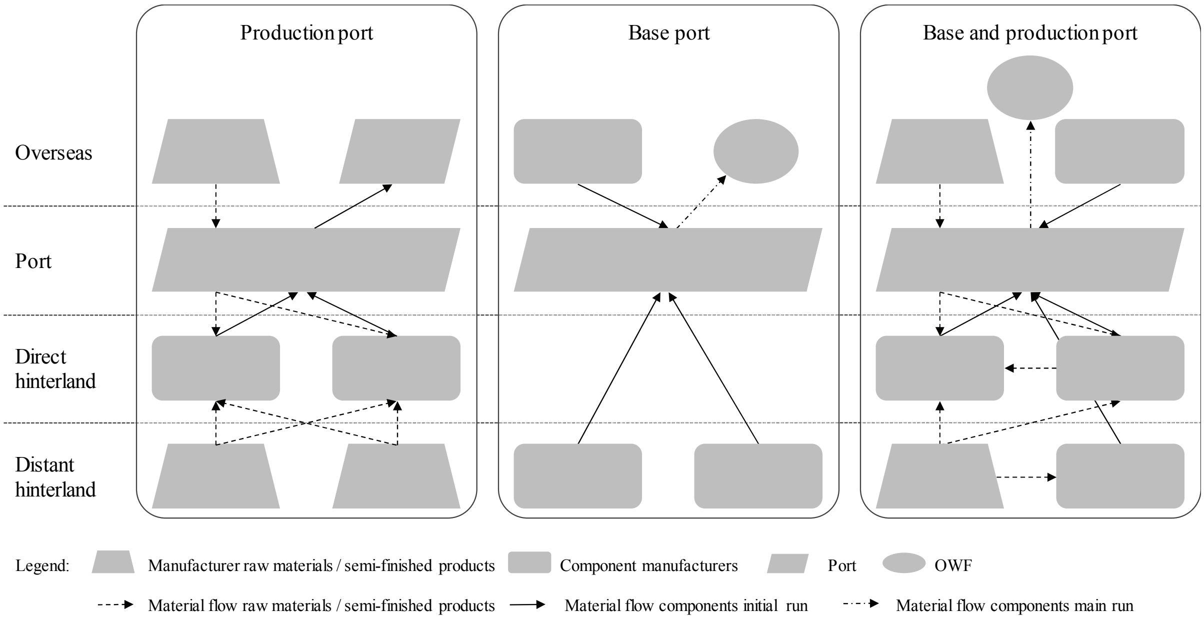


Figure 3: Extended model of the offshore logistics chain of the production and installation phase (Beinke and Görges 2012)

The starting point for examining the network are the suppliers of semi-finished products and partial systems, which supply the majority of component and system manufacturers directly or via the ports of the network. As already shown above, there are further mutual relationships between the players at this level. Subsequently, the manufacturers deliver the components to the different ports from where the components are transported to the individual OWFs where they are installed. This network of the OWE installation phase is illustrated in Figure 4 and shows that the individual players are simultaneously involved in different projects (Beinke et al. 2015).

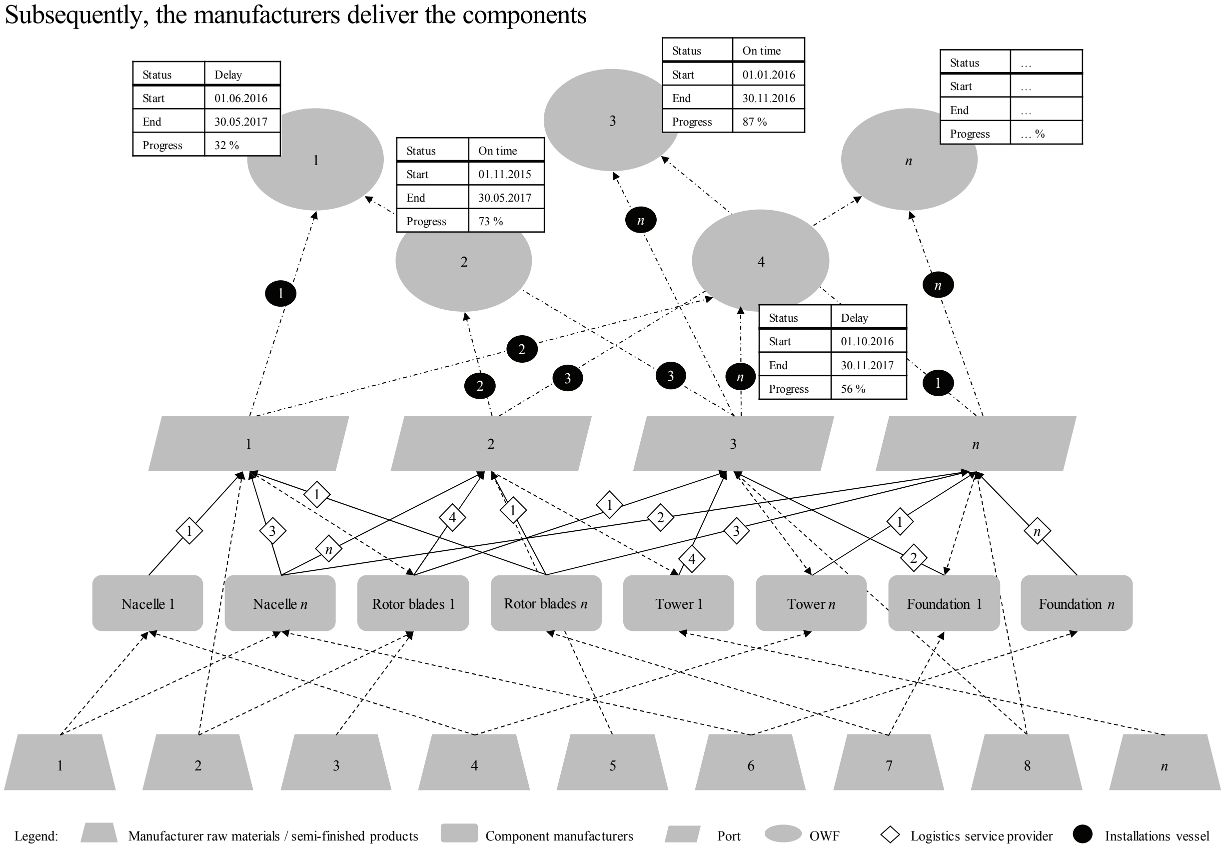


Figure 4: Network of simultaneously installed OWF projects

4. Simulation study

Proceeding on the basis of the illustrated OWE installation network, the following simulation study examines the joint use of transport and installation means. The objective of the study is to examine the degree of resource utilization and the overall installation time both in a typical scenario with tied-up resources and in a joint use scenario. To this end, the structure of the simulation and, thus, the framework conditions are explained at the beginning of this chapter. Based on this, the simulation scenarios will be described. After the description of the scenarios, the simulation will be specified.

4.1 Structure of the simulation

In the context of the simulation, three OWFs are being installed within the same period of time. The necessary components are transported to offshore locations for installation from two base ports. They are transported by means of a IV with specific loading scenarios.

Legend: 1 – Eemshaven (Netherlands) 2 – Cuxhaven (Germany) 3 – Bremerhaven (Germany) 4 – Stade (Germany) A – OWF A (N55°10‘, E5°00‘) B – OWF B (N54°25‘, E5°50‘) C – OWF C (N54°15‘, E6°40‘)

Figure 5: Locations of OWFs and ports in the simulation

Table 1: Processes and process times in the simulation

No.	Process	Predecessor process	Successor process	Dura-tion	IV involved	HLV involved	Wind limit [m/s]	Wave limit [m]
1	Preparation in production ports per component / per vessel load		1	1h / 3h				
2	Loading of 10 towers on HLV	1 & 11	6	20 h		X	14	
3	Loading of 10 rotor blades on HLV	1 & 11	6	40 h		X	12	
4	Loading of 5 nassels and 5 hubs on HLV	1 & 11	6	50 h		X	14	
5	Loading of 2 foundations to an HLV	1 & 11	6	10 h		X	18	
6	Drive to base ports	2-5	7-10	10 knot		X		3
7	Unloading of 10 towers from HLV	6	11	12 h		X	14	
8	Unloading of 10 rotor blades from HLV	6	11	25 h		X	12	
9	Unloading of 5 nassels and 5 hubs from HLV	6	11	14 h		X	14	
10	Unloading of 2 foundations from HLV	6	11	8 h		X	18	
11	Drive to production port	7-10	2	10 knot		X		
12	Preparation of 4 foundation before installation in base port	10	15	48				
13	Preparation & Testing of 5 top-structures* before installation in base port	7-9	14	190 h				
14	Loading of 5 top-structures for installation	13	16	75 h	X		12	
15	Loading of 4 foundations for installation	12	16	20 h	X		18	
16	Transport to the assembly location	14, 15	17, 18	10 kont	X		21	2.5
17	Installation of 5 top-structures	16	19	150 h	X		12	
18	Installation of 4 foundations	16	19	72 h	X		18	3
19	Drive to base port	18	18	10 knot	X		21	2.5

* One tower, one nassel, one hub and three rotor blades form a top-structure of an OWT.

The transportation of components between the production ports and the respective base port is realized by the means of HLV, which also have specific loading scenarios for the different component types. The figure 5 provides a geographic illustration of the individual ports and the OWF locations that need to be taken into account for the simulation. In addition, table 2 describes the structure of the individual OWFs.

Table 2: Structure of the three OWFs in the simulation

OWF	A	B	C
Number of OWT	120	80	60
Base port	(1)	(1)	(2)
Distance to base port	125 sm	68 sm	75 sm
Location of foundation structure manufacturer	(2)	(3)	(2)
Location of tower manufacturer	(2)	(3)	(2)
Location of nassel and hub manufacturer	(3)	(3)	(3)
Location of rotor blades manufacturer	(3)	(4)	(3)
Project start	Oct. 1	Nov 01	Dec. 1

The processes and the process times which form the basis of the simulation are summarized in table 1. The realization of the process times are subject to a variation of $\pm 10\%$. In addition, the restrictions arising from the wind speeds and wave heights are specified for the respective processes. The presented data is based on real processes, process times and restrictions which have been empirically collected in the context of the research and the development project Mon²Sea.

4.2 Simulation scenarios

In the context of this contribution, four scenarios for the installation of the three shown OWFs are examined (cf. Table 3). They differ with regard to the handling of the transport resources and with regard to the impact of the wind and the sea state on the processes. The restrictions specified in Table 2 are not taken into consideration for Scenarios 1 and 3. This means that these scenarios are reference scenarios which are independent from any weather impact. In Scenarios 2 and 4, which take into account the wind and wave restrictions, the simulation is based on historical weather data. The years between 2000 and 2004 are examined as the starting points of the installation. The variance of the weather conditions for these years is shown in the following Figure 6. Said figure presents the probability of a wind speed $\leq 12\ m/s$ and of the wave height $\leq 2.5\ m$ per month on an hourly basis.

The handling of the HLVs and IVs varies in the examined scenarios between an OWF-specific resource allocation (Scenario 1 and 2) and a resource pool (Scenario 3 and 4). One IV and four HLVs are available at the start of each project. In the case of an OWF-specific resource allocation, the resources are provided at the start of the project and leave the project once the task has been completed. In accordance with the concept of a resource pool, in Scenarios 3 and 4, the resources are available at the beginning of the installation of the respective OWF and can also be used by the other OWFs. The following Figure 7 compares these approaches.

The following Table 3 summarizes the scenarios.

Table 3: Scenarios of this simulation study

Scenario	S1	S2	S3	S4
No wind and wave restriction	X		X	
Wind and wave restriction		X		X
Strict resource allocation	X	X		
Resource sharing			X	X

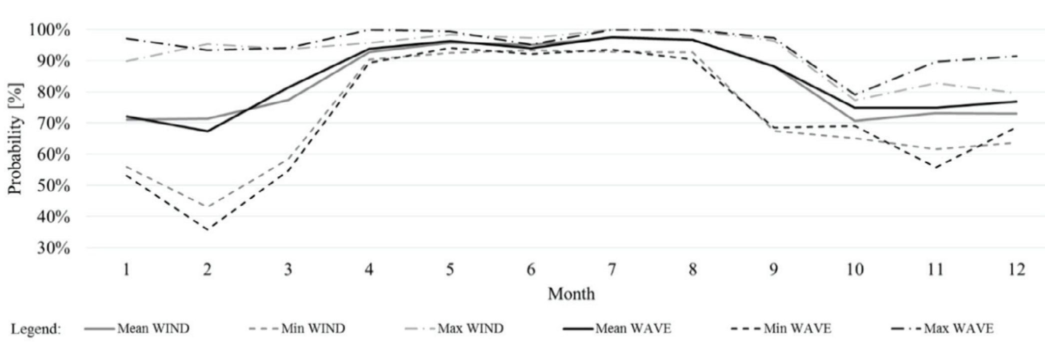
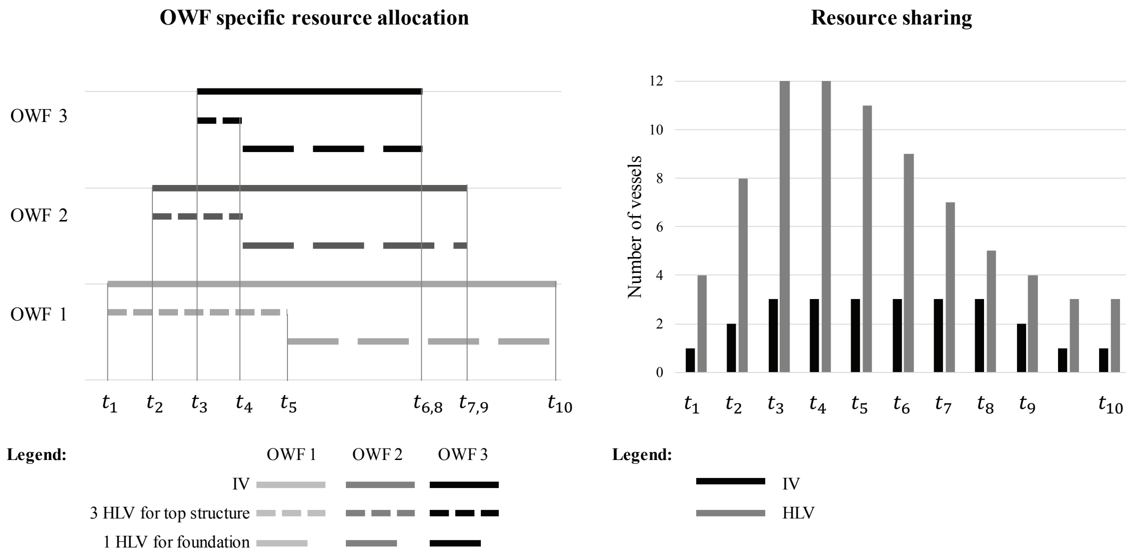


Figure 6: Probability of wind speed $\leq 12\ m/s$ and of the wave height $\leq 2.5\ m$ in the years 2000-2004



t_1 Start OWF 1 installation and foundation transport
t_2 Start OWF 2 installation and foundation transport
t_3 Start OWF 3 installation and foundation transport
t_4 End of foundation transport and start top structure transport for OWF 2 and 3
t_5 End of foundation transport and start top structure transport for OWF 1
t_6 End of top structure transport of OWF 3
t_7 End of top structure transport of OWF 2
t_8 End of installation of OWF 3
t_9 End of installation of OWF 2
t_{10} End of top structure transport and installation of OWF 1

Figure 7: OWF specific resource allocation vs. Resource sharing

4.2 Simulation specification

In order to specify the simulation, the specific parameters, the variables and restrictions as well as the indicators for measuring the performance shall be presented in the following.

Parameter

WP_i	Wind farm i, with $i \in [1,3]$
N_i	Number of wind turbines of wind farm i
S	Set of scenarios, with $\lvert S\rvert = 4$, see table 3
s	Index of scenario $s \in [1,4]$
c	Type of component ($c \in [F,T,N,B]$; foundation, tower, nacelle and sets of rotor blades)
PP_{sci}	Production port for components of type c associated to the wind farm i in scenario s
BP_{is}	Base port associated to the OWF i in scenario s
IV_{si}	Set of IV used in scenario s to install OWF i
HLV_{sci}	Set of HLV used in scenario s to transport components from the production port PP_{ci} to BP_i
v	Index of a HVL
T	Planning horizon
t	index of the planning period
PT_{jc}	Process time of operation j of component c, see table 2
$PRWave_{jc}$	Wave height restriction of operation j of component c, see table 2. For S1 and S3 the $PRWave_{jc}$ is set to $100\,m$ (No wave restriction)
$PRWind_{jc}$	Wind Speed restriction of operation j of component c, see table 2. For S1 and S3 the $PRWind_{jc}$ is set to $100\,m/s$ (No wind speed restriction)
$Start_i$	Planned start of the construction of OWF i , see table 1

Variables and Constraints

$EndInst_i$	End date of construction of OWF i
$Endtransp_{ic}$	End date for transporting components of type c of OWF i from production ports

XC_{cit} Number of component of type c installed until planning period t in the OWF i

$StartHLV_{sv}$ Start date of usage of HLV v used in scenario s

$RelHVL_{sv}$ End date of HLV v used in scenario s to transport components from the production port PP_{ci}

$EndHLV_{sv}$ Binary variable that indicates if the HLV v is utilised at planning period t under scenario s

$StartBP_{is}$ Start date of operation at base port BP_{is}

$EndBP_{is}$ End date of operation at base port BP_{is}

(1) $\forall\, i \in WP_i,\ \forall\, t \in [Start_i, EndInst_i]$, if $k \in [1,2]$, $|IV_{si}| = 1$, else $|IV_{si}| = 0$

(2) $\forall\, i \in WP_i,\ \forall\, t \in [Start_i, EndInst_i]$, if $k \in [3,4]$, $|IV_{si}| = \sum_i |IV_{si}|$

(3) $\forall\, i \in WP_i,\ \forall c \in [F, T, N, B], \forall\, t \in [Start_i, Endtransp_{ic}]$, if $s \in [1,2]$, $|HLV_{sci}| = 1$, else $|HLV_{sci}| = 0$

(4) $\forall\, i \in WP_i,\ \forall c \in [F, T, N, B], \forall\, t \in [Start_i, Endtransp_{ic}]$, if $s \in [3,4]$, $|HLV_s| = \sum_i |HLV_{sci}|$

(5) $\forall\, i \in WP_i,\ \forall c \in [F, T, N, B];\ \forall\, t \in [0, EndInst_i], \sum_i XC_{cit} = N_i$

(6) $\forall\, t' \in T, \sum_{t=1}^{t'} XC_{Tit} \leq \sum_{t=1}^{t'} XC_{Fit}$

(7) $\forall\, t' \in T, \sum_{t=1}^{t'} XC_{Nit} \leq \sum_{t=1}^{t'} XC_{Tit}$

(8) $\forall\, t' \in T, \sum_{t=1}^{t'} XC_{Bit} \leq \sum_{t=1}^{t'} XC_{Nit}$

Constraint 1 and 3 ensure that in a conventional scenario (No resource sharing), the IVs (respectively HLVs) are strictly tied to a specified wind farm during its installation. Whereas, the constraint 2 and 4 indicate that resource allocation is not restricted to a specified wind farm. The total number of IVs (respectively HLVs) used during the installation changes depending on the wind farms construction process. Constraint 5 restricts the sum of the built components during the planning period to the total number of wind turbines N for each wind farm. Constraint 6 ensures that the sum of installed towers for each wind farm does not exceed the sum of installed foundations. Constraint 7 guarantees that the sum of installed nacelles for each wind farm does not exceed the sum of installed towers. Constraint 8 ensures that the sum of installed sets of rotor blades for each wind farm does not exceed the sum of installed nacelles.

Performance Measures

OIT_{is} Overall installation time of wind farm i : $EndInst_{is} - Start_i$

$AUTHLV_{isv}$ Average usage time of HLV v used to transport the components of wind farm i under scenario s : $EndHLV_{sv} - StartHLV_{sv}$

$APUHLV_{isv}$ Average HLV usage [%] of HLV v used to transport the components of wind farm i under scenario s : $\frac{1}{AUTHLV_{isv}} \sum_{t=0}^{AUTHLV_{isv}} BinHLV_{svt}$

$AUTBP_{is}$ Average base port usage time of base port BP_{is}. $EndBP_{is} - StartBP_{is}$

4.3 Simulation results

The description and analysis of the simulation results are based on the examination of the results for the individual scenarios on the one hand and on a comparison between the scenarios on the other. The latter refers to the changes caused by the integration of the restrictions arising from wind and waves (S2 compared to S1 as well as S4 compared to S3) as well as the handling of the HLVs and IVs (S3 compared to S1 as well as S4 compared to S2). The following Table 4 shows the average values of the simulation results in relation to the performance indicators per OWF and in total and/or as an average, respectively.

Taking into consideration the restrictions caused by wind and waves leads to a significant increase in the installation time. A closer look reveals that, with 25.94 % (S2 compared to S1), the impact of the restrictions a when considering the traditional approach of a fixed resource allocation is higher than in the resource sharing approach, where the impact amounts to 22.53% (S4 compared to S3). This shows that not all OWFs achieve a reduction in the installation time (installation time of OWF 3 is 4.58 % longer in the resource sharing approach). The longer installation times results from the waiting periods during which the ships are in the port and/or during which the IVs are waiting for suitable weather conditions during the installation. For the HLVs, this leads to a deterioration in the degree to which they are utilized of approximately 3 %. As a bottleneck resource, the IV has a very high degree of utilization in all the scenarios (97-99 %).

Table 4: Simulation results

		Simulation results				Comparing of scenarios [%]			
		S1	**S2**	**S3**	**S4**	**S2 to S1**	**S4 to S3**	**S3 to S1**	**S4 to S2**
Average usage time of all HLV [d]	OWF 1	784.60	982.00	543.20	639.06	25.16	17.65	-30.77	-34.92
	OWF 2	463.60	557.32	289.90	330.08	20.22	13.86	-37.47	-40.77
	OWF 3	324.40	400.40	205.50	284.56	23.43	38.47	-36.65	-28.93
	Total	**1,572.60**	**1,939.72**	**1,038.60**	**1,253.70**	**23.34**	**20.71**	**-33.96**	**-35.37**
Overall installation time [d]	OWF 1	389.49	509.83	367.57	457.59	30.90	24.49	-5.63	-10.25
	OWF 2	241.41	289.45	184.41	208.98	19.90	13.32	-23.61	-27.80
	OWF 3	178.54	220.11	182.79	233.71	23.28	27.86	2.38	6.18
	Total	**809.44**	**1,019.39**	**734.77**	**900.28**	**25.94**	**22.53**	**-9.22**	**-11.68**
Average HLV usage [%]	OWF 1	35.07	31.41	36.73	35.29	-10.44	-3.92	4.73	12.35
	OWF 2	40.20	37.80	36.39	35.07	-5.97	-3.63	-9.48	-7.22
	OWF 3	31.64	30.38	35.50	34.39	-3.98	-3.13	12.20	13.20
	Average	**35.64**	**33.20**	**36.21**	**34.92**	**-6.85**	**-3.56**	**1.60**	**5.18**
Average base port usage time [d]	OWF 1	395.2	516.88	372.2	464.18	30.79	24.71	-5.82	-10.20
	OWF 2	247	296.28	261.6	315.5	19.95	20.60	5.91	6.49
	OWF 3	182.4	224.04	189.6	240.26	22.83	26.72	3.95	7.24
	Total	**824.6**	**1,037.2**	**823.4**	**1,019.94**	**25.78**	**23.87**	**-0.15**	**-1.66**

Another issue to bear in mind is the reduced outward flow from the base port due to the restrictions. This leads HLVs being used for longer periods of time and, consequently, to a reduction in the degree of their utilization (6.85% in S2 and 3.56% in S4). The examination of the individual OWFs when considering the weather restrictions shows that the duration of the weather-dependent processes in the overall process have a direct effect on usage and installation times. Due to longer transport routes, the installation time for OWF 1 is increased by a significant percentage when compared to installation time for OWF 2 and OWF3.

In order to describe the impact of the resource sharing approach on the performance indicators, the comparison between S4 and S2 shall be used in the following in order to also take into consideration the impact of the weather conditions in order to be closer to reality. Due to resource sharing, the usage time of the HLVs for all OWFs is reduced significantly by 35.37 %. The reduction of the usage time leads to a higher degree of HLV utilization at 5.18 %. Despite an increase in the installation time of OWF 3 by 13.60 days, the total duration of 119.11 days means a clear reduction of the total installation time for all OWFs. In this regard, the installation time of OWF 1 is reduced by 52.24 days and the installation time of OWF 2 by 80.47 days. Thus, not only a reduction of the installation time is achieved, but also a reduction in the IV usage. In addition, the resource sharing approach leads to a reduction of the overall HLV usage time by 686.02 days, which, when taking into account the higher degree of their utilization, leads to a resource usage reduction of 643.92 days.

5. Conclusion and outlook

In the context of this contribution, the network of the OWE installation phase was presented. It was inferred starting from the supply chain of a OWF project via the different port types. In doing so, the connections between simultaneous OWF projects were pointed out. Against this background, a simulation study was presented which examines the joint use of resources for the simultaneous installation of three OWFs. To this end, the processes, process times as well as the wind and wave restrictions of the processes were described. Furthermore, four scenarios were examined which differed with regard to the consideration of restrictions and with regard to the use of resources. Historical weather data from different years was used for the simulation.

The simulation was able to prove that wind and wave restrictions have a significant effect on the installation times and the usage times of the resources as well as on their degree of utilization. By means of the resource sharing approach, a significant savings potential was identified for the OWE installation. The resource usage of the IVs was reduced in the simulation by 119 days and the one of the HLVs by 686 days. It has to be noted in this regard that not all the OWFs experienced a reduction of the installation time. The increase of the installation time of the small OWF 3, which is located at a short distance from the base port, is offset by a reduction of the usage time of the HLVs of approx. 29 %.

Proceeding on the basis of the presented research results, the goal of future research is examine more OWFs and more resources, the integration of optimization strategies into the simulation, the economic assessment of the resource sharing approach as well as the examination of compensation regulations for the use of logistic objects. An extension of the system boundaries requires that the OWFs planned for the future as well as their respective supply networks be represented in the simulation. By including additional resources, an extension of the subject matter examined down to the level of the parts suppliers is possible. In addition, with regard to examination of the exclusive transport resources, an examination of the reloading resources in the port appears to be an obvious aspect to include as well.

No optimization takes place in the context of the presented simulation. An optimization of the resource allocation as well as of the installation process would probably lead to a further improvement of the performance indicators. This as well as the impact of a reduction of the resources per resource type has to be examined in further studies. The economic consideration in the presented context requires a definition of the costs of the individual process steps as well as of the overhead costs supported by empirical evidence. This also includes taking into account costs incurred due to failure or delay, which are significant in the OWE installation phase. The necessary research subject mentioned last (compensation regulations for the use of logistic objects in the resource sharing approach) constitutes a subject matter in the field of organization theory which should be addressed by an interdisciplinary research group consisting of economists, legal experts and engineers.

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