Research Article
Simulation Based Investigation of the Impact of Information Sharing on the Offshore Wind Farm Installation Process

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In the recent decades, the introduction of a sustainable and green energy infrastructure, and, by this, the reduction of emissions caused by fossil energy generation, has been focused on by industry-oriented nations worldwide. Among the technologies of renewable energy generation, wind energy has the highest deployment rate, due to the high wind resource availability and the high technology maturity reached mainly by the onshore installation of wind turbines. However, the planning and the installation of offshore wind farms are a challenging task, because of harsh weather conditions and limited resource availability. Due to the current practice of decentralised information acquisition by the supply chain partners, we investigate the impact of sharing information on the installation process of offshore wind farms by means of a simulation model. Therefore, relevant information items will be identified in order to improve the installation process.

1. Introduction

The introduction of a sustainable and green energy infrastructure as well as the associated reduction of emissions caused by fossil energy generation has been focused by industry-oriented nations worldwide during recent years as a reaction to global climate change [1]. This results in a steadily rising growth-rate of renewable energy in Europe [2].

Among the technologies of renewable energy generation, wind energy has the highest deployment rate, due to the high wind resource availability and the high technology maturity reached mainly by the onshore installation of wind turbines [3]. Suitable areas for the installation of onshore wind energy turbines are restricted and have to a large extent already been developed [4]. Consequently, offshore wind energy farms are considered to be one key element of renewable energy generation in the future. In 2015, the total cumulative installations of offshore wind turbines reached more than 10 GW, whereby 92% of these global installations have been realised in Europe. In an optimistic scenario, by 2030, 28.2% of the European energy demand can be fulfilled by wind energy [5].

Offshore wind energy is ascribed high potential on the way to a renewable and sustainable generation of energy. However, during the installation process of an offshore wind farm, the installation planning has to deal with harsh weather conditions and limited resource availability. Restrictions on installation processes based on hardly predictable weather conditions are considered to be the main source of uncertainty for the performance of the supply chain. This makes the installation of offshore wind farms a complex planning problem. Generally, the uncertainty in the offshore wind energy supply chain is handled by acquiring the necessary information in a decentralised way, so that each affected supply chain partner, for example, installation vessel operator, port operator, and component manufacturer, individually deals with occurring problems. Information is usually only shared on request between supply chain partners.

As a consequence, the authors state that the impact of uncertainties can be reduced by standardizing information flows over the entire supply chain and thereby providing a common basis for decision-making. To this end, this contribution deals with the study of the applicability of information sharing to cope with the challenges of offshore wind

Manufacture	Logistics service provider	Port operator	Vessel operator	Construction company
Production	Transport initial run	Storage & handling	Transport main run	Site installation

Customer

Other players (e.g., maritime authorities, service providers, and customs authority)
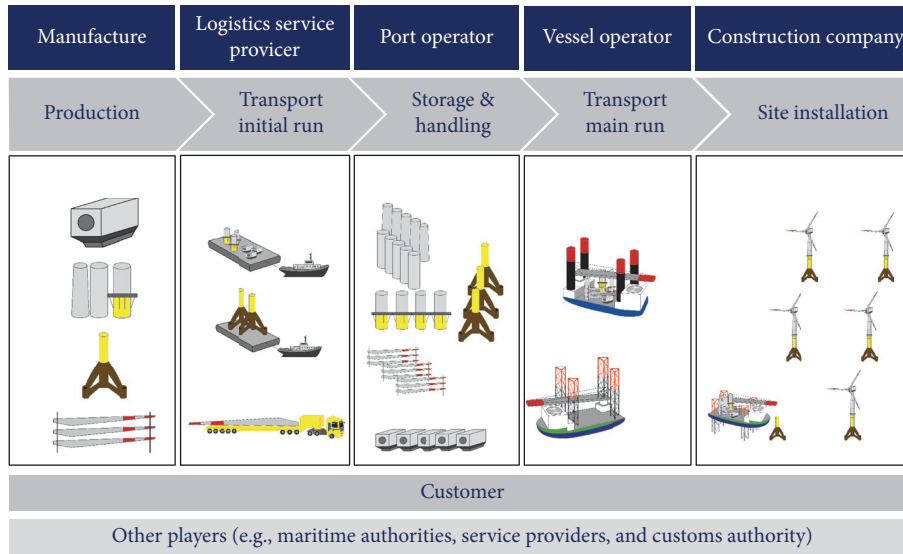
FIGURE 1: Logistics network of an offshore wind farm project (based on [14]).

energy installation processes. Indeed, information sharing plays an important role in guaranteeing and improving the performance of supply chain processes [6]. The integration and consideration of information sharing can help to reduce the impacts of uncertainties in different levels of the supply chain. Affected processes and supply chain segments can be detected by applying information sharing approaches. Therefore, preventive measures can be taken to reduce the impact of uncertainties on the supply chain.

In this paper, a study will be performed to determine the relevant information items that have to be shared to improve the installation process. In addition, different performance analyses will be conducted by defining and applying according performance measures.

2. Offshore Wind Farm Installation Process

Offshore and onshore wind energy installations show significant differences which range from the installation process to different cost structures within the life cycle of a wind turbine. Aspects that increase the costs of offshore wind energy compared to onshore installations are the connection of offshore wind farms to the energy grid, weather influenced logistics that complicate the access to the wind turbines, installation processes, and operation and maintenance of offshore wind turbines. The considerable differences in the cost structure during the installation process are mainly reasoned by the limited accessibility of offshore sites. This is caused by the harsh weather conditions at sea-like currents, waves, or high wind speeds [7]. The extra costs for construction, grid connection, and maintenance for offshore wind farm projects have to be counterbalanced by reaching scale effects. Therefore, large offshore wind farms with dozens of multimegawatt offshore wind energy turbines are erected to reach an optimal utilization of faster and steadier winds at sea [8].

While the share of production costs for an onshore wind energy turbine is about 75% of the total investment costs,

the production costs constitute only about 30–35% of the total investment costs for an offshore wind energy turbine. According to estimates the total logistics costs for an offshore wind farm have a proportion of about 15% of the total investment costs [9]. To understand the installation process and the connected logistic effort, it is necessary to know the main components of an offshore wind turbine that also have to be dealt with as transport units. An offshore wind turbine consists of a hub, a set of usually 3 rotor blades and a nacelle. This upper section is supported by a tower (consists of several sections) that is based on the foundation structure [10]. The choice of the foundation structure depends on water depths, condition of the seabed, and the anticipated wind and wave loads at the specific construction site [11]. References [11, 12] describe several types of foundation structures in detail, for example, monopiles, gravity base foundations, tripods, or jacket foundations.

There is no standardized setup of a logistics network for the installation of an offshore wind farm. The specific offshore wind farm project defines the number of wind energy turbines and the construction site at sea. Another decisive factor for the logistics network is the vessel concept for the installation. Several vessel types are suitable for offshore construction that differ in load capacity, weather restrictions, precision of crane operations, costs, travel speed, and technical risks [13].

Due to the complexity of offshore wind farm installation processes, the quality of the logistics processes significantly depends on the collaboration of the entire logistics network. Regarding this network, some key parameters determine its specification. These key parameters are the involved network partners, the installation method at sea, port characteristics, and the type and number of available construction vessels. An exemplary logistics network for an offshore wind park project in the German North Sea is shown in Figure 1.

In this scenario, the installation process starts with the component manufacturers that produce the main

components of the offshore wind energy turbine. The production of the main components is divided into foundation structures, in this case tripods, the two upper tower segments and the set of rotor blades as well as a nacelle, a hub, and the lower tower segment. The following partner in the network is the logistics service provider that arranges the transports between the component manufacturers and the port of shipment. These transports have to be carried out on waterways due to the dimensions of the components and are also influenced by weather conditions. The port operator is responsible for storing and handling of the components at the port of shipment. Finally, the components are taken over by the construction company that operates the installation vessels. These vessels execute the transports to the construction site and fulfil all stages to install the offshore wind energy turbines.

The large amount of transported material, the expensive and scarce installation equipment, and the number of interfaces within the supply chain hold a large potential for standardization of information exchange to improve the logistics processes over the entire logistics network.

3. Information Sharing in Supply Chain

In recent decades information sharing has become increasingly important in supply chain management, mainly because of different aspects like the rapid change of business processes and diverse customer demands [15]. These aspects contribute to uncertainties in supply chain management. To deal with these uncertainties and enhance the supply chain performance, the supply chain stakeholders should share their own information along the supply chain [16]. This can be achieved through a successful incorporation of information flows into the developed supply chain processes in order to optimize the processes and to obtain a reduction of costs and used resources.

There are many works that demonstrate the advantages and benefits of information sharing in the supply chain. Generally, information sharing can be distinguished in three different levels: Level 1 is referred to as decentralised information control, where each stakeholder of the supply chain operates in a decentralised way without sharing its own information with other organizations of the supply chain. Level 2 is referred to as coordinated control, where each two neighbouring inventories are coordinated by sharing the customer's information. Level 3 is characterized by a centralised operation of information. Based on electronic data interchange (EDI), all information is shared between different organizations and stakeholders of the supply chain and the optimal performance can be achieved [17].

Reference [17] considered a two-echelon seasonal supply chain model consisting of one supplier and one retailer. They evaluated the value of information sharing in the considered supply chain model with the assumption that external demand from the customer follows a seasonal autoregressive moving average (SARMA) process, including marketing actions that cannot be deduced from the other parameters of the demand process. The study considered three levels of information sharing: decentralised, coordinated (partial),

and centralised information sharing. The results show that the seasonal effect influences the average inventory levels and the expected costs of the supplier. It is also shown that the average inventory level and thus the expected cost of the supplier, in most situations, decreases when the level of information sharing increases.

Reference [18] studied information sharing in a two-stage supply chain consisting of one supplier and one retailer in which both, the supplier and the retailer, possess partial information on the demand. In this context, the authors investigated the impact of information sharing on the double marginal effect, the impact of the quality and the correlation of the supplier and the retailer's information on their information sharing behaviours. They found out that a revenue sharing contract between supplier and retailer, which ensures that the supplier and the retailer share their information completely, enhances the supply chain performance significantly.

In [19], different information sharing scenarios have been designed in order to analyse the supply chain performance through a simulation model. To achieve this, the authors applied a cross-efficiency data envelopment analysis for estimating the efficiency of each scenario. The results of their works show that sharing information on capacity and demand and full information sharing in general are good practices. However, sharing only information on capacity and/or inventory, without sharing information on demand, interferes with production at manufacturers, causes misunderstandings, which can reinforce the bullwhip effect.

Reference [20] investigated the benefits of information sharing in the case of supply chain uncertainties, which can arise due to demand and supply uncertainty. They introduced supply chain community strategies and types of demand information management closely related to information sharing methods. Then they evaluated the supply chain performance of two different types of information sharing methods. One is the planned demand transferring method (PDTM), and the other is the forecasted demand distributing method (FDDM). The supply chain performance for both methods was analysed in terms of throughput, inventory level, and service level. The results show that the FDDM performs better than PDTM in terms of throughput. However, if there is a minor variability in demand, PDTM performs better than FDDM.

Reference [21] investigated the exchange of information and material flows between supply chain partners and the effect on operational performance. They found out that the logistics integration has a significant effect on operational performance, and both information technology capabilities and information sharing have significant effects on logistics integration.

4. Role of Information Sharing in Offshore Wind Energy

A detailed process analysis at all supply chain partners of a logistics network in a German offshore wind farm project formed the basis to reveal the potential of information sharing in this context. The approach is depicted in Figure 2.
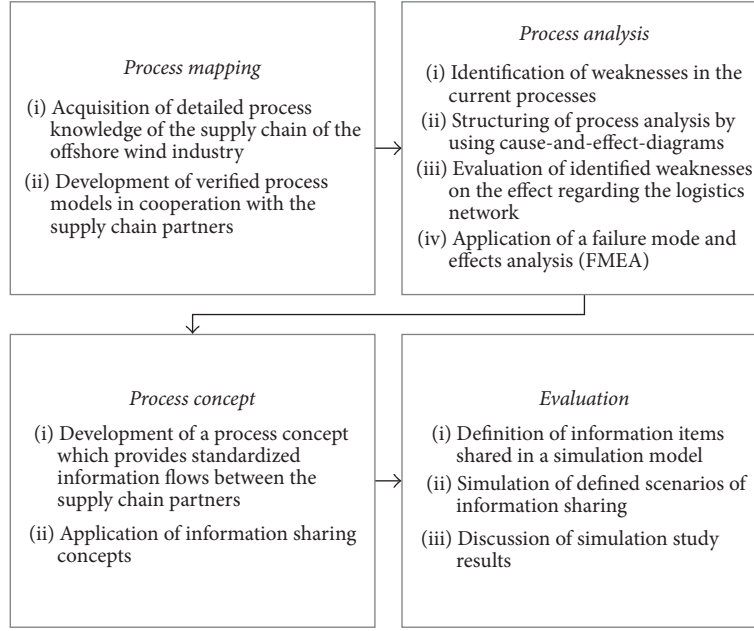
FIGURE 2: Approach for developing standardized information flows.

One central finding of the analysis is that information is handled decentralised throughout the logistics network. For example, weather forecasts that are of high importance for the feasibility of transport and installation processes are requested from different providers. That leads to different forecasts and an inconsistent basis of decision-making in the network. Capacity levels of storage areas are also an important issue in the logistics network. This is reasoned by the weights and dimensions of the components that can only be stored in heavy-load approved storage areas. Since the operation of the installation vessel is very cost-intensive, the supply with components in the port of shipment has to be secured. Therefore, the capable storage areas have to be utilized efficiently. Also the port capacity is often not shared within the logistics network.

It can be stated that little attention has been paid to the impact of information sharing on the current installation of offshore wind farms and, therefore, the first level "decentralised information control" of information sharing is in practice still being deployed. A first simulation study was presented on this topic in [22].

5. Simulation Model

5.1. Information Items Considered in the Simulation Model.
Based on the results of the process analysis presented in the precedent section, the following information items "weather forecast" and "port capacity" are identified because of their importance.

Weather Forecast. Weather data is considered as the main source of uncertainties that restricts the installation process. Therefore, the benefit of sharing the weather forecast data

TABLE 1: Scenarios of information sharing.

Information item	Scenario			
	1	2	3	4
Port capacity		X		X
Weather forecast			X	X

will be investigated. In this simulation study, the forecast time window is assumed to be one week.

Port Capacity. The port capacity is limited for each component. The challenge is to keep the capacity on a level that there is sufficient stock at all times to meet the installation demand and to avoid long lead times of the components in the port at the same time. In addition, exceeding port capacity can lead to a need of storing components in a supplement port of a third operator or returning components to the manufactures. Such problems are connected with high storage, transportation, and installation costs. Therefore, the importance of sharing the port capacity, both for installation vessels and the component manufactures, will be investigated.

5.2. Simulation Parameters.
All relevant parameters for the simulation model are mentioned in Parameters Section.

5.3. Scenarios of Information Sharing.
As mentioned before, 2 information items have been identified. From these information items, we defined 4 information sharing scenarios as a combination of them (Table 1).

The first scenario (Scenario 1) involves no direct information sharing between different involved supply chain partners. In this case, an aggregate master plan that determines

a timetable for the installation of a wind farm is generated. This plan has be executed by the manufactures of the offshore wind turbine components, distributors, port operator, and vessel operator, regardless of the progress of the installation process. Indeed, the aggregate plan indicates the number of each component to be installed in each time period (e.g., in one month) during the installation period. Therefore, different restrictions related to the weather conditions and availability of resources are taken into account. To this end, the mathematical model presented in [23] is applied to generate the aggregate plan. This mathematical model is also applied on all following scenarios.

The second scenario provides information about the port capacity for the different supply chain partners. The supply of components is performed based on the actual inventory level of port in order to keep the number of each component in the port above a specified threshold.

In case of the third scenario, the weather forecast for the installation location is shared over the entire supply chain. In this case, the component manufacturer and distributor have access to the weather forecast for the next days and thus accordingly decide to produce a component or not. On this basis, it has to be determined how many components have to be shipped to the port.

The last scenario is the result of the combination of port capacity and weather forecast information sharing. In this case, the weather forecast at the installation side and the inventory levels in port are shared continuously in the whole network during the installation process. Based on port inventory management policy and weather forecast, the port operator places new orders to the component manufacture to ensure a continuous availability of components. After receiving a port provider's order, the manufactures ship its stock to the port and, based on weather forecast, the manufacturer produces new components in order to ensure continuous shipping to the port.

5.4. Simulation Constraints and Assumptions. In summary, the installation process of offshore wind farms can be described as follows.

Some strategic decisions have to be made before the installation begins. These decisions are, for example, the number of offshore wind turbines to be installed, the envisaged duration of the installation process, the number of vessels deployed for the installation, and the capacity of different inventories.

Based on a predefined master plan (aggregate plan), the manufactures of the components produce the components, and the distributors ship the components to the port.

Based on weather forecast, the installation vessels will be available at the port for loading components and installing these components at the installation site.

The following assumptions related to the installation processes are considered by the simulation model:

(1) Given an offshore wind farm of N wind turbines, each wind turbine consists of 4 installation operations. Each operation belongs to an installation sequence which can be performed by an appropriate vessel under specific weather restrictions.

TABLE 2: Weather classification for each possible operation.

Operation	Max wind speed [m/s]	Max wave height [m]	Weather category
No operation possible (stay at port)	>12	>4.8	Very bad (Cat1)
Travelling	<12	<4.8	Bad (Cat2)
Installation of foundations	<11	<3.5	Medium (Cat3)
Installation of tower/nacelles	<6.5	<2.5	Good (Cat4)
Installation of rotor blades	<5	<2	Very good (Cat5)

(2) The components will be installed in a predefined scenario, that is, first, the foundation structure, secondly, the tower sections, then, the nacelle, and, finally, the installation of the 3 rotor blades.

(3) During the whole installation process, the number of installed sets of rotor blades should not exceed the number of installed nacelles, the number of installed nacelles should not exceed the number of installed towers, and the number of installed towers should not exceed the number of foundation structures.

In this simulation model, there are 4 component manufacturers, which have sufficient storage capacity to hold the manufactured components before being shipped to the port. Besides the components manufacturers, there are 4 distributors which transport the components from manufactures to the port, one port operator, and two installation vessels, which transport the components to the installation site and then perform the installation of those. The port capacity is limited for each component. Hence, the port capacity is limited to 9 foundations and 15 components of each top structure (tower, nacelle, and rotor blades). Regarding the meteorological data, we consider real weather data (hourly averages) using 50 years of historical data from the year 1958 until the end of 2007 from a wind farm located in the German North Sea. The wind farm is located about 90 km from the base port.

The pieces of weather data were purchased and acquired by a weather operator as part of a research project. These pieces of historical weather data are classified and grouped into different categories as shown in Table 2. More details about the processes and the process times can be found in [24].

5.5. Performance Measures. The performance measures considered to assess the defined scenarios and investigate the benefit of the impact of information sharing are as follows.

(1) Average Time in Port (AVTP). AVTP represents the average time that components are stored in the port before being loaded in the installation vessel for installation purposes. In addition, other pieces of information, for example, the minimum time and the maximum time that a component

spends in the port, will be collected, as well as the port capacity level during the installation time horizon for each component.

If m is the type of component ($m \in [F, T, N, R]$; foundation, tower, nacelle, and rotor) and N is the number of WT to build, then

$$\text{AVTP} = \frac{1}{4} \frac{1}{N} \sum_{m}^{[F,T,N,R]} \sum_{i=1}^{N} \text{TP}_{cmi}, \qquad (1)$$

where TP_{cmi} is the time that the component c of type m of the wind turbine i spent in the port before being transported to the installation site.

(2) Total Installation Time T_s. It refers to the time needed to install the complete offshore wind farm in information sharing scenario s, since the duration may change depending on the selected information sharing scenario.

(3) Average Vessel Usage Time. It includes the overall time that a vessel is used during the installation period:

$$\text{AVUT} = \frac{1}{|V|} \sum_{v=1}^{|V|} \sum_{t=1}^{Ts} \left(1 - \text{VA}_{vt}\right), \qquad (2)$$

where VA_{vt} is a binary variable which indicates, if the vessel v is available at time t. V represents a set of vessels used for the overall installation time T.

6. Simulation Results

In this section, we simulate the installation of $N = 30$ wind turbines. The installation is performed by 2 installation vessels. In the following, the main characteristics of the scenarios are summarised.

Scenario 1. Weather restrictions are considered based on historical weather data for the installation site. An aggregate master plan is generated that dictates a fixed supply of components and a static installation plan. The installation processes are conducted based on actual weather conditions; however, there is no information sharing between the partners in the process.

Scenario 2. The port capacity is shared over the entire logistics network. Besides the maximum capacity, a minimum level of components is defined that ensures the optimal supply of the installation vessel (at least 3 foundation structures and 5 top structures are always at stock).

Scenario 3. The weather forecast for the next week is shared between supply chain partners and the supply of components is carried out depending on weather forecasts corresponding to the planned installation processes.

Scenario 4. Weather forecasts for one week and port capacity is shared between the partners. The supply of components depends on weather forecasts as well as on port capacity.

Figure 3 lists the results of the simulation for each scenario. Furthermore, Figures 4, 5, 6, and 7 show the port capacity level according to component type during the installation for each scenario.

Scenario 1 (non-information-sharing scenario). We first studied the case of decentralised information control, where each stakeholder of the supply chain operates in a decentralised way without sharing its own information.

However, some information is directly given to supply chain partners when it is necessary. One example is when the maximum port capacity is reached. In this context, the port operator informs the manufacturers about the attainment of the maximal port capacity in order to avoid a possible return of components. In contrast to the second scenario where the port capacity is shared, this enables the manufactures to continuously monitor and control the port capacity level.

In addition, a time-based shipping policy is adopted in this case. In this context, the components are shipped from the manufacturers to the port at regular time intervals according to the aggregate master plan that is based on historic weather data for the installation site.

The results of Scenario 1 show that the installation takes about 195.5 days and the average time that a component spends in the port is 22 days. The average vessels time usage is 181 days which is about 92.6% of the total installation time.

Scenario 2 (port capacity information sharing). In the scenario of port capacity information sharing, the manufacturers and the distributors adopt an inventory-based shipping policy. This implies that the manufacturing and shipping of components are performed only if the port capacity level reaches a minimal level in order to keep the number of each component in the port above a specified threshold.

The results of Scenario 2 show that the installation takes about 184 days and the average time that a component spends in the port is 27.2 days. The average vessels time usage is 160.5 days which is about 87.14% of the total installation time.

Compared to the non-information-sharing scenario (Scenario 1), the port capacity information sharing scenario provides better performance measures except for the AVTP. The main reason for this is that Scenario 1 integrates weather influences, based on historic weather data in the generation of the aggregate master plan, whereas Scenario 2 does not take any historical weather data or weather forecasts into consideration. Consequently, the shipping of components from the manufactures to the port is performed without taking weather forecasts into consideration. Therefore, the objective is to keep the number of each component in the port above a specified threshold.

Compared to Scenario 1, the foundation structures are installed in a much shorter time period in Scenario 2. This scenario merely focuses on the material supply of the installation vessels and always secures a minimum amount of components on stock. Therefore an even utilization of port capacities can be reached for foundations, tower sections, and nacelles, and the total installation time is also affected due to the sufficient supply of components at all times.

Scenario 3 (weather condition information sharing). In this scenario, we investigated the impact of sharing the weather
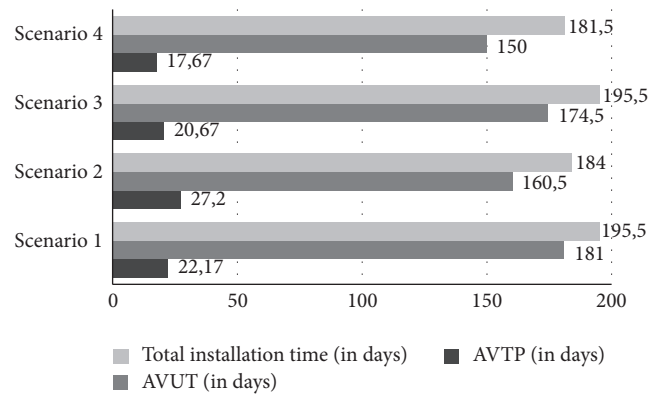
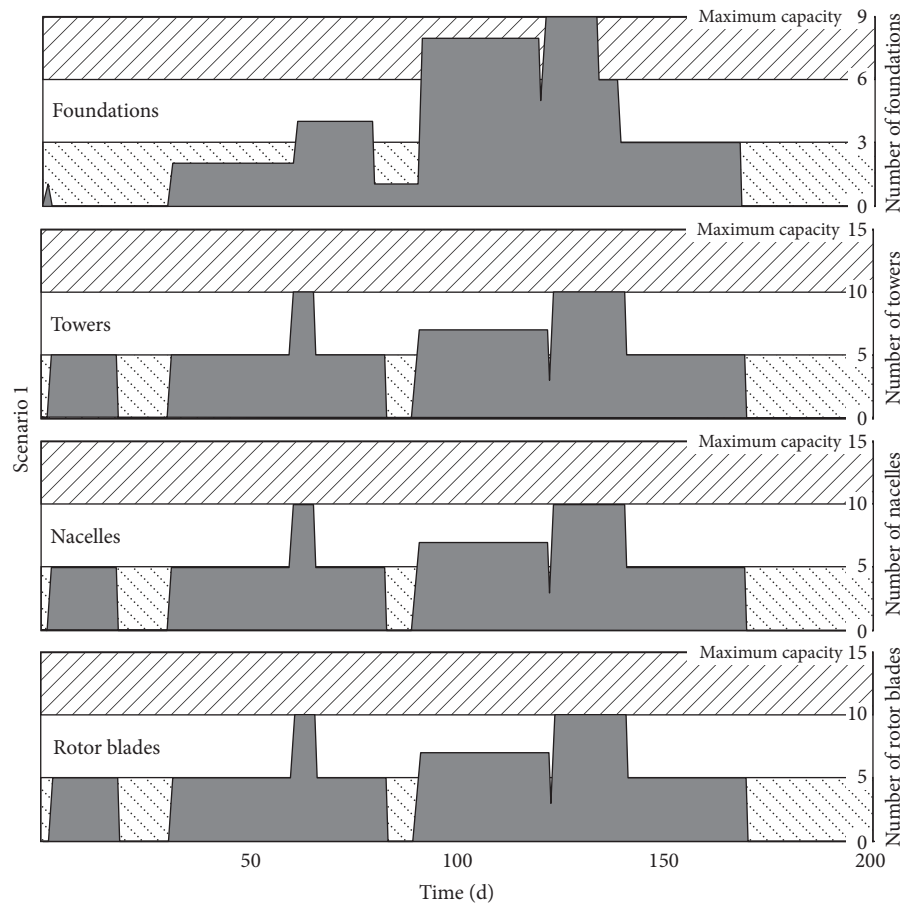FIGURE 3: Performance measures of four information sharing scenarios.

FIGURE 4: Simulation results of Scenario 1.

forecast data on the performance of the installation process. In this context, a weather-based shipping policy is adopted. This implies that components are shipped from manufactures only when the weather forecast allows their installation. The results of Scenario 3 show that the installation takes about 195.5 days and the average time that a component spends in the port is 20.67 days. The average vessels time usage is 174.5 days which is about 89.28% of the total installation time.

Compared to Scenario 1, the total installation time does not improve, because of the uncertainties related to weather
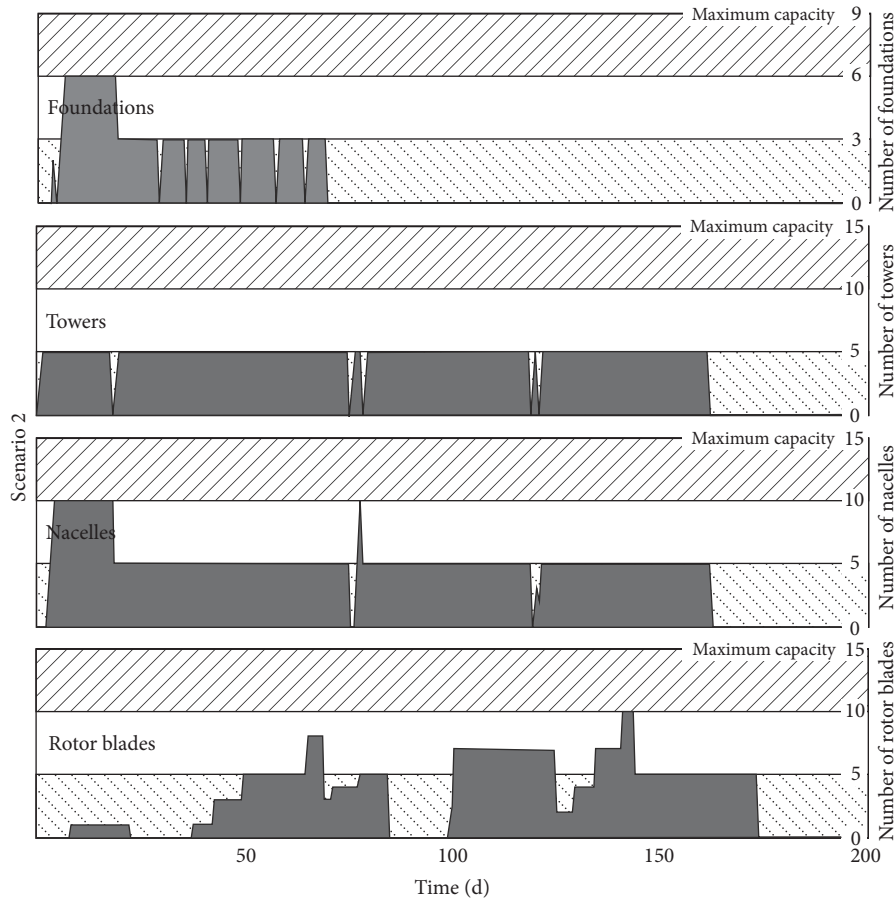
Figure 5: Simulation results of Scenario 2.

forecasts. For example, a forecast of bad weather leads to a lower supply of components in the port of shipment. If the actual weather is better than forecasted, this could lead to an insufficient supply of components to perform all feasible installation processes.

The AVTP for foundations is 13.5 days in Scenario 1, the AVTP for foundations in Scenario 3 (13 days) has only a marginal improvement when considering the weather forecasts. This is explained by the moderate weather restrictions for the installation of foundation structures. Regarding the rotor blades a significant improvement can be monitored due to the much greater influence of weather conditions on the feasibility of rotor blade installations. Moreover, the results indicate that the sharing of weather forecast data reduced 6.8% of the average time that a component spends in the port, which corresponds to a reduction of 1.5 days. Furthermore, the vessels time usage is reduced by 6.5 days.

Scenario 4 (port capacity and weather forecast information sharing). The results of Scenario 4 show that the installation takes about 181.5 days and the average time that a component spends in the port is 17.67 days. The average vessels time usage is 150 days which is about 82.62% of the total installation time.

Compared to merely exchanging port capacity (Scenario 2) or weather forecasts (Scenario 3), Scenario 4 provides better performance measures.

Scenario 4 provides the shortest total installation time because of the combination of Scenarios 2 and 3. The port capacities are utilized in an efficient way and, more importantly, good weather conditions can be exploited for installation processes. Sufficient components on stock in the port of shipment at times of sufficient weather conditions secure an efficient offshore wind farm installation.

In comparison to Scenario 1, the utilization of the port capacities for foundations can be reduced by 55.56%, for towers by 7.32%, for nacelles 27%, for rotor blades by 8.44%, and for the total port capacity by 20.36%.

7. Conclusion

In this paper, we evaluate the value of information sharing in the installation process of offshore wind farms. We identify the relevant information items, whose sharing contributes to an improvement of the installation process. To this end, a process mapping and analysis were conducted. By means of a simulation study, we investigated the benefit of sharing
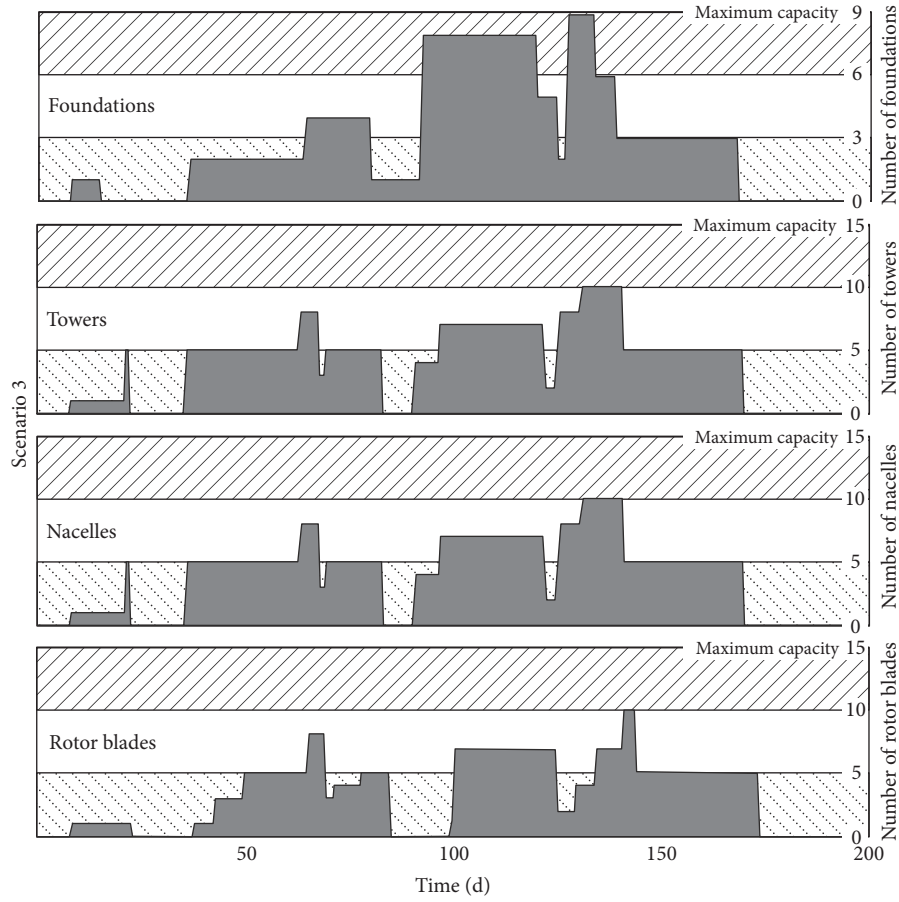
FIGURE 6: Simulation results of Scenario 3.

weather data and port capacity during the whole installation period of an offshore wind farm. Thus, 3 performance measures are used to assess different information scenarios. We found out that information sharing improves the performance of the installation process. It should be noted that the impact of sharing weather forecast data may be influenced by quality of the weather forecast. In this context, bad weather forecast data may be affecting the performance negatively, because some decisions will be taken based on this weather forecast and cannot be executed. This situation leads to undesirable efforts and higher costs. In future works, more information items and performance measures will be taken into consideration. Furthermore, the impact of information quality should be investigated.

Parameters

N: Number of wind turbines

v: Index of a vessel

s: Index of an information sharing scenario, with $|s| = 4$

m: Type of component ($m \in [F, T, N, R]$; foundation, tower, nacelle, and rotor)

WC: Set of weather condition categories: {Cat1, Cat2, Cat3, Cat4, Cat5}

t: Index of the planning period

Δt: Time interval unit (1 h); $\forall t \in T$, $t_{i+1} - t^i = \Delta t = 1$

PCm: Port capacity of component of type m

WIm: Weather condition category to install component of type m

ITm: Time required to install the component of type m

XC$mvst$: Number of components of type m built by vessel v in planning period t under information sharing scenario s. As a result the number of components of type m built until the planning period t under information sharing scenario s is $XC_{mts} = \sum_{(i=1)}^{t} \sum_{(v=1)}^{V} XC_{mvsi}$

TPcmi: Time that the component cmi spent in the port before being transported to the installation side

Ts: Planning horizon (set of planning periods) needed to install N wind turbines under information sharing scenario s that means $\forall m$ $XC_{mTs} = N$.
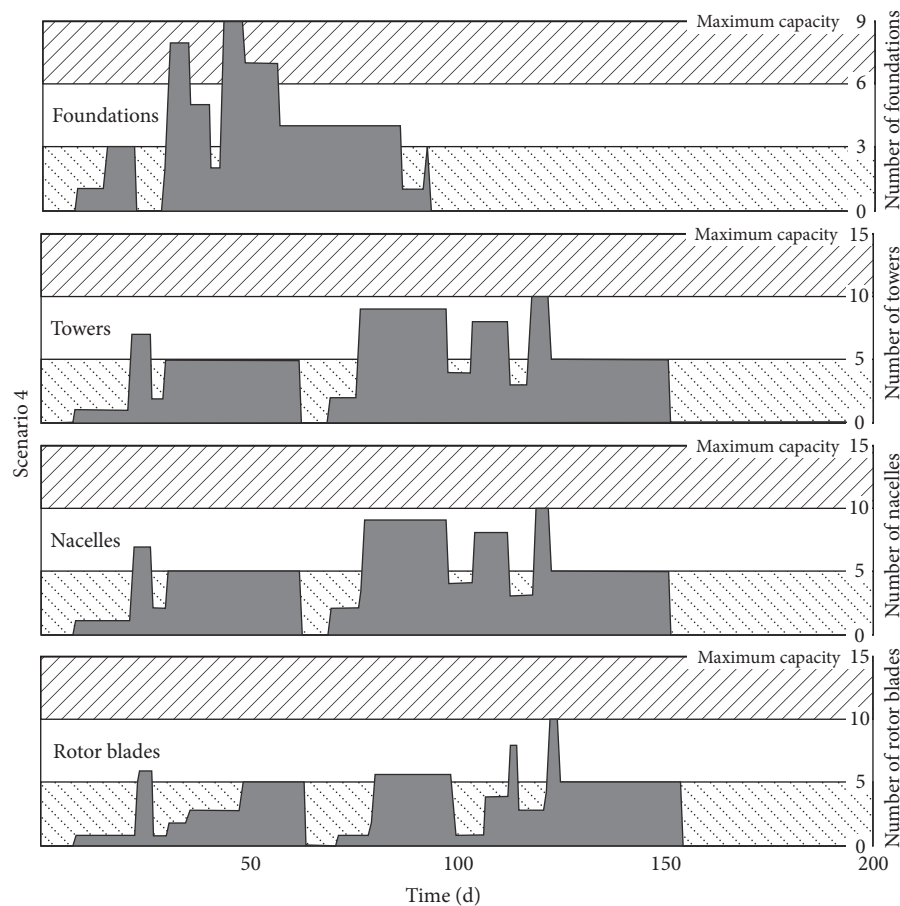
FIGURE 7: Simulation results of Scenario 4.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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