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Improving logistics scheduling and operations to support offshore wind construction phase

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ABSTRACT

The increasing construction of offshore wind farms and the expected improved profitability call for a better efficiency in offshore logistics. The purpose of this study is to propose scheduling and operations improvements for logistics to support offshore wind construction. The study conducts a literature review of scientific studies on the offshore wind logistics. Based on this review, a definition of offshore wind logistics during construction phase is proposed. It can be seen that only a few studies have focused on offshore wind logistics (except installation vessel) during wind turbine construction phase. To help closing this gap, a model is proposed to evaluate and select offshore logistics spread in order to support construction phase. Results on simulations show that logistics spread efficiency varies depending on the season, distance to shore and geographical location. Adaptation and combination of logistics concepts may be necessary to achieve best cost efficiency. The results are important as a basis for further empirical studies in this area. At the end, we propose research areas for operational improvements.

KEYWORDS: offshore wind construction · offshore logistics · efficiency · cost optimization model

“This article is part of a focus collection on ‘‘Dynamics in Logistics: Dynamics in Maritime and Transport Logistics“

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1. INTRODUCTION

Offshore wind is a young, evolving and promising industry. Wind energy is a well-accepted source for energy production because it is clean, free and renewable. Compared to the onshore wind industry, there is more space available at sea and offshore wind turbines are considered to generate less visual and noise pollution as the turbines are installed relatively far away from the coasts. Offshore winds are stronger and more constant, which gives better turbines output rates.

The main challenge for the offshore wind industry is profitability. The Levelized Cost of Electricity (LCOE) is an indicator of the profitability of an energy source. LCOE can be seen as the lifetime cost of an energy source per unit of energy generated [41]. LCOE for offshore wind used to be substantially higher (0.13 $/kWh median) than the other common energy sources, for instance onshore wind (0.07 $/kWh median), coal (0.07 $/kWh median) and nuclear (0.08 $/kWh median) [26]. It then appears crucial that offshore wind energy improves its LCOE for better acceptance. The industry is already showing some improvements and latest auction results (in Germany [9] or Belgium [13]) suggest that offshore wind LCOE might decrease to between 0.06 and 0.10 $/kWh by 2020 [17].

A way to achieve such LCOE target is to reduce the investment expenditures. The investment expenditures are estimated to represent between 19 and 23% of the sum of costs over lifetime [46]. Conducting efficiently the construction offshore of the wind turbines can contribute to minimize investment expenditures. More precisely, installation and logistics during construction, represent an area where substantial cost reductions could be achieved [28]. Prognos & Fichtner Group finds that a large part of the LCOE reduction initiatives are related to logistics [31] and according to Weise et al. [47], efficient logistics planning and controlling is expected to contribute significantly to cost savings. Moreover, a high number of offshore wind farms in the world are under construction or in pre-construction [1]. We see therefore a need for researchers and practitioners to investigate deeper on how to improve logistics during offshore wind turbine, especially during construction phase. Increasing distances from the coast [30] and rising sizes of the wind turbines [7] are also making the subject even more relevant due to more difficult logistical challenges [40]. If this objective can be reached, the wind turbine providers could potentially improve their construction costs and contribute to a better LCOE.

In this context, this study aims to develop a model for the construction costs of offshore logistics fleet and identify areas of improvement. This leads to the following research questions:

1. How to evaluate and compare possible offshore logistics spread to support wind turbine construction phase?
2. What can be done during construction project execution to improve the usage of offshore vessel fleet?

This paper commences with a literature review in Chapter 2 to explore the available knowledge on offshore wind logistics and identify research areas of improvements. A description of the methodology adopted is presented in Chapter 3. A model to plan vessel fleet and its parameters and structure are explained in Chapter 4. Chapter 5 explores improvements for logistics operations. This paper concludes with the findings of this contribution as well as with an outlook on the subject matter for subsequent research.

2. LITERATURE REVIEW

A literature review was conducted in two phases: selection and analysis. The selection phase was done by collecting a comprehensive set of articles in the focused areas, while the analysis phase was a careful and critical examination of the articles to identify patterns and recurrent themes [11].

For articles collection, several search engines, such as Google Scholar, ResearchGate, Harvard Business School Baker Library and combination of keywords (“offshore logistics”, “offshore wind”, “construction”, “planning” and “operation”) were used to identify existing knowledge related to both research questions. 26 articles were found relevant and selected for this research, published between 2009 and 2018.

A first literature analysis was conducted to understand what the concept of logistics means in the context of offshore wind industry during construction phase. Poulsen and Hasager [30] propose an all-encompassing definition for offshore wind logistics: “*Parts, modules, components, people and tools are responsibly stored and moved safely, weather permitting, onshore, as well as offshore by air/ocean/land using various transportation assets and transport equipment*”. Kaiser and Snyder [19] provide a more specific description of logistics for wind turbine during construction phase: “*We begin by classifying main installation vessels, cable installation vessels, and spread vessels. Main installation vessels are used to install foundations, turbines and substations. Cable installation vessels install inner-array or export cable. Spread vessels support the other two categories through crew and material supply, anchor handling or towing*”.

Scope of this study is the construction phase of the offshore wind turbines only. Components considered are tower, nacelle and blades (excluding foundation). Other phases of wind turbine lifecycle have been excluded, i.e. planning and development, foundation and substation construction, operation and maintenance, decommissioning and repowering. As instance, planning and development phase is involving different type of vessels such as survey vessels which do not need to transfer technicians on turbine, but conduct specific type of survey, hence a different problematic that the one encountered during construction phase. Also, construction phase has limited duration (around 1-year duration for a typical wind farm) with intensive use of logistics compared for example to operations and maintenance phase which is spread over a longer period (around 20 years) with more punctual or regular use of logistics. More precisely, offshore wind turbines construction phase may be split in the following activities: pre-assembly works in base harbor (activity 1), transport of wind turbine components from base harbor to offshore site (activity 2), installation or mechanical completion at the offshore site (activity 3), completion works offshore (activity 4), commissioning offshore (activity 5), trial operations offshore (activity 6), quality walk-downs and non-conformities correction before taking over and start of operation and maintenance phase (activity 7). To support activities 2 and 3, main installation vessel is used. Often called jack-up vessel, it is a specialized vessel with retractable legs which can be lowered into the seabed to jack-up the vessel above the surface of the water and provide a stable platform which reduces the sensitivity of operations to the sea conditions [5]. To support activities 3 to 7, different types of support vessels are used. Like main installation operations, it is also possible to use jack-up vessels. The accessibility to wind turbines offshore is then possible with gangways. Without entering into details, other type of support vessels can be Crew Transfer Vessel (CTV), accommodation vessel or “hotel vessel”, with eventually special functionalities such as Dynamic Positioning (DP) associated with transfer system (i.e. Ampelmann, Safeway or SMST system), or helicopters.

Based on above mentioned definitions and scope of this study, offshore wind logistics definition is reframed and proposed as follow: “*Main vessel(s) that transport and install wind turbine components between base port and wind farm location and support vessels that transport material and technicians to complete wind turbine construction*”.

A second literature analysis was conducted to understand the problematics encountered by logistics during offshore wind turbine construction and solutions currently proposed for planning phase. Based on our definition for offshore wind logistics during construction phase, the intention of this second literature analysis was to classify the papers in 2 categories: main installation vessel (1) and support vessels (2).

Most of the literature found was classified in category 1. Thomsen [42] provides a comprehensive description of the installation process, with detailed installation vessel characteristics. Skiba [39] introduces the challenge of installation: work at sea, work at great heights and heavy lifting works. According to the author, in 2010, availability of vessels was extremely limited and design of existing vessels did not meet offshore needs. Multiple studies have been conducted to improve the use of installation vessel, which has been identified as the bottleneck of installation process [36]. It is, therefore, understandable to see a research focus on installation vessel planning. European Wind Energy Association [14] presented in 2009 a method allowing a dynamical installation planning of shorter time periods based on up-to-date weather forecasts. Scholz-Reiter et al. [35, 36] apply a Mixed Integer Linear Programming (MILP) model to identify the optimal installation schedule for different weather conditions and the loading operations. They acknowledge the stochastic nature of weather conditions and express an interest in developing their tool and assessing further the impact of weather uncertainty. The proposed model is only applicable to small scenarios. Same author [37] presents a model capable to solve larger problems by considering longer periods of time, multiple vessels and a wider range of weather conditions. Lange et al. [23] propose a discrete simulation tool of the supply chain in order to consider available weather windows at sea optimally and use installation units efficiently. Ait Alla et al. [2] also propose a MILP model to optimize installation planning with minimal costs and address the problem of the aggregated installation planning of OWFs. Their approach considers the weather in a deterministic manner and reviewed the outcome of two installation scenarios. Barlow et al. [4, 5] present a simulation tool capable to compare the impact of various installation scenarios in terms of duration and costs and in further study determine key characteristics of an installation vessel for reducing the duration of the offshore wind farm installation. Irawan et al. [16] address optimal installation scheduling with an Integer Linear Programming (ILP) method taking into consideration weather data and vessel availability. Muhabie et al. [25] use discrete event simulation and consider weather restrictions, distances, vessel capabilities and assembly scenarios. Ritter [33] assesses for installation phase with a self-developed simulation tool the weather dependent processes relating to the entire duration for the restrictions defined, the total weather loss and time saving potentials. Sarker and Faiz [34] present a cost model developed for wind turbine installation and transportation and analyze the impact of decision variables on total cost. Vartdal [43] investigates several installation scenarios, including installation with a jack-up vessel, installation with a jack-up installation vessel and feeder vessels to support component transportation, and installation with a DP vessel. Barlow et al. [6] present an installation project in order to explore the impact of key logistical decisions on the cost and duration of the installation, and estimate that savings of up to 50% could be achieved through vessel optimization. This research area is further presented by Boulougouris [8], explaining ability to identify appropriate reactions to disrupted installation schedules (uncertain task durations, unplanned vessel breakdowns or uncertain weather conditions) using a rolling-horizon optimization tool. Backe [3] presents a logistical planning of offshore wind farm installation through mathematical optimization. Two optimization models are developed to analyze cost-effective port and vessel strategies for offshore installation operations. By applying MILP, the two models attempt to minimize total costs through port and vessel related decisions. Paterson et al. [29] present a software tool, using Monte Carlo simulation in conjunction with embedded forecasting and logistical models that played out the operations across a set of stochastic weather scenarios. The tool provides time-domain predictions for the completion of key installation phases. Based on experience and research, some installation assembly strategies have been recommended in literature: Maples et al. [24] propose specialized turbine assembly procedure instead of assembling turbine offshore as individual components. Navigant Consulting [27] review the evolution of installation concepts in the previous ten years. Vis and Ursavas [45] suggest a pre-assembly strategy comprised of a minimum number of components for installation onsite and a maximum number of turbines to be loaded on a vessel.

Literature described above is mainly focused on the main installation vessel planning and optimization and it appears that this research topic is prominent. Therefore, there is no intention on the present paper to push it further. It appears, nevertheless, that further academic contribution could be done considering operation and execution of main installation vessel. In order to tackle this gap, we try to answer research question 2.

Concerning category 2, research related is scarce. Thomsen [42] provides a comprehensive description of the type of vessels used for this phase, with detailed vessels characteristics (CTV types and offshore access systems). Navigant Consulting [27] also gives a description of possible types of vessel that could be used during construction phase and discusses some offshore logistics concepts such as accommodation vessel with “satellite” CTVs. However, it was not found any dedicated literature on how to properly plan and improve offshore logistics spread during construction phase. Considering this research gap and research question 1, the present paper aims, therefore, to develop an appropriate plan for offshore support vessels.

3. METHODOLOGY

To answer research question 1, a quantitative approach was adopted. The goal was to develop a model that is capable to evaluate and compare possible offshore vessel spreads during construction phase. The proposed model was based on Time-Driven Activity-Based Costing (TDABC) [21]. TDABC method can measure simply and precisely the cost to a more targeted level, enabling companies to carry out further analysis of the costs. For each resource, estimates of only two parameters are required: the cost per time unit of supplying resource capacity (in this contribution case, vessels, technicians and staff costs) and the unit times of consumption of resource capacity by products, services, and customers. The cost-driver rates can then be calculated by multiplying the two inputs. Kaplan and Anderson indicate that TDABC method can accommodate the complexity of real-world operations by incorporating time equations, a feature that enables the model to reflect how order and activity characteristics cause processing times to vary [20]. One of the main objectives of the model is to calculate the cost of an efficient hour worked in the turbine depending of the vessel spread used. If it were possible to calculate such indicator, it would be useful for vessel spread selection and improvement.

The steps followed in this work are described in Fig. 1. The actual system is a specific logistics setup for an offshore wind farm construction. The objective is to transfer technicians in wind turbine as efficiently as possible. Additional staff is supporting such logistics. Based on this system definition, a TDABC model is developed. Once the model is defined, simulations are run for representative logistics scenarios. Variation of one input parameter at a time is used. The conducted experiments comprise several runs of the simulation for the defined scenarios. This ensures the comparability of the scenarios. The results of the simulation experiments are presented in different cases. Finally, the simulation results are discussed. Based on experiment results, some patterns are identified and some recommendations are drawn to improve offshore vessel fleet planning.

In turn, to answer research question 2, qualitative research is adopted. The objective is to identify key research areas for efficient execution during construction phase.

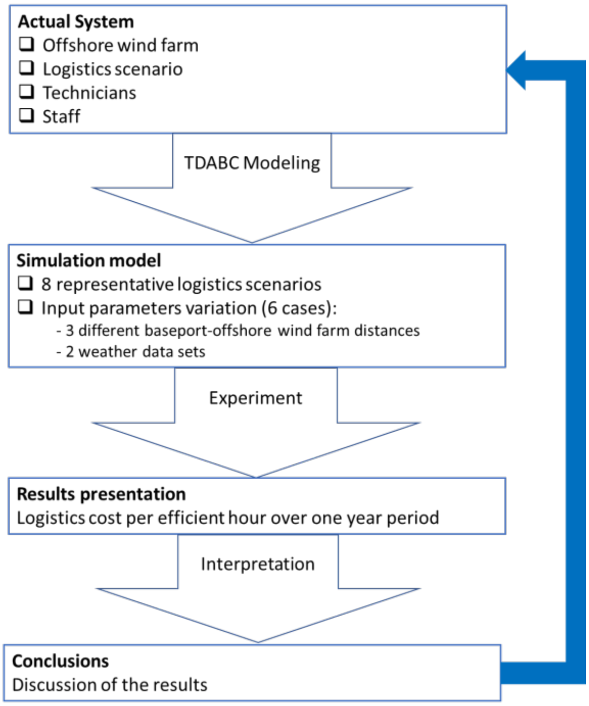

Fig. 1: Model Development Approach

4. MODEL TO IMPROVE OFFSHORE VESSEL FLEET PLANNING

4.1. Model key parameters

To assess offshore wind logistics during operation and maintenance phase, Jahn [18] identified several parameters that influence logistics setup choices such as climate conditions, distance or number of vessels. Based on findings of such work and empirical research to fit TDABC concept, key parameters are selected for the proposed model: weather data, distance from shore to wind farm, technician working hours per day, technician efficient working hour per day, support vessel costs, efficiency and maximum capacity and staff cost per day. Some parameters from Jahn are discarded, such as components quality as this is not a consideration for offshore logistics during construction phase. These key parameters are described below while an exhaustive model parameters list is provided in Appendix A.

4.1.1. Weather data

According to International Standard ISO 29400 [15], marine operations are generally weather-sensitive. They require specification of weather windows of minimum duration and operational limits on metocean parameters. Setting the operational limits too high can lead to unacceptable risk, whereas setting the limits too low can lead to excessive wait on weather or weather downtimes.

One of the main criterias for supporting vessels during construction phase is significant wave height (Hs) criteria. It represents the mean wave height (crest to trough) of the one-third highest waves [15]. According to Lange et al. [23], with significant wave heights more than one meter, works become extremely difficult or even impossible. A temporary suspension of the work must be taken into account in logistics concepts. Lange et al. says that the work is stopped at a swell of 1.5 meters Hs for safety reasons. In this study, it was assumed that a technician could be transferred by regular CTV up to 1.2m Hs, by high performance CTV up to 1.5m Hs, by small DP vessel with transfer system up to 1.8 m Hs, by large DP vessel with transfer system up to 2m Hs and jack up barge up to 2.3m Hs. These limits depend on the type of vessel used and the operation considered. They may be updated as improvements have been implemented in the industry since the study was conducted.

Wind restriction and daylight are relevant criteria in particular for helicopters. Usually, helihoist operations are not considered safe over a certain wind limit and at night. In this study, it was considered 23 m/s gust wind limit and nautical twilight restriction for such helihoist operations. Other weather criteria, such as visibility, currents, wave periods, temperatures, ice conditions may also be relevant but have not been considered in this study.

4.1.2. *Distance from shore to wind farm*

Distance (D) between base port and offshore wind farm is considered. D is an important parameter as offshore logistics travel durations are affected: when a technician is transported with a vessel from base port to a wind turbine the higher the distance, the longer the travel time and the less time available to work in the wind turbine.

4.1.3. *Technician working hours per day*

Technicians working hours per day ($Tech_{Day}$) is another key parameter considered since it is one of the main resource constraints of the problem. In principle, technicians are allowed to work a maximum of 12 hours per day offshore. This default value was used in the study.

4.1.4. *Technician efficient working hours per day*

Technicians usually do not work efficiently during their full shift in the wind turbine. For that reason, some inefficient times were identified: briefing / meetings / administration times ($Tech_{Admin}$); transfer time from the original location to the wind turbine ($Tech_{Transfer}$). $Tech_{Transfer}$ is dependent on the type of offshore logistics used; preparation time, such as putting on or off personal protective equipments ($Tech_{Prep}$); and break allowance ($Tech_{Break}$). According to regulations this break should last 1 hour per day. Technician efficient working hours per day ($Tech_{EffDay}$) is then calculated as follow

$$Tech_{EffDay} = Tech_{Day} - (Tech_{Admin} + Tech_{Transfer} + Tech_{Prep} + Tech_{Break}). \tag{1}$$

4.1.5. *Support vessel costs, efficiency and maximum capacity*

Variable costs are considered for each type of vessel: charter cost ($V_{Charter}$); bunker cost (V_{Bunker}); port fees (V_{Port}); agent fees (V_{Agent}); accommodation costs in case CTV crew is staying offshore overnight (V_{Acco}); communication costs (Internet, phone…) (V_{Comm}) and maintenance cost (V_{Maint}). It is usually considered one-day maintenance per month in the industry. For each cost, indicative values were used in the model based on industry standards and experts' knowledge.

Vessel variable V_{VCost} is thus calculated as follow

$$V_{VCost} = V_{Charter} + V_{Bunker} + V_{Port} + V_{Agent} + V_{Acco} + V_{Comm} + V_{Comm} + V_{Maint}. \tag{2}$$

Fixed costs considered are insurance costs (V_{Insur}) and mobilization / demobilization costs ($V_{Mob/Demob}$) of the vessel. Such costs are project specific. For the exercise, indicative values were used and spread over one-year period. Vessel fixed cost per day (V_{FCost}) is then calculated as follow

$$V_{FCost} = V_{Insur} + V_{Mob/Demob}. \tag{3}$$

Vessel total cost per day (V_{TCost}) is calculated as follow

$$V_{TCost} = V_{VCost} + \frac{V_{FCost}}{Vessel\ Hire\ duration}. \tag{4}$$

Other variable cost which is considered separately was accommodation cost of personnel ($Tech_{Acco}$) either onshore (in hotel) or offshore (on accommodation vessel). A vessel efficiency rate ($V_{Efficiency}$) is also considered. It shows if the vessel is capable to support transfer of technicians or material in wind turbine. Some inefficiencies are identified: vessel break downs (V_{Break}); refueling time (V_{Refuel}); permitting issues (V_{Permit}); crew change (V_{CC}); transit without transfer purpose ($V_{Transit}$) and other (V_{Other}). Indicative values are used in the model and need to be adjusted to project specificities. Vessel efficiency rate ($V_{Efficiency}$) is calculated as follow

$$V_{Efficiency} = 1 - (V_{Break} + V_{Refuel} + V_{Permit} + V_{CC} + V_{Transit} + V_{Other}). \tag{5}$$

Maximum accommodation capacity of the vessels (V_{Capa}) is also considered.

4.1.6. *Staff cost /day*

Day rates are considered and given indicative values: technician offshore ($Staff\_Cost_{Tech}$); overhead office ($Staff\_Cost_{OH\_Office}$) and overhead offshore ($Staff\_Cost_{OH\_Offshore}$). Likewise, indicative values are used in the model and need to be adjusted to project specificities.

4.2. Model description

As indicated earlier, one of the main objectives of the model is to calculate the cost of an efficient hour worked in the turbine depending of the vessel spread used. The efficient working hours per month per technician ($Tech_{EffMonth}$) is calculated as follow

$$Tech_{EffMonth} = Month_{Days} \times W_{P50Month} \times Tech_{EffDay} \times V_{Efficiency}. \quad (6)$$

$Month_{Days}$ is the number of planned hiring days per month. $W_{P50Month}$ is the vessel accessibility to a wind turbine with a probability of 50% (P50) for a particular month (in %). For each scenario, vessel quantities (V_{Qty}) are determined. Total capacity is summed up by vessel type ($V_{SumCapa}$) as follow

$$V_{SumCapa} = V_{Qty} \times V_{Capa}. \quad (7)$$

The number of offshore technicians ($Staff\_Numb_{Tech}$), overhead personnel in office ($Staff\_Numb_{OH\_Office}$) and overhead personnel offshore ($Staff\_Numb_{OH\_Offshore}$) are specified for each scenario. The following rule needs to be respected: technicians and overhead personnel are accommodated offshore on the accommodation vessel. Therefore, for accommodation vessel types

$$V_{SumCapa} > (Staff\_Numb_{Tech} + Staff\_Numb_{OH\_Offshore}). \quad (8)$$

If there is no accommodation vessel, and only transfer vessel types

$$V_{SumCapa} > Staff\_Numb_{Tech}. \quad (9)$$

For this study, we assumed an arbitrary but realistic number of 100 technicians to transfer daily offshore. This number needs to be adapted to the specificity of the project considered. Total number of technicians efficient working hours in wind turbine per month ($Tech_{EffMonth}$) is estimated as follow

$$Tech_{SumEffMonth} = Staff\_Numb_{Tech} \times Tech_{EffMonth}. \quad (10)$$

Let *i* be the vessel type and *j* be the staff type. Then

$$Logistics\_Cost_{Month} = \sum_{i=1}^{n} (Month_{Days} \times V_{Qty} \times V_{TCost} + (Staff\_Numb_{Tech} + Staff\_Numb_{OH\_Offshore}) \times Tech_{Acco}) \quad (11)$$

$$Staff\_Cost_{Month} = \sum_{j=1}^{n} (Month_{Days} \times Staff\_Numb \times Staff\_Cost) \quad (12)$$

$$Total\_Cost_{Month} = Logistics\_Cost_{Month} + Staff\_Cost_{Month} \quad (13)$$

equations (11), (12) and (13) show the logistics cost per month, the staff cost per month and the total cost per month, respectively.

The model output, i.e. key indicator that shows the cost per technician efficient hour in wind turbine (cost/efficient hour) can then be estimated as follow

$$Cost/efficient\ hour = \frac{Total\_Cost_{Month}}{Tech_{SumEffMonth}}. \quad (14)$$

4.3. Model simulation

Simulation was conducted with the proposed model by assessing different scenarios and analyzing impact of key parameters (one parameter change at a time). In order to assess and predict weather conditions, historic data were used. It was adopted two set of data from different local sites to analyze how the areas of operation could have an influence on offshore logistics. The representative weather databases found and available for this study are the DHI metocean dataset at WP1 from 1992 to 2009 (Baltic Sea) and GKSS and Helmholtz Geestacht from 1958 to 2007 (North Sea). It was then considered operational limitations (significant wave height and wind speed). Each operational limitation was compared with the weather data. When the weather conditions did not exceed the defined operational limitations, it was determined that the vessel could operate and accessibility to the wind turbine was possible. If an operation limitation was exceeded, the operation was stopped, and weather downtime was considered. To evaluate vessel accessibility to a wind turbine, a P50 probabilistic estimate was considered. P50 means there is 50% chance that the weather will exceed the specific operation limitation criteria and 50% of otherwise. This approach maximizes the predictability and avoid overly conservative estimation that would overuse capital and resources. A P50 value was calculated for each month of each year from the weather databases. The mean value for each month of the different years from the databases was then calculated. $W_{P50Month}$ is used in this study to refer to a particular P50 value of a specific month.

Considering the two types of weather with a P50 value and three distances (D=20nm, 40nm and 80nm), we were able to create six cases: North Sea P50 – D = 20nm (case 1), Baltic Sea P50 – D = 20nm (case 2), North Sea P50 – D = 40nm (case 3), Baltic Sea P50 – D = 40nm (case 4), North Sea P50 – D = 80nm (case 5), Baltic Sea P50 – D = 80nm (case 6). In each case, we then varied height vessels combinations, leading to 8 scenarios: 5 regular CTVs from shore (scenario 1), 3 high performance CTVs from shore (scenario 2), 3 regular CTVs + 1 accommodation vessel (scenario 3), 2 high performance CTVs + 1 accommodation vessel (scenario 4), 2 high performance CTVs + 2 small DP vessel (scenario 5), 2 high performance CTVs + 1 large DP vessel (scenario 6), 1 high performance CTV + 1 jack up barge (scenario 7) and 10 helicopters (scenario 8). The model was run on monthly basis over one-year period.

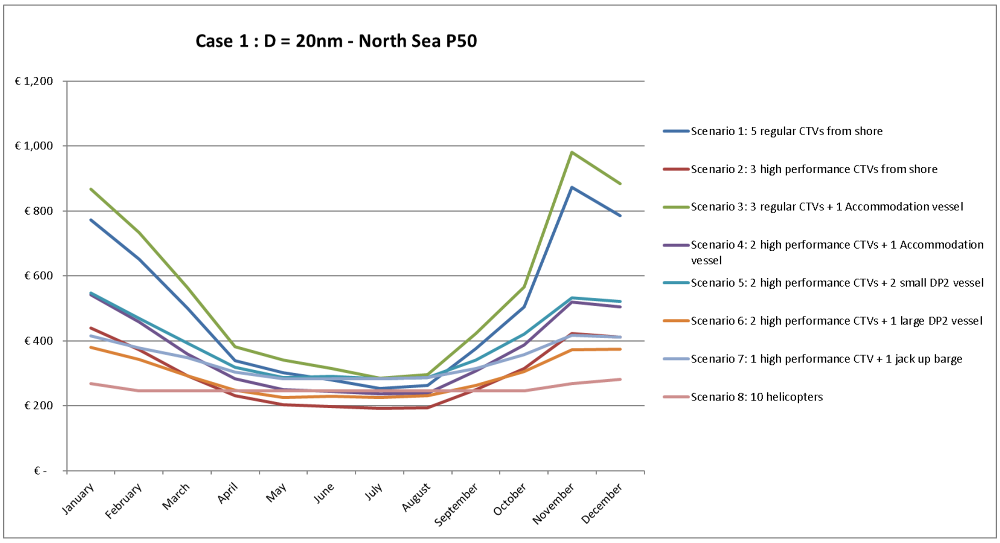

Fig. 2a: Case 1

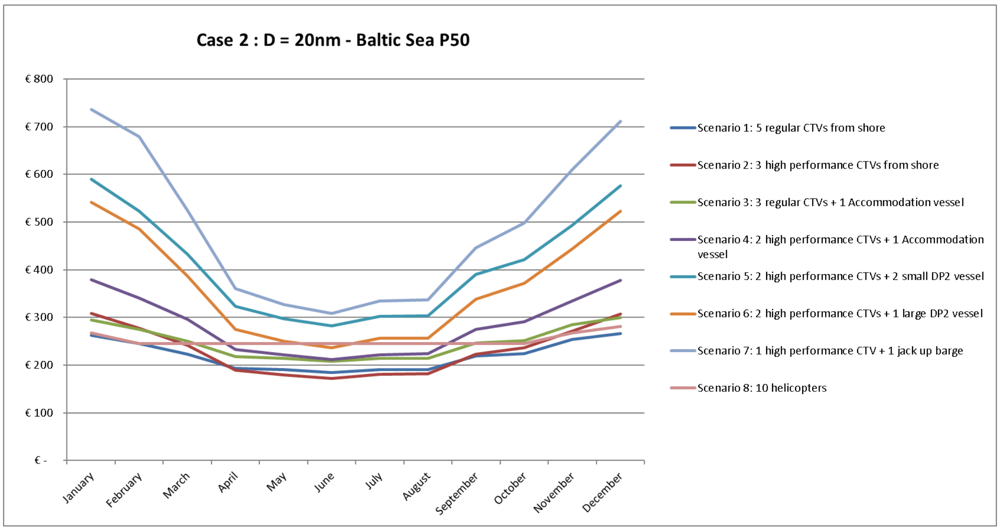

Fig. 2b: Case 2

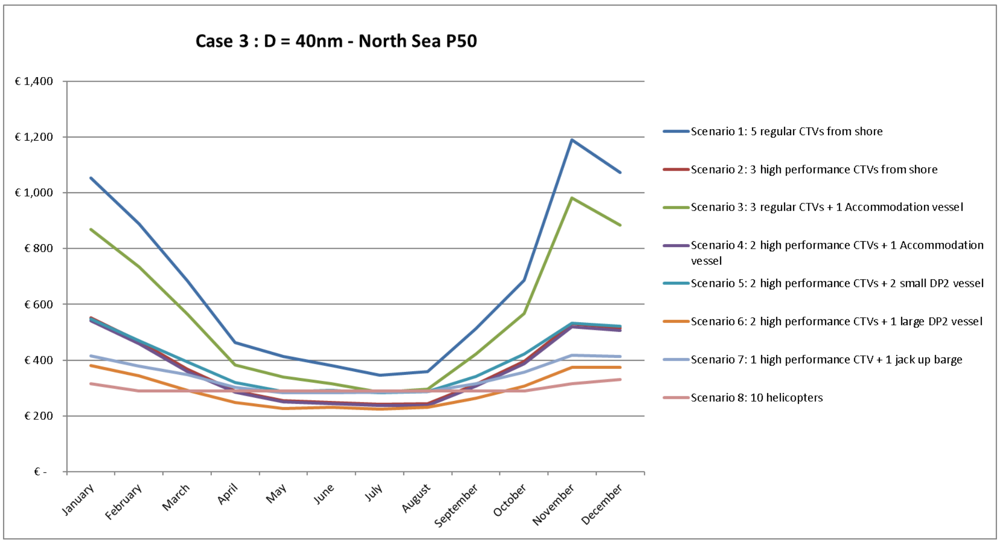

Fig. 2c: Case 3

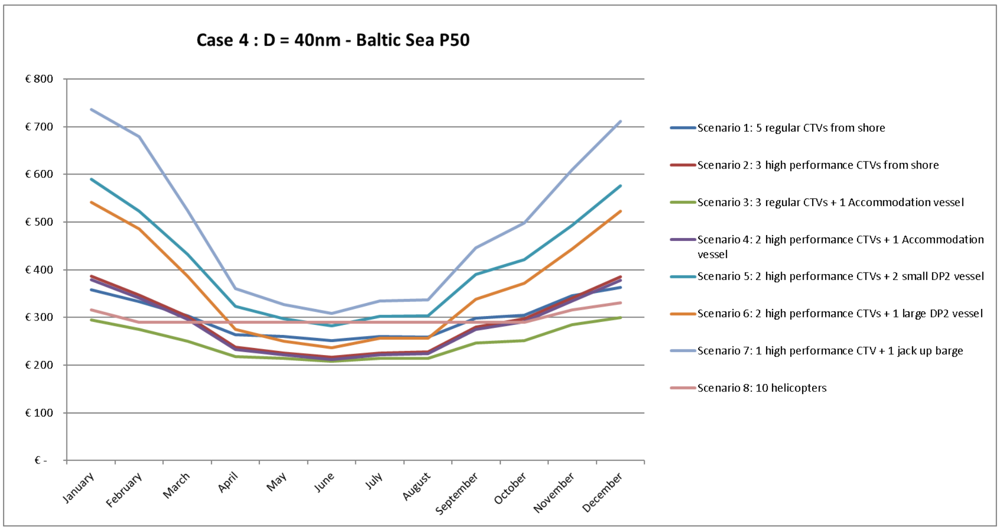

Fig. 2d: Case 4

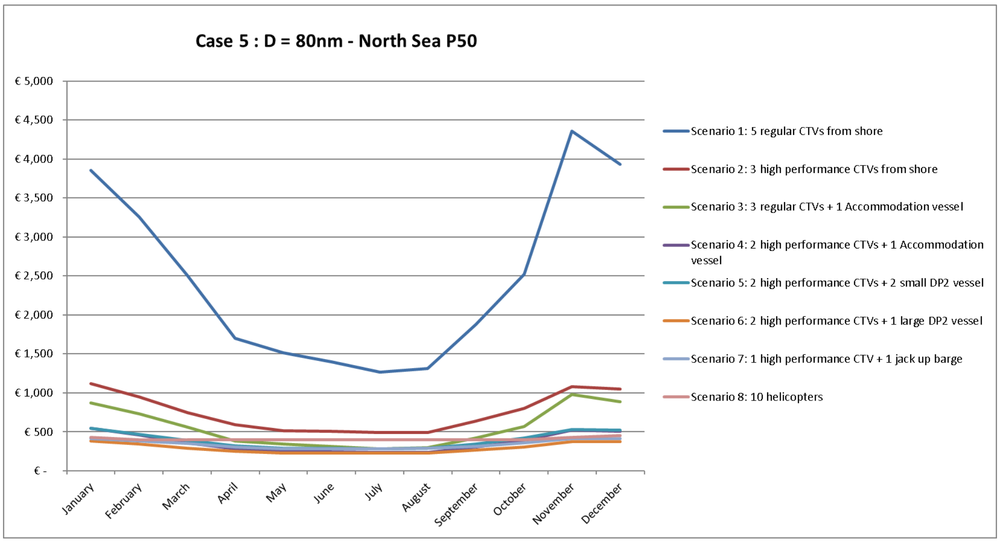

Fig. 2e: Case 5

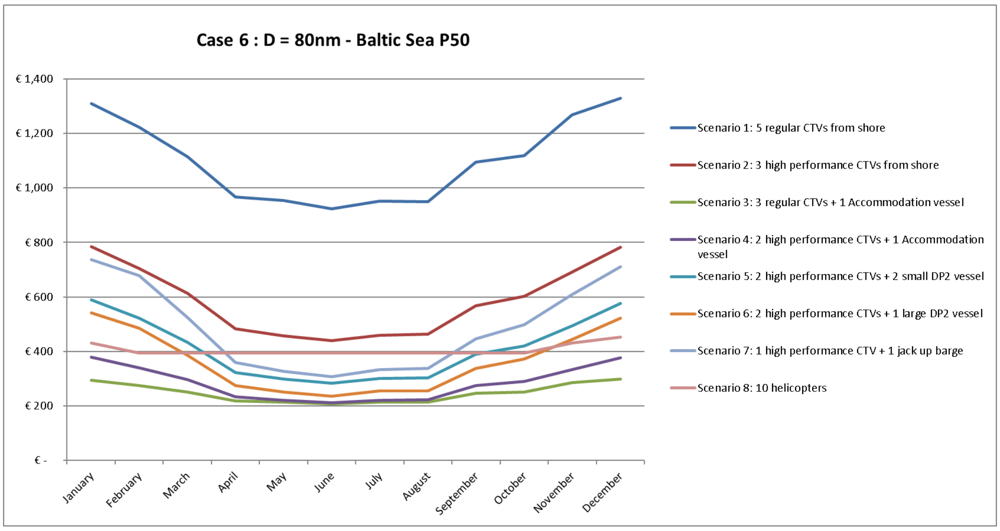

Fig. 2f: Case 6

4.4. Results discussion and limitations

The results from simulation are presented in Fig. 2a-f. They show that there is a seasonality factor in the vessel spread efficiency. Influence is more visible on regular CTVs, i.e. curve has a V-shape (see, for instance, Fig. 2c, scenarios 1 and 3) and less visible on helicopters, i.e. curve is flatter (see, for example Fig. 2c, scenario 8). Hence, the results confirm that it may not be appropriate to always have the same vessel spread during the whole year. As example, in case 3, from November till February, scenario 8 is the most efficient setup while from March till October, scenario 6 is the most efficient setup.

An identical vessel spread may not have the same efficiency in different geographical locations. For instance, scenario 6 in cases 3 and 4 (see Fig. 2c and 2d) is the most efficient in North Sea but not in Baltic Sea. In Baltic Sea in case 4, scenario 3 is the most efficient.

Distance is a key influencing factor to select vessel spread. If we compare cases 1, 3 and 5, the more efficient vessel spread differs (combination of scenarios 8 and 2 for D=20nm; combination of scenarios 8 and 6 for D=40nm; scenario 6 only for D=80nm). According to Smith et al. [40], for projects that are at a medium distance from port (between 40 km to 70 km), operators are testing vessels with higher vessel speed (from 20 to 35 knots) and higher transfers limit (from 1.5 m to 2.5m Hs). This is confirmed by proposed model results (cases 3, 4, 5 and 6). Regular CTVs are not as cost efficient as high performance CTVs, especially in the North Sea. This is not as conclusive for Baltic Sea, when regular CTVs combined with an accommodation vessel could be one of the best setup. Smith et al. also indicate that at greater distance from port (nominally beyond 70 km), operators are beginning to use service operations vessels (SOV). SOV can transfer technicians with motion-compensated gangways and also with CTV via their boat landing. This is also confirmed by proposed model results. In North Sea, large DP vessel combined with high performance CTV is showing the best cost benefit (Fig. 2e, scenario 6). This is not necessarily the case in Baltic Sea where accommodation vessel combined with CTVs may still be competitive when distances from shore are important (Fig. 2f, scenario 3).

5. IMPROVING OFFSHORE LOGISTICS COORDINATION AND EXECUTION

An important aspect for the success of a project is to properly coordinate and execute the plan and eventually improve the operations along the project. It is proposed with a qualitative approach to elaborate on this aspect to answer research question 2. Even if the logistics spread has been planned as accurately as possible, reality often disturbs the plan and it needs to be managed properly [48]. Indeed, changes in original plans are unavoidable particularly in offshore wind logistics domain, especially due to uncontrollable weather conditions. To cope with this aspect, integrated asset management concept is introduced by El-Thalji and Liyanage [12]. It is defined as systematic and coordinated activities and practices through which an organization optimally manages its physical assets and their associated performance, risks and expenditures over their lifecycles for the purpose of achieving its organizational strategic plan. From an operational prospective, Vedde Brathaug and Sagbakken [44] indicate that due to expensive assets rental and offshore personnel costs, it is important to improve coordination between personnel and equipments. It should be avoided that expensive equipment offshore is waiting for personnel arriving the next day or vice versa, or sending equipment and personnel offshore if the demand offshore has been postponed on short notice [44]. For logistics during wind turbine construction, based on review of industrial standards [15] and common practice, two key entities were identified to conduct this approach: marine coordination (MC) and construction management (CM).

According to International Standard ISO 29400 [15], management and coordination of the offshore activities of offshore installation vessels shall be handled by a MC function. Where simultaneous operations involving multiple vessels are planned to take place within the same area, marine control under the authority of a MC becomes necessary [32]. MC is primarily insuring to avoid unsafe conflict between vessel movements and moorings. Furthermore, in order to allow quick response and fast performance, MC allocates teams dynamically to CTVs. Vessel movements are monitored using an electronic sea chart display connected to an AIS receiver. In that respect, MC is a key contributor to the optimal use of vessel spread.

According to International Standard ISO 29400 [15], CM should develop a system that supports efficient scheduling and interfacing of the various offshore vessels working on construction site, optimize electrical and commissioning works to achieve the earliest possible export to the grid and minimize potential delays to critical timeline activities. This entity is as well key to properly handle and execute plan for offshore logistics spread during construction phase.

Berger [7] underlines that standardization and speed will become critical for the offshore wind industry competitive position. Industry actors such as Siemens Wind Power Offshore [38] have indicated that lean manufacturing is being implemented during installation phase. This is studied further in academic research, where based on some existing principles from optimizing production techniques Chartron and Haasis [10] propose an ad hoc model to measure and improve efficiency for logistics during offshore wind farms construction. Implementation of such model is crucial to improve learning curve during the project execution.

Finally, Lambert [22] recognizes that the structural management is often center of attention, but the behavioral management is usually underestimated, leading to failure. According to Lambert, five behavioral management components should be considered and encouraged: management methods; power and leadership; risk and rewards; culture and attitude; and trust and commitment. In the context of the offshore wind young industry, Lambert findings concerning behavioral management deserve further attention in the logistics domain.

6. CONCLUSION AND RECOMMENDATIONS

Offshore activities require logistics support which represents a significant part of the overall construction costs. Hence, offshore logistic costs need to be evaluated, managed and improved permanently and consistently to reduce construction costs.

In order to answer research question 1, a cost efficiency model was proposed to evaluate and compare possible offshore logistics spread to support construction phase. With this contribution, it was possible to run simulation using different cases and scenarios. Results of the model were discussed. It appears that logistics spread may have variable efficiency depending on the season, distance to shore and geographical location. Adaptation and combination of concepts may be necessary to achieve best cost efficiency. Some limitations should be considered: the proposed model used a number of assumptions that needs to be adjusted to the specificity of a project. Practitioners should thus not use results presented directly to select vessel spread to support construction. As example, helicopter costs can be very different if there is no helicopter company in the vicinity of the wind farm and would probably not be competitive in that case. Beside, visibility conditions (especially fog) were not assessed in the model due to lack of information. Such weather conditions should be carefully evaluated before selecting helicopter spread. As indicated earlier, other weather criteria, such as visibility, currents, wave periods, temperatures, ice conditions may also be relevant for some vessel types and would then need to be considered. It is recommended to verify in reality the capability of vessels by sea trials in the weather conditions where it is planned to be used before hiring. Performance announced by the vessel owner may not be as expected. As example, a CTV may not perform the same due to wave period difference in Baltic Sea and in the North Sea. Charter costs also depend on seasonality and commitment periods. Model could be further developed to take into consideration such variations and vessel costs presented should be adapted. Further scenarios could be evaluated, such as mix of regular and high performance CTVs, combination of small and large DP vessels or combination of helicopters with accommodation vessel setup. The model could also be run with technician resources evolution over the period studied. In the different scenarios studied, resources were considered constant, but it could be a valuable contribution to further analyze the impact of technicians' number evolution over the period when the scope of work to complete project construction is well defined.

Finally, a review is conducted in order to coordinate, execute and improve offshore logistics plan during construction phase and pave the way to answer research question 2. Marine coordination and construction management appear to be key contributors for proper coordination and execution. Moreover, standardization, lean management and behavioral management principles should be considered to improve offshore logistics.

With these findings, this study close identified gaps in planning and execution of offshore logistics during wind turbine construction, gives new basis for researchers for further empirical studies and possibilities for practitioners to implement such model and principles. Based on the results, further research agenda could be outlined with the following topics: additional scenario evaluations especially considering scope and technician resource needed over the project period; collaboration with industrial projects to apply proposed model on real cases for validation; and additional contributions on offshore logistics operational optimization during construction phase.

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APPENDIX A – MODEL PARAMETERS

Cost/efficient hour: Cost per technician efficient hour in wind turbine
D: Distance between base port and offshore wind farm (in nautical miles)
i: Vessel type
j: Staff type
$Logistics\_Cost_{Month}$: Logistic costs per month (in €)
$Month_{Days}$: Number of planned hiring days per month
$Staff\_Cost_{Month}$: Staff costs per month (in €)
$Staff\_Cost_{OH\_Offshore}$: Overhead offshore cost (in € per day)
$Staff\_Cost_{OH\_Office}$: Overhead office cost (in € per day)
$Staff\_Cost_{Tech}$: Technician offshore cost (in € per day)
$Staff\_Numb_{OH\_Offshore}$: Number of overhead personnel offshore
$Staff\_Numb_{OH\_Office}$: Number of overhead personnel in office
$Staff\_Numb_{Tech}$: Number of technicians offshore
$Tech_{Acco}$: Accommodation cost of Personnel (in € per day)
$Tech_{Admin}$: Briefing / meetings / administration duration (in hours per shift)
$Tech_{Break}$: Technician break allowance (in hours per shift)
$Tech_{Day}$: Shift duration of offshore technician (in hours per day)
$Tech_{EffDay}$: Technician efficient working hours per day
$Tech_{EffMonth}$: Technician efficient working hours per month
$Tech_{SumEffMonth}$: Total number of technicians efficient working hours per month
$Tech_{Prep}$: Technician preparation time per shift (in hours per day)
$Tech_{Transfer}$: Technician transfer time from the original location to the wind turbine per shift (in hours per day)
$Total\_Cost_{Month}$: Total costs per month (in €)
V_{Acco}: Vessel accommodation costs in case CTV crew is staying offshore overnight per day (in € per day)
V_{Agent}: Vessel agent fees per day (in € per day)
V_{Break}: Vessel break downs time (in % of time hired)
V_{Bunker}: Vessel bunker cost (in € per day)
V_{Capa}: Vessel maximum accommodation capacity
V_{CC}: Crew change time (in % of time hired)
$V_{Charter}$: Vessel charter cost (in € per day)
V_{Comm}: Vessel communication costs (in € per day)
$V_{Efficiency}$: Vessel efficiency rate in percent
V_{FCost}: Vessel fixed (in € per day)
V_{Insur}: Vessel insurance costs (in €)
V_{Maint}: Vessel maintenance cost (in € per day)
$V_{Mob/Demob}$: Vessel mobilization / demobilization costs (in €)
V_{Other}: Vessel other inefficient time (in % of time hired)
V_{Permit}: Vessel permitting issues (in % of time hired)
V_{Port}: Vessel port fees (in € per day)
V_{Qty}: Vessel quantity for a specific scenario
V_{Refuel}: Vessel refueling time (in % of time hired)
$V_{SumCapa}$: Total capacity summed by vessel type
V_{TCost}: Vessel total cost (in € per day)
$V_{Transit}$: Vessel transit time without transfer purpose (in % of time hired)
V_{VCost}: Vessel variable cost (in € per day)
$W_{P50Month}$: Vessel accessibility to a wind turbine with a probability of 50% (P50) for a particular month (in %).