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Optimization of Maintenance Operations for Offshore Wind Farms

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Purpose: The paper provides insights regarding the optimal maintenance strategies for offshore wind farms. The maintenance strategies distinct from each other with location of the operation base and manner of logistics regarding the vessels.

Methodology: The methodology for modelling the transport for maintenance operations for offshore wind farms is done with a discrete event simulation with data regarding offshore maintenance operations provided from a large-scale research.

Findings: The paper conclude with the optimal maintenance strategy based on the optimal location of the operation base in combination with the best manner of logistics to achieve the preferred requirements with the least transportation costs within the boundaries and limitations of this research.

Originality: There are no current papers regarding the maintenance operations for offshore wind farms located far in the Nord Sea.

Keywords: Offshore Wind Farms, Maintenance Strategies, Optimization, Logistics

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1 Introduction

In this paper multiple maintenance strategies for offshore wind farms are simulated and compared to optimize the total transportation costs, number of required vessels and availability of the wind turbines. This optimization has a positive effect on the price of energy and the emissions during the production of energy. Wind energy is a sustainable and renewable energy source and is becoming a greater part of the worldwide energy distribution. Currently, there are big plans to make new large offshore wind farms deeper located in the ocean. The Dogger Bank is such an example which will hold at least four large wind farms.

Offshore wind farms have advantages and disadvantages in comparison with onshore wind farms. The most important advantages are the availability of space to develop large wind farms without the environmental disadvantages for close population, mainly due to noise and sight issues, and better quality of the wind resources due to the more uniform wind distribution with higher wind speeds (Esteban, et al. 2011). The largest disadvantage is higher installation, maintenance and operation costs. Currently, the Operation and Maintenance (O&M) is estimated to account for 14 % to 30 % of total project life cycle costs of an offshore wind farm. Aspects that an operations team may encounter during the O&M phase are component reliability, accessibility via vessels, transfer of technicians and components to the turbine (Martin, et al., 2016)

Currently, the North Sea contains multiple offshore wind farms from different countries. Most offshore wind farms are relatively close located to the coast. But due to the new EU renewable energy target, there is demand for more wind turbines. As a result, larger offshore wind farms are built further located in the North Sea. These offshore wind farms have more space for a higher amount of wind turbines which is necessary to reach the energy target.

The strategy for closer located offshore wind farms are not compatible for the farther-located offshore wind farms. These new locations cause a difference in the transport and capacity for maintenance operations. Using the strategy for closer located and smaller offshore wind farms will be inefficient for these new farms and research regarding optimizing the transport, logistics and capacity becomes interesting. A strategy with a reduction in the transport costs, man-hours and capacity can have a large impact due to the large scale of the operation caused by the high amount of wind turbines in combination with the long travel distances.

The strategy for large offshore operations is given by Matti Scheu, et al. (2012. The maintenance for offshore wind farms must exceed several conditions before the operation can take place. First, the severity of the maintenance must be declared. The severity specifies the type of vessel which is required. This can be differentiated between a vessel with a crane for heavy weightlifting or without. Second, the personnel must be established. The personnel must be available, meaning enough crew must available that have not been offshore for too long in the previous time. Third, the weather conditions must allow the operation. This means that the current weather must be enough for the operation and will be for the following hours by predictive weather control. The weather condition is met by wind speeds and wave height. If all the above conditions are enough, the operation can take place. If not, the operation is set on hold until all conditions are positive.

2 Methodology

The methodology for modelling the transport for maintenance operation of offshore wind farms is done with a discrete event simulation with data regarding offshore maintenance operations provided from a large-scale research.

First, the characteristics for maintenance for offshore wind farms is analyzed. The data regarding the different maintenance jobs and the characteristics of the vessels are specified by Dinwoodie, et al. (2015). Dinwoodie, et al., describes the correct manner to verify offshore operations with key modelling assumptions. As these data are mean values, these are implemented as an exponential function to show the differentiation.

The transport routes are provided by Marine Traffic which have an intelligent global ship tracking system and therefor accumulates the most accurate and efficient offshore transport routes (MarineTraffic, 2018).

The discrete event simulations are conducted in SIMIO, a software package for visual simulations of logistic systems. The simulation optimizes an ideal situation which does not embeds all affecting conditions as some assumptions are made. The weather and sea conditions are not considered and therefor will not have a negative effect on the maintenance operations. The technician is not simulated and there is no limitation in the amount of technician. However, the maximum technician work shift is 12 hours per day, and this is implemented into the maintenance servers. There is no limitations of size, weight or amount on the vessels, operation bases or wind farms. This research does not implement helicopter usage for the maintenance operations.

3 Situation

The situation of this research is defined by the location of four large wind farms, the required maintenance and the type of vessels. These elements will be discussed in this chapter.

3.1 Dogger bank

The Dogger bank is located in the North Sea and has many favorable attributes which make it an attractive site for offshore wind farm development. The ground conditions are good with relatively shallow water depths. The water depths range from 0 m to 42 m which are suitable for a broad range of foundation construction. The wind resources are good and can reach wind speeds up to 10 m/s. The estimated capacity target of the Dogger bank is 9 Giga Watt (GW) (Forewind, 2010).
Currently, the Dogger bank is in the progress to build four large wind farms, namely Dogger Bank Creyke Beck A & B and Dogger Bank Teesside A & B. Each Creyke Beck wind farm will have a maximum of 300 wind turbines and each Teesside wind farm a maximum of 200 wind turbines (Forewind 2014a) (Forewind, 2014b). According to Marine Traffic, the offshore transport route from Den Helder to the different sites is 175 to 190 nautical miles (Marinetraffic, 2018). A summary of the essential characteristics of the Dogger bank wind farms can be seen in Table 1.

Table 1: Characteristics of the offshore wind farms

	Creyke Beck A	**Creyke Beck B**	**Teesside A**	**Teesside B**
Wind Turbines	300	300	200	200
Large Vessels	3	3	3	3
Small Vessels	13	13	11	11
Crane Vessels	2	2	2	2
Distance to Port [nm]	175	190	190	181

The generated power will be transmitted to land by a variety of phases. First, offshore collector platforms will receive power from the wind turbines via the inter-array cable systems. Transformers will be located on the collector platforms to increase the voltage of the power received from the wind turbine generators so that the electricity can be efficiently transmitted to the offshore converter platform. An offshore converter platform is, therefore, required for each project to convert the power generated by the wind farm from Alternating Current (AC) to Direct Current (DC), for efficient transmission to shore. The offshore ends of the HVDC export cables for each project terminate at one of the four offshore converter platform. Then, the generated power will be transmitted with offshore export tables to onshore converter stations. At this point the generated power will be connected to the onshore power grid (Forewind, 2014a).

3.2 Required Maintenance

According to Carrol, et al., the required maintenance can be specified in different categories which have own failure rate, operation time and required vessels. This model categories the required maintenance in three categories, namely minor failure (1), major failure (2) and major replacement (3). A minor failure occurs most often, takes least time to repair and requires the simplest vessel. Major failures happen less often, require significant longer time to repair and requires a faster vessel to prevent further failures. Major

Table 2: Characteristics of different types of maintenance

	Failure rate [failure/turbine/year]	**Operation time [hours]**	**Type of vessel**
1	6.178	7.5	CTV
2	1.062	26	FSV
3	0.264	52	HLV

replacements occur the least and has the most impact on the maintenance, as a part of the wind turbine requires replacement. The operation time is longer and requires a vessel with heavy lifting equipment. Minor and major failure may require spare parts, but these are always available. The major replacements require larger spare parts which have uncertainty of being available and the capacity must be maintained actively. The summarized specification of these maintenance types is shown in Table 2 provided by Caroll, et al. (2016).

3.3 Type of Vessels

There is a selection of vessels used for maintenance operations which differ in size, speed, capacity and function. The Crew Transfer Vessel (CTV) is the most commonly used way of accessing offshore wind turbines. The CTV's limits the maintenance operations in terms of accessibility and the capacity of technicians and spare parts (Dewan and Asgarpour, 2016). For more complex operations, i.e. major failures, a vessel with more technician and spare parts is required. The Field Support Vessel (FSV) is specified for more technician and heavier spare parts. The Heavy Lifting Vessel (HLV) is specially for large maintenance operation which require new large component, for major replacements. The HLVs are large vessels which contain cranes to lift large spare parts. The specifications of these vessels which are important for the model are shown in Table 3.

Table 3: Specifications of maintenance vessels (Dinwoodie, et al., 2015)

Vessel	**Speed [knots]**	**Maximum Operation time**	**Costs per day [$]**
CTV	20	1 operation	1.750
FSV	12	4 weeks	9.500
HLV	11	Infinite	150.000

The speed specifies the transport time to and from the wind farms. The maximum operation time specifies the ultimate time a vessel must return to shore. This time is limited due to the personnel on board, except for the HLV due to the possibilities on board. The cost per day provides an estimation of the transport costs of the operation.

4 Maintenance

The maintenance is defined by the location of the operation base, the route of the vessels and the strategy which will be applied. These factors will be discussed below.

4.1 Operation Base

The maintenance operation is running from an operation base. The operation base receives the notifications for maintenance, contains the available operation vessels, technician and spare parts. This model differentiates three different operation bases; (1) the onshore base, (2) offshore base and (3) offshore artificial island. The onshore base is in Den Helder and has all vessels, technician and spare parts available. The offshore base is an offshore floating or permanent base which contain technicians, all vessels except HLVs and spare parts required for minor and major failures. The major replacement necessities are unavailable. The offshore island is an artificial island in which all vessels, technician and spare parts are available. Both offshore bases require a restock occasionally to maintain the capacity to avoid downtime of the maintenance.

4.2 Route

The route of the vessels is provided by Marine Traffic (2018). Marine Traffic maintains live updates from offshore vessels and weather conditions. This route is planned with consideration of common routes, shortest path and sea-depth conditions. The route is straight-forward after the coast of the Netherlands is passed.

4.3 Strategies

The general maintenance approach is applicable in all strategies. The strategies are differentiated per location from the operation base and the manner of logistics. The operation base has three possibilities which differ in location and ability of performance: the onshore base at Den Helder is the main port which can handle all kinds of maintenance, contains all vessels and has infinite supply of spare parts. The offshore base is located at the center of gravity of the wind farms and is only capable of minor and major defects, while the major replacements is still run from the onshore base. The offshore artificial island is also at the center of gravity of the wind farms and can run all kind of maintenance jobs. This operation base is only in need of spare parts occasionally which is simulated as another vessel.
The manner of logistics is divided into individual and grouped logistics. Individual logistics have an individual maintenance team to operate the maintenance of each own wind farm and grouped logistics has one maintenance team to maintain maintenance of all wind farms. The summary of the maintenance strategies can be seen in Table 4.

Table 4: Maintenance strategies

Strategy	**Minor failure**	**Major failure**	**Major replacement**	**Logistics**
1	Den Helder	Den Helder	Den Helder	Individual
2	Den Helder	Den Helder	Den Helder	Grouped
3	Offshore base	Offshore base	Den Helder	Individual
4	Offshore base	Offshore base	Den Helder	Grouped
5	Artificial island	Artificial island	Artificial island	Individual
6	Artificial island	Artificial island	Artificial island	Grouped

5 Simulation Model

As stated before, the simulation model is made with the visual simulation program SIMIO. The simulation model differentiates the four offshore wind farms on the Dogger bank with minor failures, major failures and major replacements. Each wind farm is simulated as one entity which accumulates the maintenance demands for the wind turbines present. This results in a higher failure rate per maintenance demand relative to the amount of wind turbines present, which can be seen in Table 5.

Table 5: Yearly failures for each wind farm (Carroll, et al., 2016)

	Creyke Beck A	**Creyke Beck B**	**Teesside A**	**Teesside B**
Wind turbines	300	300	200	200
Minor failures	1.853,4	1.853,4	1.235,6	1.235,6
Major failures	318,6	318,6	212,4	212,4
Major replacements	79,2	79,2	52,8	52,8

As each wind farm is simulated as one entity, the travel distance between the individuals wind turbines is neglected as it takes a relatively small amount of time to travel between the wind turbines. At the beginning of each simulation, the vessels start at the operation base. The wind farms create demand for maintenance based on the failure rate. Each maintenance job relates to a certain vessel, operation time and possible spare parts. The maintenance demand notification enters the operation base which links the notification with the correct vessel and, if necessary, a spare part for major replacements. If the vessel and spare part is available, the maintenance operation starts. The vessel is transferred to the wind farm, operates the required maintenance based on the provided operation time and is transferred back to the operation base.

5.1 Requirements

The requirements describe the minimum performance for the simulation to be met with the chosen strategy and configuration. The requirements must be acquired to get enough power due to the availability of the wind turbines, minimize the transportation costs due to optimization of the usage of the vessels.

The overall performance is calculated with the availability of all wind turbines together. The availability of the wind turbines must be 95 %. Due to the presence of several wind farms and different maintenance performance, the overall performance is not the only requirement. Each sub-element must be optimized to obtain a system which performs enough in all elements. To achieve this, the requirement is set for a minimum availability of the wind turbines of each wind farm to 90 % and a minimum availability of each wind turbines due to each maintenance type to 90 %.

5.2 Experiments

The structure of each strategy is simulated in the model, this means that the operation bases, routes and data regarding the characteristics of the vessels and operation times of the maintenance jobs are set. This provides room for experiments to optimize the number of vessels required to get the objectives per strategy.

The first experiment indicates the maximum number of vessels required for the maintenance. This number of vessels is required to dismiss the waiting time between the maintenance jobs due to the lack of vessels. The second experiment indicates the minimum number of vessels required for the maintenance. This number of vessels obtains the required availability of the wind turbines due to each maintenance type. The third experiment indicates the preferred configurations regarding the availability of the whole. It varies all the combinations of number of vessels and results in the best outcome regarding all the objectives for the least transport costs. The experiments will be replicated ten times over which the average values are taken.

6 Results

First, the results of each strategy are discussed. Secondly, the experiments of each strategy are compared with each other. The best result of each strategy will be chosen for comparison. The best result will be chosen based on the best overall availability up to one decimal in combination with the least transportation costs which is based on the price per day of each vessel.

The last chapters show some interesting extra research results regarding the transport of spare parts and the effect of changing the location of the main port.

Table 6: The results of strategy 1

	CTV	**FSV**	**HLV**	**Up-time**	**Costs**
Maximum	66	36	22	97,0 %	$ 38.3M
Minimum	24	10	4	84,6 %	$ 24,8M
Optimum	38	20	6	95.1 %	$ 32.1M

6.1 Strategy 1

The results from the first strategy can be seen in Table 6. This strategy is run completely from Den Helder with individual logistics. As can be seen in the Table, the configuration of this strategy is optimal with a total of 38 CTVs, 20 FSVs and 6 HLVs. With this configuration all the requirements are met with the lowest transportation costs. The up time of all wind turbines is 95.1 % which will cost roughly 32.1 million dollars for transportation. There is a subdivision of the vessels between the different wind farms. The subdivision is based on the size of the wind farm because the Creyke Beck wind farms have 300 wind turbines and the Teesside wind farms have 200 wind turbines. The division is shown in Table 7 where the Teesside wind farms are indicated as small and the Creyke Beck wind farms as large. Both wind farms occur two times in the Dogger Bank.

Table 7: The subdivision of vessels with strategy 1

	CTV		**FSV**		**HLV**	
	Small	*Large*	*Small*	*Large*	*Small*	*Large*
Maximum	15	18	8	10	4	7
Minimum	5	7	2	3	1	1
Optimum	7	12	4	6	1	2

Table 8: The results of strategy 2

	CTV	FSV	HLV	Up-time	Costs
Maximum	44	21	11	97,1 %	$ 38,2M
Minimum	24	9	2	79,8 %	$ 21,3M
Optimum	27	18	4	95,0 %	$ 34,4M

6.2 Strategy 2

The results of the second strategy, which only differs from the first strategy with the manner of logistics, can be seen in Table 8. The best configuration is with 27 CTVs, 18 FSVs and 4 HLVs. The transportation costs for this configuration is approximately 34.4 million dollars to reach 95.0 % up-time.
A first analysis of the first two strategies shows that individual logistics is preferred over grouped logistics when only the transportation costs are considered. Another interesting fact is that grouped logistics requires less vessels to maintain the up-time over 95 %.

6.3 Strategy 3

The results of the third strategy can be seen in Table 9. This strategy is partly run from the offshore base and the onshore base with individual logistics. The optimized configuration needs 28 CTVs, 10 FSVs and 6 HLVs. This configuration has an overall up-time of 95.2 % which costs 24.2 million dollars for transportation costs.

Table 9: The results of strategy 3

	CTV	FSV	HLV	Up-time	Costs
Maximum	46	30	28	97,8 %	$ 38,2M
Minimum	14	6	4	79,8 %	$ 21,3M
Optimum	28	10	6	95,0 %	$ 34,4M

Table 10: The subdivision of vessels with strategy 3

	CTV		FSV		HLV	
	Small	*Large*	*Small*	*Large*	*Small*	*Large*
Maximum	10	13	6	9	4	10
Minimum	3	4	1	2	1	1
Optimum	5	9	2	3	1	2

Just as strategy 1, this strategy also has a subdivision of the vessels between the small and large wind farms which can be seen in Table 10.

6.4 Strategy 4

The results of the fourth strategy can be seen in Table 11. This strategy is the same as strategy 3 but with grouped logistics. This shows an optimized configuration with 17 CTVs, 8 FSVs and 4 HLVs which costs 28.5 million dollars for the transportation to achieve 95.3 % up-time.

Table 11: The results of strategy 4

	CTV	FSV	HLV	Up-time	Costs
Maximum	31	17	11	97,8 %	$ 33,6M
Minimum	13	6	2	91,1 %	$ 15,2M
Optimum	17	8	4	95,3 %	$ 28,5M

The first analysis based on the outcome of strategy 3 and 4 shows the same results as the analysis of the first two strategies. Individual logistics is preferred over grouped logistics when looked at the transportation costs but requires more vessels.

Table 12: The results of strategy 5

	CTV	FSV	HLV	Up-time	Costs
Maximum	46	30	20	95,7 %	$ 3,6M
Minimum	14	6	4	83,3 %	$ 2,4M
Optimum	16	10	6	95,4 %	$ 3.6M

6.5 Strategy 5

The results of the fifth strategy can be seen in Table 12. This strategy is completely run from the offshore artificial island with individual logistics and needs a total of 16 CTVs, 10 FSVs and 6 HLVs to achieve 95.4 % up-time. This configuration will cost 3.6 million dollars for the transportation.

Just as strategy 1 and 3, this strategy also has a subdivision of the vessels between the small and large wind farms which can be seen in Table 13.

6.6 Strategy 6

The results of the sixth strategy can be seen in Table 14. This strategy is just like the fifth completely operated from the offshore artificial island but with grouped logistics. This will need 21 CTVs, 13 FSVs and 3 HLVs for the optimized configuration. This will achieve 96.4 % up-time with transportation costs of 5.4 million dollars.

Table 13: The subdivision of vessels with strategy 5

	CTV		**FSV**		**HLV**	
	Small	*Large*	*Small*	*Large*	*Small*	*Large*
Maximum	10	13	6	9	4	6
Minimum	3	4	1	2	1	1
Optimum	3	5	2	3	1	2

The analysis between strategy 5 and 6 shows that individual logistics is preferred over grouped logistics based on transportation costs but requires more vessels.

Table 14: The results of strategy 6

	CTV	**FSV**	**HLV**	**Up-time**	**Costs**
Maximum	31	17	10	97,9 %	$ 5.8M
Minimum	13	6	Q	79,4 %	$ 3,0M
Optimum	21	13	3	96,4 %	$ 5,4M

6.7 Results regarding spare parts

Due to the minimal information regarding the spare parts for the major replacements maintenance, the results regarding the capacity management of these parts is shallow. Due to the fact it is unknown which exact type of spare part is required for the maintenance, the spare parts are simulated as one entity. When a major replacement occurs, which requires a spare part, the HLV transports one spare part to the wind farm for the maintenance operation. The amount of required spare parts and the time between them can be seen in Table 15. This data shows the optimum configuration of each strategy which is simulated over the period of a year. An average is taken over this data for further results regarding the spare parts.

Table 15: Restock characteristics of spare parts

Strategy	Required spare parts per year	Time between demand in in hours
1	235	33,45
2	228	34,47
3	250	31,44
4	266	29,55
5	252	34,47
6	238	33,03

The amount of restocks is related to the number of required spare parts, time between them and the size of the restock vessel. As the size of the restock vessel is unknown, the amount of restocks are set against each other in Table 16. This Table shows the results of the regularity a restock vessel must be transferred to the operation base. This is applicable for the strategies where the operation base is offshore.

Table 16: Characteristics of the restock vessel

Size restock vessel	Amount of restock per year	Time between restock in days
5	47.0	7.0
10	22.8	14.4
15	16.7	19.7
20	13.3	24.6
25	10.1	32.5

6.8 Results regarding the location of the main port

The main port of this research is Den Helder. This may not be the most optimum location for the main port as the Dogger Bank is in the middle of the North Sea. Due to this reason, the outcome of the best strategy may differ when the location of the main port is changed. For optimal results regarding the effect of changing the location of the main port, the strategy is chosen which operates completely from the main port, which are strategy 1 and 2. The different main ports which are compared are Den Helder and Rotterdam in the Netherlands, Hull and Aberdeen in the United Kingdom, Hamburg in Germany and Esbjerg in Denmark. These ports are terminal ports according to Searates and the marine route between the ports and the Dogger Bank is given by Marine Traffic and the distance can be seen in Table 17.

The data will be compared on the up time of the wind turbines and the associated transportation costs, this can be seen in Table 18. Interesting to see is that main ports which are further away have worse results. This will be further discussed in the conclusion.

Table 17: Distance between Dogger Bank and ports

Port	Distance to Dogger Bank [nm]
Den Helder	174
Rotterdam	195
Hull	128
Aberdeen	196
Hamburg	298
Esbjerg	221

Table 18: Results due to different main ports

Port	Up-time [%]	Transportation costs [$]
Den Helder	95.0	34.4 M
Rotterdam	94.4	36.7 M
Hull	96.4	26.3 M
Aberdeen	94.2	37.9 M
Hamburg	20.4	49.3 M
Esbjerg	87.9	42.5 M

7 Conclusion

Based on this research several conclusions can be drawn regarding the transport for maintenance of large offshore wind farms. The main conclusion to be drawn is regarding the optimal strategy within the boundaries and requirement for this research. Next to the optimal strategy, there can be concluded certain things about the manner of logistics, number of vessels and place of the operation base. The results of the optimal setting of each maintenance strategies can be seen in Figure 1. This graph shows the required number of vessels with their transportation costs to achieve the required availability of the wind farms.

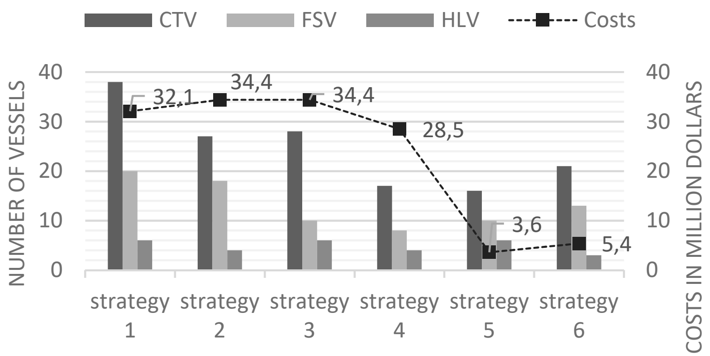

Figure 1: Results of the optimization of each maintenance strategies

The optimal strategy is when the operation base is located at the offshore artificial island, which is in the center of gravity in between the offshore wind farms, in combination with individual logistics, indicated as strategy 5. This strategy requires 3.6 million dollars for the transportation costs to reach up to 95 % up-time of all the wind turbines.

Another conclusion which can be made is based on the location of the operation base. The impact of changing the location of the operation base is enormous regarding the transportation costs. The strategies where the operation base is located onshore requires the most transportation costs as the vessels must transfer the complete offshore route for each maintenance operation. Strategies which operate partly onshore and offshore show less transportation costs but in the same order of magnitude due to the major replacements which are still operated from the onshore base. The major replacements require significant higher transportation costs. The strategy with the complete operation base offshore only requires a fraction, approximately 10 to 15 %, of the transportation costs. Therefore, it is preferred to have the operation base close to the wind farms to reduce the transportation costs.

The manner of logistics also has effect on the transportation costs. The results show that individual logistics is preferred over grouped logistics when only looked at the transportation costs. However, the grouped logistics requires less vessels to maintain the required up-time of all wind turbines but in this research, this is not considered. This conclusion will be further discussed in the discussion and recommendations.

The conclusion regarding the spare parts is that there is approximately daily need for a new spare part. These spare parts must be transferred from the main port to the wind farms. This transfer requires a vessel which can heavy lift these spare parts, such as an HLV. There are also restock vessels which can make the transfer to the offshore operation bases, but this requires more research regarding the size, costs and possibilities of these vessels.

Regarding the location of the main part is an interesting correlation noticeable. As stated, the location of the main port within the strategy where each type of maintenance is operated from onshore to emphasize the difference. The correlation is between the distance between the main port and the Dogger Bank and the performance of the operation. Even up to the point where the overall availability of the wind turbines is down to 20 %. This result stresses the importance of the location of the main port.

8 Discussion

In this section certain discussion points are listed as they possible have certain (negative) effect on the research. These effects can be due to the negligence of certain parameters but also regarding interesting new research topics.
The most important discussion point is regarding the transportation costs. The transportation costs are solely calculated on the length of each maintenance operation. This calculation does not consider other affecting costs such as the investment costs of the vessel, maintenance costs and additional costs when the vessels are not in operation. For example, the reason that grouped logistics are more expensive than individual logistics is that when a vessel arrives at the operation base it immediately has to return back to the wind farm for a new maintenance operation with additional crew and this can cost up to two times the daily price. This differs from the individual logistics because there is a higher change that a vessel will be waiting when maintenance notification arrives and prevents the additional costs. This discussion point will be further elaborated in the recommendations.

As said in the conclusion the location of the operation base has enormous impact. However, during this research it was effortless to change the location of the operation base but, this will bring a lot of issues. For example, the price of the operation bases variate and will have influence on the total transportation costs. If looked at the offshore artificial island, the results show that there will be roughly 30 million dollars available each year for other investments which potentially could cover the cost of such island.
This research differentiates three different types of maintenance and represent all the required maintenance for each wind turbines. During this research this is a good indication of the required maintenance and is enough to distinguish the results between the strategies. However, when a research demands more realistic values regarding the exact outcome of transportation costs, length of maintenance operations and maintenance costs, it is required to differentiate between more types of maintenance and with additional data. In short, this research indicates the differences between different logistic strategies but not exports specific raw data regarding realistic scenarios.

9 Recommendations

The first recommendation is based on the transportation costs. As earlier stated, the transportation costs in this research are not completely investigated. For instance, the transportation costs can include the investment of vessels, the costs of operation bases and the amount of technician. This field of study requires a lot of investigation regarding different kind of elements and further research will result in more realistic values regarding the transportation of maintenance operations.

The second recommendation is regarding the routing of the vessels. This research has a simplistic manner of routing the vessels. In further research, the vessels must involve the maximum duration of the vessel's operation. When this is involved, the vessel can stay at the wind farm for this period and can maintain multiple maintenance operations during one trip. Potentially, this will be positive for the response time of the operation, the number of required vessels and the total transportation costs.
The third recommendation is to investigate regarding the spare parts. The maintenance operation requires spare parts and within this research several assumptions were made but to be confident about the transport of spare parts and the required capacity, further research is required. The research can involve the exact statistics regarding the requirement of the spare parts for the wind turbines but also involve the physical characteristics. These characteristics can provide information regarding the capacity of the vessels, requirements of the lifting equipment. This research will result in more realistic values regarding the costs and capacity of spare parts.

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