A tool to simulate decommissioning offshore wind farms

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Abstract. Decommissioning is an emerging practice for the offshore wind industry. To date, the Yttre Stengrund and Vindeby Offshore Wind Farms are the only installations to have been fully dismantled. While every project requires a decommissioning plan to gain consent; they are high-level estimates of the expected strategy, time required and costs. This is due to the lack of reliable data or experience. However; if underestimated, decommissioning may result in significant and unexpected outgoings at the end of a farm lifecycle. Simulation is an effective way to test a plan is both executable and cost-effective, as well as optimising activities for an individual site. Therefore, a stochastic tool was developed to simulate a wide range of decommissioning methods, considering the impact of uncertain factors such as weather and costs on time and expenditure. It is the first detailed simulation model developed for this crucial project phase. This paper describes the scope of the model; documents the validation activities undertaken; and demonstrates the model’s capabilities. It was found that while further validation against real-case scenarios is necessary, the model can indicatively forecast costs and time for a given strategy as well as optimise scenarios and mitigate risks.

1. Introduction
Decommissioning is an emerging practice for the offshore wind industry. To date, Yttre Stengrund (2016) [1] and Vindeby (2017) [2] are the only Offshore Wind Farms (OWFs) to be dismantled. While every OWF project requires a decommissioning (DCM) plan to gain consent, there are no established methods or real data available on the costs or time required. If miscalculated, DCM could result in significant unexpected outgoings at the end of an OWF lifecycle. Estimates found in the DCM plans for the Thanet, Lincs, Sheringham Shoal and Gwynt Y Môr farms range significantly from ~€37,021/MW to €131,758/MW [3], demonstrating the uncertainty surrounding the project phase. Topham and McMillan provide a summary of the elements to be removed and the respective DCM options [3]. From a review of available DCM plans, the predominant assumption is that elements such as cabling will be left in-situ, while foundations (monopile and jacket) will be cut below the sea-bed and lifted. However; every farm is different and strategies are dependent on a number of factors that are unique to that site. Best practice, available equipment and legal requirements may also change significantly over the course of an OWF lifecycle, altering expectations. This makes predicting the time and costs required in 20-25 years’ time extremely difficult.

With an absence of standard processes, this phase should be monitored and plans updated throughout the project lifecycle to mitigate risk and optimise strategies in terms of cost and time where possible. Both real-life experience and detailed modelling are required to test strategies and accurately
forecast costs. Therefore, a tool was developed as part of the FP7 EU LEANWIND project that can simulate a wide range of DCM as well as disposal strategies, estimating time and expenditure (DECEX) as well as salvage revenue. This paper describes the scope and structure of the DCM model, providing an overview of the inputs and outputs. It also presents a case-study and sensitivity analysis, formulated to validate results and demonstrate the model’s capabilities.

2. Overview

The DCM model is a stochastic tool that simulates a strategy input by the user to dismantle the turbines and foundations of an OWF. Developed in Excel and MATLAB, the model runs the strategy at the selected site over an hourly time-series, simulating the day-to-day logistics from dismantling each element at site; processing at port; and delivering materials to their final destination for either disposal, recycling, re-sale, or re-conditioning and returning to the farm (e.g. in the case of re-powering an OWF). The model utilizes Monte Carlo simulation to consider the impact of uncertain factors on results, such as weather and costs, which are varied by drawing random values using probability distributions per simulation. Results take an average across all simulations and are summarised for the user in a separate Excel file.

Section 2.1 further documents the Metocean data and database files that are pre-loaded with information ready for selection by the user; while section 2.2 details the input Excel tabs that are used to define each specific scenario; and section 2.3 summarises outputs.

2.1. Metocean data and database

Table 1. Database of resources available

| Vessels & Equipment | Technicians |
|---------------------|-------------|
| Number available;  | Number available; |
| Speed;              | Cost - annual or hourly salary. |
| Maximum time offshore; | |
| Operation durations - positioning, access, lifting; | |
| Operational significant wave height (Hs) and mean wind speed (Uw) limits - transit, positioning, access, lifting; | |
| Fuel consumption;  | |
| Costs - fuel, day rate, mobilisation/demobilisation, sea-fastening; | |
| Number of technicians required. | |

| On-land transport | |
|-------------------| |
| Number available; | |
| Speed;            | |
| Fuel consumption; | |
(Table 1) including details of the resources available (vessels and equipment; technicians; and on-land transport) and their respective operational weather restrictions as relevant (e.g. maximum Hs for a vessel to transit to site). The user can update details as needed and then select items from the database in the input file (section 2.2) to define and easily adjust their strategy.

Due to the uncertainty of weather conditions and the potential impact on time and costs, the user must specify operational durations and weather limits per vessel as well as a forecast time of e.g. 12-24 hours. Before deploying a vessel, the model checks conditions for that forecast time within a randomly selected year of the time-series, considering the most stringent operational weather limitation of the vessel. As the forecast time may not cover the entire task duration, the user can also define the minimum probability of Weather Windows (WW) being available e.g. at least 80% probability. Prior to simulation, the model will analyse the time-series to determine the probability of windows available on average per month for each possible operation in a given task (transit, positioning, access, lifting, access, de-positioning, transit). During simulations, the model then checks whether the probability of a window that month is greater than or equal to the minimum required by the user. This technique was chosen to minimize the computational time required to consult the hourly time-series for a full task during simulations. Specifying a high probability of WW availability reduces the likelihood that activities would have to be called off due to a break in weather conditions. It also allows the user set a flexible “season” e.g. a high probability will increase the likelihood that activities take place in Spring/Summer but allow for some opportunistic activity depending on site conditions. Future work would optimise the code to check WW availability for full tasks during simulations and has been done for an installation model described in [4].

2.2. Inputs

| Table 2. Input requirements |
|-----------------------------|
| **Farm details**            |
| • Number of simulations;    |
| • The site (metocean data file); |
| • Project and device lifetime; |
| • Distances from offshore site to port and from port to on-land recycling, disposal and re-conditioning centres.  |
| • Number of turbines;       |
| • Inner-array distance;     |
| • Ports;                    |
| • Maximum time available to complete DCM; Season start/end; Number of stages; Average annual energy production; |

**Costs and revenues**

• Project management and contingency;
• Survey and monitoring;
• Ports;
• Average annual Operation and Maintenance 9;
• Disposal cost and recycling revenue per material;
• Re-sale depreciation calculator to determine re-sale price = % of the original cost based on useful life remaining; 10
• Re-conditioning factor = % of the original cost to restore or upgrade a component.

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6 It is assumed that any components intended for re-sale do not require transport beyond the port.
7 The user can specify up to three different ports for different activities including an operational port where vessels are mobilised from and return to for maintenance; and ports where vessels deposit materials due to be recycled, disposed of; or re-conditioned.
8 The user can specify the amount of time available, the season during which offshore operations can occur and if decommissioning should be undertaken in stages, allowing for some continued energy production.
9 This is only applied if DCM is undertaken in stages, allowing a portion of the OWF to continue operating.
10 The default assumes that an item will lose 10% of its value for every 10% of life lost until it reaches a minimum of 10% re-sale value. This default is a best-guess and can be adapted by the user.
Strategy and resources

Dismantling strategies must be detailed for the turbine and foundation respectively including:

- The components to remove in a given task. All foundation components will be dismantled as part of one task but the turbine can either be dismantled in a single task or per component e.g. all blades, then gearboxes, generators etc.;
- The number of components to remove in a task, which is only relevant when the user is dismantling turbines per components;
- For each component, the user specifies the dismantling operation duration; the weight; post-DCM strategy (determines the port destination as per 7); and any processing time required to break down or treat the component at port.
- The vessels, technicians and on-land transport required. The user can select a single vessel or a DCM and feeder vessel combination e.g. a barge and tug boat, which transport materials from site while a heavy-lift vessel remains onsite.
- Components should be further broken down into their recoverable materials to calculate the salvage or re-sale revenues and disposal or re-conditioning costs. The level of detail is at the user’s discretion.

The user must complete an excel input file (summarised in Table 2). To consider uncertainty in costs, these are varied per simulation by generating random values from a beta distribution similar in shape to a normal distribution curve. A standard deviation of 10% is currently assumed.

2.3. Results

Once the inputs are complete, the MATLAB model simulates the logistics of dismantling offshore and transporting materials to port and on to the nearest landfill, recycling or re-conditioning centre locations. Outputs include a breakdown of costs and revenue, total time and energy production if relevant. These are recorded per simulation as well as the average total and annual results across all simulations. In addition, the model outputs the average distance travelled by vessels and vehicles, facilitating analysis of the potential environmental impact. The DCM model also provides a list of tasks completed for the final simulation to facilitate analysis of how a strategy performed.

3. Validation

While acknowledging the lack of experience and accurate cost figures available, this section presents a hypothetical OWF case-study to validate the model outputs against estimates in the current literature. Sensitivity analysis was undertaken as an additional method of validation, demonstrating that the impact of varying assumptions is as expected and that the model can facilitate comparative analysis despite uncertainty in the inputs. For example, increasing the number of vessels available reduces the time required to complete activities etc. It also demonstrates the model capabilities, highlighting areas for potential optimisation and cost reduction.

3.1. Case-study

The case-study was defined based on a combination of the Lincs OWF DCM plan [5] and an 800MW farm detailed in a BVG Associates study [6,7]. Consisting of 100×8MW turbines on monopile foundations, the site is located 40km from the main operational port and the study uses measured metocean data for a representative site in the North Sea (UK). One port is specified, 30km from the recycling, disposal and re-conditioning centres on-land. An unlimited number of years are available to complete DCM, which can occur all year round, weather permitting, but must be completed in a single stage i.e. the farm ceases operation (see explanation of these variables in 8). The

11 Figures converted using Dec 2009 exchange rate, and scaled from 270MW farm to 800MW farm.
project and device lifetimes are 20 and 25 years respectively meaning that device components have a re-sale value of 20% of the original cost (as explained in section 2.2). The re-sale price is determined by multiplying this percentage by the unit cost (user specified). For this study, this was defined based on a turbine cost of £1,251k/MW [7]\(^\text{12}\) and the component cost breakdown based on [8]. Project management is set at 5% of total costs [5] with an additional contingency of 10%. Table 3 summarises the specific cost and revenue inputs assumed.

### Table 3. Case-study costs & revenues

| Cost/revenue source                          | Amount (£) |
|---------------------------------------------|------------|
| Survey and Monitoring                       | 3,331,043 [5] |
| Port costs                                  | 113,256 [5] |
| Disposal costs (landfill or recycling)      | 57/t [9]\(^\text{13}\) |
| Recycling revenue – steel                   | 400/t [10]\(^\text{14}\) |
| Recycling revenue – copper                  | 4,400/t [11]\(^\text{15}\) |
| Recycling revenue – cast iron               | 122/t [12]\(^\text{16}\) |
| Recycling revenue – aluminium               | 1,500/t [13] |

### Table 4. 8MW turbine and foundation components weight and materials

| Component          | Materials          | Weight | Disposal strategy |
|--------------------|--------------------|--------|-------------------|
| **Total rotor mass** |                   | 195t   |                   |
| Hub casing         | nodular cast iron  | 90t    | Recycling         |
| Blades (3)         | carbon fibre       | 105t   | Disposal          |
| **Total nacelle mass** |                | 285t   |                   |
| Gearbox            | 65% steel 35% copper | 114t  | Re-sale          |
| Generator          | Steel components   | 11.4t  | Recycling         |
| Main shaft & bearings |                | 2.28t  | Re-sale          |
| Transformer & power convertor |             | 43.32t | Disposal        |
| Housing            | fiberglass         | 558t   | Recycling         |
| **Tower**          | Tubular steel      | 558t   | Recycling         |
| **Monopile**       | Hollow steel       | 900t   | Recycling         |
| **Transition piece** |                | 300t   | Recycling         |

The DCM strategy is based on the Lincs OWF methodology and timings to dismantle 3.6MW turbines and demolish monopole foundations. However; the figures have been scaled-up based on industry

\(^{12}\) Figures converted to euro using exchange rate May 2012.

\(^{13}\) It is expected that most materials disposed of would go to landfill/incineration (£47/t, converted to euro using April 2017 exchange rate) except for composites where landfill is banned in some countries. Here would expect a charge to recycle or the component would be re-sold.

\(^{14}\) Based on projected figures for 2017.

\(^{15}\) Based on price for copper #1 and converted to euro using April 2017 exchange rate and rounded.

\(^{16}\) Based on price for sheet iron and converted to euro using April 2017 exchange rate and rounded.
feedback to consider 8MW turbines, resulting in 33 hours per turbine and 17 hours per foundation. It is assumed that cabling will be left in-situ. The component weights, materials and disposal strategy are presented in Table 4 and are based on figures in the existing literature [14-20].

Considering the resources, it is assumed that a) the farm has 72 technicians available who are paid an annual salary of €50,000; b) there are 10 vehicles that can each travel at 70km/h, cost €1,500 per day and have a weight capacity of 40t [21]; c) and DCM will be undertaken using a combination of DCM and feeder vessels. Vessels were defined based on information from [21-24]. The DCM vessel is a jack-up that can travel at 10kn/h with a capacity of 7600t. The maximum time offshore is 21 days and it has a day rate of €125,000 with a mobilisation cost 4× the day rate. The number of technicians required is 24. The feeder vessel is a combination of a barge and tug boat that can travel at 6kn/h and has a capacity of 220t. The maximum time offshore is 7 days and it has a day rate of €83,000 with a mobilisation cost 4× the day rate. The number of technicians required is 12. A total of 2 jack-ups and 2 barges are available. Table 5 outlines the operational weather limits considered for each vessel type. The minimum probability required for a WW is 80% with a 24-hour forecast required before a vessel is deployed to a new task (as explained in section 2.1).

Table 5 Vessel operational weather limits

|                      | Jack-up vessel (DCM) | Barge & tug boat (Feeder vessels) |
|----------------------|-----------------------|-----------------------------------|
| Max wave height (Hs) transit (m) | 3.5                   | 2.5                               |
| Max Hs positioning (m)        | 1.5                   | n/a                               |
| Max wind speed positioning (m/s) | 8                    | n/a                               |
| Average positioning time      | 3                     | n/a                               |
| Max wave height access (m)    | 1.5                   | n/a                               |
| Max wind speed access (m/s)   | 8                     | n/a                               |
| Average crew access time      | 2                     | n/a                               |
| Max wave height lifting (m)   | 3                     | 1.5                               |
| Max wind speed lifting (m/s)  | 16                    | 8                                 |

3.2. Results

Table 6 Results

| Cost                      | Amount (€) | Revenue | Amount (€) |
|---------------------------|------------|---------|------------|
| Project management        | 7,300,017  | Recycling revenue | 92,493,454 |
| Contingency               | 14,587,706 | Re-sale revenue  | 50,027,074 |
| Survey & monitoring       | 3,330,103  | Total DCM revenue | 142,520,528 |
| Port                      | 113,335    | Total time       | 537.11 days |
| Vessels                   | 138,326,062| Total DCM costs  | 171,917,300 |
| Technician                | 7,200,000  |                      |            |
| On-land transport         | 214,619    |                      |            |
| Disposal                  | 845,459    |                      |            |
| Total DCM costs           | 171,917,300|                      |            |
| Total DCM revenue         | 142,520,528|                      |            |
Table 6 presents the mean results for 1000 simulations of the base case-study scenario. As illustrated in Figure 1, these were validated against cost estimates in the existing literature. This review extends the figures referenced in [3] to include predictions for Yttre Stengrund OWF [25] as well as from industry (DNV GL [26]) and research (BVG Associates [6, 7])

![DCM Cost Comparison](image)

**Figure 1. DCM Cost Comparison [3, 5-7, 16, 25-26]**

The LEANWIND case-study result is significantly larger than estimates from existing DCM plans or predictions for the Yttre Stengrund farm. However, it is extremely close to the Gwynt Y Môr estimate when considering inflation and interest and is within DNV GL’s estimated range of €200,000-€600,000/MW. While it is clear from the range of estimates that DCM costs are extremely uncertain, the model’s average position suggests as a first indication that outputs are reasonable, although it should be noted that they are 35.5% lower than the BVG projections and at the lower end of the DNV GL range. This may suggest that results are still optimistic, which could be due to the limitation of the scope to just the turbines and foundations. However, it is also important to remember that the BVG figures are for projects with FID 2020 and are based on the output of a cost model. The structure and scope of the BVG model are not available, so it is not possible to identify where potential differences in the assumptions and functionality of the models could account for the variation in results.

In terms of time, fewer estimates exist for comparison. However, Figure 2 provides an illustration of available projections.

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17 Converted from sterling to euro using May 2012 exchange rate.
18 Figures from [3] were converted to euro using the respective exchange rate on the date of publication.
While again suffering from a lack of reliable data, LEANWIND results (0.67 days/MW) fall within the lowest and highest predictions available (0.34-2.6 days/MW). Based on the above comparisons, it can be concluded that the LEANWIND DCM model is producing logical results. However, the following section includes sensitivity analysis to illustrate the impact of key assumptions from the base case-study and further validate that the model is working as expected. It also illustrates how, despite the uncertainty in the data and consequently in the results, the model could be used for comparative analysis and to optimise scenarios.

3.3. Sensitivity Analysis

Due to computational time restrictions, only 100 simulations were run for sensitivity analysis. This section outlines a selection of the studies and the implications of results.

**Varying the number of vessels and technicians available ×2** (Figure 3): As expected, DCM took less time with more resources. In this scenario, the reduced time outweighed the added cost of additional resources. Conversely, DCM took more time with less resources, although the reduced number of vessels and technicians mitigated a substantial increase in the overall cost. More in-depth analysis could examine the optimal number of vessels and technicians considering the trade-off between time and cost-effectiveness.

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19 To ensure consistent comparison, only time considering offshore or post-decommissioning activities were used i.e. does not consider pre-decommissioning tasks like surveys etc. in the time taken.
Varying operational weather restrictions ± 50% in steps of 10%: Reducing the maximum Hs and Uw for each operation increased the time and cost of DCM while an increase meant more WWs, reducing the time required waiting and associated costs. However, this did not consider the added cost of vessels with improved capabilities. Further research could find the ideal balance within fleet in terms of vessel capabilities and cost.

Varying operation durations +100% and -80% in steps of 20%: As anticipated, increasing operation durations increased the time required to complete activities. However, there is a limit to the impact of reducing this parameter as the number of WWs increase and wait time is eliminated. This would change depending on the site e.g. harsher conditions may still show a significant difference as the durations decrease while less harsh conditions may show less impact as durations increase.

Varying the distance from port (site to shore) between 10-110km in steps of 10km (Figure 4): Generally, it was found that time and cost decreased/increased when distance from operational port decreased/increased from the case-study (40km). However, the impact is not a uniform decrease/increase. On further investigation, it was found that the greater the distance, the less likely it was that WWs would be available for feeder vessels to transit to and from the farm to take materials back to shore. If feeder vessels could not be deployed, the DCM vessel would return to port with materials when it reached the maximum time allowed offshore. This would ultimately decrease the overall number of times vessels would transit to and from the farm, reducing the effect of this parameter. This accounts for some of the variation in impact, specifically the more gradual increase in time and costs further from shore.

![Figure 4. Distance from shore - with and without feeder vessel](image)

It should be noted that results will depend on the vessel capabilities input by the user and finding the optimum balance of vessels could significantly reduce costs and maximise time efficiency. This paper further examines the benefits of the combined DCM and feeder vessel scenario, considering the need for feeder vessels seems to reduce further from shore. At 40km from shore, using a single vessel increased the DCM time by 12% (515 to 577 days), but reduced costs by 29% (€213,140/MW to €151,636/MW). Therefore, while the use of feeder vessels may save time, the additional cost could negate any benefit. The decision will depend on the priorities of the wind farm owner.

4. Conclusion

Results of the DCM model case-study indicate that DCM costs will be higher than current estimates in DCM plans. This may be due to farm size or the difference considering inflation. However, estimates from DNV GL and the BVG study suggest the model may still be producing quite optimistic figures. These conclusions are of significance to the industry and particularly farms nearing the end-of-life phase who will shortly face such costs. Farm operators may choose re-powering rather than full DCM
to extend the lifecycle. However, considering developments in technology and general wear-and-tear over a project lifetime, re-powering would still require partial DCM in the form of substantial upgrades and replacing obsolete components and infrastructure.

Ideally DCM expenditure would be accurately estimated and mitigated for at planning stage. Developers would consider the potential salvage value when selecting farm technology to help offset costs. It is also important to optimise strategies, minimising costs. While further validation against real-case scenarios is necessary, the DCM model is the first simulation tool that can provide a detailed estimate of the time and cost of a project scenario. It also facilitates cost-benefit analysis of different procedures, technologies and resources during this phase e.g. optimal strategies; different substructure designs; or the number of vessels in a fleet etc. It should be noted that the model can be used independently or in conjunction with a full lifecycle financial model to determine the % contribution of this phase on a project LCOE [4].

This paper outlines how the model has been validated in so far as possible against existing cost and time estimates, providing on overview of these as well as a case-study that can be used as a first template for future DCM studies. The paper also demonstrates how sensitivity analysis can be employed in the absence of concrete figures to test a model is working as expected, although studies illustrate the significant impact of the inputs chosen. This re-emphasises the need to gather real data and experience for accurate results. Despite uncertainty in inputs, analysis shows how the model can identify general trends, potential time/cost savings and areas for further optimisation. In particular, the selected studies show the importance of ensuring strategies are optimised for a given farm scenario and site conditions e.g. a strategy may suit OWFs close to shore with benign weather conditions, but the optimal scenario may change further offshore in more extreme conditions.

It should be noted that this is a first version of the DCM model, and was developed defined to account for the key elements of a DCM strategy. For example, the priority is to simulate dismantling the turbine and foundation as current DCM plans assume cabling will be left in-situ and substations could be considered as an additional turbine and foundation. However, the model scope could be extended. Future development will also increase the number of resources that can be specified (e.g. this is currently limited to four vessel types and one category of technician) and include more detailed options regarding ownership of vessels versus chartering etc. Future versions should also simulate pre-DCM activities. For example, site preparation including the removal of harmful noxious substances and liquids (e.g. cooling oil from transformers and from turbine gear boxes etc.); salvaging high-value, re-usable components that might be damaged during dismantling (e.g. SCADA equipment etc.).

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