A Decision Support System for Strategic Maintenance Planning in Offshore Wind Farms

[1]Xiaodong Li*, [1]Djamila Ouelhadj*, [1]Xiang Song*, [1]Dylan Jones, [1]Graham Wall,
[2]Kerry E. Howell, [2]Paul Igwe, [3]Simon Martin, [4]Dongping Song, [5]Emmanuel Pertin

[1] *Centre for Operational Research and Logistics (CORL), Department of Mathematics,
University of Portsmouth, UK*
[2] *Plymouth Business School, University of Plymouth, UK*
[3] *Computational Heuristics Operational Research Decision Support Group, Stirling University, UK*
[4] *Management School, Liverpool University, UK*
[5] *Institut Superieur D'etudes Logistiques (ISEL), Le Havre University, France*

This paper presents a Decision Support System (DSS) for maintenance cost optimisation at an Offshore Wind Farm (OWF). The DSS is designed for use by multiple stakeholders in the OWF sector with the overall goal of informing maintenance strategy and hence reducing overall lifecycle maintenance costs at the OWF. Two optimisation models underpin the DSS. The first is a deterministic model that is intended for use by stakeholders with access to accurate failure rate data. The second is a stochastic model that is intended for use by stakeholders who have less certainty about failure rates. Solutions of both models are presented using a UK OWF that is in construction as an example. Conclusions as to the value of failure rate data are drawn by comparing the results of the two models. Sensitivity analysis is undertaken with respect to the turbine failure rate frequency and number of turbines at the site, with near linear trends observed for both factors. Finally, overall conclusions are drawn in the context of maintenance planning in the OWF sector.

Key words: offshore wind, renewable energy, Operations and Maintenance (O&M), decision support, stochastic optimisation

* Corresponding author. Tel.: +44 (0)23 9284 6355

E-mail addresses:

xiaodong.li@port.ac.uk (X. Li),

djamila.ouelhadj@port.ac.uk (D. Ouelhadj)

xiang.song@port.ac.uk (X. Song)

1. Introduction

The EU aims to achieve 20% of energy consumption from renewable sources in order to reduce carbon emissions by 2020 (Bilgili *et al.*, 2011; Laura and Vicente, 2014). The UK government has also set the figure of 15% as the target for 2020 (O'Keeffea and Hagett, 2012; Higgins and Foley, 2014). Over the past decade, wind energy has been a significantly developing renewable energy source (Ding and Tian, 2012). According to the interviews conducted by Ochieng *et al* (2014), wind power is one of the few renewable technologies that demonstrate a rapid development in the past decades. It will therefore provide a major proportion of electricity production out of all the renewable sources (Freris and Infield, 2009) and make a great single contribution to the 2020 target (O'Keeffea and Hagett, 2012; Appiott *et al.*, 2014). There are five distinct phases during the life cycle of an offshore wind farm: development and consenting, production and acquisition, installation and commissioning, operation and maintenance (O&M) and decommissioning (Myhr *et al.*, 2014). The O&M starts when the OWF begins operating and continues until the final decommissioning stage. Although the cost of the O&M phase is generally not as large as the construction phase, it is still significant due to the length of the long-term operation during the life cycle. O&M costs are of the order of £25-40 million for a typical 500MW OWF (The Crown Estate, 2010). These kinds of cost accounts for 18% of the total offshore wind system (Carbon Trust, 2008). Hence the expenditure on O&M may be seen as a key element of the energy production costs in OWFs.

One of the challenges of performing maintenance operations in OWFs is the transport of personnel, spare parts and large components to individual wind turbines by vessels or helicopters (Halvorsen-Weare *et al.*, 2013). Due to the expensive purchase price or charter-in rate, the use of specialised vessels or helicopters can account for a high percentage of the O&M costs. The maintenance activities for an offshore wind project need a fleet of vessels, such as component transport vessels, crew transfer vessels, crane vessels, and vessels for specialised tasks such as cable-laying (Halvorsen-Weare *et al.*, 2013). The type of vessel or helicopter used for maintenance depends significantly on the distance from the port to the OWF (Laura and Vicente, 2014). Vessel efficiency is becoming a key factor in determining overall vessel demand, which is defined in terms of working time required for recovering different faults, taking into account weather delays.

O&M costs are not only caused by repair and replacement of components, but also by production loss due to downtime (Scheu *et al.*, 2012). Maintenance management aims at improving the availability of the production systems and reducing the overall maintenance cost (Ding and Tian, 2012). The revenue loss can be presented by calculating the required time of planned and unplanned service and the productivity level. Minimisation of downtime strongly depends on the accessibility of the installed facilities. Maintenance of any offshore system is not an easy job because of restricted logistics and accessibility.

In order to minimise the expected costs in the lifetime of an OWF, an optimal plan for O&M should be developed in order to handle the component failure risk (Nielsen and Sorensen, 2011). The central question in developing the optimal plan is the decision of when and how to organise maintenance activities. The existing industry experiences imply that production loss might result from the lack of inspection/repair prior to component failure. A survey of offshore wind energy companies was conducted by the work of Pahlke (2007), with 70% of the respondents expressing the need for decision support tools whereas only a few of them had such models available for use (Scheu *et al.*, 2012; Hofmann and Sperstad, 2013). The literature review presented in this paper shows that the developed decision support tools to date use mainly simulation techniques, whilst the use of mathematical optimisation modelling is limited.

The maintenance frequency affects activity demand and costs associated in the operation time of vessels and technicians, especially the corrective maintenance for component

breakdown. The unplanned events for repairs/replacement of failed OWF components account for a high percentage of the maintenance tasks, typically between 50-70% (Van Bussel, 1997). The maintenance practices of OWFs can be optimised with respect to the failure rates and service costs of wind turbines in the marine environment. The development of an optimised maintenance schedule for OWFs could potentially minimise the maintenance expedition costs, through the use of statistical data on offshore wind turbine failure rates (Kooijman *et al.*, 2004).

In this paper, a Decision Support System (DSS) is developed to give multiple stakeholders in offshore wind farms a tool to assist them in making decisions to conduct cost effective maintenance in OWFs. The maintenance operations include selection of maintenance strategies for project developers, identification of the annual number of required technicians for HR managers, and the required chartered vessels for O&M planners, in order to achieve a minimum cost. Deterministic and stochastic optimisation models are proposed to optimise personnel, transport, and breakdown costs of O&M. The deterministic model is used when the failure rate is known, whilst the stochastic model is utilised in case the failure data is unknown from operational practices. The optimisation models and the solution method are integrated into the DSS to build an efficient decision tool for optimising and analysing maintenance activities. The DSS has been developed part of the 2OM (Offshore Operations & Maintenance Mutualisation) project, financed by the EU Interreg IVA France (Channel) – England programme.

The rest of the paper is organised as follows: In Section 2, an overview of existing decision support on offshore wind maintenance is presented. Sections 3 and 4 describe the DSS and the optimisation models for the strategic planning of offshore wind farm maintenance. Experimentation results and sensitivity analysis of the system are demonstrated in Section 5. Finally, some concluding remarks and suggestions for further research are provided in Section 6.

2. An overview of decision support tools for offshore wind maintenance

Computational decision tools are able to support complex decision making in the energy sector, such as the recent tools developed by Hunt *et al.* (2013) and Chang (2014) for the planning and coordination of renewable energy systems. A performance analysis of a renewable energy system usually underpins this kind of tool to aid decision making. Most of the developed decision support systems in the wind energy sector are specific to onshore developments and only a small number of those are suitable for offshore projects (Pahlke, 2007). The tools are more likely applicable offshore in a limited geographical area rather than a large extent such as the North Sea, which contains a large number of current and proposed wind farms from several countries (Wanderer, 2009).

As O&M costs account for around one third of the life cycle cost of an offshore wind farm, there is a need to develop cost-effective O&M strategies to achieve a significant saving in the cost of energy during the life of OWFs. A number of researchers over recent years have created decision support tools for different purposes in offshore wind production, such as to forecast the operations of a wind farm (Scheu *et al.*, 2012), to estimate the O&M costs including revenue loss (Dinwoodie *et al.*, 2013), to assess offshore wind energy potential (Schillings *et al.*, 2012), and to simulate the operational phase of an offshore wind farm with all maintenance activities and costs (Hofmann and Sperstad, 2013). A common objective of these tools is to find the optimal maintenance strategy/planning for a particular offshore wind farm, rather than a global strategy for multiple farms. The decision tools may calculate the maintenance cost on the basis of levelised production cost (LPC), which is seen as an efficient way for analysis and evaluation of risk and total cost during the life span of offshore turbines (Myhr *et al*, 2014), Dinwoodie *et al*. (2015) investigated the performance amongst

the existing simulation models of operation and maintenance for offshore wind farms; they also identified key model assumptions that impact model results.

The Norwegian offshore wind cost and benefit model – NOWIcob (Hofmann and Sperstad, 2013) can simulate the operational phase of an offshore wind farm with all maintenance activities and costs. Several input parameters, both controllable options and the uncontrollable external factors, can be changed in the model to assess their impact on performance parameters such as the O&M costs and availability. Controllable options are all strategic choices that the wind farm operator can directly decide upon. Uncontrollable external factors include all parameters that are outside the direct influence of the wind farm operator such as the market environment and weather conditions.

Most of the tools concentrate on the modelling of failures and repair, although these two parameters are often assumed to be deterministic. Nevertheless stochastic modelling is suggested to simulate the variability of the failure rates of wind turbine components, since a deterministic approach would not give realistic results. Discrete-event simulation is a powerful computational technique, which has been to solve problems with stochastic data (Willis and Jones, 2008).

Operational research (OR) has a long tradition in improving operations and especially in reducing costs (Dekker *et al.*, 2012). In therenewable energy sector, a range of OR approaches have been applied in production scheduling, transportation routing and maintenance supply planning. For example, Zhang *et al.* (2013) presented an optimisation model for scheduling power generation in a wind farm. Similar works in scheduling and capacity planning of renewable energy have been reviewed by Connolly *et al.* (2010) and Beerbuhl *et al.* (2015). OR techniques have also been used on the optimisation of offshore wind O&M. A mixed integer programming model with binary variables is usually applied to aid decision making in vessel fleet composition problems (Halvorsen-Weare *et al.*, 2013; Hvattum and Nonas, 2013). Vessel properties and contracts should be taken into account to configure the vessel fleet with crews for execution of maintenance operations in OWFs. The most common objective function is to minimise the fixed costs of vessels and ports, variable costs using the vessels, expected downtime costs of delayed correct maintenance activities and penalty and/or transportation costs. The optimal solutions are constrained typically by a limited number of vessels, necessary time spent on a maintenance task, the locations of maintenance resources, and the sea state suitable for carrying out O&M activities.

When modelling O&M practices for OWFs, the reliability of the wind turbines is a key parameter that will affect the output of the project, i.e. energy output and cost per unit of energy produced. However, a lack of publically available offshore wind turbine failure data is a challenge in the decision making of corrective maintenance operations. A number of models have been developed to predict the revenue (Krokoszinski, 2003), or to estimate the O&M costs (Van Bussel and Bierbooms, 2003; Obdam *et al.*, 2007) by considering the wind turbine reliability. Reliability models can be utilised to quantify the failure rates of offshore wind turbines and identify the repair time for each type of failure. The energy losses due to wind turbine failures, downtime and maintenance tasks are viewed as an element of maintenance cost. Nevertheless, a significant proportion of failure rates used in previous studies are extracted from onshore wind farm data, and the effect of the marine environment on the offshore wind turbine reliability has not been considered.

From the review of the existing decision support and optimisation models for maintenance in OWFs, there is little research on the integration of optimisation models within the decision support systems. An efficient DSS with user interface for multiple purposes is proposed in this paper, by an integration of decision aiding and optimisation models. The two versions of

196 the optimisation models, associated with deterministic and stochastic reliability parameters,
197 are formulated on the basis of offshore wind farm O&M practices.

198

3. Description of the DSS for offshore wind O&M

200 The Decision Support System (DSS) proposed is designed to assist multiple offshore wind
201 stakeholders for determining cost effective maintenance resources for an offshore wind farm.
202 The system can also be used to understand sensitivities of the operation and maintenance
203 costs due to changes in the maintenance and logistics strategy, and to provide an estimate
204 of the maintenance cost. As shown in Figure 1, the DSS requests system and user input
205 data. The tool then identifies the minimum cost to meet the maintenance demand on the
206 basis of the input data. The DSS embeds two optimisation models in order to generate
207 optimal maintenance costs on the resources required to conduct the maintenance. Finally
208 the requirement of maintenance resources, facilities in port and training courses are given as
209 outputs of the system.
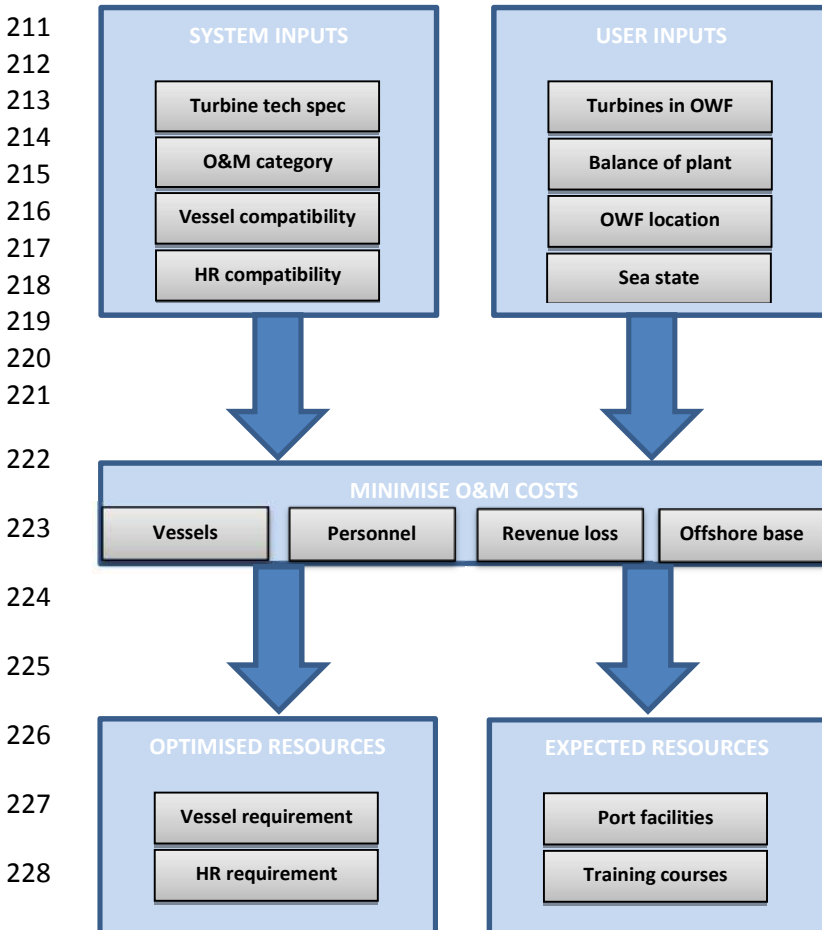
210

Figure 1: Decision Support System framework

231

3.1 System inputs

5

233 System input data is entered into the DSS prior to users providing the information of a
234 particular project, including the technical specification of existing wind turbines in the current
235 market, characteristics of the pre-defined maintenance categories, and compatibility of
236 vessels and technicians on different maintenance categories. The wind turbine specification
237 is imported from the 4cOffshore website (http://4cOffshore.com). Categorisation of
238 maintenance activities and compatibility of vessels and technicians are underpinned by the
239 practical data collected from a wide range of experts in the offshore wind sector.

240 • *Categorisation of maintenance*

241 In order to design the DSS, expert opinions about O&M in the industry were collected from
242 different stakeholders in the offshore wind sector, such as O&M managers, O&M consultants,
243 technicians, and port managers, by the use of an online survey, interviews and working
244 groups. Further details are available at the 2OM project WP 4: communication (Li *et al.*,
245 2015). According to the responses from the industry experts, offshore wind maintenance
246 activities are classified into nine categories (see Table 1) in the DSS, four preventive and
247 five corrective categories. The number of vessels and technicians should be identified in
248 order to undertake the different maintenance tasks.

Preventive maintenance (PM):	Corrective maintenance (CM):
Cat. C1: PM on wind turbines	Cat. P1: CM for wind turbine repair
Cat. C2: PM on foundations	Cat. P2: CM for wind turbine minor replacement
Cat. C3: PM on substations	Cat. P3: CM for wind turbine major replacement
Cat. C4: PM on cables	Cat. P4: CM for substation repair / replacement
	Cat. P5: CM for cable repair / replacement

249   Table 1: Preventive and corrective maintenance categories

250

251 For each category, the length of time required for preparation, repair and logistics are
252 determined. The *preparation time* is the duration of mobilisation of all necessary resources.
253 *Repair time* covers the time that the technicians use during repair or replacement. *Logistics*
254 *time* typically incurs when a turbine component is ordered from the manufacturer. In addition,
255 the size of maintenance crew is also determined depending on the workload of each
256 maintenance category. The main activities in both preventive and corrective maintenance
257 are the transport of the maintenance crew and components and the execution of repair or
258 replacement. The most suitable vessel and the crew with the necessary skills should be
259 selected to execute an inspection or correct a failure according to the compatibility of each
260 vessel and personnel type.

261

262 • *Compatibility of vessels and technicians (HR)*

263 A range of vessels can be chartered, on a short-term or/and long-term lease, to carry out
264 maintenance tasks during the planning horizon. Crew transfer vessels are utilised widely in
265 the offshore energy field, such as oil and gas. Crane vessels and jack-up vessels are used
266 to replace wind turbine components, depending on the size of the work. Helicopters can
267 support the transportation of personnel and equipment in emergencies and can reduce the
268 length of downtime. Daughter ships must work with a mother ship offshore; they can offer
269 preventive inspection and corrective repairs on wind turbines. In practice, at most one
270 mother ship may undertake maintenance works for a particular offshore wind farm. The

compatibility of each vessel type varies with the maintenance categories. The length of lease of each type of vessel should cover its requirement for different maintenance categories. Each type of vessel has a given service speed, restricted use due to weather conditions and lease cost.

Currently no single standardisation of maintenance technicians exists in the offshore wind industry. With respect to the personnel data from survey responses, technicians involved in the DSS are classified into four groups in terms of job function and base location.

- Onshore-based turbine technicians are responsible for maintaining the condition of the turbines.
- Offshore-based turbine technicians are considered only if an offshore platform is utilised, such as a mother ship with daughter ships.
- Foundation technicians are in charge of the maintenance work on the turbine foundation.
- Electrical technicians undertake the repair and/or replacement in both substations and cables.

When the personnel are scheduled for offshore maintenance works, the shift length may impact on the efficiency of the activities. In practice, the length of an on-duty shift is seen as a hard constraint to restrict the daily workload.

3.2 User inputs

A graphical friendly user interface provides users with an easy way to use the system, by inputting a series of input variables about OWF(s) and outputting the corresponding O&M resource requirements. The user input variables include data on the turbines, balance of plant, location and sea state, which therefore focus on the technical, structural and environmental information of an offshore wind farm. The input variables for a particular offshore wind project are fed through the system in order to produce for the user a series of O&M resource requirements.

3.3 Cost optimisation

The bulk of the system is comprised of a series of key assumptions, objective functions and constraints that use the data inputs to generate the required maintenance resources at a minimum cost, in particular vessels and technicians. The optimal costs are acquired by the deterministic or stochastic models which are described in detail in Section 4. The objective of the models is to minimise the O&M costs, including the costs of personnel, vessel, and production loss due to downtime. The major constraints considered are the available working time of personnel, capacity, compatibility and weather restriction of each vessel type. The deterministic model is used for the case with known technical failure rates of wind turbine components. Otherwise, the failure frequency is assumed as a probabilistic parameter in the stochastic model.

3.4 System outputs

According to the cost estimation from the DSS, the OWF management team will decide on the most suitable maintenance strategy with respect to some operational issues in practice, e.g. available space and support workers in the maintenance base port. There are three optional maintenance strategies that are defined in the DSS in terms of vessel and personnel resources required; namely *port based*, *port with helicopters* and *offshore based*.

317 The three optional strategies have distinct requirements for vessels/helicopters, human
318 resources (HR), port facilities, and personnel training courses. The optimised vessels and
319 human resources are determined by the proposed optimisation models to meet the
320 maintenance requirements. Essential port facilities and personnel training courses are
321 suggested by the DSS, such as sufficient storage space and parking space as port facilities;
322 project management and under-water work skills as training programmes.

323 For a port based strategy, different types of vessels are used to carry out maintenance,
324 which is usual for most of the existing offshore wind farms as the distance to port is not great.
325 In order to minimise the rescue time, helicopters may be considered to assist urgent repairs
326 with a quick response. However, additional facilities are required in the base port, such as a
327 heli-pad and fuel pumps. With such strategies, with or without a helicopter, the majority of
328 the O&M resources are located at the onshore maintenance port, and all vessels and
329 helicopters are assumed to return by the end of each day. With the increased distance
330 between the wind farm and the shore in the new generation offshore wind farms, operators
331 may tend to use offshore based maintenance. In this way, a mother ship with daughter ships
332 may stay offshore for a period of time to reduce the travel distance, compared to other types
333 of vessels. Additional training courses are needed for these offshore based technicians.
334 Such an offshore based platform does not only offer a quicker response for unforeseeable
335 failures, but can also be used in preventive inspections.

336

4. Optimisation models

338 To reduce the costs of maintenance activities in an OWF, we propose deterministic and
339 stochastic optimisation models to minimise personnel, vessel, and breakdown costs. These
340 two optimisation models are integrated into the DSS. The deterministic model is intended for
341 use by stakeholders with access to accurate failure rate data. The stochastic model is
342 intended for use by stakeholders who have less certainty about failure rates.

4.1 Notation and assumptions

344 Index k denotes the category of maintenance. $k = 1\ldots4$, indicate the preventive maintenance
345 activities; $k = 5\ldots9$, indicate corrective maintenance. Four kinds of maintenance technicians
346 are considered in the model $i = 1\ldots4$ represent onshore based turbine technician,
347 foundation technician including underwater maintenance, electrical technician for
348 maintenance of cables and substations, and offshore based turbine technician respectively.
349 A variety of vessels are used to transfer the crew to execute different maintenance tasks,
350 type $j = 1\ldots5$ denote crew transfer vessel, crane vessel, jack-up, helicopter and daughter
351 ship (working with a mother ship respectively).

352
353 $i \in I$: Set of technician types
       $i = 1: turbine\ technicians\ (onshore\ based)$
354 $i = 2: foundation\ technicians$
       $i = 3: electrical\ technicians$
       $i = 4: turbine\ technicians\ (offshore\ based)$
355
356 $j \in J$: Set of vessel types
       $j = 1: crew\ transfer\ vessels$
       $j = 2: crane\ vessels$
       $j = 3: jackups$
       $j = 4: helicopters$
       $j = 5: daughter\ ships$
357

358      $k \in K$: Set of maintenance categories
$k = 1$: $preventive\ maintenance\ of\ wind\ turbines$
$k = 2$: $preventive\ maintenance\ of\ substations$
$k = 3$: $preventive\ maintenance\ of\ foundations$
$k = 4$: $preventive\ maintenance\ of\ cables$
$k = 5$: $corrective\ maintenance\ for\ wind\ turbine\ repair$
$k = 6$: $corrective\ maintenance\ for\ wind\ turbine\ minor\ replacement$
$k = 7$: $corrective\ maintenance\ for\ wind\ turbine\ major\ replacement$
$k = 8$: $corrective\ maintenance\ for\ substation\ repair/replacement$
$k = 9$: $corrective\ maintenance\ for\ cable\ repair/replacement$

359

360   C_i^P: $annual\ salary\ of\ technician\ type\ i$
C_j^F: $annual\ fixed\ cost\ of\ vessel\ type\ j$
C_j^V: $variable\ cost\ per\ hour\ of\ vessel\ type\ j$
C^M: $annual\ charter\ cost\ for\ mothership$
R^L: $revenue\ loss\ per\ hour$

361   d_j: $distance\ to\ shore\ for\ vessel\ j$
s_j^V: $average\ speed\ of\ vessel\ type\ j$
F_k: $annual\ maintenance\ frequency\ of\ category\ k$
H_i^P: $number\ of\ working\ hours\ for\ technician\ type\ i\ in\ one\ day$
H_j^V: $number\ of\ working\ hours\ for\ vessel\ type\ j\ in\ one\ day$
L_i^P: $annual\ number\ of\ available\ working\ days\ for\ technician\ i$
L_j^V: $annual\ number\ of\ available\ working\ days\ \ for\ vessel\ j$

362

L_k^{Repair}: $length\ of\ maintenance\ (repair)\ time\ for\ category\ k$
$L_k^{logistics}$: $length\ of\ logistics\ time\ for\ category\ k$
$L_j^{Prepare}$: $length\ of\ preparation\ time\ for\ vessel\ j$
L_j^{Travel}: $length\ of\ travel\ time\ from\ shore\ to\ offshore\ wind\ farm\ for\ vessel\ j$

363   q_k: $number\ of\ techincians\ required\ for\ maintenance\ category\ k$

364   Q_j: $the\ capacity\ of\ vessel\ j\ to\ carry\ technicians$
U_k: $the\ number\ of\ maintenance\ unit\ for\ k$
N: $the\ number\ of\ turbines$
$V^{daughter}$: $maximum\ number\ of\ daughter\ ships\ carried\ by\ a\ mother\ ship$
r^{Array}: $the\ average\ length\ of\ array\ cable\ required\ for\ a\ wind\ turbine$
r^{Sub}: $the\ average\ number\ of\ wind\ turbines\ connected\ by\ a\ substation$

365

$Z_{ik}^P \begin{cases} 1: technician\ i\ is\ compatible\ to\ execute\ maintenance\ k \\ 0: technician\ i\ is\ not\ compatible\ to\ execute\ maintenance\ k \end{cases}$
$Z_{jk}^V \begin{cases} 1: vessel\ j\ is\ compatible\ to\ execute\ maintenance\ k \\ 0: vessel\ j\ is\ not\ compatible\ to\ execute\ maintenance\ k \end{cases}$

366

367   *Decision variables:*
x_{ik}: $number\ of\ required\ technicians\ type\ i\ for\ maintenance\ k$
X_i: $annual\ number\ of\ technicians\ type\ i$

368

y_{jk}: $number\ of\ required\ vessel\ type\ j\ used\ for\ maintenance\ k$
Y_j: $annual\ number\ of\ vessel\ j$

369

$b_{ik}^P \begin{cases} 1: if\ technician\ type\ i\ is\ used\ to\ execute\ maintenance\ k \\ 0: otherwise \end{cases}$

370

$$b_{jk}^V \begin{cases} 1: \textit{if vessel type j is used to execute maintenance k} \\ 0: \textit{otherwise} \end{cases}$$

371

$$b^M \begin{cases} 1: \textit{a mother ship is used} \\ 0: \textit{otherwise} \end{cases}$$

372

373 As personnel in the model are assumed to be full-time workers, the personnel cost is
374 estimated using the annual salary (C_i^P) of each technician type i. There are two costs
375 considered for vessels: fixed cost of charter (C_j^F) per vessel of type j and a variable cost (C_j^V)
376 in respect to the hours that a vessel is used in maintenance. The fixed cost is a charge
377 incurred at the beginning of an annual or monthly lease. A mother ship is usually required
378 when daughter ships stay offshore for maintenance activities, so a separate cost is
379 considered for the charter of a mother ship (C^M). Downtime due to maintenance service
380 execution also contributes a significant portion of the maintenance cost. It is referred as
381 revenue loss in terms of the hourly rate of production income (R^L) and length of downtime.
382 All turbines in a given offshore wind farm are assumed homogenous with respect to
383 manufacture model and production capacity.

384

385 Travel time (L_j^{Travel}) for vessel type j is calculated by the distance (d_j) and its speed (s_j^V).
386 The preparation time of a vessel ($L_j^{Prepare}$) depends on the vessel type j, while the
387 repair/replacement time (L_k^{Repair}) and logistics time ($L_k^{Logistics}$) are pre-determined by the
388 category of maintenance k. All the above timing data are constants in the model.

389 Weather conditions give a safety restriction at which a vessel type can operate at wind
390 turbines, in terms of wave height and wind speed. If the weather conditions reach one of the
391 operational limits of the vessel, the maintenance activities will be postponed. As DSS
392 supports strategic decisions on optimal maintenance resources, it is not a tool that
393 determines the daily maintenance activities with respect to weather conditions. The
394 parameter (L_j^V) is used to represent the number of available days that vessel type j can
395 undertake maintenance tasks. Another parameter, the number of available days for
396 technicians i (L_i^P), would be restricted by the use of vessels. The number of working hours in
397 each day for vessels (H_j^V) and technicians (H_i^P) are equal, which should be a key operation
398 constraint to restrict the daily workload.

399 A maintenance team is usually sent to execute an inspection or repair; the number of
400 technicians (q_k) in such a team depends on the work size of maintenance category k. Each
401 maintenance category requires compatible technicians and vessels in action. For instance, a
402 major replacement of large turbine components must be executed by a jack-up vessel,
403 rather than small or medium size vessels. The compatibility of each technician and vessel
404 type is represented by the binary data Z_{ik}^P and Z_{jk}^V. The binary data taking the value 1
405 indicates that the given type of technician or vessel is compatible to work for the specific
406 maintenance categories, otherwise it takes the value 0. According to the data acquired from
407 O&M specialists in the sector, the two binary data sets, compatibility of technicians i and
408 vessels j for maintenance category k, are clarified in Tables 2 and 3.

409

Z_{ik}	1	2	3	4	5	6	7	8	9
1	1	0	0	0	1	1	1	0	0
2	0	0	1	0	0	0	0	0	0
3	0	1	0	1	0	0	0	1	1
4	1	0	0	0	1	1	1	0	0

410 Table 2: Compatibility of each technician type

Z_{jk}	1	2	3	4	5	6	7	8	9
1	1	1	1	1	1	0	0	1	1
2	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	0	1	0	0
4	0	0	0	0	1	0	0	1	0
5	1	0	0	0	1	0	0	0	0

Table 3: Compatibility of each vessel type

A daughter ship ($j = 5$) travels for a short distance and time at sea. All other types of vessels ($j = 1 \dots 4$) must depart from the onshore maintenance port. The optimisation model takes into account the maintenance operations of one offshore wind farm. The model does not consider the vessel routes for implementing the maintenance activities. The travel distance of a vessel departing from an onshore port or a mother ship will take the average level value, to all wind turbines in an offshore wind farm.

4.2 Deterministic optimisation model

The deterministic optimisation model is formulated and used for the case with known technical failure rate of wind turbine components. This model is designed, as an option, in the DSS for users who know the failure rates of OWF components; so the frequency of each maintenance category is recognised to be deterministic input data.

4.2.1 Objective function

The objective function consists of minimising the total amount of the five different costs that occur when executing all the maintenance activities at an OWF during a given period (e.g. one year). The total cost contains personnel cost, fixed and variable costs of vessels, mother ship cost and downtime cost that is the revenue loss while a wind turbine is failed or under inspection.

$$\begin{aligned} Total~O\&M~cost \\ = Personnel~cost + Vessel~fixed~cost + Vessel~variable~cost \\ + Mothership~cost + Downtime~cost \end{aligned}$$

A maintenance unit (U_k) is defined according to the maintenance categories and the components in an offshore wind farm. For instance, a maintenance unit for category 1 (preventive maintenance on wind turbines) is one wind turbine; while a maintenance unit for category 2 (preventive maintenance on substations) represents a substation. An average number of wind turbines connected to a substation is defined as a rate (r^{Sub}). A maintenance unit of cable implies 100km. Array cable is estimated in respect to the average length of cable required on each turbine (r^{Array}), and length of an export cable is approximated by the distance to shore and number of the substations.

$$U_k = N \qquad\qquad\qquad k = 1,3,5,6,7 \qquad\qquad (1a)$$
$$U_k = N / r^{Sub} \qquad\qquad k = 2,8 \qquad\qquad\qquad (1b)$$
$$U_k = (N \cdot r^{Array} + D \cdot N / r^{Sub}) / 100 \quad k = 4,9 \qquad (1c)$$

- Annual personnel cost

Total personnel cost is determined by the annual salary (C_i^P) and the number of full-time technicians employed (X_i) in each type *i*.

$$Personnel\ cost = \sum_{i \in I} C_i^P \cdot X_i \qquad \forall i \in I$$

<div align="right">(2a)</div>

- Vessel fixed cost

The fixed cost of vessel of type j is determined in terms of the charter rate (C_j^F) per lease period (e.g. a year or a repair event). Crew transfer vessels, helicopters and daughter ships are assumed to chartered annually, so the number of such vessel types (Y_j) are critical to estimate the total fixed cost. Crane vessels and jack-up vessels are usually chartered monthly at events that a major repair or a replacement is required.

$$vessel\ fixed\ cost = \sum_{j \in J} C_j^F \cdot Y_j \qquad \forall j \in J$$

<div align="right">(2b)</div>

- Vessel variable cost

The variable cost rate is hourly (C_j^V) for each type of vessels. The travel time of vessel j from maintenance port to offshore wind farm is defined ($L_j^{Travel} = \frac{d_j}{s_j^V}$) by the travel distance over the vessel speed. The actual length of travel time for each maintenance task is usually made up by a returned trip ($2L_j^{Travel}$). The travel time and the length of time required for repair/replacement on the maintenance category (L_k^{Repair}) are the two major elements to determine the length of required time of vessel j.

$$Vessel\ variable\ cost = \sum_{j \in J} \sum_{k \in K} C_j^V \cdot b_{jk}^V \cdot \left(L_k^{Repair} + 2L_j^{Travel}\right) \cdot U_k \cdot F_k$$

<div align="right">(2c)</div>

$$where\ b_{jk}^V\ is\ a\ binary\ variable\ indicating\ whether\ vessel\ type\ j\ is\ selected$$
$$for\ maintenance\ k\ or\ not.$$

- Mother ship cost

The charter expenditure (C^M) of a mother ship must be accounted in the O&M cost when a daughter ship is used to undertake maintenance works. So the cost of leasing a mother ship relies on whether or not offshore based maintenance is executed ($b^M = 0\ or\ 1$).

$$Mother\ ship\ cost = C^M \cdot b^M$$

<div align="right">(2d)</div>

- Downtime cost

Any revenue loss due to breakdown of turbines or balance of plant is identified as downtime cost, which is constructed by the hourly rate of potential production income (R^L) and length of downtime for each period (l_t^D). The length of downtime contains preparation time ($L_j^{Prepare}$) and a single trip travel time (L_j^{Travel}) of the vessel j selected, and repair time (L_k^{Repair}) and logistics time ($L_k^{Logistics}$) of each maintenance category k.

  o Vessel preparation time ($L_j^{Prepare}$) is a constant, which depends on the vessel type.

483   o The length of repair/replacement time (L_k^{Repair}) is given as a constant of the
484   maintenance category k. It is not related to the type of vessels or technicians used.

485   o Similar as the repair time, logistics time ($L_k^{Logistics}$) is another constant parameter
486   associated with each maintenance category.

487

488 Hence, the total downtime cost is evaluated by:

489
$$Downtime\ cost = R^L \cdot l^{Downtime} \tag{2e}$$

490

491 Where

$$l^{Downtime} = \sum_{k \in K} \left(\sum_{j \in J} \left(L_j^{Travel} + L_j^{Prepare} \right) \cdot b_{jk}^V + L_k^{Repair} + L_k^{Logistics} \right) \cdot U_k \cdot F_k$$

492 $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (2f)

493

494 The objective of the deterministic model is to minimise the sum of the five costs (z_d).

495

$$Min\ z_d = \sum_{i \in I} C_i^P \cdot X_i + \sum_{j \in J} C_j^F \cdot Y_j + \sum_{j \in J} \sum_{k \in K} C_j^V \cdot b_{jk}^V \cdot \left(L_k^{Repair} + 2L_j^{Travel} \right) \cdot U_k \cdot F_k$$

$$+ C^M \cdot b^M + R^L \cdot \sum_{k \in K} \left(\sum_{j \in J} \left(L_j^{Travel} + L_j^{Prepare} \right) \cdot b_{jk}^V + L_k^{Repair} + L_k^{Logistics} \right) \cdot U_k \cdot F_k \tag{3}$$

496

497 4.2.2 Constraints

498 A variety of constraints for the use of vessels and technicians are taken into account in the
499 strategic maintenance planning.

500

501 *Constraint set 1*: The working time of compatible technicians should cover the related
502 repair/replacement of a maintenance category k.

503
$$x_{ik} \cdot H_i^P \cdot L_i^P \geq q_k \cdot L_k^{Repair} \cdot F_k \cdot U_k \cdot b_{ik}^P \qquad\qquad \forall\ i \in I, k \in K$$
504 $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (4)

505

506 *Constraint set 2*: The total working time of each technician type must be larger than the
507 length of time required to undertake all related maintenance.

508
$$X_i \cdot H_i^P \cdot L_i^P \geq \sum_{k \in K} q_k \cdot L_k^{Repair} \cdot F_k \cdot U_k \cdot b_{ik}^P \qquad\qquad \forall\ i \in I, k \in K$$
509 $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (5)

510

511 *Constraint set 3*: As vessels are used to transport technician team(s), and may stay in the
512 offshore wind farm during the maintenance execution for reasons of personnel safety and
513 security, the available time of the selected vessel(s) should cover the time of a 2-way travel
514 and the related repair/replacement of maintenance category k.

515
$$y_{jk} \cdot \left(H_j^V - 2L_j^{Travel} \right) \cdot L_j^V \geq L_k^{Repair} \cdot F_k \cdot U_k \cdot b_{jk}^V \qquad\qquad \forall\ j \in J, k \in K$$
516 $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (6)

517

518 *Constraint set 4*: The total available time of each vessel type must be larger than the length
519 of time required for undertaking all related maintenance.

13

520

$$Y_j \cdot \left(H_j^V - 2L_j^{Travel}\right) \cdot L_j^V \geq \sum_{k \in K} L_k^{Repair} \cdot F_k \cdot U_k \cdot b_{jk}^V \qquad \forall j \in J$$

521   (7)

522

523 *Constraint set 5*: The number of technicians transported by all vessels used for maintenance
524 *k* is restricted by the overall maximum capacity of the vessels.

525

$$\sum_{i \in I} x_{ik} \leq \sum_{j \in J} y_{jk} \cdot Q_j \qquad \forall k \in K$$

526   (8)
527 *Constraint set 6*: The number of technicians of type *i* used for all maintenance categories *k*
528 must be less than the number of technicians of type *i* recruited.

529

$$x_{ik} \leq X_i \qquad \forall i \in I, k \in K$$

530   (9)

531

532 *Constraint set 7*: The number of vessels of type *j* used for all maintenance categories *k* must
533 be less than the number of vessels of type *j* chartered.

534

$$y_{jk} \leq Y_j \qquad \forall j \in J, k \in K$$

535   (10)

536

537 *Constraint set 8*: Technician type *i* can be used for maintenance category *k* only if the vessel
538 is compatible with the maintenance category.

$$x_{ik} \leq M \cdot Z_{ik}^P \qquad \forall i \in I, k \in K$$

539   (11)

540

541 where *M* is an arbitrarily large positive number

542

543 *Constraint set 9*: Vessel type *j* can be used to execute maintenance category *k* only if the
544 vessel type is compatible to the maintenance category

545

$$y_{jk} \leq M \cdot Z_{jk}^V \qquad \forall j \in J, k \in K$$

546   (12)

547

548 where *M* is an arbitrarily large positive number

549

550 *Constraint set 10:* A binary decision variable is defined to indicate whether technician type *i*
551 is selected to execute maintenance category *k*.

552

$$x_{ik} \leq M \cdot b_{ik}^P \quad and \quad x_{ik} \geq b_{ik}^P \qquad \forall i \in I, k \in K$$

553   (13)

554

555 *Constraint set 11:* Each maintenance category *k* must be served by at least one type of
556 technician.

557

$$\sum_{i \in I} b_{ik}^P \geq 1 \qquad \forall k \in K$$

558   (14)

559

560 *Constraint set 12:* A binary decision variable is defined to indicate whether vessel type *j* is
561 selected to execute maintenance category *k*.

562

$$y_{jk} \leq M \cdot b_{jk}^V \quad and \quad y_{jk} \geq b_{jk}^V \qquad \forall \, j \in J, k \in K$$

563   (15)

564

565 *Constraint set 13:* Each maintenance category *k* must be served by at least one type of
566 vessel.

567

$$\sum_{j \in J} b_{jk}^V \geq 1 \qquad \forall k \in K$$

568   (16)

569

570 *Constraint set 14:* The number of each type of technicians must be at least the number
571 required to carry the associated maintenance works.

572

$$x_{ik} \geq q_k \cdot b_{ik}^P \qquad \forall \, i \in I, k \in K$$

573   (17)

$$X_i \geq q_k \cdot b_{ik}^P \qquad \forall \, i \in I, k \in K$$

574   (18)

575

576 *Constraint set 15: A mother ship will be used ($b^M = 1$) if any daughter ship (j = 5) is*
577 *organised to undertake maintenance jobs.*

578

$$b^M \geq b_{jk}^V \qquad j = 5, \qquad \forall \, k \in K$$

579   (19)

580

581

582 *Constraint set 16:* Offshore based turbine technicians (*i*=4) must be transported by the
583 daughter ships (*j*=5) with use of a mother ship for maintenance *k*.

$$b_{ik}^P = b_{jk}^V \qquad i = 4, \qquad j = 5, \qquad \forall \, k \in K$$

584   (20)

585 *Constraint set 17:* The number of daughter ships used is restricted by the maximum parking
586 space of a mother ship.

$$Y_j \leq V^{daughter} \qquad j = 5$$

587   (21)

588

589 ### *4.3 Stochastic optimisation model*

590 The second optimisation model in the DSS treats the failure rates of OWF components as a
591 stochastic parameter. This stochastic programming model is integrated into the system for
592 users who provide frequency of each maintenance category as probabilistic scenarios. The
593 advantage of stochastic programming is that it attempts to identify a solution to an
594 optimisation problem while directly addressing uncertainty.

595 There are three major approaches to stochastic programming, namely probabilistic or
596 chance constraint, modelling future response or resource, and scenario-based analysis
597 (Novak and Ragsdale, 2003). To avoid non-convex constraints and calculation of the
598 resource function with multi-dimensional integration, a range of scenarios of the failure rate
599 for corrective maintenance will be implemented as an effective way to achieve the cost
600 optimisation. A number of additional parameters and decision variables are defined for the
601 failure rate with probability in a set of scenarios.

602     $w \in W$: Set of scenarios (1…243 in the model)
603

F_{ks}: failure rate of category k in scenario s

Pro_{ks}: probability of failure rate of category k in scenario s

JF_{kw}: failure rates for category k in joint scenario w

$JPro_{kw}$: probability of failure rate of category k in joint scenario w

$TPro_w$: total probability of joint scenario w

604     $TPro_w = JPro_{1w} * JPro_{2w} * … * JPro_{kw}$

605 To simulate the variance of corrective maintenance frequency in the stochastic model, failure
606 rates of all OWF components are provided by a set of scenarios of probabilistic data. As
607 shown by Table 4, each of the five categories is given by three optional levels of failure rate:
608 low, mid and high. A corresponding probability of occurrence is associated with each single
609 scenario. The mean values of failure rates used in the stochastic model are the same as the
610 ones used in the deterministic model.

k	F_{ks}			Pro_{ks}		
	Low	*Mid*	*High*	*Low*	*Mid*	*High*
1	1.920	4.275	7.125	0.25	0.50	0.25
2	0.020	0.040	0.120	0.15	0.70	0.15
3	0.030	0.080	0.240	0.15	0.70	0.15
4	1.008	2.250	3.750	0.25	0.50	0.25
5	0.110	0.320	0.960	0.25	0.50	0.25

611   Table 4: Probability distribution of maintenance frequency for category *k* in scenarios

612 In respect to the five corrective maintenance categories in Table 4, 243 joint scenarios (3^5)
613 would be considered to predict the maintenance requirements. For instance, the failure rates
614 of the maintenance categories *k* in joint scenarios 1 (JF_{k1}) is (1.092, 0.020, 0.030, 1.008,
615 0.110). The associated joint probability in joint scenarios 1 ($JPro_{k1}$) is (0.25, 0.15, 0.15, 0.25,
616 0.25). Then by using the equation the total probability ($TPro_1$) is 0.25 * 0.15 * 0.15 * 0.25 *
617 0.25 = 0.0003515625.

618 The total personnel cost and fixed vessel cost are expressed in the same way as in the
619 deterministic model, which consists of optimising the number of each type of technician and
620 each type of vessel. Vessel variable cost, mother ship cost and downtime cost are
621 determined in terms of the joint scenarios associated with the stochastic combination of
622 failure rates in the five corrective maintenance categories. The objective function considers
623 the mean cost of vessel variable cost, mother ship cost and downtime cost are considered in
624 the objective function, with respect to the different failure rates.

$$Min \ \ z_s = \sum_{i \in I} C_i^P \cdot X_i + \sum_{j \in J} C_j^F \cdot Y_j$$

$$+ \sum_{j \in J} \sum_{k \in K} \sum_{w \in W} C_j^V \cdot b_{jk}^V \cdot \left(L_k^{Repair} + 2L_j^{Travel} \right) \cdot U_k \cdot JF_{kw} \cdot TPro_w + \sum_{w \in W} C^M \cdot b_w^M \cdot TPro_w$$

$$+ \sum_{k \in K} \sum_{w \in W} R^L \cdot \left(\sum_{j \in J} \left(L_j^{Travel} + L_j^{Prepare} \right) \cdot b_{jkw}^V + L_k^{Repair} + L_k^{Logistics} \right) \cdot U_k \cdot JF_{kw} \cdot TPro_w$$

625   (22)
626
627 Subject to

$$x_{ikw} \cdot H_i^P \cdot L_i^P \geq q_k \cdot L_k^{Repair} \cdot F_{kw} \cdot U_k \cdot b_{ikw}^P \qquad \forall\, i \in I, k \in K, w \in W \qquad (23)$$

$$X_{iw} \cdot H_i^P \cdot L_i^P \geq \sum_{k \in K} q_k \cdot L_k^{Repair} \cdot F_{kw} \cdot U_k \cdot b_{ikw}^P \qquad \forall\, i \in I, w \in W \qquad (24)$$

$$y_{jkw} \cdot \left(H_j^V - 2L_j^{Travel}\right) \cdot L_j^V \geq L_k^{Repair} \cdot F_{kw} \cdot U_k \cdot b_{jkw}^V \qquad \forall\, j \in J, k \in K, w \in W \qquad (25)$$

$$Y_{jw} \cdot \left(H_j^V - 2L_j^{Travel}\right) \cdot L_j^V \geq \sum_{k \in K} L_k^{Repair} \cdot F_{kw} \cdot U_k \cdot b_{jkw}^V \qquad \forall\, j \in J\, w \in W \qquad (26)$$

$$\sum_{i \in I} x_{ikw} \leq \sum_{j \in J} y_{jkw} \cdot Q_j \qquad \forall\, k \in K, w \in W \qquad (27)$$

$$x_{ikw} \leq X_{iw},\ X_i = X_{iw} \cdot TPro_w \qquad \forall\, i \in I, k \in K, w \in W \qquad (28)$$

$$y_{jkw} \leq Y_{jw},\ Y_i = Y_{jw} \cdot TPro_w \qquad \forall\, j \in J, k \in K, w \in W \qquad (29)$$

$$x_{ikw} \leq M \cdot Z_{ik}^P \qquad \forall\, i \in I, k \in K, w \in W \qquad (30)$$

$$y_{jkw} \leq M \cdot Z_{jk}^V \qquad \forall\, j \in J, k \in K, w \in W \qquad (31)$$

$$x_{ikw} \leq M \cdot b_{ikw}^P \quad and \quad x_{ikw} \geq b_{ikw}^P \qquad \forall\, i \in I, k \in K, w \in W \qquad (32)$$

$$\sum_{i \in I} b_{ikw}^P \geq 1 \qquad k \in K, w \in W \qquad (33)$$

$$y_{jkw} \leq M \cdot b_{jkw}^V \quad and \quad y_{jkw} \geq b_{jkw}^V \qquad \forall\, j \in J, k \in K, w \in W \qquad (34)$$

$$\sum_{j \in J} b_{jkw}^V \geq 1 \qquad k \in K, w \in W \qquad (35)$$

$$x_{ikw} \geq q_k \cdot b_{ikw}^P \qquad \forall\, i \in I, k \in K, w \in W \qquad (36)$$

$$X_{iw} \geq q_k \cdot b_{ikw}^P \qquad \forall\, i \in I, k \in K, w \in W \qquad (37)$$

$$b_w^M \geq b_{jkw}^V \qquad j = 5, \forall\, k \in K, w \in W \qquad (38)$$

$$b_{ikw}^P = b_{jkw}^V \qquad i = 4, j = 5,\ \forall k \in K, w \in W \qquad (39)$$

$$Y_{jw} \leq V^{daughter} \qquad j = 5\ \ \forall\, w \in W \qquad (40)$$

629

630

Sufficient technicians and vessels should be used to meet the maintenance requirement $(F_{kw} \cdot U_k)$ in each joint scenario w (Eq.23 - Eq.26). Vessel capacity to carry technicians (Q_j) is still a key constraint here (Eq.27). The number of all technicians for maintenance k in joint scenario w $(\sum_{i \in I} x_{ikw})$ who are transported by a compatible vessel j is restricted by the vessel's maximum capacity $(\sum_{j \in J} y_{jkw} \cdot Q_j)$. Vessel j or technician i can be selected to execute maintenance k in joint scenario w only if the vessel or technician is compatible to the maintenance category (Eq.30 and Eq.31). The mother ship contributes a separate vessel cost (Eq.38), which is incurred $\left(b_{4kw}^P = b_{5kw}^V = 1\right)$ if at least one daughter ship (y_k^V) is used with offshore based technicians (x_k^P) in a joint scenario w.

640

5. Implementation and experimental results

The DSS is implemented on Visual Basic for Application (VBA) as a user interface. The optimisation models, deterministic and stochastic, have been implemented in Xpress, and integrated in the DSS. VBA provides a platform with a high degree of flexibility and control, for constructing the user interface. It also gives the ability to simply import/export data from/to an external database (Agilent Technologies, 2007). Xpress is used to search the optimal solution(s) based on the input data for a particular offshore wind farm. An execution of the DSS using a sample case is described in this section, which will detail the input data and output results. The sensitivity of the DSS is also tested by changing the failure rates and size of OWF.

5.1 System input data collection

The essential system input data of the DSS was collected using an online survey, which was completed by different offshore wind stakeholders. Twenty-nine experts in the sector gave responses to the online survey, including O&M managers, O&M consultants, engineering technicians, and port managers. Further details of the online survey and responses are available on the 2OM project WP1: Maintenance Decision Support Tool (Li *et al*, 2015a). Following on from the survey, a number of interviews to key experts in the industry (including O&M managers and port managers), were arranged in order to acquire further practical information of O&M and to validate the DSS and receive constructive feedback on how the DSS could be improved. In addition, working groups with specialists from the sector was another efficient way to understand the operational issues in offshore wind maintenance. All collected data has been filtered and aggregated, and then entered into the DSS as the system inputs.

Characteristics of the nine maintenance categories are pre-defined in the system, including preparation time, repair/replacement time, logistics time and number of technicians required for each maintenance category. The categorisation of preventive (scheduled) and corrective (unscheduled) maintenance is described in section 3. For the technical specification of wind turbines, such as rated capacity and rated wind speed, they are available from the 4cOffshore website (http:// 4cOffshore.com).

The VBA-based user interface allows users to modify the parameters and save the settings in the system input data. The saved information can be loaded to the memory for running the system. The user-defined settings are transferred to the software to make decisions for the particular wind farm.

5.2 Sample case

In order to evaluate the proficiency of DSS an implementation with sample data has been carried out. A user input data form has been created with a series of questions to ask the user for the technical, structural and environmental information for an offshore wind farm. The input information is comprised of wind turbines, balance of plant, location and sea state (see Figure 2). The data of Rampion offshore wind farm is used for the user inputs as a sample. Rampion wind farm was a case study for the 2OM (Offshore Operations & Maintenance Mutualisation) project, financed by the EU Interreg IVA France (Channel) – England programme, so the proposed models have been tested on estimated data from the Rampion wind farm since the site (in common with other similar round 3 UK sites) has not yet been built. Rampion offshore wind farm is off the South Coast of the UK, and it is one of

690   the new 'round 3' sites designated by the UK government. 116 wind turbines are currently
691   planned to be installed at the farm, which are specified technically by the rated capacity of
692   3.45MW and the rated wind speed of 12.5m/s. The average distance from onshore to the
693   farm is 16.9km and the water depth range is between 19 and 39m. Monopile foundations are
694   used to give each wind turbine a total height of 140m. Two 23-km export cables and 140km
695   array cables will be installed. The mean wind speed over the last 10 years is 10m/s.

696
697   Figure 2: User input data form
698

699   Figure 3 shows the information about costs and capacity of each vessel type. The cost and
700   working time of maintenance technicians are also presented in the same data input form of
701   the DSS. All types of vessels except the helicopters are selected in the case study, by
702   clicking the selection boxes, to undertake maintenance works. All personnel types are
703   selected to take part in the maintenance planning.

704

705
706   Figure 3: System input data form of vessels and technicians

Maintenance frequency for both preventive and corrective activities, as the critical parameters to identify the workloads, must be supplied at the next stage (see Figure 4). For preventive maintenance, the frequency indicates how often the user plans to conduct an inspection / repair on each OWF component. Similar data for the corrective maintenance depends significantly on the component failure rates. Two options of mathematical models, namely deterministic or stochastic, are implemented in the DSS to generate solutions with minimum cost. In case users can just supply the mean value of maintenance frequency, they need to give the data in the 'mean frequency' column and choose deterministic optimisation. The users who have probabilistic maintenance frequencies for each corrective category can input multiple level frequency data with the incurrence probabilities. The user can then select the stochastic optimisation model in order for the DSS to take into account the various levels of frequencies and provide more realistic solutions. Figure 4 illustrates the frequency of both preventive and corrective maintenance. The stochastic model is used to optimise the maintenance planning by giving the probabilistic data at low, mean and high levels.

Preventive maintenance	Corrective maintenance		
Maintenance category	*Maintenance frequency*		
P1: Inspection / repair on turbines	1		
P2: Inspection / repair on substations	1		
P3: Inspection / repair on foundations	0.5		
P4: Inspection / repair on cables	0.25		

Preventive maintenance	Corrective maintenance		
Maintenance category	*Low frequency*	*Mean frequency*	*High frequency*
C1: Repair on turbines	1.920	4.275	7.125
C2: Replacement of minor parts (<2000kg)	0.020	0.040	0.120
C3: Replacement of minor parts (>2000kg)	0.030	0.080	0.240
C4: Repair/replacement on substations	0.008	0.250	0.750
C5: Repair/replacement on cables	0.110	0.320	0.960

Go to deterministic optimisation	Go to stochastic optimisation

Figure 4: Maintenance frequency inputs

In this study, the deterministic and stochastic models were coded and solved using Xpress IVE software on a work laptop with Corei5 2.8gigahertz and 4gigbytes RAM. All optimal solutions in respect to different input data were acquired within a reasonable range of implementation time. With regards to the expected maintenance workload, the DSS computes the number of hours of use of each vessel type and technicians in different maintenance categories. All the results are determined by the optimisation models in order to meet the demand. As the results show in Figure 5, no offshore-based vessel and technician, including mother ships, daughter ships and offshore-based turbine technicians, are used in this plan although they are clicked as available maintenance resources. The offshore based maintenance strategy does not give an obvious advantage at a relatively short distance (16.9km) from the OWF to shore. The majority of the personnel working hours on both preventive and corrective maintenance are also found in the onshore-based turbine technician teams, which is consistent with the usage of maintenance vessels. Figure 5 shows that crew transfer vessels (CTVs) are assigned to all of the preventive maintenance (530 hours) and most of the corrective maintenance (4529 hours). Crane vessels and jack-

742 up vessels are responsible for replacement of components in corrective maintenance. Since
743 the helicopter was not selected in the input data, no work hours are allocated to it.
744
745 By comparing the maintenance hours between preventive and corrective tasks, 91% of the
746 vessel hours and 77% of personnel hours are spent on corrective maintenance, which
747 implies that the reliability of turbine components influences significantly the requirement of
748 maintenance resources. Therefore it is important to determine a trade-off between the
749 amount of preventive and corrective maintenance to reduce cost of corrective maintenance
750 activities. Additionally, the essential operation facilities in a maintenance base port and the
751 qualification training courses for different technical level or administrative personnel are also
752 recognised to match the requirement of O&M activities, in a separate output form.

753

Preventive Maintenance (scheduled)

Maintenance category	Vessel time requirement (Hour)					Crew time requirement (Hour)			
	CTVs	Crane vessels	Jack-up vessels	Helicopters	Daughter ships	On. Tur	Foundation	Electrical	Off. Tur
Cat. P1: Inspection / repair on turbines	330	0	0	0	0	1856	0	0	0
Cat. P2: Inspection / repair on substations	6	0	0	0	0	0	0	48	0
Cat. P3: Inspection / repair on foundations	165	0	0	0	0	0	1392	0	0
Cat. P4: Inspection / repair on cables	29	0	0	0	0	0	0	86	0
Sum	530	0	0	0	0	1856	1392	134	0

Corrective Maintenance (unscheduled)

Maintenance category	Vessel time requirement (Hour)					Crew time requirement (Hour)			
	CTVs	Crane vessels	Jack-up vessels	Helicopters	Daughter ships	On. Tur	Foundation	Electrical	Off. Tur
Cat. C1: Repair on turbines	4516	0	0	0	0	8164	0	0	0
Cat. C2: Replacement of minor parts (<2000kg)	0	144	0	0	0	546	0	0	0
Cat. C3: Replacement of major parts (>2000kg)	0	0	556	0	0	2687	0	0	0
Cat. C4: Repair/replacement on substations	6	0	0	0	0	0	0	15	0
Cat. C5: Repair/replacement of cables	7	0	0	0	0	0	0	20	0
Sum	4529	144	556	0	0	11397	0	35	0

Back   Next

754
755 Figure 5: Requirement of vessel and personnel time
756

757 The optimised costs, including vessel, personnel and downtime costs, are illustrated in the
758 cost estimation form (shown in Figure 6). Fixed and variable costs are considered in
759 chartering a vessel, as well as other expenditures such as fuel consumption. Personnel cost
760 is assumed to be an annual salary for each type of technician. The downtime cost is
761 computed by the potential energy production during the breakdown and the wholesale
762 electricity price. The DSS is able to provide an optimised O&M cost with different selected
763 vessels and personnel; and it assists the project stakeholders to decide on the most suitable
764 maintenance strategy.

765 It is not easy to investigate the ratios of vessel fixed cost and personnel cost between
766 preventive and corrective works since they represent a single payment for each vessel or
767 technician that is shared by both preventive and corrective maintenance. But the vessel
768 variable cost should be proportional to the preventive and corrective workloads. As
769 demonstrated by the results shown in Figure 6, the vessel variable cost spent on corrective
770 maintenance is significantly higher than that of preventive maintenance. The downtime cost
771 is broken down by separating the total amount into different maintenance categories.
772 Corrective maintenance on wind turbines contributes a significant percentage (83%) of the

773 cost due to turbine breakdown. Such a high percentage could result from the higher
774 frequency of corrective activities, and the longer replacement and logistics times.

775

776 Figure 6: Maintenance cost estimation
777
778
779 In addition, the deterministic model has been implemented to find the optimal solution in the
780 sample case. A comparison of the results between the deterministic and stochastic models
781 is given on Table 4. The stochastic model suggests hiring one additional turbine technician
782 than the deterministic model as it considers potentially higher wind turbine failure rates. For
783 the same reason, one additional lease period of crew transfer vessel and jack-up vessel are
784 required to meet the higher maintenance demand. As a corresponding result of greater
785 amount of maintenance resources, all of the optimised costs from the stochastic model are
786 higher than those for the deterministic model. With the larger number of turbine technicians,
787 the personnel cost presents 8% higher than deterministic model. The vessel fixed and
788 variable costs from the stochastic model demonstrate 51% and 19% increase, respectively.
789 Taking into account the relatively minor difference of 8% in the downtime costs, there is a 15%
790 aggregate gap between the total costs from the deterministic and stochastic optimisation
791 models. The more accurate technical data of breakdown rates, the more correct requirement
792 of maintenance resources can be determined.
793
794 Table 4: Comparison of results between the deterministic and stochastic models

	Deterministic model	Stochastic model
Technicians		
Turbine technician (onshore)	7	8
Foundation technician	3	3
Electrical Technician	3	3
Turbine technician (offshore)	0	0
Vessels		
Crew transfer vessel	2	3
Crane vessel	1	1
Jack-up vessel	1	2
Helicopter	0	0
Daughter ship	0	0
Costs		
Personnel cost (£1,000,000)	0.615	0.663
Vessel fixed cost (£1,000,000)	0.557	0.842
Vessel variable cost (£1,000,000)	1.122	1.330
Mother ship cost (£1,000,000)	0	0
Downtime cost (£1,000,000)	2.833	3.050
Total cost (£1,000,000)	5.127	5.885

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5.3 Sensitivity analysis

A sensitivity analysis has been conducted to evaluate the impact of an increase in the number of wind turbines installed in an OWF on the number of vessels and technicians needed to meet the maintenance demand, and the corresponding total costs. Although economies of scale may suggest that a lower cost per turbine may be achievable. The failure rates of different components in an OWF are another key parameter to determine the maintenance workload and the related costs. Therefore, the solutions from the DSS were investigated by changing value of the component failure rates and the number of wind turbines, in order to investigate its sensitivity in different situations.

- *The effect of failure rates*

An investigation with respect to failure rates was implemented with a variety of changes in failure rates, increasing and decreasing by 25% and 50%, in order to test the sensitivity of required maintenance resources. The numbers of technicians and vessels required to carry maintenance works illustrate the corresponding changes (see Table 5). One additional turbine technician is needed to meet the maintenance requirement with every 25% increase in the failure rates. The numbers of foundation technicians and electrical technicians are stable regardless of the increased or decreased failure rates. The effects on electrical and foundation technicians are not that significant because of the relatively lower breakdown frequency in foundations, substations and cables. No mother ship and offshore-based technicians are considered to take the maintenance tasks, with the changing failure rates. Such a result could be resulted from the nature of failures on offshore wind turbines; and relatively higher cost of mother ship might be another reason. The number of crew transfer vessels demonstrates an increase pattern; and longer charter lease of crane vessel and jack-up vessel are also requested to satisfy the growing maintenance demands. No helicopter is scheduled to provide service in maintenance plan, although it was assumed as available maintenance resource. This could result from the relatively higher costs and restricted compatibility to maintenance categories on this transportation mode.

Table 5: The effect of the varying failure rates on personnel, vessel and costs

|	Decreased by 50%	Decreased by 25%	Base rate	Increased by 25%	Increased by 50%
Technicians					
Turbine technician (onshore)	6	7	8	10	11
Foundation technician	3	3	3	3	3
Electrical Technician	3	3	3	3	3
Turbine technician (offshore)	0	0	0	0	0
Vessels					
Crew transfer vessel	2	2	3	3	4
Crane vessel	1	1	1	1	2
Jack-up vessel	1	2	2	2	2
Helicopter	0	0	0	0	0
Daughter ship	0	0	0	0	0

As show on Figure 7, with the increased failure frequency by 25%, the personnel cost increases by 8-14% and vessel costs increase by 15-35%. The increase in downtime cost is more significant, 20-35%, compared to the investment on vessel and personnel. The downtime costs contribute more than 50% of the total costs in all the scenarios. In addition, the increase results in 18-31% aggregate growth in overall maintenance cost, as show by Figure 8.
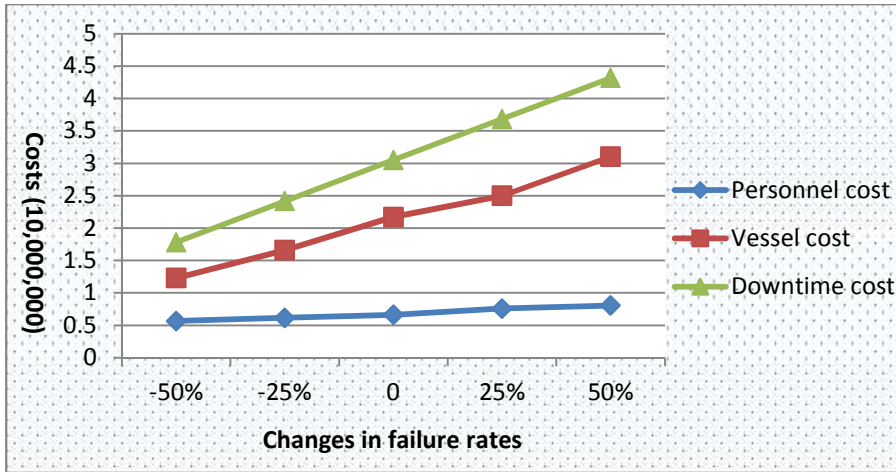
850

851 Figure 7: The effect of the failure rates on personnel, vessel and downtime costs
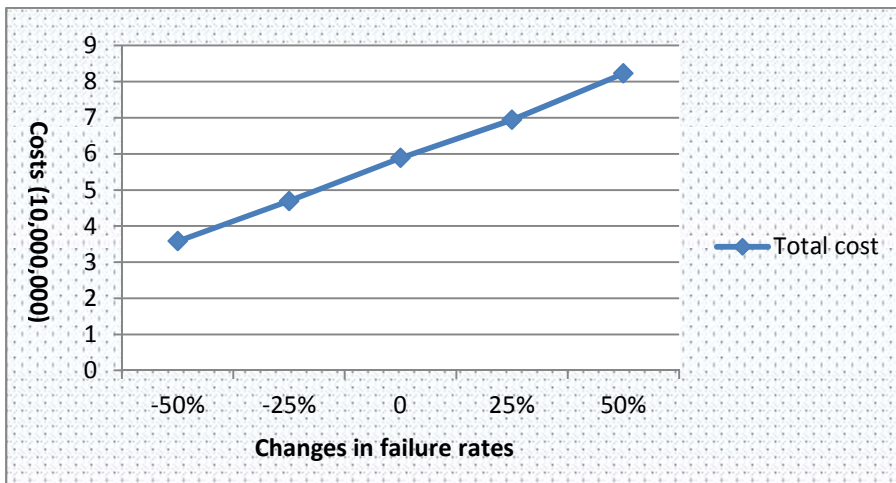
852

853 Figure 8: The effect of the failure rates on total cost

854

The effect of the number of wind turbines

856 The effect on the total optimised costs given by the DSS was also investigated by varying
857 the number of wind turbines. Such sensitivity test is used to determine whether the DSS is
858 suitable to a variety of offshore wind farms with different sizes, and to observe the variance
859 in the required maintenance resources. Nine scenarios considering, 100, 125 … 300 wind
860 turbines, have been used to acquire the optimal solutions from the DSS. The stochastic
861 decision making model was selected to implement this sensitivity analysis.

862 All costs including personnel, vessel and downtime present a near-linear increase, as show
863 on Figure 9. Since the personnel cost is contributed to by hiring maintenance technicians; it
864 is observed that there is no significant variance by varying the number of wind turbines. The
865 largest increase of personnel cost responding to 25 additional wind turbines is 15%, which
866 was found between 100 and 125 turbines; and the smallest increase is 4% between 250 and
867 275 turbines. The variance of the vessel cost is observed from 6% to 26% with each
868 increment of 25 wind turbines. The downtime cost is also affected; the maximum increase is
869 25% that is given between 100 and 125 turbines. The change of total maintenance costs is
870 also demonstrated by a similar shape on Figure 10, which increases from 5.05 to 14.1
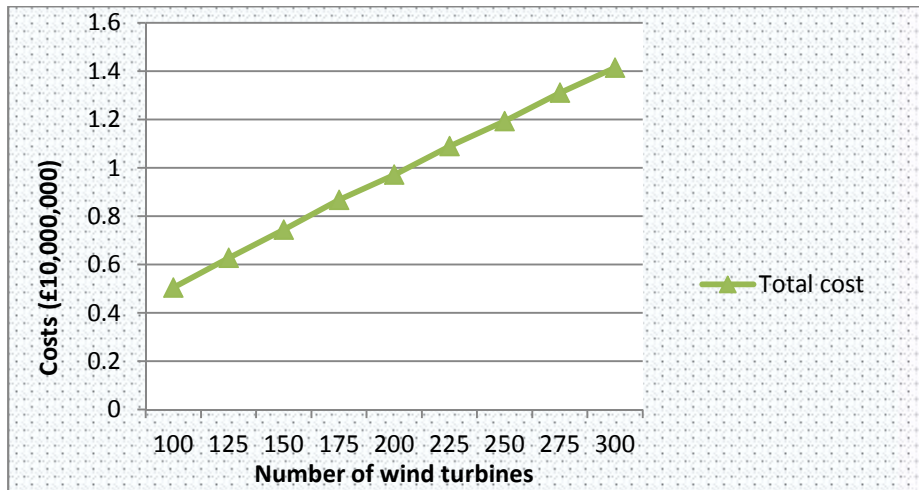871 million with the growing size of the OWF.

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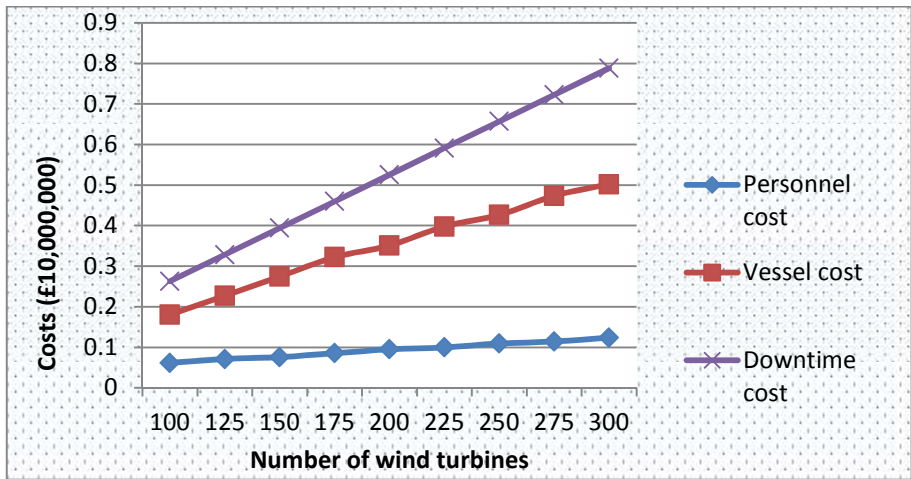
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874   Figure 9: The effect of the number of wind turbines on personnel, vessel and downtime costs

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876

877   Figure 10: The effect of the number of wind turbines on total cost

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5.4 Comparison and validation of the performance of the proposed model using the case study of Dinwoodie et al. (2015)

This section evaluates and compares the performance of the proposed model to the results of the models published by Dinwoodie *et al.* (2015) using their case studies. As the deterministic model supplies more accurate results, which is more comparable with other model results. In the paper, a set of reference cases have been used to verify four decision support or simulation models: Strathclyde analysis tool, NOWIcob decision support tool, University of Stavanger (UiS) Simulation model and ECUME model. A base case consists of 80 wind turbines with the rated capacity of 3.0 MW, which is located 50km from an onshore maintenance base. Cables, substations and foundations in the wind farm were not considered for O&M operations in the offshore wind farm. Three vessel types were considered to carry out the annual services and five categories of corrective maintenance,

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891 including manual resets, minor repair, medium repair, major repair and major replacement.
892 There are three crew transfer vessels (CTV), one field support vessel (FSV), and one heavy-
893 lift vessel (HLV) available in the base case. As no offshore based platform is involved in the
894 maintenance strategy, onshore-based turbine technicians only are considered to take part in
895 all the O&M activities. In addition, spare parts logistics are neglected for simplicity in order to
896 carry out the comparison with the different models.

897 A comparison of results of the proposed deterministic model and the models in the literature
898 is presented in Table 6. In the base case, all the cost results with the particular number of
899 CTVs and technicians from the proposed model in the DSS are allocated within the result
900 ranges published in the paper. The DSS model provided the maximal annual loss of
901 production £21.54 million against other models, with an assumption of keeping 100%
902 productivity under a desirable environment. Vessel cost is lower than other model results but
903 repair cost stays at the highest level. In aggregate, therefore, direct O&M cost of the DSS
904 model (£16.83 million) is just higher than the ECUME model but below three models.

905

906 Table 6: Results for the base case

|	DSS Model	Strathclyde CDT	NOWIcob	UiS Sim Model	ECUME model	Average
Annual loss of production	£21.54 m	£17.28 m	£16.63 m	£15.48 m	£18.64 m	£17.91 m
Annual direct O&M cost	£16.83 m	£22.44 m	£25.17 m	£17.93 m	£14.48 m	£19.37 m
Annual vessel cost	£10.73 m	£17.84 m	£19.18 m	£12.24 m	£9.30 m	£13.86 m
Annual repair cost	£4.50 m	£3.00 m	£4.39 m	£4.08 m	£3.58 m	£3.91 m
Annual technician cost	£1.60 m	£1.60 m	£1.60 m	£1.60 m	£1.60 m	£1.60 m

907

908 The base case is implemented first, and then a number of other cases are generated from
909 the base case for investigating the quantitative sensitivity, such as more (5) CTVs and fewer
910 (1) CTVs, more (30) and fewer (10) technicians, failure rates down (50%) and up (200%).
911 Figure 11 shows direct O&M costs for the base case and other cases. By comparing with the
912 results of the other four models presented on the paper (Dinwoodie *et al*., 2015), the
913 quantitative trend is relatively consistent across the reference cases. The DSS results
914 provide relative lower direct O&M costs in most of the reference cases, especially the almost
915 minimal O&M cost in the case of more CTVs. Only the case of failure rates up affects the
916 direct O&M cost on the DSS model more significantly than the other models.

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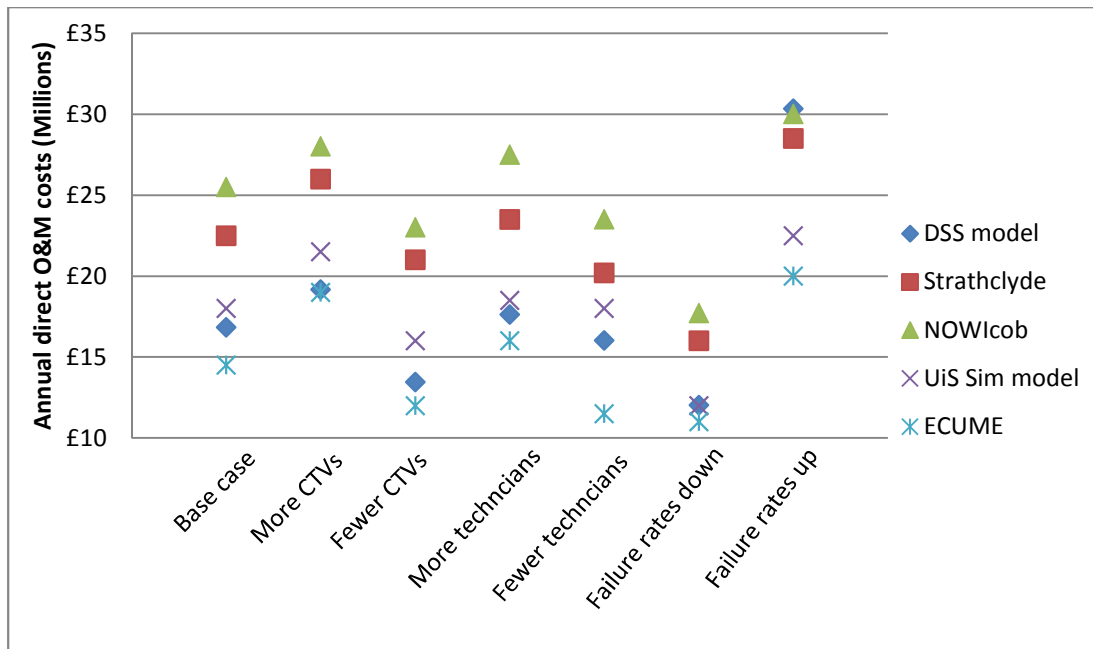
Figure 11: Annual direct O&M cost of the models for the reference cases

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In addition, it is investigated to compare the annual direct O&M costs between optimal number of CTVs from DSS and other models applied in the related reference cases. The optimal solution to achieve the minimised total cost suggests that five CTVs, one FSV and one HLV are used to cover the maintenance requirement within the base case. It gives the same number of CTVs as the reference case of more CTVs, but the overall cost in the DSS optimal solution almost reaches the lowest boundary of result range of other four models. A similar investigation was carried out to compare the cost performance of the optimal number of technicians with other models. The DSS solution suggests that eleven technicians should be involved in maintenance activities and the corresponding annual O&M cost is located nearby the mid-point of the result range in the case of fewer technicians.

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6. Conclusion and future work

935

6.1 Conclusion

937

As offshore wind is a relatively new technology, and there are a limited number of tools available to support O&M planning activities, a decision support system has been designed in this paper to assist multiple stakeholders in designing cost effective O&M decisions. The system proposed includes two optimisation models to minimise the total cost of O&M activities, including personnel cost, fixed vessel cost, variable vessel cost, mother ship cost and revenue loss, in offshore wind maintenance during a given period of time.

944

According to the results obtained from the DSS, offshore wind project developers can prepare O&M resources and organise works in advance to meet the requirement of necessary maintenance activities. All required maintenance resources will be used in a cost effective way in order to optimise the costing performance; and the revenue loss is seen as

949 another key element in O&M cost. Additionally, the costs are significantly affected by the
950 reliability of offshore wind turbines and the size of the farm.
951
952 The implementation results imply that the reliability of OWF components has an immediate
953 effect on the maintenance costs, as the majority of the costs are generated by corrective
954 maintenance. Hence, the stochastic programming model (described in Section 4.2) is able to
955 supply more realistic solutions if failure rates parameters are not known with certainty, since
956 it takes into account a probabilistic failure rates for each OWF component. Such probabilistic
957 data is critical to determine the unforeseen requirement of vessels and technicians for
958 corrective maintenance, in order to maximise the availability of energy production. The
959 stochastic model is thus aimed at OWF stakeholders who do not have significant certainty
960 about turbine failure rates due to lack of knowledge. On the other hand, the deterministic
961 model could be used by OWF stakeholders who are in the position to make more accurate
962 conclusions about the failure rates due to their industrial knowledge. Thus the 15% gap in
963 total costs between the deterministic and stochastic models can be seen as a proxy to the
964 value of information regarding turbine failure rates The DSS also gives an opportunity to
965 understand the sensitivities of the O&M costs due to changes in failure probability and OWF
966 size. The sensitivity results illustrate near-linear changes in O&M costs by varying the failure
967 rates and the number of turbines. Hence, the DSS is able to help offshore wind stakeholders
968 to understand the strategic resource requirements associated with the maintenance of an
969 offshore wind farm. Utilisation of vessels and technicians could potentially be included as
970 further objectives in the optimisation models. In addition, the correlation between preventive
971 maintenance and component failures could be an extra parameter to consider in the further
972 research.
973
974
975 ### *6.2 Future work on the incorporation of weather conditions*
976
977 The effect of weather is one of the most significant factors causing uncertainty in the
978 planning of offshore wind farms. Currently, weather is only accurately predictable on a
979 timescale far shorter than the strategic planning periods considered by the models
980 developed in this paper. The usage examples given in Sections 4 and 5 have been
981 populated by using long-term average weather data from the United Kingdom. However, it is
982 recognised that weather conditions different from the average will result in a performance
983 significantly different from that predicted by the model. The suggested course of action for
984 stakeholders that are concerned by the variance is therefore to execute the model for
985 multiple weather scenarios with different input data in each scenario. The optimal course(s)
986 of action could then be determined by a technique such as discrete news-vendor analysis,
987 which allows for either probabilistic or non-probabilistic analysis, dependent on whether the
988 stakeholder wishes to assign probabilities to the chances of a weather scenario occurring or
989 not.
990
991 Calculation of the effects of a given weather scenario on the input data of the models
992 presented in Section 4 requires a significant level of understanding of offshore wind
993 operations. As well as the obvious restrictions on accessibility of platforms, the weather will
994 have an effect on the vessel travel times and potentially the vessel availability and charter
995 costs as a poor weather season may induce increased demand for vessels in the smaller
996 time periods of adequate weather conditions. There may also be some effect on the failure
997 rates as harsher than average weather may cause a larger number of failures. The effect on
998 personnel should also not be neglected as seasickness and more challenging working
999 conditions could reduce the number of working hours, number of available technicians in
1000 each category and the number of available working days per technician per year. The above
1001 paragraph states the considerations in the negative "worse weather than average" scenarios;
1002 however the same reasoning also applies in reverse to the positive "better weather than

1003 average" scenarios. It is recognised that accurate compilation of the above data for multiple
1004 weather scenarios will only be possible for stakeholders with knowledge of and access to
1005 wind farm operations data. Therefore it is suggested that, similar to the failure rate case
1006 detailed in Section 4, two options for usage of the models are available. Stakeholders
1007 without access to detailed weather effect data may use the models as presented with solely
1008 the average case to gain an estimate of costs and resources, with the caveat that weather
1009 conditions significantly different to the average will results in significantly different resource
1010 and cost levels. Stakeholders with access to detailed operational data are recommended to
1011 use the approach outlined in the above paragraphs, forming multiple weather data effect
1012 scenarios and making decisions, possibly with use of a further analysis technique, based on
1013 the model results from across the set of weather data effect scenarios.
1014
1015 **Acknowledgement**

1020

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