

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

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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

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## 42 1. Introduction

43 The EU aims to achieve 20% of energy consumption from renewable sources in order to  
44 reduce carbon emissions by 2020 (Bilgili *et al.*, 2011; Laura and Vicente, 2014). The UK  
45 government has also set the figure of 15% as the target for 2020 (O’Keeffe and Hagett,  
46 2012; Higgins and Foley, 2014). Over the past decade, wind energy has been a significantly  
47 developing renewable energy source (Ding and Tian, 2012). According to the interviews  
48 conducted by Ochieng *et al* (2014), wind power is one of the few renewable technologies  
49 that demonstrate a rapid development in the past decades. It will therefore provide a major  
50 proportion of electricity production out of all the renewable sources (Freris and Infield, 2009)  
51 and make a great single contribution to the 2020 target (O’Keeffe and Hagett, 2012; Appiott  
52 *et al.*, 2014). There are five distinct phases during the life cycle of an offshore wind farm:  
53 development and consenting, production and acquisition, installation and commissioning,  
54 operation and maintenance (O&M) and decommissioning (Myhr *et al.*, 2014). The O&M  
55 starts when the OWF begins operating and continues until the final decommissioning stage.  
56 Although the cost of the O&M phase is generally not as large as the construction phase, it is  
57 still significant due to the length of the long-term operation during the life cycle. O&M costs  
58 are of the order of £25-40 million for a typical 500MW OWF (The Crown Estate, 2010).  
59 These kinds of cost accounts for 18% of the total offshore wind system (Carbon Trust, 2008).  
60 Hence the expenditure on O&M may be seen as a key element of the energy production  
61 costs in OWFs.

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

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

80 In order to minimise the expected costs in the lifetime of an OWF, an optimal plan for O&M  
81 should be developed in order to handle the component failure risk (Nielsen and Sorensen,  
82 2011). The central question in developing the optimal plan is the decision of when and how  
83 to organise maintenance activities. The existing industry experiences imply that production  
84 loss might result from the lack of inspection/repair prior to component failure. A survey of  
85 offshore wind energy companies was conducted by the work of Pahlke (2007), with 70% of  
86 the respondents expressing the need for decision support tools whereas only a few of them  
87 had such models available for use (Scheu *et al.*, 2012; Hofmann and Sperstad, 2013). The  
88 literature review presented in this paper shows that the developed decision support tools to  
89 date use mainly simulation techniques, whilst the use of mathematical optimisation modelling  
90 is limited.

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

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

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

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

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

120 Computational decision tools are able to support complex decision making in the energy  
121 sector, such as the recent tools developed by Hunt *et al.* (2013) and Chang (2014) for the  
122 planning and coordination of renewable energy systems. A performance analysis of a  
123 renewable energy system usually underpins this kind of tool to aid decision making. Most of  
124 the developed decision support systems in the wind energy sector are specific to onshore  
125 developments and only a small number of those are suitable for offshore projects (Pahlke,  
126 2007). The tools are more likely applicable offshore in a limited geographical area rather  
127 than a large extent such as the North Sea, which contains a large number of current and  
128 proposed wind farms from several countries (Wanderer, 2009).

129  
130 As O&M costs account for around one third of the life cycle cost of an offshore wind farm,  
131 there is a need to develop cost-effective O&M strategies to achieve a significant saving in  
132 the cost of energy during the life of OWFs. A number of researchers over recent years have  
133 created decision support tools for different purposes in offshore wind production, such as to  
134 forecast the operations of a wind farm (Scheu *et al.*, 2012), to estimate the O&M costs  
135 including revenue loss (Dinwoodie *et al.*, 2013), to assess offshore wind energy potential  
136 (Schillings *et al.*, 2012), and to simulate the operational phase of an offshore wind farm with  
137 all maintenance activities and costs (Hofmann and Sperstad, 2013). A common objective of  
138 these tools is to find the optimal maintenance strategy/planning for a particular offshore wind  
139 farm, rather than a global strategy for multiple farms. The decision tools may calculate the  
140 maintenance cost on the basis of levelised production cost (LPC), which is seen as an  
141 efficient way for analysis and evaluation of risk and total cost during the life span of offshore  
142 turbines (Myhr *et al.*, 2014), Dinwoodie *et al.* (2015) investigated the performance amongst

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

145  
146

147 The Norwegian offshore wind cost and benefit model – NOWIcob (Hofmann and Sperstad,  
148 2013) can simulate the operational phase of an offshore wind farm with all maintenance  
149 activities and costs. Several input parameters, both controllable options and the  
150 uncontrollable external factors, can be changed in the model to assess their impact on  
151 performance parameters such as the O&M costs and availability. Controllable options are all  
152 strategic choices that the wind farm operator can directly decide upon. Uncontrollable  
153 external factors include all parameters that are outside the direct influence of the wind farm  
154 operator such as the market environment and weather conditions.

155

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

162

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

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

191

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

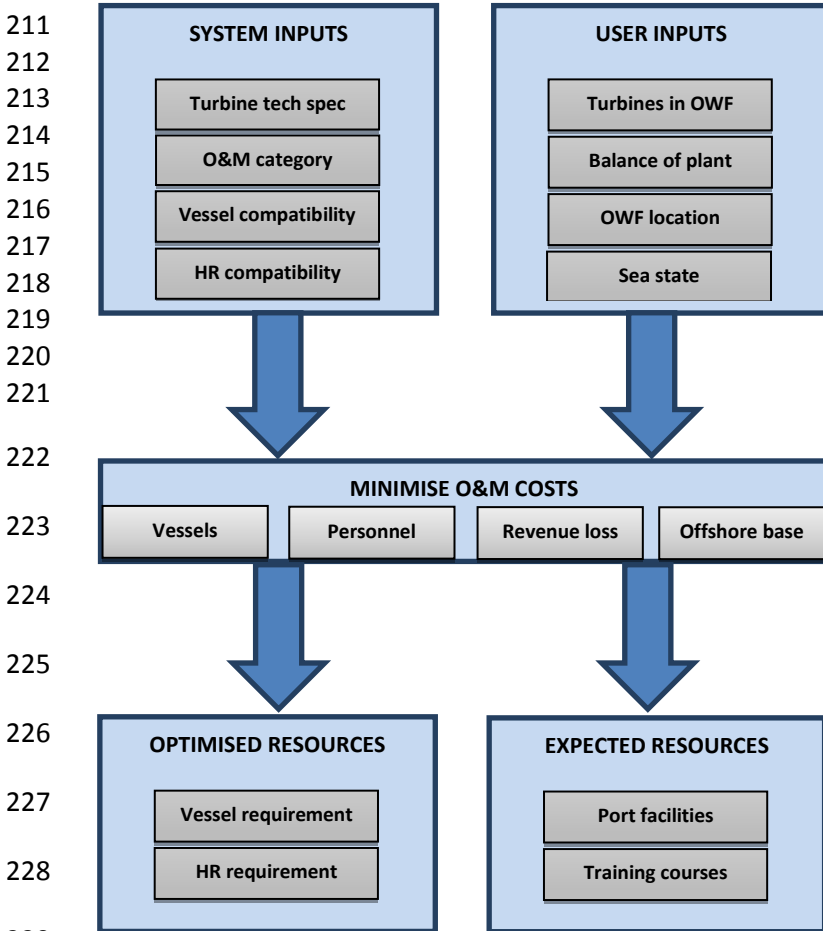
196 the optimisation models, associated with deterministic and stochastic reliability parameters,  
197 are formulated on the basis of offshore wind farm O&M practices.

198

### 199 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



230 Figure 1: Decision Support System framework

231

#### 232 3.1 System inputs

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

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

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

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

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

289

### 290 **3.2 User inputs**

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

298

### 299 **3.3 Cost optimisation**

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

310

### 311 **3.4 System outputs**

312 According to the cost estimation from the DSS, the OWF management team will decide on  
313 the most suitable maintenance strategy with respect to some operational issues in practice,  
314 e.g. available space and support workers in the maintenance base port. There are three  
315 optional maintenance strategies that are defined in the DSS in terms of vessel and  
316 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

#### 337 **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.

##### 343 **4.1 Notation and assumptions**

344 Index  $k$  denotes the category of maintenance.  $k = 1..4$ , indicate the preventive maintenance  
345 activities;  $k = 5..9$ , indicate corrective maintenance. Four kinds of maintenance technicians  
346 are considered in the model  $i = 1..4$  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  $j = 1..5$  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 technicians 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  $Z_{ik}^P$   $\begin{cases} 1: \text{technician } i \text{ is compatible to execute maintenance } k \\ 0: \text{technician } i \text{ is not compatible to execute maintenance } k \end{cases}$   
 $Z_{jk}^V$   $\begin{cases} 1: \text{vessel } j \text{ is compatible to execute maintenance } k \\ 0: \text{vessel } j \text{ is not compatible to execute maintenance } k \end{cases}$

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

370

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

371

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

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

411 Table 3: Compatibility of each vessel type

412

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

419

## 420 **4.2 Deterministic optimisation model**

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

425

### 426 4.2.1 Objective function

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

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

432

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

$$441 \quad U_k = N \quad k = 1,3,5,6,7 \quad (1a)$$

$$442 \quad U_k = N / r^{Sub} \quad k = 2,8 \quad (1b)$$

$$443 \quad U_k = (N \cdot r^{Array} + D \cdot N / r^{Sub}) / 100 \quad k = 4,9 \quad (1c)$$

444

- 445 • Annual personnel cost

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

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

448 (2a)

449 • Vessel fixed cost

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

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

455 (2b)

456 |  
 457 • Vessel variable cost

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

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

465 (2c)

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

468 |  
 469 • Mother ship cost

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

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

474 (2d)

475 |  
 476 • Downtime cost

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

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

- 483 | ○ 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 | ○ 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:

$$489 \quad Downtime\ cost = R^L \cdot l^{Downtime} \quad (2e)$$

491 Where

$$492 \quad l^{Downtime} = \sum_{k \in K} \left( \sum_{j \in J} (L_j^{Travel} + L_j^{Prepare}) \cdot b_{jk}^V + L_k^{Repair} + L_k^{Logistics} \right) \cdot U_k \cdot F_k \quad (2f)$$

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

$$495 \quad \begin{aligned} Min\ z_d = & \sum_{i \in I} C_i^P \cdot X_i + \sum_{j \in J} C_j^F \cdot Y_j + \sum_{j \in J} \sum_{k \in K} C_j^V \cdot b_{jk}^V \cdot (L_k^{Repair} + 2L_j^{Travel}) \cdot U_k \cdot F_k \\ & + C^M \cdot b^M + R^L \cdot \sum_{k \in K} \left( \sum_{j \in J} (L_j^{Travel} + L_j^{Prepare}) \cdot b_{jk}^V + L_k^{Repair} + L_k^{Logistics} \right) \cdot U_k \cdot F_k \end{aligned} \quad (3)$$

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

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

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

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

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

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

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.

520

$$Y_j \cdot (H_j^V - 2L_j^{Travel}) \cdot L_j^V \geq \sum_{k \in K} L_k^{Repair} \cdot F_k \cdot U_k \cdot b_{jk}^V \quad \forall j \in J \quad (7)$$

521

522

523 *Constraint set 5:* The number of technicians transported by all vessels used for maintenance524 *k* is restricted by the overall maximum capacity of the vessels.

525

$$\sum_{i \in I} x_{ik} \leq \sum_{j \in J} y_{jk} \cdot Q_j \quad \forall k \in K \quad (8)$$

526

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

$$x_{ik} \leq X_i \quad \forall i \in I, k \in K \quad (9)$$

530

531

532 *Constraint set 7:* The number of vessels of type *j* used for all maintenance categories *k* must533 be less than the number of vessels of type *j* chartered.

534

$$y_{jk} \leq Y_j \quad \forall j \in J, k \in K \quad (10)$$

535

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.

$$x_{ik} \leq M \cdot Z_{ik}^P \quad \forall i \in I, k \in K \quad (11)$$

539

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

$$y_{jk} \leq M \cdot Z_{jk}^V \quad \forall j \in J, k \in K \quad (12)$$

546

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

$$x_{ik} \leq M \cdot b_{ik}^P \quad \text{and} \quad x_{ik} \geq b_{ik}^P \quad \forall i \in I, k \in K \quad (13)$$

553

554

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

556 technician.

557

$$\sum_{i \in I} b_{ik}^P \geq 1 \quad \forall k \in K \quad (14)$$

558

559

560 *Constraint set 12:* A binary decision variable is defined to indicate whether vessel type *j* is561 selected to execute maintenance category *k*.

562

$$y_{jk} \leq M \cdot b_{jk}^V \quad \text{and} \quad y_{jk} \geq b_{jk}^V \quad \forall j \in J, k \in K \quad (15)$$

563

564

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

567

$$\sum_{j \in J} b_{jk}^V \geq 1 \quad \forall k \in K \quad (16)$$

568

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

$$x_{ik} \geq q_k \cdot b_{ik}^P \quad \forall i \in I, k \in K \quad (17)$$

573

$$X_i \geq q_k \cdot b_{ik}^P \quad \forall i \in I, k \in K \quad (18)$$

574

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

$$b^M \geq b_{jk}^V \quad j = 5, \quad \forall k \in K \quad (19)$$

579

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  $k$ .

$$b_{ik}^P = b_{jk}^V \quad i = 4, \quad j = 5, \quad \forall k \in K \quad (20)$$

584

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

$$Y_j \leq V^{daughter} \quad j = 5 \quad (21)$$

587

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  $TPro_w = JPro_{1w} * JPro_{2w} * \dots * JPro_{kw}$

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  $0.25 * 0.15 * 0.15 * 0.25 * 0.25 = 0.0003515625$ .

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.

$$\begin{aligned}
 \text{Min } z_s = & \sum_{i \in I} C_i^P \cdot X_i + \sum_{j \in J} C_j^F \cdot Y_j \\
 & + \sum_{j \in J} \sum_{k \in K} \sum_{w \in W} C_j^V \cdot b_{jk}^V \cdot (L_k^{Repair} + 2L_j^{Travel}) \cdot U_k \cdot JF_{kw} \cdot TPro_w + \sum_{w \in W} C^M \cdot b_w^M \cdot TPro_w \\
 & + \sum_{k \in K} \sum_{w \in W} R^L \cdot \left( \sum_{j \in J} (L_j^{Travel} + L_j^{Prepare}) \cdot b_{jkw}^V + L_k^{Repair} + L_k^{Logistics} \right) \cdot U_k \cdot JF_{kw} \cdot TPro_w
 \end{aligned} \tag{22}$$

625

626

627 Subject to



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

641

## 642 **5. Implementation and experimental results**

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

652

### 653 **5.1 System input data collection**

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

666 Characteristics of the nine maintenance categories are pre-defined in the system, including  
667 preparation time, repair/replacement time, logistics time and number of technicians required  
668 for each maintenance category. The categorisation of preventive (scheduled) and corrective  
669 (unscheduled) maintenance is described in section 3. For the technical specification of wind  
670 turbines, such as rated capacity and rated wind speed, they are available from the  
671 4cOffshore website ([http:// 4cOffshore.com](http://4cOffshore.com)).

672

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

677

678

### 679 **5.2 Sample case**

680 In order to evaluate the proficiency of DSS an implementation with sample data has been  
681 carried out. A user input data form has been created with a series of questions to ask the  
682 user for the technical, structural and environmental information for an offshore wind farm.  
683 The input information is comprised of wind turbines, balance of plant, location and sea state  
684 (see Figure 2). The data of Rampion offshore wind farm is used for the user inputs as a  
685 sample. Rampion wind farm was a case study for the 2OM (Offshore Operations &  
686 Maintenance Mutualisation) project, financed by the EU Interreg IVA France (Channel) –  
687 England programme, so the proposed models have been tested on estimated data from the  
688 Rampion wind farm since the site (in common with other similar round 3 UK sites) has not  
689 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

<i>Please select</i>	<i>Vessel type</i>	<i>Fixed cost (GBP/year)</i>	<i>Variable cost (GBP/hour)</i>	<i>Speed (miles/h)</i>	<i>Personnel space</i>
<input checked="" type="checkbox"/>	Crew transfer vessel	182500	30	40	12
<input checked="" type="checkbox"/>	Crane vessel	90000	2000	25	12
<input checked="" type="checkbox"/>	Jack-up vessel	102000	1600	20	12
<input type="checkbox"/>	Helicopter	875000	1000	220	3
<input checked="" type="checkbox"/>	Daughter ship	0	120	30	3
<input checked="" type="checkbox"/>	Mother ship	6570000	0	0	12

<i>Please select</i>	<i>Personnel type</i>	<i>Annual salary (GBP)</i>	<i>Work shift (hour)</i>	<i>Work day (days/year)</i>
<input checked="" type="checkbox"/>	Turbine technician (onshore)	48000	10	180
<input checked="" type="checkbox"/>	Foundation technician	45000	10	180
<input checked="" type="checkbox"/>	Electrical technician	48000	10	180
<input checked="" type="checkbox"/>	Turbine technician (offshore)	58000	12	180

Wholesale price of electricity: 1.5 GBP/GW

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

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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 incurrance 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

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Figure 4: Maintenance frequency inputs

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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 4gigabytes 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
<b>Sum</b>	<b>530</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>1856</b>	<b>1392</b>	<b>134</b>	<b>0</b>

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
<b>Sum</b>	<b>4529</b>	<b>144</b>	<b>556</b>	<b>0</b>	<b>0</b>	<b>11397</b>	<b>0</b>	<b>35</b>	<b>0</b>

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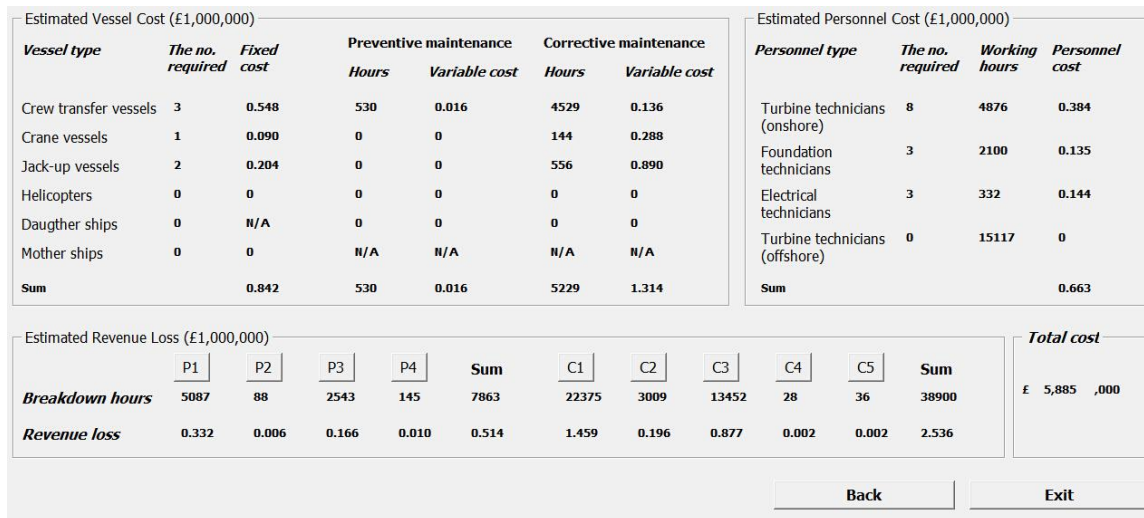
754  
 755 Figure 5: Requirement of vessel and personnel time  
 756

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

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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.

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 794

Table 4: Comparison of results between the deterministic and stochastic models

	Deterministic model	Stochastic model	795
<b>Technicians</b>			<b>796</b>
Turbine technician (onshore)	7	8	797
Foundation technician	3	3	798
Electrical Technician	3	3	799
Turbine technician (offshore)	0	0	800
<b>Vessels</b>			<b>801</b>
Crew transfer vessel	2	3	802
Crane vessel	1	1	803
Jack-up vessel	1	2	804
Helicopter	0	0	805
Daughter ship	0	0	806
<b>Costs</b>			<b>807</b>
Personnel cost (£1,000,000)	0.615	0.663	808
Vessel fixed cost (£1,000,000)	0.557	0.842	809
Vessel variable cost (£1,000,000)	1.122	1.330	810
Mother ship cost (£1,000,000)	0	0	811
Downtime cost (£1,000,000)	2.833	3.050	
<b>Total cost (£1,000,000)</b>	<b>5.127</b>	<b>5.885</b>	

812

813 **5.3 Sensitivity analysis**

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

822  
 823 • **The effect of failure rates**

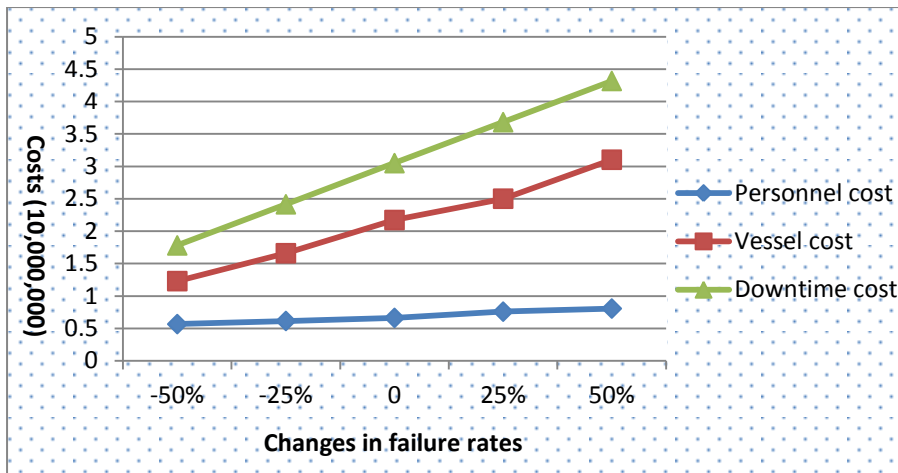
824 An investigation with respect to failure rates was implemented with a variety of changes in  
 825 failure rates, increasing and decreasing by 25% and 50%, in order to test the sensitivity of  
 826 required maintenance resources. The numbers of technicians and vessels required to carry  
 827 maintenance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

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

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

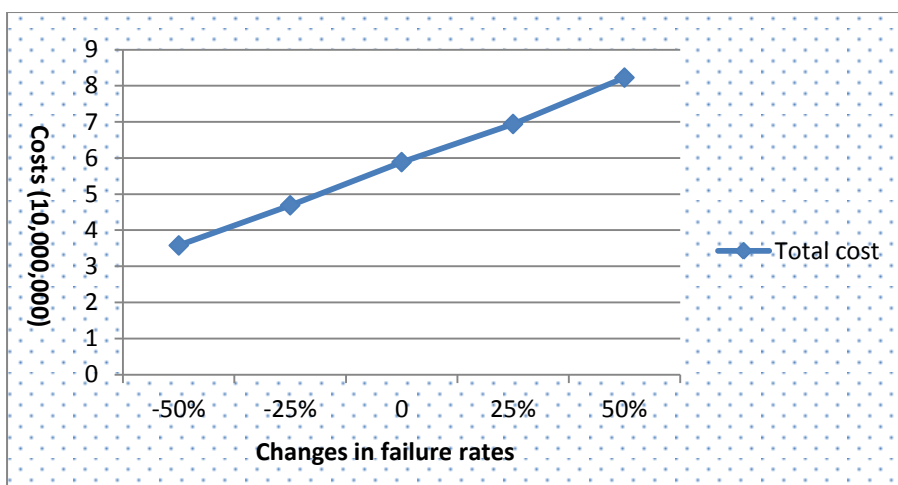
842  
 843 As show on Figure 7, with the increased failure frequency by 25%, the personnel cost  
 844 increases by 8-14% and vessel costs increase by 15-35%. The increase in downtime cost is  
 845 more significant, 20-35%, compared to the investment on vessel and personnel. The  
 846 downtime costs contribute more than 50% of the total costs in all the scenarios. In addition,  
 847 the increase results in 18-31% aggregate growth in overall maintenance cost, as show by  
 848 Figure 8.

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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

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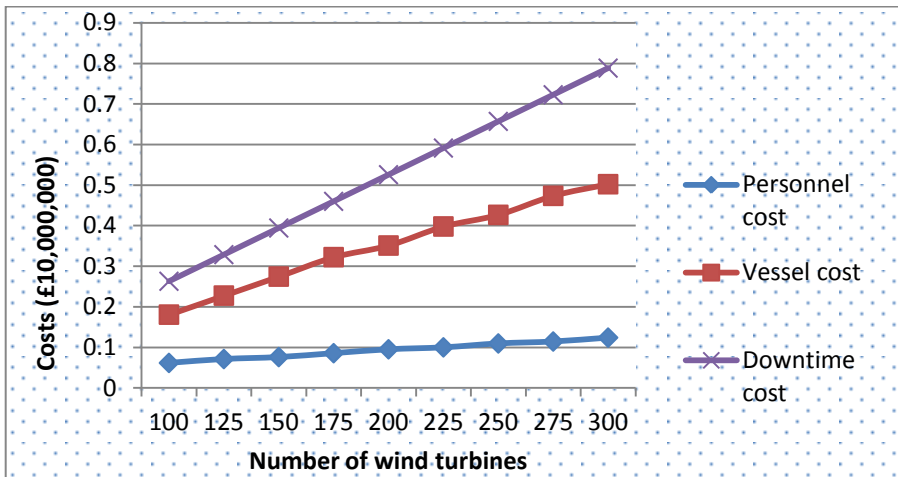
855 ***The effect of the number of wind turbines***

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.



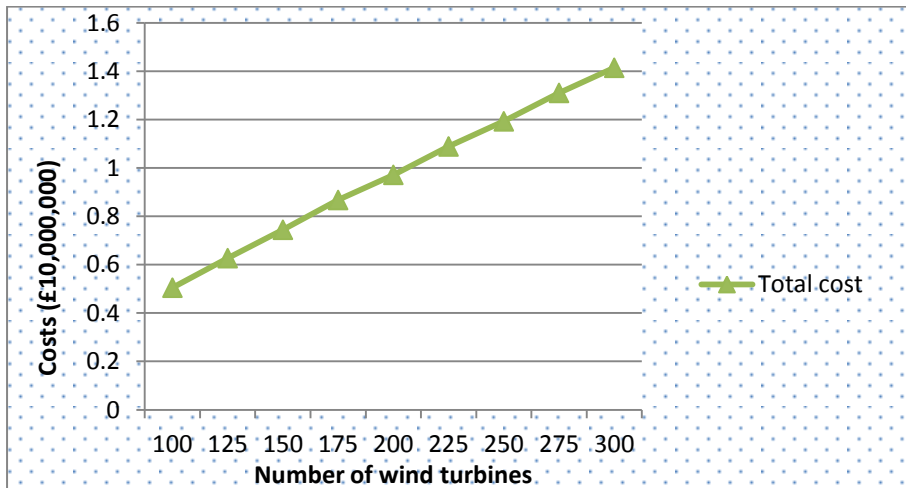
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873

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

875



876

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

878

879 **5.4 Comparison and validation of the performance of the proposed model**  
880 **using the case study of Dinwoodie et al. (2015)**

881 This section evaluates and compares the performance of the proposed model to the results  
882 of the models published by Dinwoodie *et al.* (2015) using their case studies. As the  
883 deterministic model supplies more accurate results, which is more comparable with other  
884 model results. In the paper, a set of reference cases have been used to verify four decision  
885 support or simulation models: Strathclyde analysis tool, NOWIcob decision support tool,  
886 University of Stavanger (UiS) Simulation model and ECUME model. A base case consists of  
887 80 wind turbines with the rated capacity of 3.0 MW, which is located 50km from an onshore  
888 maintenance base. Cables, substations and foundations in the wind farm were not  
889 considered for O&M operations in the offshore wind farm. Three vessel types were  
890 considered to carry out the annual services and five categories of corrective maintenance,

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

	<b>DSS Model</b>	<b>Strathclyde CDT</b>	<b>NOWIcob</b>	<b>UiS Sim Model</b>	<b>ECUME model</b>	<b>Average</b>
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

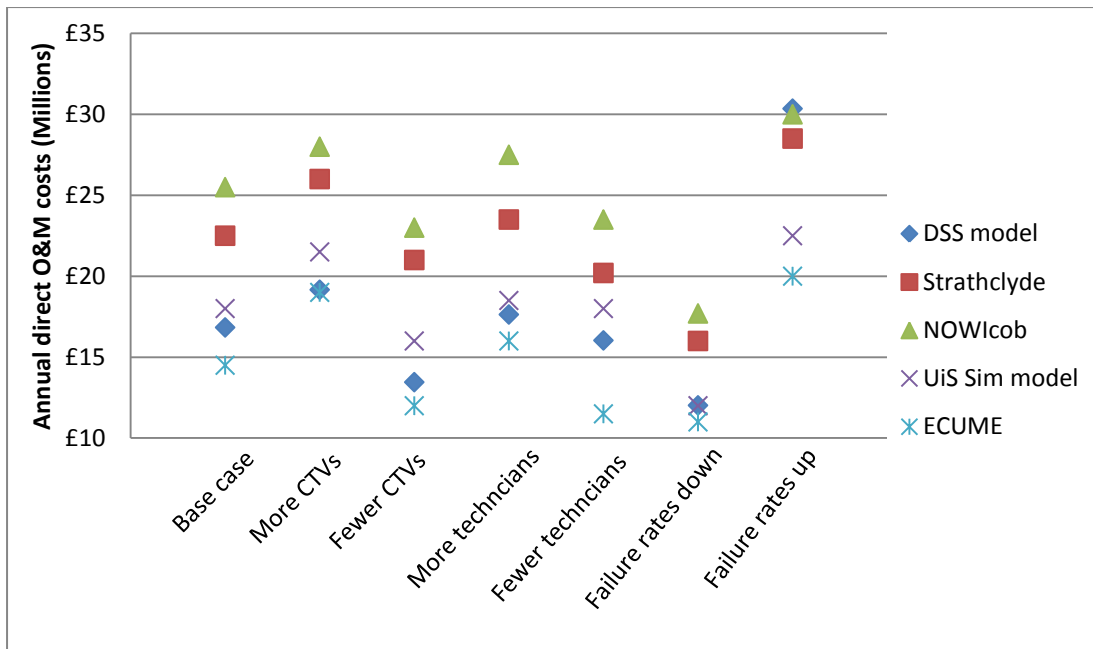
907

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.

917

918

919



920

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

922

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

933

## 934 6. Conclusion and future work

935

### 936 6.1 Conclusion

937

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

944

945 According to the results obtained from the DSS, offshore wind project developers can  
 946 prepare O&M resources and organise works in advance to meet the requirement of  
 947 necessary maintenance activities. All required maintenance resources will be used in a cost  
 948 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**

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1018 thank also all participants who have been involved in the online surveys, interviews and  
1019 working groups for the project.

1020

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