Deliverable 6.1: Best practice guidelines for offshore array monitoring and control with consideration of offshore wind and oil & gas experiences

Fraunhofer IWES and Partners of Work Package 6

This project has received funding from the European Union’s Seventh Programme for research, technological development and demonstration under grant agreement No 608597

D6.1: Best practice guidelines for offshore array monitoring and control with consideration of offshore wind and oil & gas experiences
Project: DTOcean - Optimal Design Tools for Ocean Energy Arrays
Code: DTO_WP6_ECD_D6.1

	Name	**Date**
Prepared	Work Package 6	2014-07-14
Checked	Work Package 9	
Approved	Project Coordinator	

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement No. 608597 (DTOcean).

Abstract

This deliverable D6.1 “: Best practice guidelines for offshore array monitoring and control with consideration of offshore wind and oil & gas experiences” presents the results from the work in the DTOcean WP6 “System Control & Operation” within the task T6.1. The purpose of this task is to assess existing array level operation, maintenance and control methods and tools. Potential sources of knowledge for this will be the onshore and offshore wind industry and the offshore oil and gas industry. Offshore wind farms face very similar challenges with respect to foundations, submersed electrical systems, personnel and vessel access to array devices, transport of materials, etc. The offshore oil and gas industry has worked with floating or bottom fixed concrete and steel structures for several decades. Main experiences to be analysed here are expected to be related to corrosion problems and long term stability of mooring systems. Even though not explicitly mentioned in the deliverable title, control and operational strategy aspects will also be assessed.

This deliverable report analyses in the 2nd section the developments made in the above mentioned sectors with respect to operation and maintenance planning tools. Section 3 assesses existing approaches for maintenance strategies with their relevance to the work in DTOcean WP6. The 4th section discusses the application of advanced control strategies at an array level under different optimisation targets: decrease of power production costs, assure the grid integration with respect to different grid codes, decrease of load and the active power (frequency) / reactive power (voltage) control. The final section of the deliverable, Section 5 summarises the results of the assessments made.

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1 INTRODUCTION

The work in the task 6.1 is targeted to assess existing approaches for the addressed research and development work in WP6 of the DTOcean project. This document reflects the results of this assessment process. The actual technological state with respect to operation, maintenance and control of offshore installations in the various fields of the "blue industry" are also described. Since the scope of the DTOcean project is restricted to the energy generation from wave and tidal resources, the document will discuss these items exclusively, which does not mean that relevant information from other fields will be excluded.

In the following section, information regarding the optimised operation of offshore facilities will be discussed. For this purpose, experience from the oil and gas industry will be assessed. Further information can be gathered from the first experiences with offshore energy generation arrays, for example wind farms. Although the amount of operational experiences is limited in this field, it is likely to provide valuable context. To extend the information base, relevant and applicable information from onshore wind farms will also be analysed.

The third section of this document will analyse existing approaches for optimised maintenance for offshore installed systems. The approaches outlined are applicable to all sectors of the industry. They will be assessed with respect to their impact on the maintenance strategies for offshore wave and tidal energy generation arrays.

In section 4, control strategies which are currently under development in the field of wind farm control will be analysed. Main aspects here will be the power quality (reduction of power fluctuations), the active/reactive power control to support the frequency / voltage stability of the electrical grid, primary/secondary grid control, etc.). Experiences made in the onshore and offshore wind industry will be investigated and evaluated with respect to the applicability in wave and tidal arrays.

The fifth section will summarise the results of the assessments. Conclusions will be drawn with respect to the applicability of the identified approaches from other offshore industry sectors to support the development of the algorithms and tools for the operation and maintenance strategies for offshore wave and tidal energy generation units in array configurations as outlined in the DTOcean WP6 objectives.

2 ANALYSIS OF OPERATION AND MAINTENANCE PLANNING TOOLS

2.1 Experiences from the wind industry (onshore and offshore)

There is a very comprehensive survey of available operation and maintenance planning software tools outlined by Hofmann [1]. This article summarises the characteristics of those tools, which are divided into five main categories:

1. Total project costs over the entire wind farm life time
2. Operation and maintenance cost estimation
3. Production, failures and reliability
4. Micro siting and layout
5. Component costs

Most of the tools are considered to be applicable to offshore wind farms by the author. About half of the tools are non-commercial. The fourth category mentioned (micro siting and layout) has less relevance to the work carried out in System Control and Operation within the DTOcean project, although it is likely to have applicability elsewhere in the project.

Three of the tools mentioned by Hoffmann have been selected for a detailed evaluation to identify their suitability for supporting the programming work in DTOcean/WP6. These tools are:

- the “ECN O&M Tool” (see [2]), developed by the the Energy Research Centre of the Netherlands (ECN)
- ECN’s “Operation and Maintenance Cost Estimator (OMCE)”, see [3])
- “Norwegian offshore wind power life cycle cost and benefit model (NOWIcob)” – A tool for reducing the maintenance costs of offshore wind farms, introduced by Hoffmann (the author of the above mentioned survey) and Bakken Sperstad, see [4].

The results of the detailed evaluation of the tools mentioned above and of a general evaluation of most of the tools in Hoffmann’s survey, it can be considered that valuable input for the algorithm / tool development in WP6 can be obtained from the approaches as developed in the offshore wind sector. At the moment, the exact path of the development and, in particular, of the functional range to be covered by the algorithms and tools to be developed in the tasks of WP6 is not yet defined in detail. Therefore, the detailed analysis of the relevant tools mentioned by Hoffmann in [1] will be analysed in more detail during the course of the work in WP6. This analysis will be focused on the special requirements of the respective algorithms and tools individually.

2.2 Experiences from the offshore oil and gas industry

Investigation of the offshore oil and gas industry showed that there is a limited amount of publicly available information regarding operation and maintenance planning / optimisation for this sector. This may be due to the fact that most of the activities in this field being carried out by private contractors, which offer a complete package (including the monitoring of the condition of the offshore installation, the analysis of faults and the repair of such faults) for operation and maintenance of oil and gas offshore installations. Such contractors use their internal products / procedures and, due to competition issues, do not document their strategies publicly. Most of the contractors state that they use optimisation software but give no details regarding specifically which software this is.

The information extracted from our analysis of the situation in the offshore oil and gas sector as carried out here can be summarized as follows:

- Regular inspections are carried out with respect to corrosion on foundations and floaters. Depending on the water depth, divers, ROV submarines and robots are used for this (see [5] and [6]).
- The strategies employed are very similar to those used for offshore wind farms (or vice versa). Some aspects are not applicable to offshore wave and tidal arrays, e. g. the identification of leakages on pipelines.
- Transportation is often made with helicopters and high speed boats.

In general, there is a tendency towards a very quick reaction time to the occurrence of a fault rather than a cost saving solution. This may be related to the fact that in the offshore oil and gas industry there are less financial constraints than in the wave and tidal energy sector.

In the specialized case of station keeping and mooring systems, experiences form the oil and gas industry could be of value. Mooring line integrity is crucial to the station-keeping ability of the mooring system for exploration platforms, offloading buoys and vessels. A variety of novel in-situ condition monitoring techniques have been trialled over the years by the oil and gas industry to measure component performance, including mechanical, optical, acoustic and magnetic techniques (see[7], [8] and [9]). However, many concepts have suffered from poor reliability in service and in some cases this has led to warning alarms being ignored [10].

Commonly used methods for mooring and station keeping used at present include:

- direct tension measurement using inline load cells [11],
- indirect tension measurement using inclinometers [12],
- strain measurement of mooring legs using strain gauges or vibrating wires [13];

For subsea monitoring systems, the transfer of data from the equipment to the data acquisition device is usually achieved by either cable or an acoustic 'wireless' system, with the latter system subject to lower data transmission rates. Load measurements may be used to determine the integrity of the lines or to inform re-tensioning procedures in the case of facilities with winch equipment. Thresholds for maximum loads measured during service before the component must be replaced can be found in offshore standards for particular components (e.g. for synthetic ropes the limit is 70% of the minimum break load [14]). In addition to the acquisition of data, general inspections to assess damage are carried out in-situ using remotely operated vehicles (ROVs) [15]. If damage has been detected during an ROV survey, it is necessary to recover the line in order to carry out a more detailed inspection and assessment.

For wave and tidal array applications any significant offshore operation will incur large costs. Indeed in order to reduce costs, mooring line inspections may be limited to devices which are subjected to the brunt of environmental loading. For the rest of the array it is likely that array operators and developers will rely on a combination of ROV surveys and load monitoring to determine line integrity, with load measurements and component testing used to inform reliability predictions.

2.3 Other relevant experiences

Although no wave and tidal arrays have yet been deployed, the first studies and tools for planning and optimizing O&M strategies are underway. For example, the MerMaid software (Marine Economic Risk Management aid) of Mojo Maritime Ltd. [16] is the first commercial software to simulate the impact of scheduling and met-ocean conditions on complex marine operations specifically for marine renewable energy (MRE) projects.

Also, early work on thorough techno-economic analysis of MRE converters has already analysed the impact of O&M on the energy production and costs from a global perspective. Two different approaches are generally implemented to cope with the simulation of logistic operations. On the one hand, the statistical approach, as employed by Raventos et al. [17], relies on scatter diagrams and probability of exceedance for describing the resource. As such, the probability of occurrence for a given weather window (duration and accessibility criteria) can be determined. On the other hand, the time series approach, as implemented by Teillant et al. [18] and O'Connor et al. [19], makes use of measurements of the resource for a period of time as long as possible at the site of interest. These holistic techno-economic assessments can serve as a basis to design a first simplified version of the O&M module for DTOcean tool.

Also, significant work has been performed or is ongoing under a number of European and national funded projects such as ORECCA, EquiMar or MARINA Platform as well as in the demonstration project in test sites such as EMEC, Galway Bay, OWC's at Pico and Mutriku, the Tidal Test Center in the Netherlands, Nissum Bredning, etc. (see information on the MARINET website [20]. These activities have produced significant knowledge related to O&M of the first wave and tidal prototypes which will be extremely valuable to integrate in the first array O&M strategies.

3 ANALYSIS OF MAINTENANCE STRATEGIES

3.1 Description of maintenance strategies

Maintenance in principle should support the operability of technical systems. There are different approaches towards maintenance strategies as shown in Figure 1. This section will discuss the suitability of the different maintenance approaches for application in the maintenance process for power generation units in wave and tidal offshore arrays for energy production. A definition of the different maintenance approaches and terms mentioned is given in the European standard EN 13306 [21]. A comprehensive discussion of those approaches and their applicability in offshore wind projects can be found in [22]. The following sections will describe the approaches in principle and will also discuss their implications on the maintenance strategies of ocean energy devices.

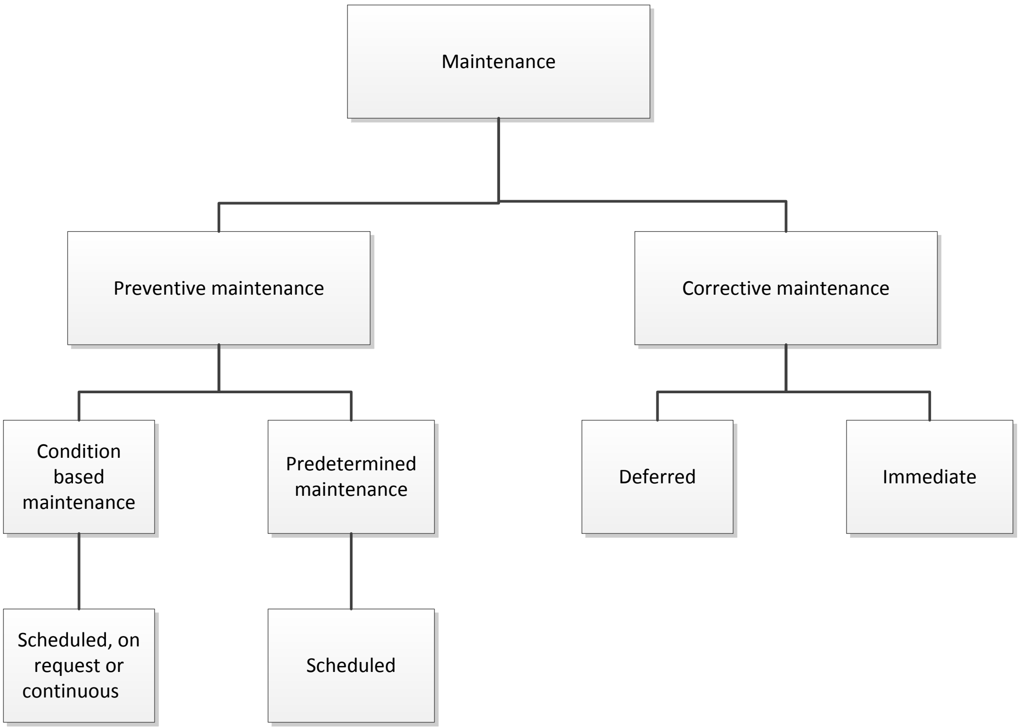

Figure 1: Maintenance Strategies [21]

3.2 Corrective maintenance

Corrective maintenance means that a component will be repaired / replaced after its failure is recognized. This strategy is used in various fields of industry, where access to the components can be made on an ad hoc basis and spare parts, which are known to be required regularly, can be stored, so that downtimes are not caused by mobilization times and the time taken to order materials is reduced to what is deemed an acceptable short period. The corrective maintenance is sometimes also named as “break down” maintenance strategy, because corrective maintenance will be done once the unit is “broken down”.

The corrective maintenance approach splits into two subtypes, depending if a deferred or immediate reaction is required. In case of a deferred reaction, the component can continue operation for a (very) short period before it fails completely. In cases where the component has failed already and the system has stopped working, an immediate action is required to bring the system back to operation.

With respect to ocean energy array units, the corrective maintenance strategy is not sufficient, since it may take long periods to gain access to a unit due to weather conditions or due to the availability of logistics (ships for transport of personnel and materials as well as for movement and lifting operations, availability of large components as spare parts, etc.). In principle, component failures can cause severe consequential damages, which then may include the danger of a total loss of the affected array unit. Another disadvantage of the corrective approach is that a unit may be down for an unacceptably long period (e.g. during the entire winter season, when sited in a Nordic sea area) with the related losses of energy production. Figure 2 shows the dependency of the remaining life time of components related to the different maintenance strategies. The red dash line represents the corrective or break down maintenance approach.

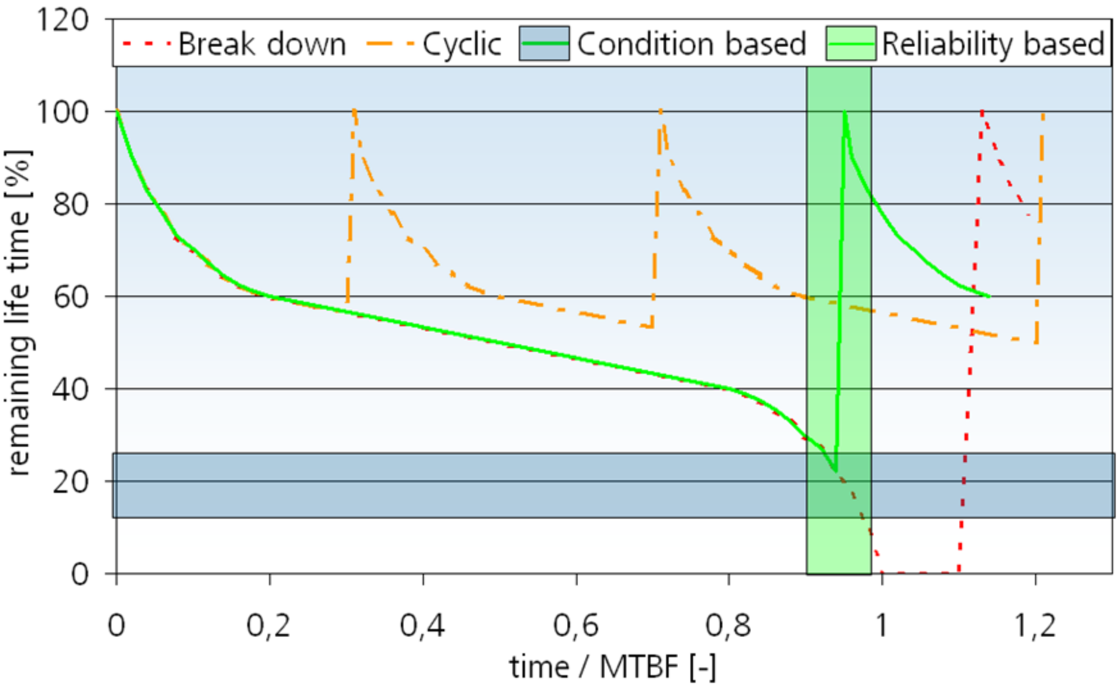

Figure 2: Remaining component life time under different maintenance strategies

3.3 Preventive maintenance

The preventive (or sometimes named predictive) maintenance approach can be divided in two main streams, the "condition based maintenance" and the "predetermined maintenance".

3.3.1 Predetermined Maintenance

The predetermined maintenance (sometimes also named as "cyclic maintenance") approach is based on regular maintenance and repair activities. Components or parts of it will be maintained or replaced within fixed intervals. The frequency of such intervals need to be defined by the supplier of the components and will be typically (semi-)annual.

3.3.2 Condition based maintenance

More sophisticated preventive strategies are the condition based and the reliability based maintenance. Both aim at finding the optimum point in time for carrying out the required maintenance actions.

Condition monitoring based approach

The condition monitoring based maintenance approach as a sub strategy of the condition based maintenance uses measured and processed information about the actual condition of components in an array unit to identify the actual remaining life time of those components. The estimated remaining component life time is then used to define the optimum time to perform a maintenance action on this component.

This condition monitoring process requires a certain number of hardware (sensors, PLCs, etc.) and software (algorithms for signal processing, fault detection, etc.) to be installed in each unit of an offshore array and can have implications for increasing investment costs.

The time domain dependency of a component's remaining lifetime under the monitoring based approach is illustrated by the blue shaded area in Figure 2, which demonstrates how to find the point in time where the remaining life time falls below a tolerance criteria. The main task of this strategy is to find out the propagation of degradation over the time of operation, i.e. the most important stressing parameters and their influence on the life time curve.

Reliability based approach

Another sub strategy on the condition based maintenance is the reliability based maintenance approach. This approach tries to find the right time for maintenance measures to take place through analysing a comprehensive database filled with experience from the past regarding the reliability behaviour of all components of the same kind. For example, a certain type of a hydraulic pump is known from fault statistics information to fail after 10 000h of operation. With the knowledge of the real operational hour of that pump in the respective array unit, the point in time to replace the pump is known.

The time domain dependency of a component's remaining lifetime under the reliability based approach is shown in Figure 2 by the green shaded area. The reliability based maintenance strategy tries to identify the "Mean Time between Failure (MTBF)", a measure which is synonym to the remaining life time, of a component and by that the probability for the occurrence of a component failure. This identification process is based on comprehensive fault statistics. Fraunhofer IWES runs, under the "Offshore scientific monitoring and evaluation programme (Offshore~WMEP)", as described by Faulstich in [23] and [24]. The Offshore~WMEP is a fault statistics data base with information over almost 20 years of operational experiences from onshore wind turbines and is currently extended with operational experiences from wind turbines in offshore wind farms. This fault statistic data base can be used as a starting point for the algorithm development in WP6 within the DTOcean project.

The condition based maintenance strategy can transform unscheduled outages into planned maintenance activities and reduce or even avoid downtimes as well as maintenance costs. For the deployment of wave and tidal energy devices and arrays, these two strategies (monitoring based and reliability based) may be combined to get the necessary information for preventive and planned measures to reduce maintenance costs.

However, for the condition based maintenance a detailed documentation of all maintenance measures of a large population of offshore array units and a purposeful structured data base are necessary to extract sound conclusions out of the operational experience. After a certain period and with adequate statistical basis some reliability characteristics such as failure rates, repair times, etc., with respect to technical concepts (e.g. generator or gearbox-type), the operating conditions (e.g. wave conditions or ambient temperatures) or the age of the array units can be determined with such documentation. This provides a number of possibilities for optimizing availability of offshore array units both in design and construction and in operation and maintenance.

In reality, the O&M strategy for large offshore wave and tidal arrays will be a mixture of the monitoring based and reliability based approaches. Some components, such as the rotating electro-mechanical drive train elements, can be monitored quite well with industrial standard condition monitoring systems. Vibration measurement will provide information on e.g. damages to the surfaces of rollers elements in bearings, particle detectors for the lubricant oil can identify wear of bearing cages, etc. Analysis of the 1st, 2nd and higher order harmonics of shaft rotating frequencies can point to misalignment and cracks.

Other main components, such as fibre reinforced plastic materials tend to show no significant signs of wear or a modification of modal frequencies before failure. For those components, a reliability based approach in combination with measurement of the accumulation of actual load cycles (“load counting” or “load tracking”) can define the optimum time for repairing or replacing the component.

3.4 Applicability of maintenance strategies for offshore wave and tidal array units

This section will assess the applicability of the described maintenance strategies to generation units in wave and tidal offshore arrays.

3.4.1 Applicability of the corrective maintenance approach

The corrective maintenance strategy covers a high risk of downtimes for the system to be maintained. This is always a challenge for systems where ad hoc access is possible at any time during operation and if no consequential damages are expected in case of a shut down due to a component failure. Where this is the situation, the corrective maintenance may be a cost effective strategy. Components will be used up to the very end of their life time. The components which are known to fail regularly need to be kept in store to avoid downtimes due to spare part lead times. This could cause a high capital lockup as well as a high demand for storage space in case of large and expensive components for offshore wave and tidal array units.

For application in offshore arrays, this strategy seems not entirely suitable. Due to the technical complexity and the extreme load conditions of the array units as described in the scenarios defined by DTOcean deliverable D1.1, severe consequential damages on failure of critical components can be expected. Even without the occurrence of those consequential damages, the probability for long downtime even at failure of minor components (e. g. fuses in a frequency converter) is too high to be tolerated. For example, if a wave energy unit fails at the beginning of the winter season at a North Sea site, access can be hindered for several weeks or longer. This would mean that the unit is not operational at a time when the energy generation would be comparatively high.

Even it is deemed not to be cost effective, the corrective maintenance strategy will be considered in the optimisation algorithms to be produced by WP6, since a user may wish to investigate / compare the costs of this strategy. Furthermore, spontaneous failures of components will occur in all technical system. Therefore, a measure to cope with the occurrence of such failures needs to be implemented in the algorithms and tools to be developed by WP6.

3.4.2 Applicability of the predetermined (cyclic) maintenance approach

Predetermined maintenance is based on fixed intervals (e. g. every year) for performing maintenance activities. This makes planning relatively easy, however, the work effort for maintenance activities increases linearly with the number of offshore wave and tidal array units to be maintained.

In the case of offshore installations, the available time slots are not equally distributed over all seasons of a year. With an increasing number of offshore arrays, this may lead to an accumulation of the activities in the good weather season, causing higher demand for personnel and logistics and therefore leading to higher prices. In addition, components may be intact at the time of replacement and therefor are not being used to their maximum life time or capacity, which will increase costs for spare parts. On the other hand, predetermined maintenance allows easy scheduling of work and materials.

The predetermined maintenance strategy may be a cost effective or mandatory option for various components of offshore array units. Therefore, it will be considered in the algorithm / tool development scope of WP6.

3.4.3 Applicability of the condition based maintenance approach

The condition based maintenance approach also allows an adequate scheduling of the logistics (spare parts as well as personnel). There will be a sufficient pre-warning time delivered either by the condition monitoring system or by the fault statistic information before the failure of a component. It can then be decided if a component which is supposed to fail can be either replaced at the next scheduled predefined maintenance action. If the period to the next scheduled maintenance action is too long, measures for extending the life time of the component known to fail soon can be taken, e. g. by de-rating the power output (see section 4). Additionally, those components can be maintained along with a corrective maintenance action necessary for another unit in an offshore array.

Furthermore, the knowledge of the actual array unit condition increases the operational reliability and therefore the energy production. By analysing the cause of a developing or occurred component failure, technological weak points of an offshore wave or tidal generation unit can be identified. The weak or potentially faulty components can be strengthened in all array units of the same type and can improve the technical quality of the production of such units.

The condition based maintenance approach may lead to higher investment costs for the array units mainly caused by the necessary installation of monitoring hardware and software (see [25]). Also, the required access to extensive technical documentation of the main components of an array unit and the gap free collection of information about component failures will lead to an increased effort over the operational life time of an offshore array. But these disadvantages will be over compensated by the described potential for O&M cost reduction in the medium to long term.

The condition based maintenance approach aims to reduce the O&M costs for an offshore array by the extension of the maintenance intervals with respect to the real remaining life time of components. Components can be used to their maximum life time, which saves maintenance costs. Therefore, the main focus for the development of the algorithms is to analyse the cost of maintenance activities within WP6 and associated with condition based maintenance.

3.4.4 Selection procedure for the optimised maintenance approach

As can be seen from the discussion of the advantages and disadvantages of different O&M strategies in the previous sections, the identification of the optimum maintenance approach is a complex and critical process. Further discussion will be carried out within the DTOcean which will decide how to cope with this level of complexity in the algorithm and tool programming in particular.

At this point, a principle exclusion of one of the approaches described above is not recommended. Some components of an offshore array unit may fail spontaneously and then need immediate (“corrective”) maintenance action. Other components may have to be maintained on a predetermined basis. Some components’ remaining lifetime could be estimated quite accurately using condition monitoring systems or fault statistics data bases, which then would allow a condition based approach.

The selection process to find the optimum operation and maintenance strategy may be even too complex to leave it to the user of the tool alone to define the strategy (or a combination of strategies) at the start-up of the optimisation process. Therefore, the aim of the future work in WP6 will be to support the user of the optimisation tool in finding the optimum strategy by making proposals for an optimum combination of the above mentioned strategies as far as possible. The course of the work in WP6 will show how this can be achieved efficiently.

4 ANALYSIS OF ARRAY CONTROL STRATEGIES

4.1 Background and aims of array control strategies

Development of array level control strategies aimed at optimising power output and reducing fatigue loads in large wind farms has been carried out for several years. However, such control strategies are still at the research and development level. The aerodynamic principles that govern the operation of typical wind turbines are largely the same as those governing the operation of rotating horizontal axis tidal turbines. Thus, in theory, the control strategies developed in the wind industry would be transferable to horizontal axis tidal devices. However, their applicability to other types of ocean energy converter, whose design and operation have few similarities to typical wind turbines, is less clear. For wave energy arrays hydrodynamic interactions can have either a positive or negative effect on power production and this is dependent on the incident wave conditions, array layout and control strategy of the individual devices (see [26] and [27]).

The control strategies proposed by the wind industry generally focus on minimising the aerodynamic (or hydrodynamic in the tidal turbine case) interactions between devices in an array. The theory behind many of these control strategies is that maximising the power output of each individual turbine does not necessarily optimise the output from the array as a whole. This is because the operation of upstream turbines modifies the flow and influences the performance of the downstream turbines.

The aerodynamic coupling that exists between individual tidal turbines is a function of the axial induction factor and the yaw offset angle of the turbine. The axial induction factor is a function of the blade pitch angle and tip speed ratio, both of which can be controlled. The power of an individual turbine is maximised when the axial induction factor is 1/3, and most variable speed turbines are controlled such that the axial induction factor is 1/3. However, when considering the power production of the whole array an induction factor of 1/3 in the upstream turbines reduces the amount of power available for capture by downstream turbines. It has been shown that by reducing the induction factor of the upwind turbines the wake deficit and turbulence produced by those turbines is reduced. From a control point of view this can be achieved using parameters that are generally controllable anyway. The axial induction factor, a, is a function of the blade pitch angle and the tip speed ratio. Control of these parameters (the pitch angle via the pitch actuators and the tip speed ratio via the generator reaction torque) is state of the art in tidal turbine technology.

Active yaw control can also be used to reduce interactions between turbines. The yaw offset angle can skew the wake direction, possibly reducing wake interference and increasing the power production in the other turbines. With respect to individual turbine control, an increase of the yaw offset angle would reduce the power. However, if the increase in power from the downstream turbines due to the change in wake angle direction exceeds the level of power decrease in the upstream turbines, the total array power would increase. Centralised controllers that account for the interactions between turbines due to wakes effects are discussed in more detail in the sections that follow.

On the electrical side one of the key issues in the wind industry is ensuring that farms comply with local grid codes. This generally requires some form of centralised controller to regulate the active and reactive power injected into the grid by the whole farm. Detail on the specific requirements of such controllers and how they are implemented in the wind industry is provided in the sections that follow.

In these sections, the control of arrays of ocean energy generators with respect to improvements in terms of costs of power generation and with respect to the integration of the ocean power plant into an electrical network are described in more detail.

4.1.1 Decrease of costs of power production

In an offshore array (wind or wave and tidal) the operation of one individual generator may influence other generators nearby. Firstly, the fact that energy is extracted from a tidal current or a wave by one generator may decrease the power output of other generators in the surrounding area. Secondly, the mechanical load also acting on close generators may be influenced.

In the case of a current-based technology the so called wake-effect is decisive for these influences between the generators within an array: extracting energy from a free flow field leads to a wake behind the turbine, which is characterised by a decreased current speed with respect to the free flow field upstream of the turbine. Consequently, the turbines located in this wake environment see a lower inflow power and may thus operate at lower power output.

Another characteristic of a wake is an increased turbulence, which is in particular caused by the turning rotor of the turbine. Both the decreased inflow power and increased turbulence do influence the mechanical loads on the turbines in the wake.

In the case of free flow turbines, it is possible to influence the wake characteristics by controlling the causative turbine. E.g., pitch control can be used to decrease the power extraction from the stream and thus increase the current speed in the wake. While the power output of the controlled turbine is decreased, this measure in turn may lead to an increasing power output of the downstream turbines. On the other hand turbulence intensity in the wake is decreased, which may be advantageous for the fatigue loads of downwind turbines. By applying a coordinated control to the overall array of generators, the total power output may be increased even if some of the generators are operating at lower power set points.

Another aim of array control may be dedicated to influencing the mechanical loads acting on the turbines. One approach is to minimize the collective mechanical loads on the total array of generators. Another approach is to minimize specific loads on individual generators, e.g. considering the turbine state of health.

Both control aims, i.e. maximization of power output and minimization of mechanical loads lead to a decrease of power production costs and are thus in the original and best interest of the operator. Note that both aims may be counteracting, i. e. increasing the power output maybe also increase the loads on components. The above mentioned approaches of array control are in the state of research.

4.1.2 Grid integration

With a rising share of renewable energy generators, their proper integration into the electrical grid becomes more and more important for the stable grid operation. Proper integration means that instead of simply feeding in active power, such generation plants have to fulfil several tasks for supporting the stable grid operation. Such tasks have been formulated by many grid operators in the frame of guidelines, the grid codes. The tasks commonly comprise the control of active power, reactive power or voltage and a defined reaction to grid frequency variations. This means, already today, they have to participate in network control up to a certain extent, and this extent will further increase. In the following section a short introduction to network control will be given.

Two control mechanisms are applied for the stable operation of the electrical grid: Frequency control and Voltage control.

Frequency control ensures a continuous adaption of active power generation and consumption. The active power balance is related to grid frequency via all synchronous generators connected to the grid. Frequency is –in good approximation – uniform in the network, it is thus used as a control variable for a decentralised control system for maintaining the active power balance in the grid. This network frequency control makes use of a large number of power plants as actuators, which adapt their active power feed-in according to the needs of the system. The active control system comprises three levels: primary, secondary and tertiary control. The ability of the electrical network to maintain system frequency within a given range during a disturbance is called frequency stability.

Voltages at a node in the grid are related to the local reactive power balance: reactive power consumption at a node leads to a local voltage decrease, due to voltage drops at reactances in the grid, e.g. in lines or transformers. While a lack of active power may be compensated by all power plants which participate in frequency control, reactive power is compensated locally. This is carried out by the network voltage control, by means of reactive power feed-in at the specific nodes or at electrically close nodes.

The aims of network frequency control and voltage control are:

- Stable grid operation: frequency stability and voltage stability
- power quality on consumer level: e.g., the voltage rms value and the frequency have to be kept within a tolerance band around the rated values
- Keep frequency limits, voltage limits and current limits of the network components
- Economic grid operation: Reactive power flow cause active power losses, and should thus be kept small. Also, low voltage levels cause active power losses in transport of active power (voltage control only).

Figure 3 shows the schematic of a wind farm control system. A central farm controller (considered as “central park Controller” in the figure) receives measurements, e.g. of active power at the point of common coupling (PCC). In order to follow its set point, e.g., of active power, it sends individual set point signals to the wind turbine controllers. Those local controllers command the final actuators, e.g. the pitch motors. The reliability of the farm communication system, in terms of delays and determinism, is crucial for a stable control. Note that, commonly, active and reactive power control loops are considered separated in the wind farm controller (see [28], [29], [30]).

Very dynamic control requirements, such as reactive current provision in case of grid faults, are executed only locally at the turbines. In this case, it is not important to exactly reach the set point at the PCC; instead, the fast reaction is decisive for the grid operator.

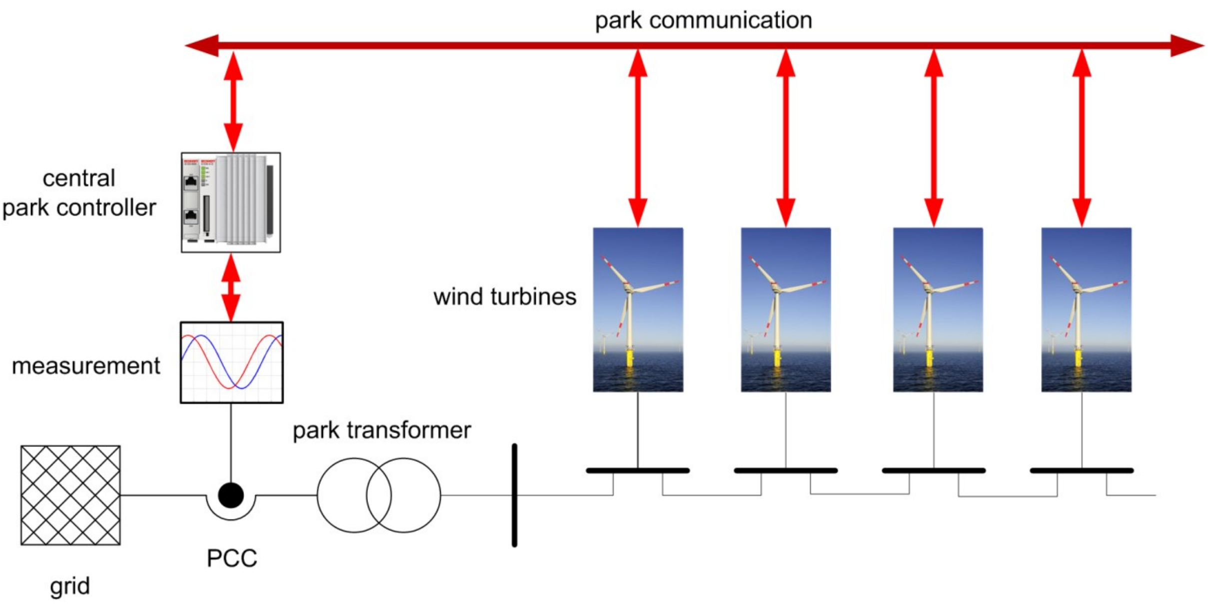

Figure 3: Schematic of a central wind farm control system

Although, the use of advanced control algorithms to improve the grid compatibility of offshore wind farms (and later on will reach the same level of importance for offshore wave and tidal arrays), the grid integration is not the main aspect of the work in DTOcean WP6. Therefore, the following section will focus only on the impact of control strategies to the costs of the power production.

4.2 Experiences from the wind industry (onshore and offshore)

In this section, control strategies will be analysed which are under development in the field of wind farm control. Main aspects here will be the increase of the power output of an entire array by de-rating the power output of individual units in an offshore array. A second aspect of the power de-rating is the decrease of loads and, therefore, the extension of the life time of the array units Both aspects support the decrease of the overall costs for the power production of an offshore energy generation array. Experiences made in the wind industry and in other relevant fields will be investigated and evaluated with respect to their applicability in wave and tidal arrays.

4.2.1 *Control Strategies for Decrease of Costs of Power Production*

Optimal power production without considering wake effects

An analysis of publications from the wind sector have shown that some authors have proposed coordinated power output optimising strategies without considering wake effects in the wind farm. The aims are, apart from reaching the required set points at the PCC, a reduction of electrical losses. Also start/stop processes may be minimised. In [31], de Almeida et al. propose a strategy for dispatching active and reactive power to the individual turbines, aiming at reducing park internal electrical losses and, therefore, increase the overall power output.

Moyano and Peças Lopes propose in [32], the authors propose an optimised dispatch, aiming at minimising start/stop processes of wind turbines, while keeping the active and reactive power commands at the PCC. The problem is separated into two linked optimisation problems, one for the start/stop processes, and one for the dispatch of active and reactive power set points. A short-term prognosis of wind power in the time frame of 6 hours is assumed. Possible boundary conditions to be considered could be the P/Q-Limits of the single turbines and nodal voltage limits.

Optimal power production considering wake effects

Corten and Schaak demonstrate in [33] using measurements, that a certain reduction in “axial induction” (and thus in active power) of the upwind turbines results in a slight increase of total wind farm power output, while it reduces the axial loading (below rated wind speed and for the case when wind is parallel to the turbine rows).

Even though the effects of wakes are understood in principle, the problem of considering the wake effects in wind farm control lies in the accuracy of modelling. Such control concepts are thus still in the level of research and development.

Within the EU funded research project Aeolus (Distributed Control of Large-scale Offshore Wind Farms, ended in 2011), the partners aimed at developing control principles for optimising both the wind farm power and the fatigue loads [34].Two approaches were followed in the project; they are described below.

In a centralised approach, the controller aimed at meeting an active power reference under the range of regular disturbances. Additionally, the fatigue loads at the turbines were aimed to be minimised [35] by adapting the power reference of individual turbines. A model of the wind field was employed in the controller, which described the dynamic development of wakes inside the wind farm; combined with the model of wind turbines, this formed an overall wind farm model. An optimal control approach was chosen, and, since the complexity of the optimisation problem led to high computational effort in particular for large wind farms, a hierarchical control concept was proposed: the slow top level control, which employed the wind field model, derived the overall wind farm operation point, receiving slow measurements. The details of this controller were published by Soleimanzdeh and Wisniewski in [37]; the controller scheme is given in Figure 4.

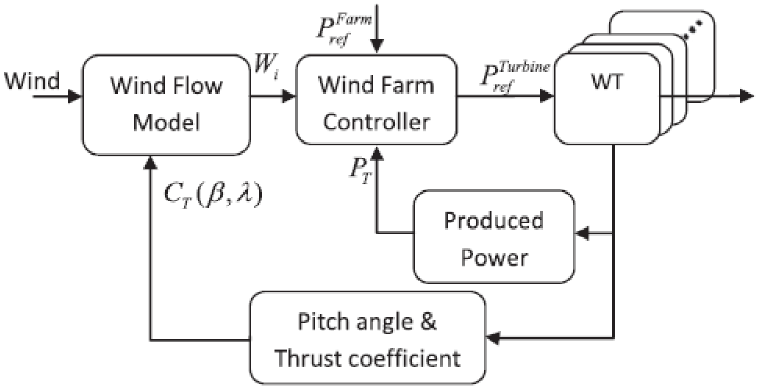

Figure 4: A schematic of controller for mitigating structural loads, employing a wind flow model [37]

The low level aims at quickly compensating disturbances, such as wind turbine shut downs or local gusts which are not predicted by the model. It receives high-sampled measurements and commands from the top level control [36]. E.g., in case of a wind turbine shut down, it redistributes (reconfigures) the power references to the turbines quickly. In a case of gusts, the fast controller decreases fatigue loads on the turbine which may be caused by the gust.

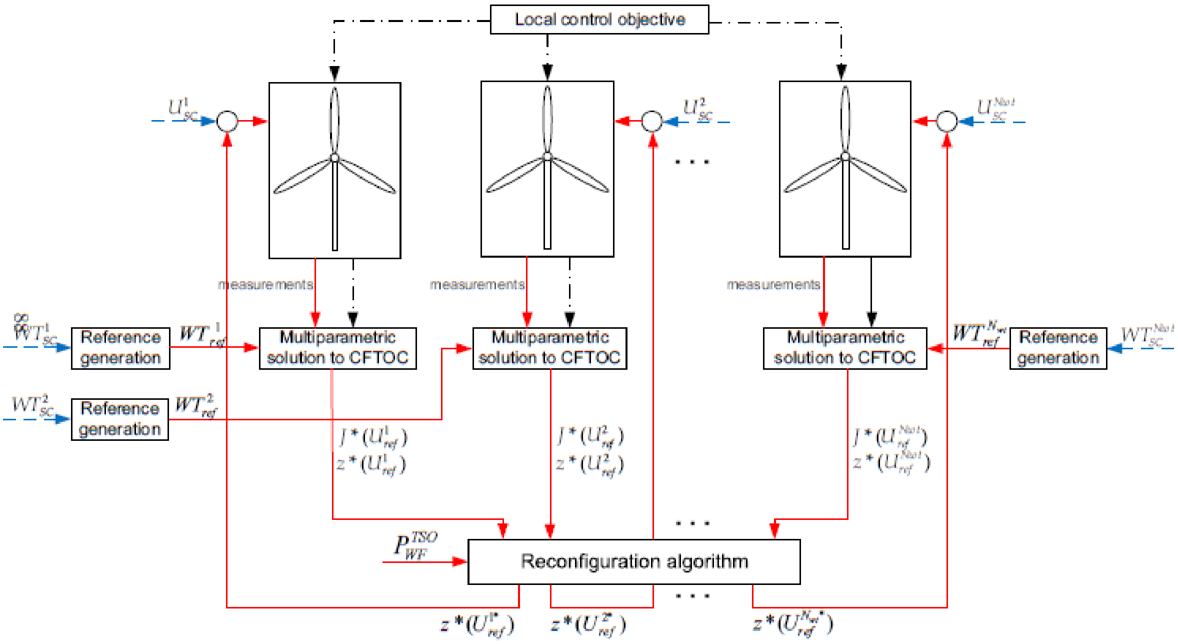

Figure 5: Schematic drawing of the low level controller [36]

Figure 5 shows the schematic drawing of the low level controller. The black lines represent information which is fixed (offline calculated). The blue lines represent the inputs from the top-level (supervisory control), which are updated at a slow sampling rate. The red lines represent signals which are updated at the fast sampling of the low level controller. CFTOC stands for Constrained Finite Time Optimal Control. For further details refer to [36].

In an approach for distributed control, decentralised controllers are located in each wind turbine and communicate only with neighbouring wind turbines. An advantage of this distributed concept is its modularity, which makes it easy to add turbines or set them out of operation. Furthermore, it may be more robust to failures of single control channels, as only few turbines are affected [34].

Performance assessment of the control approaches is given in Aeolus Deliverable 5.6 “Assessment and validation of relative performance of control strategies” [38]

4.2.2 Applicability of Wind Park Control Strategies in Ocean Energy arrays

Due to many parallels in the technology of wind farms and ocean energy arrays, several of the control concepts for wind farms may be transferred to the field of ocean energy. In the following chapter, an assessment will be given.

Control for Grid Integration

In principle, expectations for ocean energy arrays from grid operators are similar to those for wind farms. The transferability of the control approaches depends on the type of control which can be one of the following:

- Active power limitation and participation in frequency control: regarding farm/array level control, concepts are also applicable for ocean energy. De-rating control of individual turbines/generators is different. For rotating devices applying rotor torque control and pitch control, the concepts are transferable.
- Synthetic inertia: here, the main advantage of wind turbines is the real inertia of the large rotating rotor, i.e. large energy storage. Storage capabilities of ocean energy devices have to be examined. Control on individual devices level will be different when it comes to applying the storage.
- Reactive power control: regarding farm level control, concepts are also applicable for ocean energy, if individual devices are able to follow reactive power set points. If a full converter or DFIG is employed, the according control concepts can be used from wind energy industry.
- FRT: fault ride through capabilities is not executed on farm level control. Individual devices have to be enabled to follow the requirements. Again, in a case of a full converter or DFIGs, the relevant control concepts can be used from wind energy industry.

Control for decreasing costs of power production

Regarding the transferability of control principles aiming at reducing costs of power production, the following implications can be made:

- Optimal dispatch without considering wake effects: concepts proposed for wind energy control may in principle be applied to ocean energy arrays.
- Optimal dispatch considering wake effects: “wake effects” in ocean energy in principle could be quite different from the ones of wind energy. Only for rotating marine current turbines, the effects and modelling approaches may be potentially transferable.

4.2.3 Relevance of wave and tidal array control strategies to the DTOcean project

The aim of the discussion of different control strategies in chapter 4 is to allow other WPs in the project to assess possible implications for their own work.

As for now, interactions with the control aspects of WP6 with WP2 “Array layout” seem valuable with respect to the load calculation. Considering the control strategy for minimising loads to individual array units by de-rating the power output may influence distances between those units in wave and tidal arrays. Also of relevance for the array layout definition may be the power set point de-rating of individual array units to increase the total energy yield on an array level.

The approach of de-rating the power output of individual units in an offshore array will also have implications on the design of the electrical grid as it is analysed in WP3. Using the concept of a centralised farm controller can help the smooth out power peaks which may be the design driver for cable cross sections within the internal grid architecture and for the main grid connection of an offshore wave and tidal array. The cable cross sections and the related material consumption per cable length unit will have significant impact on the cable costs. Therefore, a discussion with WP3 is deemed to be useful here.

Since the generation of a guaranteed active or reactive power output of a wave and tidal offshore array may lead to new economic models for the array operation, WP8 may also consider the information given with respect to the active support of grid stability (voltage and frequency) on a general basis. In this case, WP6 will be open for a detailed discussion of the relevant aspects.

In any case, WP6 will consider the de-rating controller approach to reduce loads on components and, therefore, extend the remaining operational time of offshore wave and tidal arrays in the algorithms and tools for O&M cost calculations. The information will be used to find an optimum balance between expected energy production losses and the urgency of maintenance actions to get array units back operational.

Further use of the information with respect to the control strategies are likely to appear in the course of the DTOcean project, of which WP6 will explore.

5 WP6 ALGORITHM/TOOL DEVELOPMENT APPROACH

The aim of the algorithms/tools to be developed in WP6 will be to calculate the cost of specific component maintenance operations considering the following aspects:

1. When does the component have to be maintained?
2. What equipment is required for the maintenance action?
3. What material is required for the maintenance action?
4. What personnel are required for the maintenance action?
5. How long will the maintenance action take (incl. travel time to/from site, work time, etc.)

The first step of the development work in WP6 will be to define the components, which will be considered for the cost calculation process. This will include the main components such as gearboxes, hydraulic rams, support structure elements, etc. The approach here will be to define a set of relevant components for each of the wave or tidal energy conversion units as described in the scenarios defined by WP1. For each type of these components, a data base entry will be generated, covering all the relevant information about the specific component.

The point in time (see aspect 1 as mentioned above) for the maintenance action will be defined by the remaining life time of the component. This information comes either from a manufacturer's maintenance requirement (i. e. "change gearbox oil every 12 months") or from experiences about the MTBF of the component out of a fault statistic data base or from the measured remaining life time coming from a condition monitoring system.

For consideration of the aspects 2-5, the respective information needs to be defined for all components in scope of the WP6 development and will be stored in the component data base. To give an example here: The replacement of a rotor blade of a SEAGEN type turbine will require a crane ship which can lift up to 10 tons to a height of 10m. As materials, a complete blade for replacement is required. For the blade transport, there are several options: the blade can be stored on deck of the crane ship or can be delivered by a separate transport vessel. The maintenance action needs to be performed by the crane ship crew and two mechanics detaching the old blade and reassemble the new one. As a result of this scenario, the data to be stored for the component "rotor blade" will be (as a selection):

- Weight (e. g. 10 tons)
- Length (e. g. 8m)
- Height above sea level for handling (in this case to connect it to the blade flange)
- Crane required for handling (yes/no)
- Number of people required to handle it

- Required space for transport
- Required time to attach
- Required time to detach
- Special environmental requirements (e. g. needs to be stored in a dry area)
- etc.

As can be seen from this simple example, there will be a lot of parameters required to be defined for each component, of which, reasonable estimations will be made throughout the course of this project.

Considering the fifth aspect of the above mentioned list, there will be a requirement for information from the logistics data base which will be defined in WP5. For this purpose, WP6 will pass information to the selection algorithm of the WP5 tool containing the weight and size of the component. The WP5 tool then will propose a suitable vessel. In case the transport of the component will be made with a separate vessel, this information needs also to be exchanged between the WP5 and WP6 tools.

The outcome of this calculation will be a price for replacing the component at a fixed date. Within the optimisation process, several parameters need to be varied in several optimisation loops, until the minimum cost value is found. One of the parameters can be the date for the maintenance action when the price for the vessels varies during the year. Another parameter can be to hire a larger crane ship with transport capacity to avoid the need for a separate transport vessel.

As can be seen from the example above, the optimisation problem to be solved here is very complex and requires connection to other WPs and their specific algorithms and tools. To get started with this complex development work, WP6 proposes to define a simulation model for the interaction of the different sub tools of WPs 2 to 6. This simulation model will in a first step connect the sub tools of the mentioned WPs. It could contain in the first approach very simple functions as representatives for the complex algorithms to be developed in the course of the DTOcean project. Once developed, the simplified sub tool models can be replaced by the subsequent fully functional versions. This will allow increasing the complexity of the main tool step by step to trace for possible problems, e. g. for algebraic loops, convergence problems, etc.

6 CONCLUSIONS

The analysis of existing tools for the operation and maintenance optimisation as described in section 2 of this report shows, that there are a variety of examples available from the offshore wind industry. Even though these examples do not deliver the integrated algorithms, the principle approach taken can be seen clearly. This allows sources to obtain ideas for the work to be carried out in WP6 regarding the optimisation of the operation and maintenance aspects of offshore wave and tidal arrays. Using such examples, a strategy for the development of the cost functions in WP6 can be derived. Further information, mainly focused on the mooring /station keeping aspects of offshore arrays can be obtained from the offshore oil and gas industry. Finally, the initial results of current EU projects will deliver input for the algorithm / tool development tasks in WP6.

The analysis of the described maintenance strategies in section 3 has revealed that all the strategies need to be included in the algorithms that are to be developed in WP6. Even if the corrective maintenance seems to be unsuitable for application in offshore wave and tidal arrays, the spontaneous fault occurrence needs to be reflected in the cost calculation algorithms. The pre-determined maintenance may be mandatory for several components and may be the most cost efficient solution for the other parts. Therefore, this strategy will also be considered. The condition based maintenance strategy is the most promising approach to be used in offshore wave and tidal arrays. But this strategy will require the most effort, both when it is to be applied to a real wave and tidal offshore array and also when it is to be covered by the operation and maintenance cost calculation tools to be developed by WP6. A clear aim of this development work must be to give as much assistance as possible to the user of the tool for the selection process of the optimised (combination of the) maintenance approach(es).

The impact of advanced control algorithms on an array level, as described in the fourth section, will mainly focus on the reduction of loads on the downstream or “down wave” units in an offshore array. In addition, the de-rating of the power output can be used in two different ways. Firstly, the de-rating of specific groups of array units can increase the overall power output and, therefore, increase the energy generation / revenue. Secondly, the de-rating individual array units can extend their operability until the next predefined maintenance action is due or until a suitable weather window is available to perform the required maintenance action. The impact of the array control strategies will be considered in the algorithm/tool development of WP6 in particular with the de-rating of power output to extend the remaining life time of array unit components to calculate production loss costs to be compared to the costs for an extra maintenance action on the respective unit. The calculations will then also consider possible increase of power output of nearby units.

To summarise the analysis of available input from the offshore industry (wind as well as oil and gas), the following points can be made:

- There are solutions for optimised operation and maintenance approaches available from the offshore wind industry. Since the technological solutions of offshore wind farms are very similar to those of tidal arrays using turbine based power generation, most of the approaches can be used as models for the development work in WP6. looking ta wave energy arrays, the development of new approaches to apply the array level control strategies is required.
- From the offshore oil and gas industry, suitable information about operation and maintenance optimisation is mainly available with respect to mooring and station keeping system.
- Offshore oil and gas tend to use faster, but more expensive approaches for operation and maintenance. It is arguable if those expensive solutions are applicable to offshore wave and tidal arrays with respect to inacceptable high operational costs.
- The maintenance strategies described in section 3 are all applicable to wave and tidal array units and their components.
- Selection of the optimised (combination of the) maintenance approach(es) is very complex; Therefore, the user of the optimisation tool needs to be supported by the algorithms to be developed in WP6 in the selection process.
- The control algorithms at an array level, in particular the de-rating approach, will influence the algorithms/tools to be developed in WP6 but also may have impact on other research carried out in the DTOcean project.

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8 ACRONYMS

WP	Work Package
ECN	Energy research Centre of the Netherlands
NOWIcob	Norwegian offshore wind power life cycle cost and benefit model
OMCE	Operation and Maintenance Cost Estimator
O&M	Operation and Maintenance
MRE	Marine Renewable Energy
OWC	Oscillating Water Column
MTBF	Mean Time Between Failure
PCC	Point of Common Coupling
CFTOC	Constrained Finite Time Optimal Control