Leeghwaterstraat 44
2628 CA Delft
P.O. Box 6012
2600 JA Delft
The Netherlands

www.tno.nl

T +31 88 866 22 00
F +31 88 866 06 30

TNO report

TNO 2018 R11187

MONITOR PROJECT

Public Summary

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Author(s)	Sjoerd van der Putten, TNO Koen Hermans, ECN
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Management Summary

MONITOR SHM-system

The main goal of the MONITOR consortium, consisting of Gemini Windfarm, Van Oord, Mecal, Damen Verolme Rotterdam, ECN (now part of TNO) and TNO, is to develop and validate a robust and effective offshore wind farm support structure Structural Health Monitoring (SHM) system, including the underlying methodologies to interpret the collected data. Such a system enables a wind farm operator to know the structural health of all support structures within an offshore wind farm and to take appropriate action timely.

The MONITOR project Phase 1 started in November 2015 and finished in March 2018. The project was a successful cooperation and has resulted in the initial design of the MONITOR SHM system including the underlying tools.

The project has been supported by a grant of the Netherlands Ministry of Economic Affairs, Nationale regelingen EZ-subsidies, Topsector Energie, via the Rijksdienst voor Ondernemend Nederland RVO.

SHM-methodology

The SHM methodology developed in the project is aimed at the reduction of the degree of uncertainty on the predicted fatigue damage in the support structure of offshore wind structures in a justified and cost effective way. Fatigue is the governing design criterion for the wall thickness of monopile and jacket support structures, transition pieces and wind turbine towers. It imposes the need for a high quality construction process in terms of rolling, welding and post-weld treatments. Thus, fatigue has a large impact on the construction costs of offshore wind support structures.

The methodology that is developed combines measurements on a limited number of wind turbines with models and data-interpretation tools that convert the measurable quantities to an updated fatigue damage prediction in the most critical fatigue details in all the support structures and towers within a wind farm. In this way a limited investment in measurement and ICT infrastructure results in a significant reduction of windfarm operational uncertainties.

The main system components within the MONITOR SHM-system are the measurement system, the Optimal State Estimator (OSE) tool, the Fleet Leader tool and the Multi-asset correlation (MAC) tool.

MONITOR SHM-system main system components

The MONITOR measurement system consists of two major components: A dynamic response measurement system in the tower and accessible part of the support structure on a limited number of representative support structures within a wind farm. This measurement system is specifically targeted at acquiring in depth information about the dynamic response of the structure given a certain load condition. As such

the uncertainties related to the dynamic loading and response are reduced for the measured wind turbines.
The second part of the measurement system consists of a selection of SCADA data that are already available from the operating system of all wind turbines. The SCADA data is used to utilize the in depth information about the dynamic response for the measured wind turbines for the whole wind farm.

A measurement program has been specifically developed for a two years demonstration measurement campaign at the Gemini offshore wind farm. For this envisaged validation campaign, three wind turbines locations (2% of the total number of locations) are instrumented: two Fleet Leader wind turbines and one validator wind turbine.

The OSE tool is a data-interpretation tool that combines the measured dynamic response from the measurement system with a structural model of the measured support structures to obtain a more accurate prediction of the fatigue loading (in terms of stress ranges) at any detail in the support structure. This utilizes the uncertainty reduction by the measurement system for the complete support structure of the measured support structures.

The OSE is successfully applied to an offshore wind turbine using acceleration- and strain measurements and numerical model simulation results. In the execution of the project, numerous simulations have been carried out that have validated the effectiveness and accuracy of the tool.

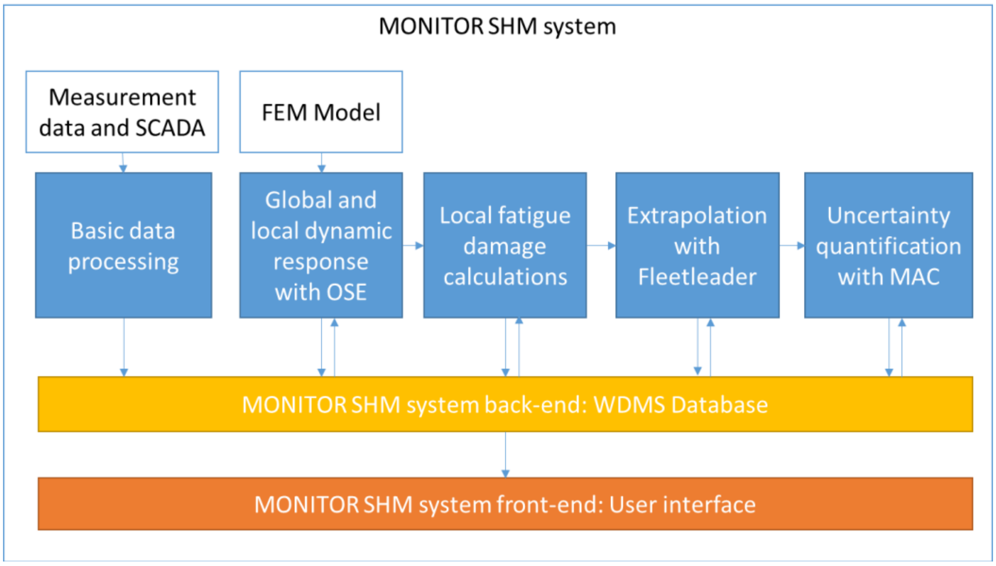


Figure 1: Monitor SHM system overview

The Fleet Leader is a data-interpretation tool that trains a neural network containing the relations between SCADA data and the fatigue load or damage at selected fatigue details. Based on the empirical relations determined from the measured wind turbine locations, the loads on all wind turbines in the farm can be estimated, using their SCADA data as an input. In the project the Fleet Leader tool has been updated towards an integrated tool in the MONITOR SHM system. The added functionality of the update results in output that includes the damage equivalent load effects for each ten minute timeseries using state-of-art fatigue models.

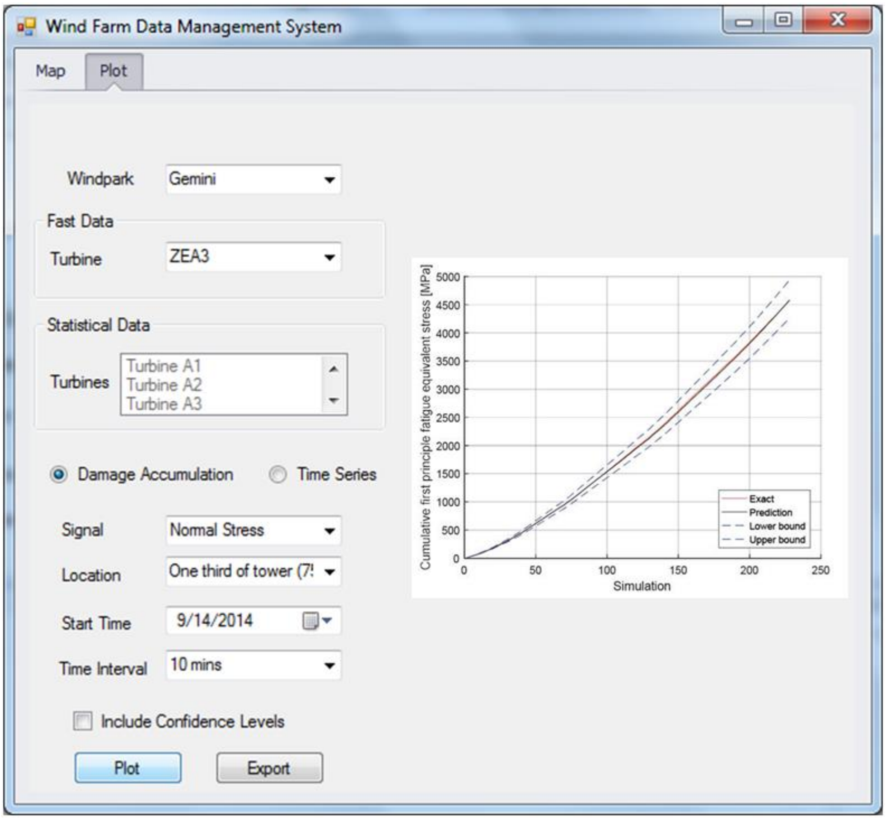
The newly developed multi-asset correlation tool (MAC-tool) is a probabilistic tool that addresses a bandwidth to the updated fatigue damage prediction based on the measurement system and other data-interpretation tools. This is done by means of a Bayesian Network approach that is fed by the results from the Fleet Leader and the SCADA data. By considering the same probability of exceedance as used in the design the same level of reliability can be achieved for the updated prediction based on the SHM-system.

In the project it has been proven that the Fleet Leader and MAC tool are together capable of estimating the fatigue on the un-instrumented wind turbines and evaluating the uncertainty on this estimation. The tools run in a robust and time efficient way. However the estimation accuracy does decline significantly when the un-instrumented structure features different geometrical properties and environmental conditions such as water depth and soil stiffness. This should be further investigated. Since the investigations focus on fatigue damage accumulation and little fatigue failures are expected at the start of the operational lifetime, there are no objections to instrument later in the lifetime. Finally, it is recommended to measure at least one year to capture enough data to train the models and ensure accurate predictions for a large range of conditions.

The integration of the MONITOR tools (OSE, Fleet Leader and MAC) has been done via the development of the back-end of the MONITOR SHM system. This back-end part consists of a database system that has been developed in-house by ECN, called WDMS (Wind Data Management System), which has been connected to the three tools in the project via dedicated MATLAB scripts. To facilitate automatic interaction between the tools a client – server model setup is implemented via the WDMS. The back-end has been tested and proves to be a stable backbone that meets the requirements of the SHM system.

MONITOR SHM-system demonstration

The MONITOR SHM system is developed with a desktop based front-end. The SHM front-end includes the means to present the measured and processed results from the MONITOR methodology to a wider group of stakeholders. This stakeholders group is comprised of the wind farm operator, wind turbine and support structure manufacturers, wind farm owner, and researchers. During the execution of the project multiple interviews and web-sessions took place to identify the needs and requirements from the users. A demonstration version has been set up for the purpose of collecting feedback and evaluating different options. For the final MONITOR front-end, a web-based version is foreseen.



Windpark: Gemini

Fast Data

Turbine: ZEA3

Statistical Data

Turbines: Turbine A1
Turbine A2
Turbine A3

● Damage Accumulation ○ Time Series

Signal: Normal Stress

Location: One third of tower (7!

Start Time: 9/14/2014

Time Interval: 10 mins

☐ Include Confidence Levels

Figure 2 - Plot of the MONITOR SHM system front-end

Overall project conclusions

At the conclusion of the MONITOR project the OSE and MAC tools from TNO and the Fleet Leader tool from ECN have reached a Technology Readiness Level, suitable to implement in a demonstrator structural health monitoring system (TRL 6). The activities in the project have converged to a SHM demonstrator tool, including a functional SHM database and user-interface tool. The database consists of the raw measurement data, the processed measurement data, results of the OSE, Fleet Leader and MAC calculations and other relevant information that is required to know the structural health of all support structures within an offshore wind farm.

The combination of the OSE, Fleet Leader and MAC tools in one system provides not only data assimilation (via the OSE), but also a data extrapolation for monitoring structures in a cluster (Fleet Leader) and a calculation of the reliability and accuracy of the results (MAC). The three individual tools are comparable to the international state-of-the-art, and connect to existing research very well. In an integrated system, in particular the Fleet Leader and MAC tool will distinguish such system from market alternatives. The resulting MONITOR support structure monitoring system is a unique integrated system with demonstrated tools that will enable a wind farm operator to know the structural health of multiple support structures within an offshore wind farm, with a target reliability and accuracy.

1 Introduction

1.1 General

The title of this project is “Smart Monitoring Methodology for Offshore Wind Farm Support Structures”, or in brief project MONITOR. The project has been supported by a grant of the Netherlands Ministry of Economic Affairs, Nationale regelingen EZ-subsidies, Topsector Energie, via the Rijksdienst voor Ondernemend Nederland. The consortium is very pleased with the support of the Dutch government and is looking back on a successful project.

1.2 MONITOR project

This document summarizes the results of the work executed in the MONITOR Project Phase 1 that took place from 2015 to 2018.

The MONITOR Project as a whole has the main goal to develop and verify a robust and effective offshore wind farm support structure monitoring system, including the underlying methodologies to make an interpretation of the collected data. Such a system enables the industry to understand the structural behaviour of multiple support structures within an offshore wind farm.

The project is divided in two phases. Phase 1 of the project comprised of R&D activities that contribute to the above goal. The tools and methodology have been developed from Technology Readiness Level TRL 4 to TRL 6. The objective of Phase 2 of the project is to bring the tools from TRL 6 to TRL 8 via a demonstration project that aims to start in 2018.

In this Phase 1, first a structural response monitoring system has been developed that is used to monitor the fatigue consumption of all relevant details of an individual offshore wind turbine support structure. Next an extrapolation concept has been elaborated towards a methodology that relates the structural behaviour of representative individual wind turbine support structures to the structural behaviour of all individual wind turbine support structures. The next step comprised of the development of the data analysis methodology that is required to guide the monitoring data in an effective way, together with the development of the Structural Health Monitoring (SHM) system that will be used by operators or designers to know the structural health of the support structures.

The result of the project is a generic MONITOR SHM system and methodology which can be used for several offshore wind turbine support structure types with different external conditions.

1.3 MONITOR project SHM system

In this report several tools and processes within the MONITOR SHM System are addressed. The below scheme provides an overview of the hierarchy and relations of the tools and processes.

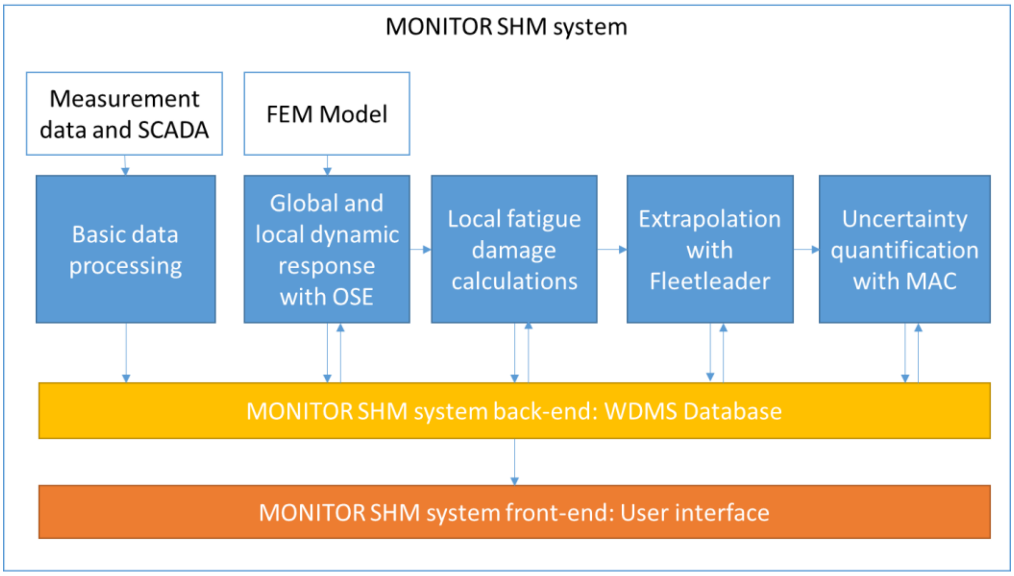


Figure 3: MONITOR SHM system overview

The main tools that have been developed in this project are the Optimal State Estimator (OSE) from TNO, the Fleet Leader from ECN, and the Multi Asset Correlation (MAC) tool by TNO. An explanation of the tools is provided in the first section of the report. The back-end and front-end of the MONITOR SHM System have been developed to connect the tools and to present the data and information to the users.

1.4 Structure of the report

The five work packages that are summarized in the following sections of this report match the above activities:

WP	WP title	Report section
	Management Summary	1
3	Structural health methodology	2
1	Effective and robust monitoring system design for a single wind turbine	3
2	Effective and robust monitoring system design for a complete OWF	4
4	Monitoring data analysis methodology	5
5	Structural Health Monitoring-tool	6
	Overall project conclusions	7

Section 8 lists the reports that are the deliverables of the activities performed in the work packages.

2 WP 3: Structural Health Monitoring methodology

2.1 Introduction

2.1.1 *Relevance of fatigue for offshore wind support structures*

Fatigue is the dominant failure mechanism for offshore wind support structures. This is caused by a combination of the metocean conditions (wind and waves), the presence of many fatigue sensitive details (mainly welds) and the need to design economically optimized support structures (in order to minimize LCoE).

Figure 4 Illustration of aspects that make fatigue relevant for offshore wind support structures (sources: climatecentral.org, sif-group.com)

As a result fatigue is often the governing design criterion for the wall thickness of monopile and jacket support structures, transition pieces and wind turbine towers. It also imposes the need for a high quality construction process in terms of welding and post-weld treatments. As a result, fatigue has a large impact on the construction costs of offshore wind support structures.

Quantification of fatigue is important for the technical operational life of the support structures. Usually support structures are designed for an operational life of 20 or 25 years. Any deviation from the theoretical operational life can have serious impact on the power production capacity (in case of unexpected failure) and the business case for offshore wind farms. Naturally this impact can be negative (e.g. more maintenance than anticipated) as well as positive (e.g. less maintenance than anticipated and/or a longer operational life than expected). The latter is expected to be more likely because the support structures are designed for a high level of reliability.

2.1.2 *Development and assessment of fatigue damage*

Development of fatigue damage in steel offshore wind support structures involves the initiation of small cracks from initial defects in the steel or welding material due to fluctuating stresses. These cracks are most likely to initiate in areas with relatively large fluctuating stresses and/or high local stress concentrations, for example near circumferential welds around the mudline and connections between members of jacket structures. After initiation, a crack will propagate with a growth rate which is dependent on the local stress fluctuations at the crack front and the capability of the material to resist these stress fluctuations. After a period of crack propagation the crack can reach a certain critical size. The size of this critical crack is structure- and detail specific, and amongst others, depends on the consequences of reaching it (e.g. complete loss of the wind turbine or repairable damage). The process described above is schematically illustrated in Figure 5. Figure 5 also includes a schematic indication of the effect of various uncertainties involved in the development of critical fatigue damage. This is done with the distribution functions[1] drawn next to and inside the figure. From the distribution function at the top right of the figure, the moment in time at which a critical crack is expected (i.e. the mean value scenario) can be determined. As can be seen in the figure, the degree of uncertainty (i.e. bandwidth) on this expectation is significant for fatigue cracking in offshore wind support structures. In order to achieve reliable support structures with a sufficiently low probability of failure for fatigue, design methods adopt safety approaches to arrive at an upper bound fatigue damage development scenario (see figure).

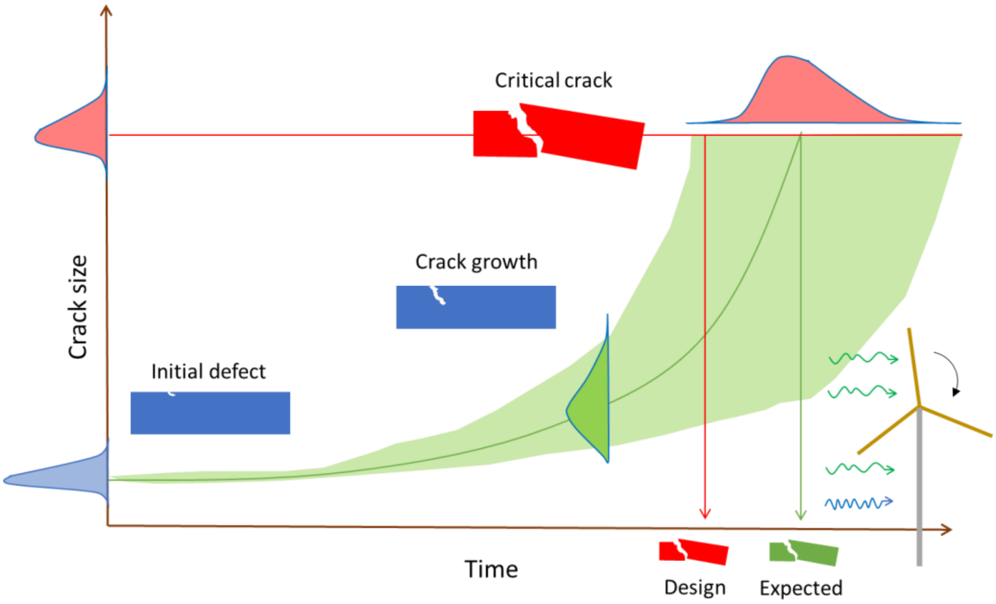


Figure 5 Illustration of the development of fatigue damage in time and the main uncertainties

2.1.3 *Aspects of uncertainty*

A relatively large portion of the uncertainty is caused by the uncertainty on the crack propagation over time (the green area in Figure 5). This is caused by a combination of many aspects in the chain from metocean conditions at wind farm level to critical fatigue damage in a specific detail of a specific support structure within the wind farm.

Figure 6 gives an overview of these main aspects which are individually elaborated on below the figure.

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[1] Functions that give the likelihood of a certain parameter value or crack growth scenario

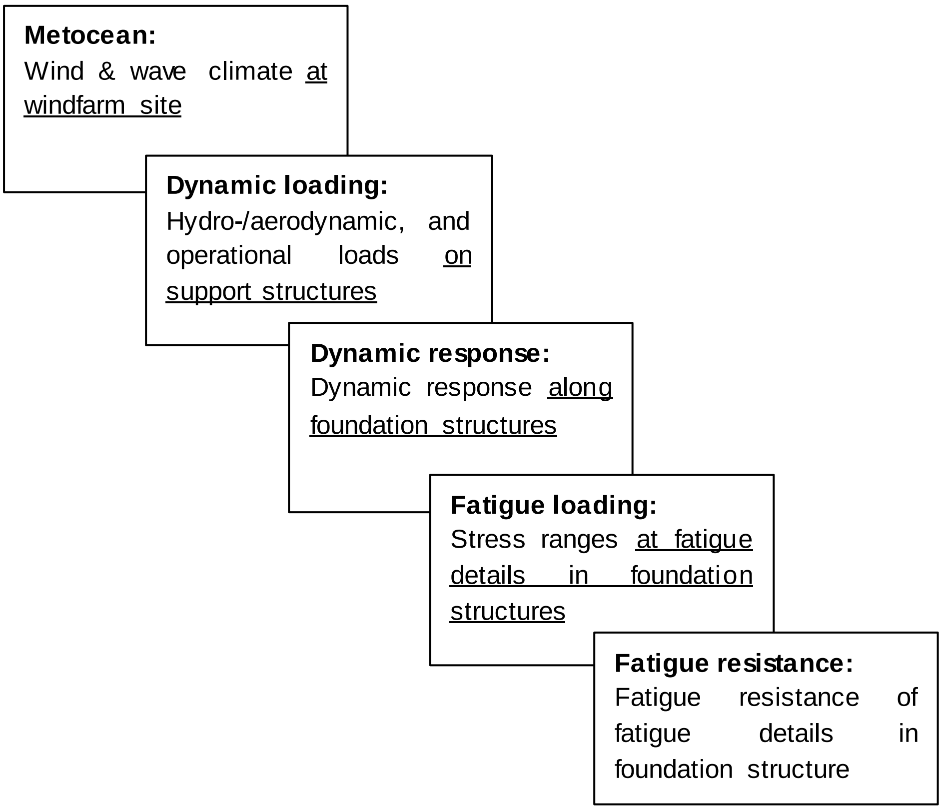

Figure 6 Overview of main aspects involved in fatigue of offshore wind support structures

Metocean conditions:

On a windfarm level, the site specific wind and wave climate are the driving factors behind the dynamic loading on (individual) wind turbines. For the fatigue design of offshore wind structures long term statistical distributions of the site specific wind speed, wave height, and wind and wave direction are used. These are based on metocean assessments which, amongst others, include long term measurement data from offshore metocean masts. The remaining uncertainty on this aspect is the difference between the assumed statistical distributions and the actual wind and wave climate during the operational life of the wind park. The uncertainty on this aspect applies to the complete wind farm.

Dynamic loading

Offshore wind structures are loaded by various type of dynamic loads, see Figure 7. Dynamic wind and wave loads are directly caused by the metocean conditions as described above and the operational settings of the wind turbine. In common design practice the dynamic loads on, and the dynamic response of, the support structure are calculated in parallel in an iterative process between the support structure designer, and the wind turbine designer. Usually worst case assumptions are done in order to conservatively cover all wind turbine locations within a wind farm by performing the iterative process for one or two locations only. On the dynamic loading side the remaining uncertainty is the difference between the calculated and the actual dynamic loads given a certain metocean and operational condition. This is mainly driven by the accuracy and the reliability of hydro- and aerodynamic models, and the degree of conservatism in the design. The degree of uncertainty for this aspect applies to, and differs for individual wind turbines within a windfarm.

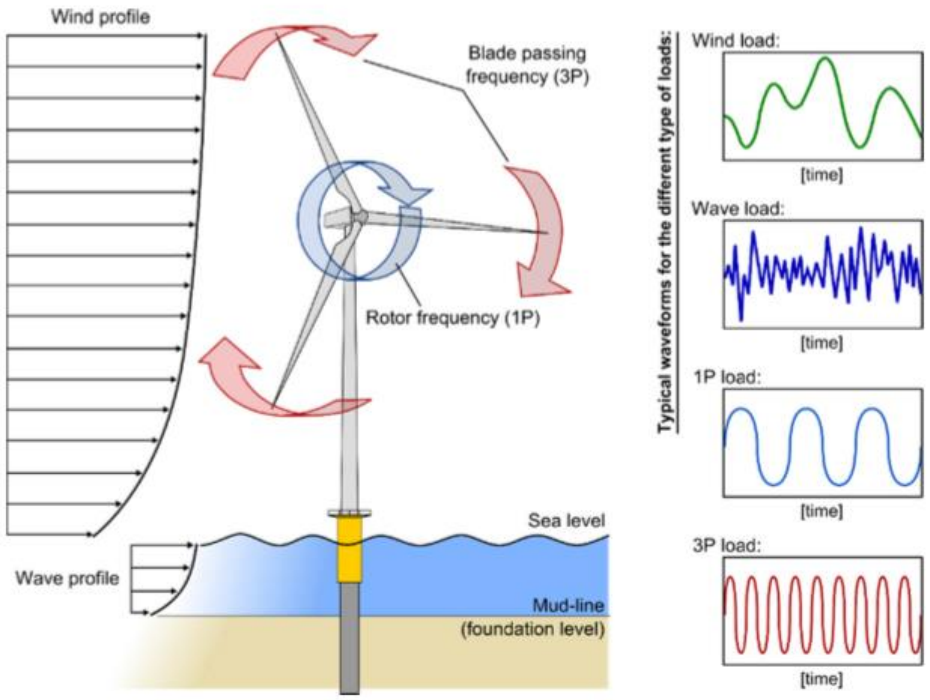

Figure 7 Illustration of external dynamic loads on offshore wind turbines (source: Nikitas)

Dynamic response:

The dynamic loads result in global motion i.e. the dynamic response of the support structure and tower. In design practice this global dynamic response is defined in terms of fore-aft and side-side bending moments, shear forces and accelerations. Besides on the load, the global dynamic response depends on the dynamic characteristics of the structure. These are driven by the mass, stiffness and damping properties of the structure and its boundary conditions. Some of these properties are difficult to quantify accurately (e.g. dynamic soil stiffness and various sources of damping). As described above it is common design practise to calculate the global dynamic response alongside with the dynamic loads in an iterative process between the support structure designer, and the wind turbine designer. In the last step of this process the support structure designer often applies the interface loads and accelerations obtained from the aero-elastic analysis of the wind turbine designer on a detailed finite element model of each individual support structure in the wind farm. The remaining uncertainty related to this aspect is the difference between the calculated and the actual global dynamic response of the support structure and the tower given a certain dynamic load set. This is mainly driven by the accuracy of the quantification of input parameters for the structural model (including quantification of various sources of damping). The degree of uncertainty on this aspects differs for and applies to individual cross sections within the support structure and tower of individual wind turbines within a wind farm.

Fatigue loading:

The global dynamic response results in stress fluctuations i.e. stress ranges at the various fatigue sensitive details in the support structure. These stress ranges are either defined in terms of nominal stress ranges (excluding stress concentrations effects due to the local geometry at the detail) or hotspot stress ranges (including stress concentration effects due to the local geometry at the detail), depending on the type of fatigue detail.

The nominal stress range approach is usually used for details with relatively limited stress concentration effects (e.g. circumferential welds in monopiles). The conversion of the global dynamic response to the stress ranges can be done in a relatively simple way by dividing the global bending moments and/or shear forces by the relevant cross section properties to obtain nominal stresses. These nominal stress ranges are then used in conjunction with stress concentration factors (SCF) based on parametric formulas from design standards to account e.g. for plate misalignments and/or changes in the wall thickness. The SCF's from design codes stand in close relation to the assumed fatigue resistance (described in the next section).

For details with a more complex local geometry (e.g. welded attachments) usually the hotspot stress range approach is used. In this case the SCF's due to the local geometry at the detail are obtained with a detailed finite element model (FEM) in which the area near the considered fatigue detail is modelled in a very refined way. This model is then used to calculate the ratio between the nominal stress and the hotspot stress for a representative unit load case applied at a sufficiently large distance from the considered detail. This ratio, or SCF, is then applied on the nominal stress ranges at the detail derived. In both approaches additional stress concentrations due to the weld geometry are usually accounted for on the fatigue resistance side (described in the next section). The remaining uncertainty related to this aspect is the difference between the calculated local stress range (including stress concentration effects) and the actual local stress range given a certain global dynamic response. This is mainly driven by the accuracy of the quantification of the SCF (either by parametric formulas or FEM). The degree of uncertainty on this aspect differs and applies to individual fatigue details within the support structure.

Fatigue resistance:

Depending on the resistance against fluctuating stresses (i.e. fatigue resistance), the fatigue loading as described above can result in the initiation and propagation of fatigue cracks near fatigue sensitive details (as illustrated in Figure 5). The fatigue resistance of details in the support structure depends on many aspects. Amongst others[2] the type of detail, the influence of corrosion, scale effects, notch effects and the execution quality of the welding process play an important role for offshore wind support structures. In common design practise the fatigue resistance is taken into account by means of designing S/N curves for specific details and various circumstances covering the main influencing aspects on the fatigue resistance.

The S/N curves give the relation between the magnitude of the stress range and the number of cycles a detail can survive until failure occurs. The curves are determined from fatigue tests on small specimens[3] in laboratories. The adopted failure criterion in the tests is the number of cycles performed until a through thickness crack is reached. For most real scale offshore wind support structures this failure criterion means a crack that is close to, or equal to the plate thickness . In order to achieve a sufficient level of reliability the design S/N curves are based on the mean value of the

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[2] It needs to be stated that the mentioned aspects are not intended to be complete

[3] For tubular joints larger test pieces are used

experimental results minus two times the standard deviation. As such the design S/N curves are associated with a 97.7% probability of survival. Dependent on the accessibility for inspection and repair and the location of the fatigue detail along the support structure (atmospheric zone, splash zone or submerged) an additional design fatigue factor or partial material factor needs to be applied to achieve a higher probability of survival. The remaining uncertainty related to this aspect is the difference between the assumed fatigue resistance and the actual fatigue resistance given a certain fatigue loading (i.e. stress ranges). This is driven by many aspects. The degree of uncertainty on this aspect differs and applies to individual fatigue details within the support structure.

2.2 MONITOR Project SHM-methodology

2.2.1 Aim of the SHM-methodology

The aim of the SHM-methodology developed in this project is to reduce the degree of uncertainty on the predicted fatigue damage in the support structure of offshore wind structures in a justified and cost effective way. The underlying goals are to minimize the need for inspections, potentially extend the operational life of wind farms and to support more economic future support structure and tower designs.

The principle and effect of the envisaged reduction of uncertainty is schematically illustrated in Figure 8.

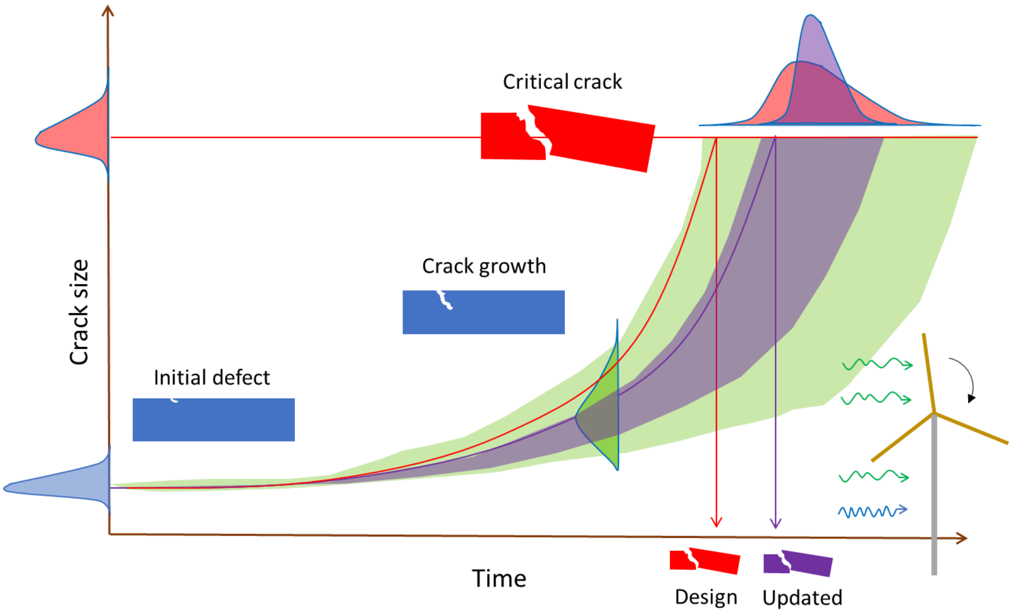

Figure 8 Schematic illustration on principle of reduction of uncertainty

2.2.2 Description of SHM-methodology

In order to achieve the envisaged reduction of uncertainty in a justified and cost effective way a methodology was developed that combines measurements on a limited number of wind turbines with models and data-interpretation tools that convert the measurable quantities to an updated fatigue damage prediction in the most critical fatigue details in all the support structures and towers within a wind farm. An overview of this concept is given in Figure 9 where the middle part of the figure gives the main SHM-system ingredients. The advanced data-interpretation tools that are developed within WP1 and WP2 of this project are indicated in red.

An important feature of the methodology is that it focuses on uncertainty reduction based on measurable quantities. The considered measurable quantities in this project that can be measured cost effectively are the dynamic structural response (accelerations and dynamic strains in the tower and accessible part of the support structure) and the SCADA data from all wind turbines that are already available from the operating system. This means that the uncertainty reduction is focussed around the middle part of the chain of aspects, as is illustrated in Figure 10. Uncertainties regarding the dynamic behaviour and fatigue loading are explicitly reduced by taking account of the measurements and data-interpretation tools. Uncertainty reduction on the environmental conditions and dynamic load are implicitly reduced as well because these aspects affect the measurements of the structural response. For the fatigue resistance the SHM-methodology adopts similar assumptions as used in the design to achieve the same level of reliability as in the design. In the future it might be possible to extend the SHM-system to also reduce the uncertainties on these aspects.

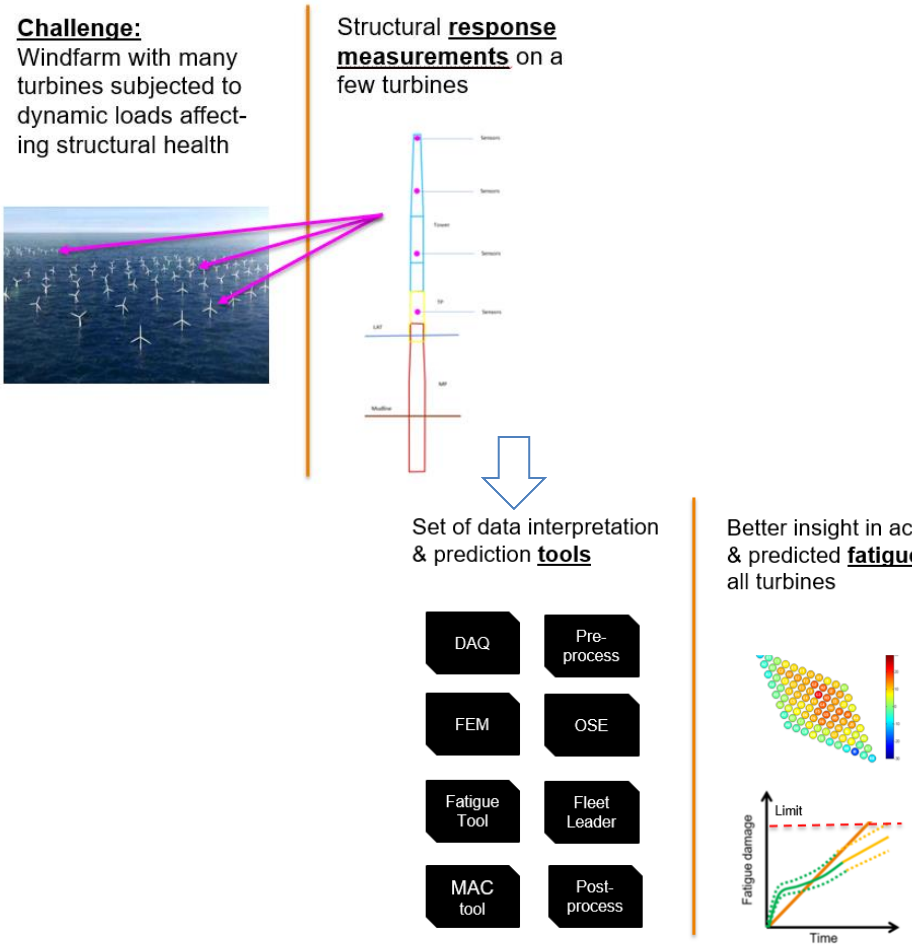

Figure 9 Overview challenges (left), ingredients (middle) and envisaged output (right) of the developed SHM-methodology.

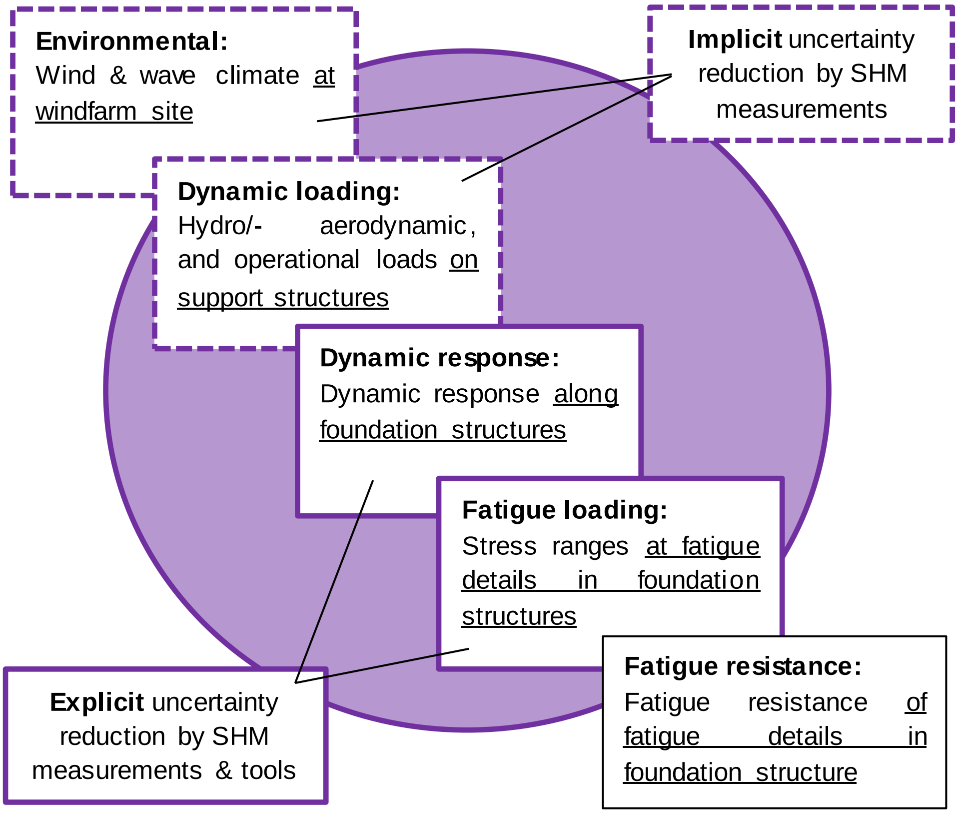

Figure 10 Illustration of focus of uncertainty reduction by SHM-system

2.2.3 *Description of the main system components*

This section briefly summarizes the function and main features of the main system components within the SHM-system. For more detailed information the reader is referred to the sections of WP1, WP2 and WP4 in this report.

Measurement system:
The measurement system consist of two major components: A dynamic response measurement system in the tower and accessible part of the support structure on a limited number of representative support structures within a wind farm. This measurement system is specifically targeted at acquiring in depth information about the dynamic response of the structure given at a certain load condition. As such the uncertainties related to the dynamic loading and response are reduced for the measured wind turbines.
The second part of the measurement system consists of a selection of SCADA data that is already available from the operating system of all wind turbines. The SCADA data is later used to utilize the in depth information about the dynamic response for the measured wind turbines for the whole wind farm (see description of Fleet Leader later in this section).

Optimal State Estimator:
The Optimal State Estimator (OSE) is a data-interpretation tool that combines the measured dynamic response from the measurement system with a structural model

of the measured support structures to obtain a more accurate prediction of the fatigue loading (in terms of stress ranges) at any detail in the support structure. This utilizes the uncertainty reduction by the measurement system for the complete support structure of the measured support structures. Because this component includes model assumptions as well, the performance needs to be validated in the envisaged field demonstrator in the follow-up of this project.

Fleet Leader:
The Fleet Leader (FL) is a data-interpretation tool that trains a neural network containing the relations between SCADA data and the fatigue load or damage at the considered fatigue details. The neural network is trained by data and OSE results from the measured wind turbines. By assuming the relation between SCADA data and fatigue loads is the same[4] for all wind turbines within the wind farm the reduction of uncertainty for the measured wind turbines is mobilized for all wind turbines in the wind farm. The neural network training and the assumption that the relation between SCADA data and fatigue loads is the same for all wind turbines within a wind farm introduces a new remaining uncertainty. As a consequence the bandwidth for non-measured wind turbines will be larger than the bandwidth for measured wind turbines. This is addressed by the multi-asset correlation tool which is described next.

Multi-asset correlation tool:
The multi-asset correlation tool (MAC-tool) is a probabilistic tool that addresses a bandwidth to the updated fatigue damage prediction based on the measurement system and other data-interpretation tools. This is done by means of a Bayesian Network approach that is fed by the results from the Fleet Leader and the SCADA data. By considering the same probability of exceedance as used in the design, the same level of reliability can be achieved for the updated prediction based on the SHM-system.

2.2.4 *Envisaged output of SHM-system*

In order to achieve clear insight in the difference between the fatigue life predicted during the design and the updated prediction of the fatigue life based on the SHM-system it is important to present the results in a clear and consistent way.

As an example the envisaged output graph for the development of fatigue damage for a single fatigue detail is given in Figure 11. It is envisaged to produce this graph for all considered fatigue details in all support structures. To enable consistent comparison between the design and the updated prediction, the prediction from the design needs to be compensated for the actual metocean conditions during the measurement period. For the future predictions the statistical distributions for the metocean conditions, as used in the design, are used as a basis. This is because

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[4] Additional conversion factors are needed for foundation structures with different section properties and fatigue detail characteristics than the measured support structures.

long term monitoring of actual conditions would be required to update the statistical distributions of the metocean conditions as well.

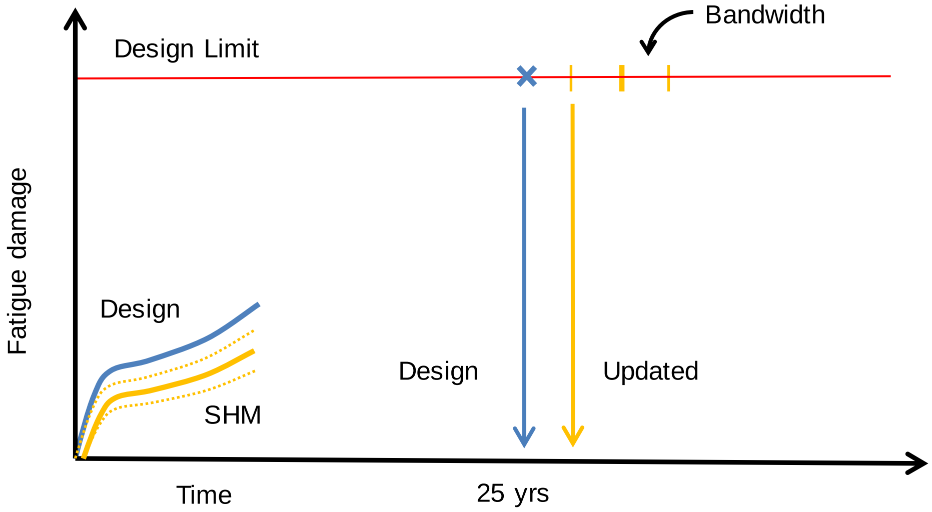

Figure 11 Illustration of the envisaged output for individual fatigue details

In order to create a clear overview of the status of the fatigue damage development in all support structures and towers of the windfarm, it is envisaged to produce a map of the complete windfarm with an indication of the relative criticality of each wind turbine as well. A schematic impression of this is given in Figure 12.

It is envisaged to make all results available through a web based user-interface. This has been demonstrated in WP5 of this project. Next to the web based user-interface, short summarizing reports for each season or year could be made.

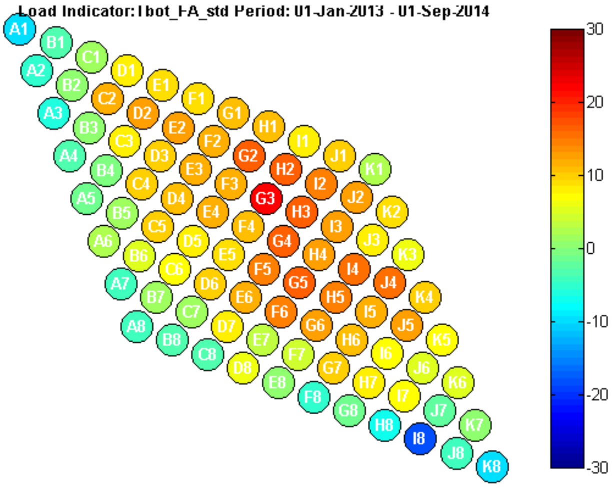

Figure 12 Schematic impression of map with indication of criticality of support structure fatigue

2.3 Discussion

2.3.1 Critical aspects

The SHM-methodology as described involves a number of critical aspects. These are elaborated on below.

At first the methodology relies on real-time availability of good quality SCADA data from all wind turbines in a wind farm. The details about the availability of SCADA data are yet unknown.

The ability to extrapolate the SHM-results from the monitored period to a future fatigue life prediction, relies on measurements of quantities for which long term statistical distributions are available. At the moment it is envisaged to consider the actual undisturbed wind speed at hub height and the wind direction.

In terms of validation a critical aspect of the methodology is that the results below the accessible part of the support structure cannot be verified by measurements at the moment. As many fatigue details in this area are critical for the fatigue life, it is suggested to at least perform a sensitivity study based on numerical simulations and the validation results that can be obtained. On the longer term it might become feasible to include sensors in the non-accessible part of support structures for new built wind farms prior to offshore installation.

2.3.2 Future opportunity

A potential future extension of the SHM-methodology as developed in this project, is to reduce uncertainties on the fatigue resistance side as well. This can for example be done by means of condition inspections and/or monitoring. This would also open up the opportunity to adopt a fracture mechanics based approach instead of the S/N curve approach. This would provide more explicit information about the crack size development which could be useful for inspection and maintenance planning. This is most relevant for the fatigue details that can be inspected (i.e. details above the mudline).

3 WP 1: Effective and robust monitoring system design for a single wind turbine support structure

3.1 Introduction

A main challenge in this project is to monitor the fatigue consumption of all relevant details of the OWT structure and not to limit the monitoring to only a few structural details. This requires to design an effective structural response monitoring system as the number of sensors needs to be limited and it may not be possible to install sensors at all relevant details. Ideally, all relevant details are already identified within the design phase. However: inspections may reveal other relevant details after the monitoring system has been installed. The monitor system should also be able to make an estimation of the loading at those locations. The selected approach is to combine the measurements of the limited number of sensors with a detailed numerical model of the structure in order to make an estimation of the “measured” response of the whole structure. Such approach has already been successfully been applied by TNO for slamming loading (J.T. Tuitman, 2007). Knowing the “measured” response of the whole structure allows one to compute the “measured” local structural response at all relevant details of the OWT structure.

The structural response monitoring system should be robust enough to be operational during the full design life time of the OWT support structure. It is very likely that a few sensors will become inaccurate, or even fail during this period. The monitoring system should be sufficiently redundant in such a way that it remains operational when a few sensors fail. It is also necessary that erroneous sensor readings are recognized and disregarded within the processing of the monitoring data. Also the operator should be informed that a sensor gives incorrect readings. It may be acceptable to replace some sensors during planned maintenance of the OWT but the monitoring system should be robust enough to remain operational till the planned maintenance window of the OWT after failure of a (few) sensor(s) or when not reachable any more during operational lifetime the main measurements must still be in operation.

The elaborated method in the MONITOR Project is to derive the response of the whole structure from the measurements, which also allows to check the consistency of the readings of individual sensors. If one sensor is not consistent with the other sensors, its readings are most likely incorrect. Then this data is disregarded and the operator is informed that the sensor is malfunctioning. As the most likely response of the structure is derived from the data of all sensors and the numerical model, it allows to include more sensors than the minimum required to make the estimation. The required redundancy of the monitoring system is simply obtained by installing more sensors than the required minimum, which allows for failing of some sensors during the monitoring program.

The design of the sensor plan is an iterative process together with the development of the tool to process the sensor readings. This design/development process is illustrated in Figure 13:

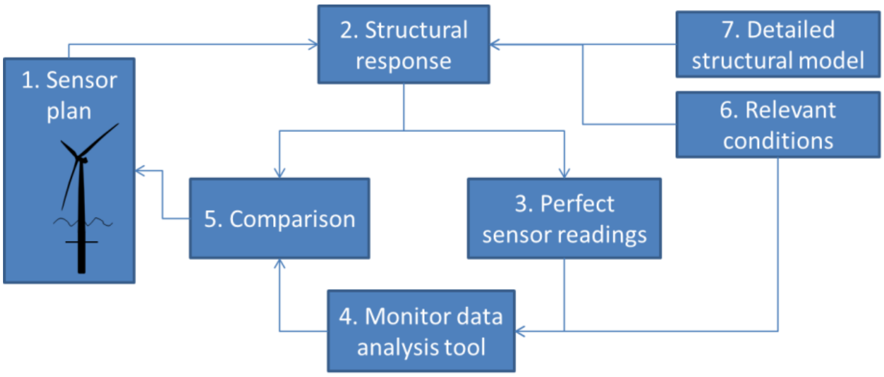

Figure 13: Design of the monitoring system

The deliverables of this work package can be found via the list of reports in Section 7. These deliverables are:

- a first version of the design of the sensor plan for the single OWT based on an engineering judgement in the consortium, as presented during project management meeting,
- the details of the parametric FE model of the structure, presented via two MECAL reports,
- the details of the Phatas simulations that have been performed by ECN, presented via the ECN report,
- the demonstration of the monitoring data analysis tool, presented via two TNO reports.

3.2 First version of the design of the sensor plan for the single OWT based on an engineering judgement in the consortium

Based on the design documents of the Gemini support structures, a preliminary sensor plan for a single OWT is proposed as follows:

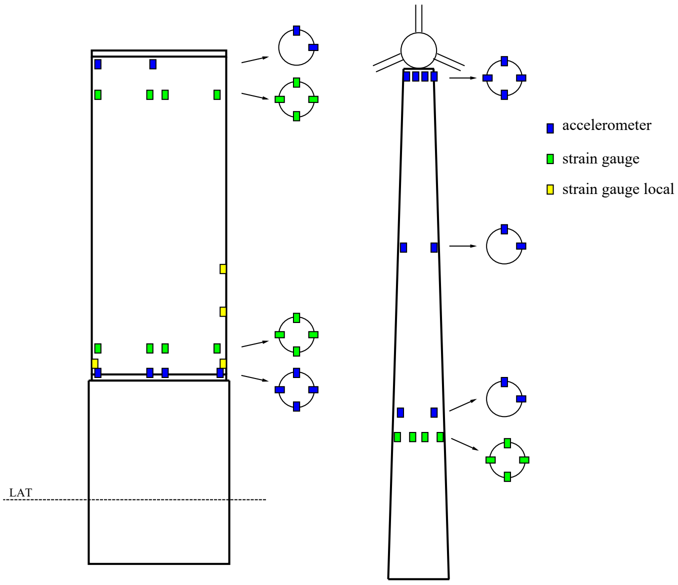

Figure 14: Design of the monitoring system

This sensor plan captures the main characteristics of the relevant modes of the structure and is the basis for the development of the simulations that are performed in the subsequent activities in WP1. The selected wind turbine location is the ZEA3 location, which is a representative location in terms of water depth, wind conditions and soil characteristics.

3.3 Details of the parametric FE model of the structure

Via two reports MECAL presents the FE model of the Gemini offshore wind farm position ZEA3 wind turbine support structure. The modelling and assessment is performed by MECAL and this model has been used by TNO for the OSE assessments. This report describes the finite element modelling of the support structure and the results of following analysis which were performed for verification of the model.

- Modal analysis of the support structure with rotor nacelle assembly(RNA).
- Transient analysis of the support structure for model verification.
- Fatigue analysis of the support structure.

All the assessments were based on the FE model. The FE model has been modelled with at least the details as per agreement with the other partners of the project. The model contains the monopile (MP), the transition piece (TP), the grouted connections and the wind turbine tower. The Rotor Nacelle Assembly is modelled as point mass for simplification of the model as only the support structure is studied here. All the components have been parametrically modelled. The results from the modal analysis matches closely with the modal analysis results from the PHATAS model which is done by ECN (see next paragraph) and the frequency analysis results performed by Ramboll during the design phase. The results of the transient analysis are compared with the response of the ECN model and the dynamic response predicted by both the models is very comparable.

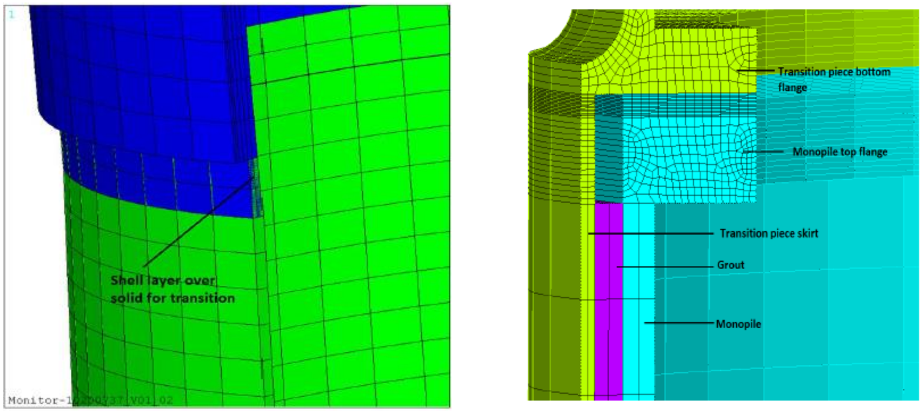

Figure 15 Snapshots from MECAL model

With the provided loads of ECN a strength assessment has been carried out on the MP and on the TP. On the modelled detail of the flange connection between MP and TP the hotspot in the outer fillet radius of the TP flange has been found, which is similar to the hotspot shown in the Ramboll documentation. Please note, that no conclusions to the real strength on MP and TP can be drawn, as the components only have been modelled in a simplified way and because not the real design loads were used for the assessment.

3.4 Details of the Phatas simulations

In this ECN contribution the model parameters of a 4MW offshore wind turbine in the Gemini wind farm at position ZEA3 are described. The structural properties are taken from the design reports of Ramboll. The model is created in the aero-elastic simulation tool from ECN called Phatas. The model is used to calculate the structural dynamic response of the support structure for various operational and environmental conditions. The first and second natural frequency calculated with the Phatas model are within 0.5 % of the Ramboll design frequencies.

3.5 Demonstration of monitoring data analysis tool

3.5.1 *Introduction*

For offshore wind structures the main deterioration causes are corrosion and fatigue. Fatigue is a design driver that has a significant effect on capital costs (material, welding and installation) and inspection costs. Offshore wind turbine (OWT) support structures have to carry wind turbines that are becoming larger and heavier. Condition monitoring can lead to insight into fatigue, consumed lifespan and to the remaining lifespan of the support structure in case of wind turbine replacement.

Monitoring the fatigue consumption of all relevant details of the OWT structure remains a challenge because it may not be possible to install sensors at all relevant details. Also, while ideally all relevant details are already identified within the design phase, inspections may reveal other relevant details after the monitoring system has already been installed. The monitor system should also be able to make an estimation of the loading at those locations.

The Optimal State Estimator (OSE) described in this report combines measurements from a limited, but sufficiently redundant number of sensors, with a detailed numerical model of the structure in order to make an estimation of the “measured” response of the whole structure. Knowing the “measured” response of the whole structure allows one to compute, using a Finite Element (FE) model of the structure, the “measured” local structural response at all relevant details of the OWT structure

3.5.2 *Optimal State Estimator (OSE) overview*

State estimation uses a numerical (finite element) model of a dynamical system which is combined with measurement data. The numerical model in general does not describe the real world system dynamics exactly. Measurements also contain measurement noise and only give partial information about the system.

The estimation process combines model and measurements by first defining residuals between measurements and model results, residuals of the model evolution equations and residuals between assumed and estimated initial conditions. A cost functional of these residuals is then minimized resulting in an optimal estimated state evolving with time. The estimates are optimal in a user defined sense, because the residuals are weighted according to the confidence the user has in the measurement data, model equations, and initial conditions.

To use a full finite element model with hundreds of thousands of degrees of freedom is very costly computationally. Therefore the OSE is based on a description in terms of modal degrees of freedom. Often a few modes below a certain cutoff frequency are sufficient to obtain good results, significantly reducing the system size and CPU times for the OSE solver. The OSE results are the evolution of the modal degrees of freedom with time. Transformation between modal and local coordinates then gives the optimal estimates of requested quantities such as nodal displacements, accelerations, stresses, strains and loads.

(J.T. Tuitman, 2007) describes the theory of the OSE in more detail. In this report the OSE is treated from a computational point of view. Discussion is limited to the different computational modules of the OSE and how these are connected. Figure 16 shows a flow chart of the OSE used in this study

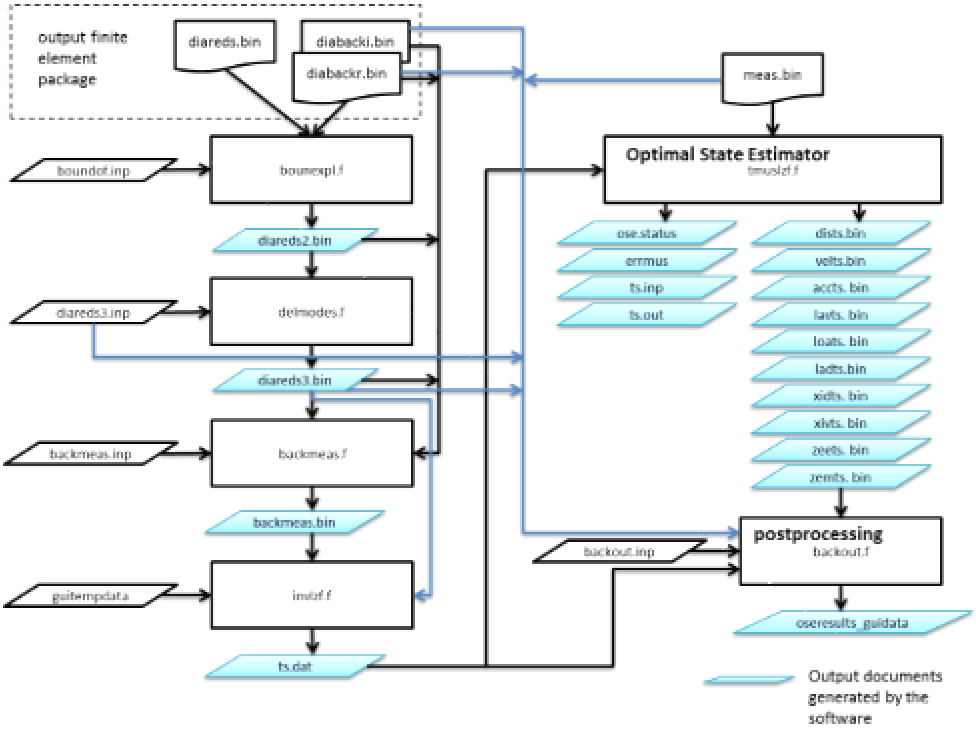

Figure 16 Flow chart of the Optimal State Estimator and its pre- and post-processing

3.5.3 *Application of the OSE using simulated OWT response to realistic weather conditions*

For a realistic test of the OSE the MECAL FEM model discussed in the previous sections is used in the OSE with the “virtual measurements” from the PHATAS simulations provided by ECN. PHATAS is a simulation model where the response of OWT structures to realistic wind, wave loading and operational conditions is computed. This simulation includes nonlinear aerodynamic damping as well. The results of several 10 minute long PHATAS simulation runs are available with acceleration, displacement and bending moment output. Bending moment is converted to strain and used together with accelerations as “measurement” input in the OSE.

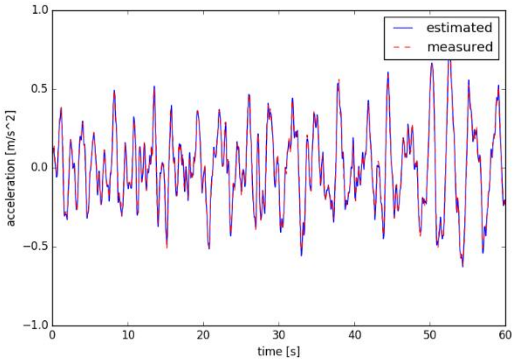

Figure 17 PHATAS model “measured” acceleration at the top of the OWT and the estimated output from the OSE using the MECAL FEM model. Only accelerations are used as measurements in the OSE

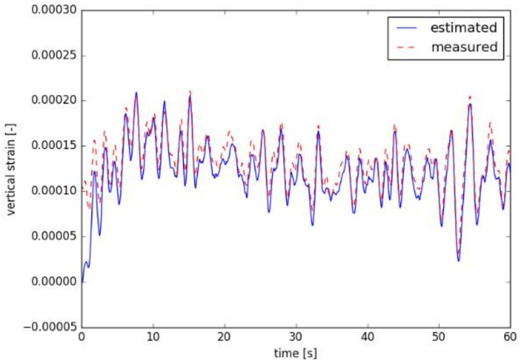

Figure 18 PHATAS model “measured” strains at Z_LAT=40.5 and the estimated output from the OSE using the MECAL FEM model. Both strains and accelerations are used as measurements in the OSE

3.5.4 *OSE Stability, Robustness and Redundancy*

As explained the OSE is a numerical method which converts a data set of field sensors on an OWT system into the most optimal shape in terms of its Eigen modes. This enables to establish e.g. stress cycles throughout the complete structure, even when no sensor is near some point of interest, e.g. some weld or connection. These stress cycles can then be used in e.g. a fatigue or structural integrity analyses.

However, when the field sensor data becomes compromised, the OSE still needs to produce “reasonably” good results. Therefore the sensitivity to several compromised data sets has been investigated. Examples of compromised data are added noise, failing of single sensors or structural offset in sensor data. Depending on the type of disturbance, either the OSE itself can become numerical unstable or the noise compromises the outcome to a certain extent.

To stabilize the OSE algorithm, it seems wise to use relative short time frames of several minutes in which the weather conditions do not change too much. The system was also tested for various levels of added noise. Up to 15% of noise, the OSE results is rather insensitive but for higher values this will have an effect on the resulting stress cycle and therefor for the e.g. fatigue lifetime prediction. In future work,further sensitivity analyses have to be performed to better understand the OSE performance in case sensors fail or structural offset occurs.

3.5.5 *Conclusions*

The Optimal State Estimator (OSE) is successfully applied to an offshore wind turbine using acceleration and strain measurements in the state estimation. It has been observed that it is necessary to include strain gauge data as measurements because accelerations alone lead to a drift in the displacement results. The inclusion of even a single strain gauge in the OSE eliminates drift and makes accurate estimation of displacement and displacement derived quantities (strains, stress) possible.

The OSE is faster than real-time for a 10 minute run at 100 Hz sample rate with 5 acceleration signals and 1 strain signal as measurements. This makes the OSE suitable for the intended field application.

4 WP 2: Effective and robust monitoring system design for a complete OWF

4.1 Introduction

Modern offshore wind farms are comprised of hundreds of wind turbines. Environmental conditions such as water depth and effective soil stiffness vary greatly throughout the wind farm. For this reason offshore support structures are designed per individual wind turbine location, ensuring the natural frequency support structure falls within the prescribed range as specified by the wind turbine manufacturer. Certain geometrical features such as diameter, length and wall thickness may be grouped in only a limited number of variations to ease the manufacturing process of the support structures and the wind turbine towers. For the Gemini offshore wind farm, all towers are constructed with equal dimensions, and there are only two types of transition piece. The monopiles are constructed in three distinctive diameters, while monopile length is unique for each location as a result of location specific soil parameters.

In order to make well informed decisions on lifetime extension or effective maintenance actions for heavily loaded structures, one would like to have an insight in the accumulated fatigue damage of all wind turbines and their support structures in the wind farm. However, instrumenting a support structure introduces significant costs, and it is simply not economically feasible to measure all wind turbines in the wind farm. In this work package, the insights in the structural behaviour of the limited number of instrumented wind turbines are used to estimate the fatigue accumulation for the (majority of) un-instrumented wind turbines in the field. ECN is applying its Fleet Leader methodology to achieve this goal, while TNO has put to use its knowledge on Bayesian networks to evaluate the uncertainty in the estimations of the un-instrumented wind turbines.

4.2 Effective monitoring of a complete OWF using the Fleet Leader methodology

The Fleet Leader concept has been introduced in the We@Sea project[5], and entails a methodology and software tool for estimating un-instrumented wind turbines in a wind farm. In this work package, the Fleet Leader methodology has been applied to estimate the fatigue load on support structures using wind turbine simulations from WP1 as training data (PHATAS and ANSYS). More details can be found in ECN-X—17-030 [6].

Fleet Leader methodology

In a wind farm, the SCADA parameters (operational parameters, e.g. power generation, yaw direction, pitch angle, etc.) are measured at all wind turbines. However, only a few wind turbines are selected as the ‘Fleet Leaders’, for which the mechanical loads are also measured. Using the measurements on these ‘Fleet Leader’ wind turbines, empirical relations are established between the load indicators

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[5] Obdam, T.S., Rademakers, L.W.M.M. and Braam, H. – Flight leader concept for wind farm load counting – final report, ECN-E—09-068, 2009.

[6] Hermans, K.W. and Hu, B. – Fleet Leader extrapolation for wind farm load estimation, ECN-X—17-030, 2017

of interest and the SCADA parameters. The empirical relations are established using machine learning and are stored in an artificial neural network.

Based on the empirical relations determined from the ‘Fleet Leaders’, the loads on all turbines in the farm can be estimated, using SCADA data of all wind turbines as an input.

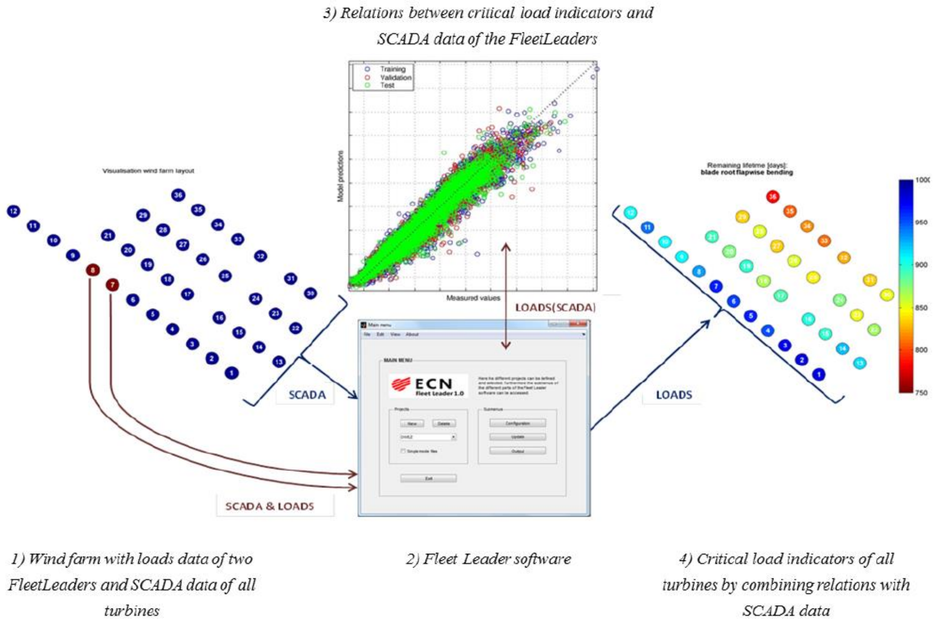

Figure 19 Fleet Leader methodology

Training data and results

The load cases of interest include global shear force, bending moment and hotspot stress in the support structure. The damage equivalent value (deql) was determined from the time series by applying the Rainflow cycle counting algorithm.

A selection of SCADA signals was made to act as an input for the un-instrumented turbines. The selection included the mean and standard deviation of generator power, rotor speed and pitch angle. This selection was sufficient to reach good estimation results for a validation set of the same turbine in slightly different conditions (empirical fitness $R^2 > 0.9$). Adding tower top (or nacelle) acceleration to the SCADA set does increase the R^2 value and limits the variance of the estimations.

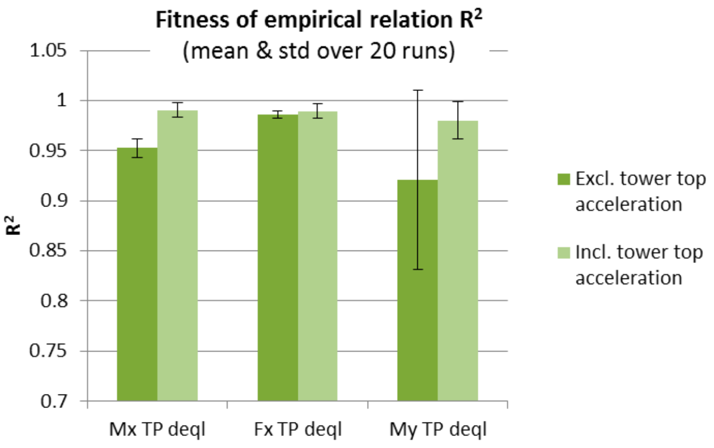

Figure 20 Comparison of empirical fitness R^2 with and without tower top acceleration (error bars equal ±standard deviation of estimation result)

Since all support structures have an unique geometry and are expected to behave differently, it is not sufficient to validate the estimation on the same structure. Therefore, two additional offshore wind turbines in Gemini have been modelled in PHATAS[7] that are believed to display significantly different structural behavior. The position of all the simulated turbines are shown in Figure 21.

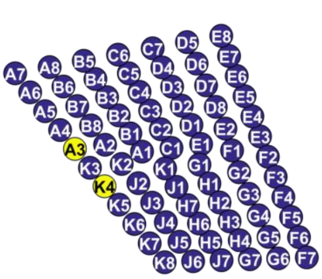

Figure 21 Position of simulated turbines in Gemini offshore wind farm

For each of the three modelled wind turbines, the empirical relations have been determined separately. One by one, the wind turbines act as the 'Fleet Leader' wind turbine (i.e. instrumented turbine), and the damage equivalent stress is determined for the other two wind turbines. The empirical fitness of the estimation (R^2) and percentage error of the accumulated fatigue is shown in Figure 22.

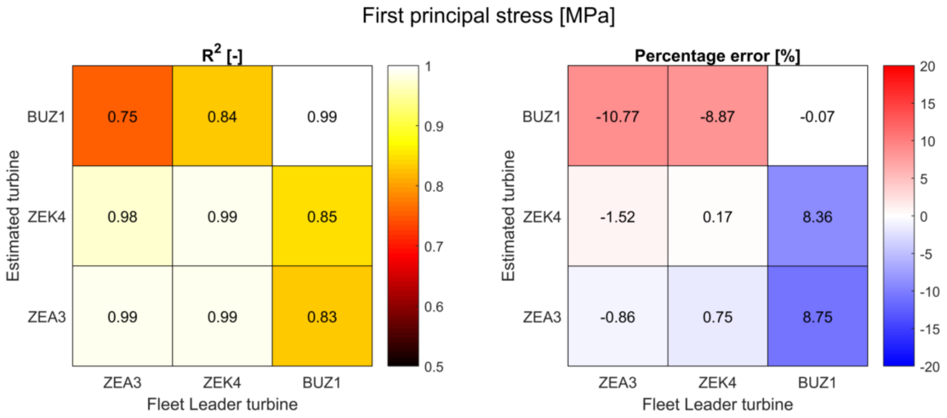

Figure 22 Empirical fitness and percentage error of accumulated hotspot stress for three distinctive Fleet Leader turbines

The estimation errors are clearly larger when the empirical relations of one wind turbine are used to estimate the response of another wind turbine. It is therefore recommended to instrument multiple Fleet Leader wind turbines and split the wind farm in clusters of similar structural behaviour.

Clustering

As a measure of structural behaviour, the resultant stress at the mudline for the serviceability limit state loadcase was chosen (denoted by $\sigma_{RES,ml,SLS}$) because this

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[7] Read more about this choice in ECN-X—17-030

was reported in the design documentation for all 150 foundations. An unsupervised clustering algorithm (K-means) was applied to find three distinct clusters as shown in Figure 23. The distribution of the clusters follows the distribution of monopile diameter. Hence it is recommended to instrument at least three wind turbines covering the three clusters to minimize the estimation error due to the range in structural behaviour. The position of the Fleet Leaders in the cluster can be chosen based on the deviation of $\sigma_{\mathrm{RES,ml,SLS}}$ from the cluster average (Figure 24), combined with an understanding of the wake effects. The wind turbines representing the clusters best are V2 (cluster 1), G6 (cluster 2), and A4 (cluster 3).

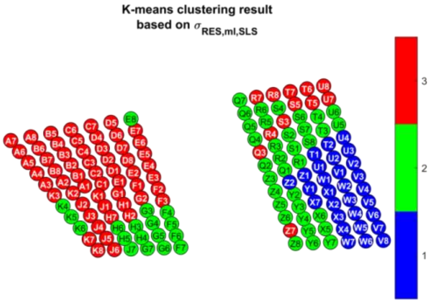

Figure 23 Cluster recommendation of structural behaviour

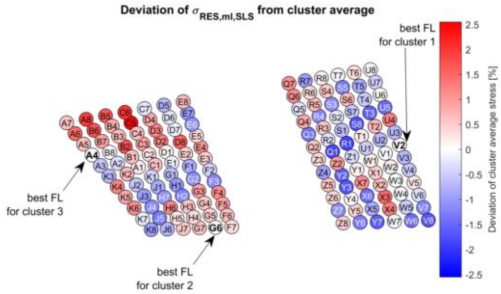

Figure 24 Deviation from cluster average

4.3 Evaluating uncertainty by means of Bayesian network modelling in MAC tool

Uncertainties are an inherent part of the estimation of fatigue accumulation and lifetime consumption. The TNO contribution in WP2 aims at developing a probabilistic model to quantify the different uncertainties. This model can thereafter provide the upper and lower confidence bound of the estimated variable and is brought together in the Multi-Asset Correlation (MAC) tool, further described in reference [8].

By means of a Bayesian network the relationships between the random variables can be determined. In a Bayesian network, a joint probability distribution function is created of a network of nodes. Each node is conditioned on its parent nodes by means of a conditional probability.

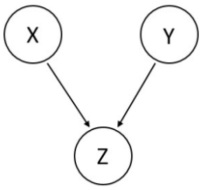

Figure 25 Node in Bayesian network

For the global load effects of fatigue equivalent shear force (Fx) and bending moment (Mx, My) at the transition piece, a Bayesian network structure is created as shown in Figure 26. For the first two principal hotspot stresses a slightly adjusted structure is

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[8] Allaix, D.L. and Courage, W.M.G. – Monitoring the fatigue damage accumulation in the support structure of offshore wind farms by using Bayesian networks, June 2017

chosen as given in Figure 27. Here the sideward acceleration (accY) at the tower top is omitted from the structure.

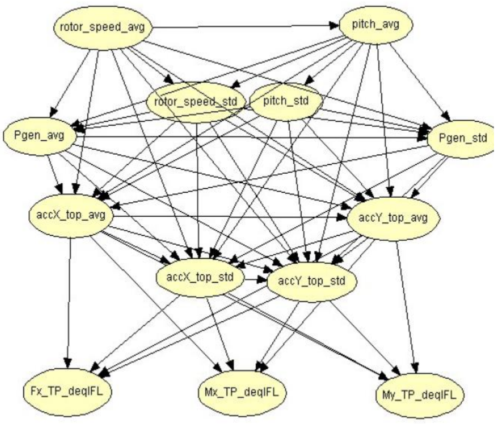

Figure 26 Bayesian network structure of global load effects

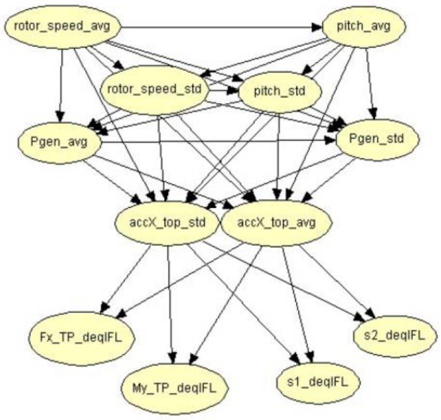

Figure 27 Bayesian network structure of hotspot stresses

The uncertainty of the Fleet Leader estimation (from SCADA to load effect) is introduced by means of a random variable θ.

$$\theta_{WT1-WT2} = \frac{F_{WT2,PHATAS}}{F_{WT2,FL(WT_1)}}$$ Equation 1

Results

The MAC tool was fed with the simulated datasets and Fleet Leader estimations, and the 95% confidence interval can be shown (Figure 28). Also a prediction of the future accumulation can be given based on the recorded relations (Figure 29).

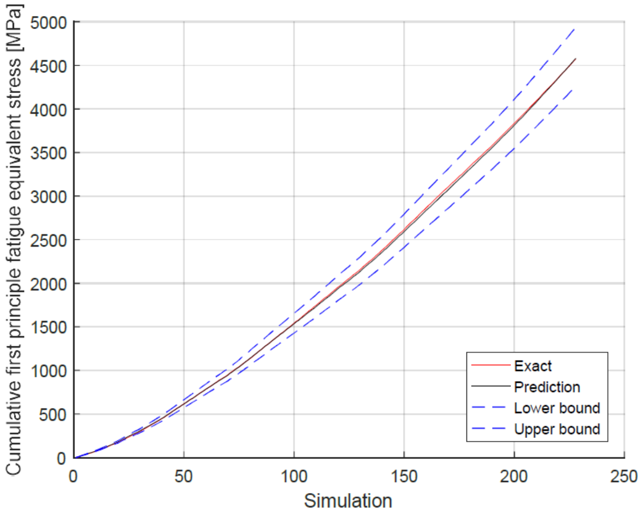

Figure 28 Prediction of fatigue equivalent hotspot stress for ZEA3 – wind turbine BUZ1 as Fleet Leader

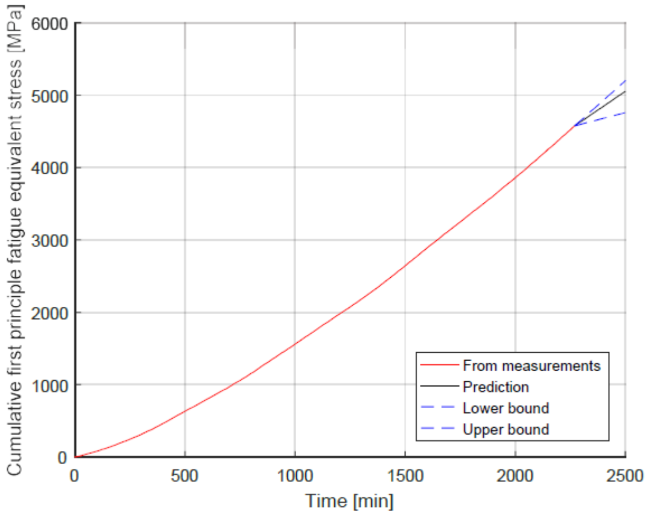

Figure 29 Prediction for fatigue equivalent hotspot stress for wind turbine BUZ1

4.4 Conclusion and recommendations

By understanding the relations of SCADA signals and load effects, the fatigue accumulation for un-instrumented wind turbines can be estimated. The Fleet Leader and MAC tool are together capable of estimating the fatigue on the un-instrumented wind turbines and evaluate the uncertainty on this estimation. The estimation accuracy does decline when the un-instrumented structure features different geometrical properties and environmental conditions such as water depth and soil stiffness. It is therefore recommended to instrument support structures of different geometry. Splitting the wind farm in three clusters based on pile diameter, and instrumenting at least one wind turbine in each of the clusters, ensures a good spread of the structural behaviour and minimized estimation errors. The effect of wakes on the choice of the instrumented wind turbine must still be investigated in more detail.

Furthermore, it is recommended to measure at least one year in order to capture sufficient data to train the models and ensure accurate predictions for a large range of conditions. Since the investigations focus on fatigue damage accumulation, and little fatigue failures are expected at the start of the operational lifetime, there are no objections to instrument later in the lifetime. Based on the established relations, the fatigue damage of the past can be estimated from the recorded SCADA signals of the past. Also the future accumulation can be predicted by extrapolating the recorded relations (though more uncertainty is introduced in a future prediction, compared to a hindcast based on recorded SCADA).

5 WP 4: Monitoring data analysis methodology

5.1 Introduction

The integration of the MONITOR tools is done via the back-end part of the MONITOR SHM system. This back-end part consists of a database system that was developed in-house by ECN, called WDMS (Wind Data Management System). The first section describes the functionality of the WDMS for the MONITOR SHM system application.

In the work performed in WP 4 the main data interpretation tools, which are the Optimal State Estimator (OSE), Fleet Leader and Multi-Asset Correlation (MAC) tools complemented by a Fatigue analysis module have been made fit for purpose for integration. The tools are not ready for operational use yet but have been proven in a basic setup with simple timeseries of simulated measurement data as input. The anticipated development steps in a next phase towards TRL 8 are listed. The results are described in the second section.

The final effort in WP 4 has been a measurement plan specifically written for a two years demonstration measurement campaign at the Gemini offshore wind farm.

5.2 Back-end of SHM tool

5.2.1 Introduction

The primary data analysis in MONITOR is done by the three analysis modules:

- The TNO Optimal State Estimator For Offshore Wind turbines
- The ECN Fleet Leader and
- The TNO Multi Asset Correlation tool.

Together the output of these modules will make an estimation of the wind turbine support structure fatigue accumulation and remaining lifetime. The estimation is based on the sequential application of the modules, e.g. the input of the optimal state estimator are measured or simulated signals are created and its output is input for the Fleet Leader of which its output is used by the MAC module. The modules are not restricted to input from other modules only. For example, the Fleet Leader module uses output of the OSE module and measured signal data as input.

To facilitate the interaction between the modules, we need a central container to store and retrieve data. To keep freedom of design we chose a client – server model setup. In this we can use the server to synchronize data storage and retrieval. And after analysing the options, the project partners have chosen a database system that was developed in-house by ECN, called WDMS (Wind Data Management System). Figure 30 provides the MONITOR SHM system overview including the modules, the WDMS and the user interface.

For years ECN has developed and used WDMS to store meteorology and wind turbine measurements in the form of time series. It’s build upon the PostgreSQL DBMS and is an ideal platform for this application. You will read more about WDMS in the next chapter.

So central in the data processing of MONITOR is the WDMS. Every module will read from and write to the WDMS. Next to storage we have the option to do data pre- and post processing tasks, if client applications require this. For example: generation of statistical aggregates if it's part of the next client input requirements. The approach gives all clients a uniform and central place to read intermediate or final results. In other words: the WDMS facilitates storage, synchronization primitives and logging to the clients.

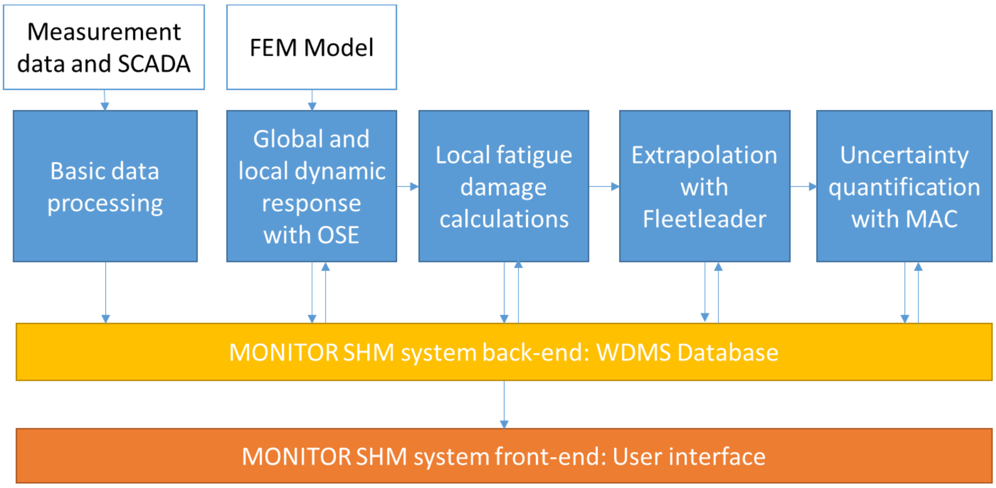

Figure 30: MONITOR SHM system overview

It is good practice to acquire and save measured data or signals as soon as possible without conversions or processing. This keeps the data acquisition process free of extra tasks, which is preferable as this is a time critical process. If the data acquisition system(s) keeps filtering and conversions to a minimum, we can use the WDMS to do this “offline”. If for example a filter was too strict we can “repair” the signal by updating the settings in WDMS and not in the data acquisition and no data was lost

5.2.2 *WDMS*

WDMS functionality

The ECN Wind Data Management System is designed to register and process signals measured during wind turbine test campaigns. The campaigns are run to fulfil the requirements to report PV and/or loads characteristics of wind turbines. The requirements bring a lot of standardized functions to the WDMS which can be used in MONITOR. Even so, the existing set of features or functions can be extended because of its flexible design.

The functionality of the WDMS can be summarized into the following functions:

- Basic FIR signal filtering,
- Signal validation mechanisms
- Signal processing, by using existing and creating pl/pgsql functions,
    - Combining signals,
    - Creating a pseudo signal,
    - Resampling signals,
- Event logging,
- Rain flow counting and

- Damage equivalent load calculation.

The WDMS has been in development at ECN for about 12 years and is at its fourth major release. It's a client - server package and ideal for this application. The server is based on PostgreSQL an open source DBMS and a number of database extensions developed by ECN. The client is a MS Windows application used to manage and view signals and other "objects" in a WDMS. The application is used to process data acquired during wind turbine prototype type testing measurement campaigns. These measurement campaigns run continuously for one but mostly multiple years, in some cases generating about 8GB per day.

Following the design decision in MONITOR, WDMS will be used for data processing only, unless the analysis doesn't fall in the scope of one of the analysis modules. WDMS is well suited for signal unit conversion with calibration values that can change over time, transformation into different coordinate systems, resample or filter signals, rain flow counting, calculating statistical aggregates or damage equivalent loads.

Data sources
In the operational setup the primary data source are the ECN data acquisition systems in the instrumented wind turbines and the SCADA data of all wind turbines. For the phase one proof of concept we will use the output of the aeroelastic code PHATAS to feed the MONITOR data processing.

After the first data is processed, the results are written to WDMS in the form of signals and available for the next analysis step. The WDMS will store all the intermediate results as "new" data. In case of "high" speed data post-processing (like calculation of statistical aggregates) this will be performed in WDMS if required.

Data driven processing
The data processing will be data driven (as opposed to in a timely interval), like the well know consumer – producer pattern. A three sequence approach will be followed: between the DAQ and OSE, OSE and FL and between FL and MAC. This means that the data acquisition system will drive the computations. This design comes natural as processing can only be done when data is available and "should" be done as soon as possible to get the highest bandwidth.

For data driven processing basically two synchronization primitives are needed, "wait" and "notify", both provided by the WDMS. Where the data acquisition is driven by time, e.g. a measurement recorded every ¼ of a second, a data driven process will start processing as soon it is notified that new data is available. Figure 31 presents the logical view of the wait-notify mechanism. In our case the OSE, Fleet Leader and MAC modules will be in a waiting state after their initialization until (per process) a notification is received that new data is available.

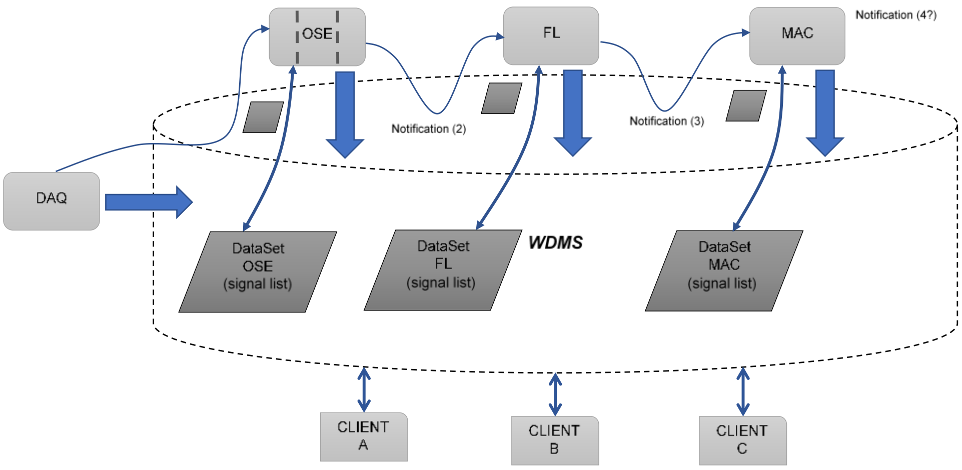

Figure 31: Logical view of the wait-notify mechanism

A typical processing “flow” will look as follows; as soon as the acquisition system has acquired enough data, it will be saved to file and the file will be registered at the WDMS. Files are typically stored in block lengths of 10 minutes. This action will be noticed by the OSE which will then “wake-up” and retrieve the 600 seconds of new data, in order to do its task. The practical time series length for the OSE is 600 seconds, so we can expect processing bursts at 600 second intervals. The OSE will write its result back to the WDMS and this will send a notification to be picked up by the next processing steps (i.e. the rainflow count and/or Fleet Leader module).

As the desired data resolution of the Fleet Leader module is one sample every 600 seconds, the module can ignore data notifications until “enough” data is processed by the OSE for it to find a sizeablel input size. The latter can be detected in a number of ways.

This sequence will continue until the MAC module has generated its results. At that moment users can find final results and intermediate results in the WDMS. Note that during data processing, the data acquisition system was working at the “background”, logging the measurements to file. Also note that if data processing of one burst of data lasts longer than 600 seconds, the processing will eventually run behind the data acquisition and run into problems.

The measured data comes from various sources, SCADA systems, data loggers and third party devices. To log them we use the ECN data acquisition software ‘DAISY’. This will “synchronize” and store all signals together in one HDF5 [6] binary file. This is an open file format readable by the WDMS and a lot of other software packages. Although the DAISY package is ready for usage, we can expect to expand the tool set with at least an acquisition process for the wind turbine SCADA data and possibly other third party devices.

Data storage and availability

Data is stored at two places in the system, in the file system as binary files and in the WDMS as table content. In essence both types of data are stored on the file system but their context is different. The data in the binary files are the measurements done by the data acquisition system and are the most valuable as all other data is derived from it.

The I/O part of the WDMS forms the interface to the data files that gives us the ability to request measurements at any time interval, thereby giving client programs virtually random access to signals but only if the data is valid. For this, WDMS stores availability information for every measurement. Preferably it's provided by the data acquisition system, or if supported by rule based validation or by manual post validation.

The data availability check(s) ensures that no invalid data is used in data processing, avoiding the possible introduction of skewness because of invalid data.

Any generated data from clients is usable in the same way as the measured data. Pseudo signals can have (other) pseudo signals as source. This allows the user to build elaborate signal trees, depending on measured data and global variables [5].

5.2.3 *Interface requirements*

The three applications accessing the WDMS are written in FORTRAN (OSE), Matlab (Fleet Leader, MAC) and C# (MAC). For these clients, interfaces are defined during the proof of concept development in the first stage of the MONITOR project. Successful application shows the feasibility of the path taken. Appendix A lists the available functions and their usage. The interfaces are designed for usage by their target client although any client application can make use of it.

5.2.4 *Running the software*

The above analysis tools are developed by ECN and TNO. The goal is to run all analysis modules and a single WDMS database on one server although there is flexibility to scale up to multiple servers. Only when the computational effort of the real life demonstrator gets too large, the decision could be made to scale up in two steps by first offloading the PostgreSQL data to a dedicated server and if even more processing capacity is needed the modules can be installed on their own system.

At the time of writing, there are some difficulties in running all the modules on a single system:

- TNO and ECN developers cannot yet access a computer on the network of the other party
- The MAC tool makes use of a commercial software, for which only TNO has a license.
- Fleet Leader needs manual interaction in the GUI to process the data.
- Also the OSE should be accessible to the TNO developers

It makes sense to run the proof of concept demonstration on a PC at TNO.

5.2.5 *SHM tool Back-end Recommendations*

The proof of concept shows the way forward. The data process structure will not change much in a live application so although the demonstrator uses simulation data the data processing chain is solid. The glue between the processes is the WDMS that is in active use and has since long proven its worth. Using the stable WDMS saves the project from building a communication framework and gives a place for tasks outside the scope of the three major processes. This stable measurement platform thus increases the feasibility of the software in the MONITOR project.

The tasks at hand consist of the following steps:

- Update of OSE, Fleet Leader and MAC tool to store and retrieve of data from WDMS,
- Validate HDF5 usage WDMS,
- Build and validate DAISY process(es);
    - HDF5 writer (validation),
    - SCADA reader for “unknown” wind turbine interface - OPC connectivity?! (build),
    - Data acquisition (validation),
    - Update/create manual DAISY,
- Update developers manual WDMS.

5.3 Data interpretation models

In the below paragraphs the OSE, Fleet Leader and MAC tools are discussed by an overview of the steps toward field application and full functionality. The fatigue tool module is introduced via a general description and a summary of the technical requirements.

5.3.1 Required Actions to full functionality and estimate of complexity for OSE

Table 1: Actions to full functionality and estimate of complexity for OSE

Action	Relevance	Complexity
Tests OSE: Robustness for 2 loading directions Influence of measurement noise on fatigue result	Confidence for field application and insight in sensitivity of the whole tool chain	low
Automatic adaptation of OSE uncertainty matrices depending on input signals	Increased robustness for different wind/wave conditions in the field. It is expected that the OSE is more sensitive for lower wind loads. Not performing this action can lead to erroneous results for the idle to low wind conditions	medium
FEM model field wind turbine and extraction data needed by OSE	Without field wind turbine FEM model the OSE cannot function	medium
Implementation FEM specific data in WDMS	Not needed for single field wind turbine experiment, needed for ease of use in practice	medium
Multiple wind turbines OSE processing	Not needed for single field wind turbine experiment, but for evaluation of multiple wind turbines, or application of the OSE for an entire field	high

5.3.2 Actions to full functionality and estimate of complexity for Fleet Leader

Table 2: Actions to full functionality and estimate of complexity for Fleet Leader

Action	Result	Relevance	Complexity
Prepare for real life SCADA input	A functional link to SCADA system of 150 wind turbines	High	Medium
Prepare for continuous dataflow	A data driven updating method (using ‘wait’ and ‘notify’)	Medium (can act as post-processing and run independently from data acquisition)	Medium
Update validation method	Different way of assessing the validity of FL estimations	Medium	Medium
Change FL estimations based on a priori knowledge of different support structure behaviour	More accurate estimations for un-instrumented wind turbines with varying support structure	Medium (will drastically improve estimations for other clusters when small number of instrumented wind turbines are chosen)	High (adjustments to training algorithm at its core)

5.3.3 Actions to full functionality and estimate of complexity for MAC tool

Table 3: Actions to full functionality and estimate of complexity for MAC tool

Action	Result	Relevance	Complexity
Prepare for real SCADA input	A functional link to SCADA system of 150 wind turbines	High	Medium
Prepare for continuous dataflow	Capability of updating prediction as soon as data are available	Medium	Medium
Change of fatigue damage indicator	Prediction of the fatigue consumption according to design standards	High	Low
Validation of the tool based on real data	Assessment of the validity of the predictions of fatigue	High	Medium

	damage in the wind farm		

5.3.4 Fatigue tool-module

General description

In the framework of the MONITOR SHM-methodology the function of the fatigue tool module is to translate the dynamic response at fatigue sensitive details in the support structure into a structural health indicator. In this application the structural health indicator is the predicted development of fatigue damage in the support structure.

The dynamic response at the considered fatigue details in the support structure (i.e. the input for the fatigue tool module) can be defined as the time varying section forces, stresses or strains near the considered details. These are either obtained through direct measurement (in case strain gauges are located in the close vicinity of the considered detail) or by application of the OSE-tool (for details in the monopile were no strain gauges can be installed). Dependent on the type of fatigue detail and the method to account for potential stress concentration effects due to the local geometry near the fatigue detail, the stress or strain input for the fatigue tool module can either be defined as nominal -or hotspot stresses or strains.

The output of the fatigue tool module is the development of the fatigue damage or crack growth for a time span equal to the duration of the input time traces (e.g. 10 minutes). Within the MONITOR SHM-framework the output of the fatigue tool module is used to as input for the Fleet Leader -and the MAC-tool. Subsequently these tools extrapolate the results from the wind turbines with a response measurement system to the non-measured wind turbines within the wind farm and provide an updated fatigue life prediction per considered detail including a bandwidth to account for remaining uncertainties.

Functional and technical requirements

The first step in the application of the fatigue tool module is to read/import the input dynamic response from the WDMS-database.

The fatigue tool module then needs to convert the dynamic response to a fatigue load that can be used for calculation of the fatigue damage or crack growth. Usually this is defined in terms of the stress range spectrum at the considered detail. This step involves the application of any conversion factor that is needed to go from dynamic response to fatigue load required for the calculation of the fatigue damage or crack growth (e.g. the section modulus to go from bending moment to stresses, the Youngs-modulus to go from strains to stresses and/or any stress concentration factor). After application of this conversion factor the time trace of the relevant stresses needs to be converted into a stress range spectrum. This can be done by means of a cycle counting method like rain-flow counting.

After the stress range spectrum is obtained a fatigue damage law needs to be applied to convert the fatigue load into fatigue damage or crack growth prediction. Two main options are available for this, an S/N curve approach or a fracture mechanics approach. The first is widely used in design practice of offshore and civil structures, and gives information when the fatigue damage exceeds a certain failure criterion. The basis for this method are laboratory fatigue experiments on scaled test pieces.

A fracture mechanics approach is more complex but also provides information about the expected crack size. This method can be useful in combination with crack condition inspections.

The last step of the fatigue module is to write/export the results to the WDMS-database. It is very important that the results from the fatigue tool module are correctly labeled with the corresponding metocean and operational condition. It is assumed that correct data labeling is arranged by the data-flow management in the WDMS-database.

Below two sets of technical requirements are derived. The first set the minimum required for the Gemini Windfarm field demonstrator. The second includes a list of future extensions, including a fracture mechanics approach.

Minimal required for field demonstrator

- Create an import/export interface between WDMS-database and fatigue tool module
- Include possibility to apply generic conversion factor (e.g. partial material factor)
- Include possibility to apply detail specific conversion factor (e.g. section modus, or SCF)
- Include application of an accurate and time efficient cycle counting algorithm
- Include application of S/N curve fatigue damage calculation
- Configure the fatigue tool module for application within field demonstrator
    - Derive and apply input parameters for selected fatigue details
    - Derive and apply input parameters for pseudo[9] fatigue details

Potential future extensions of fatigue tool module

- Include option to choose between S/N curve or fracture mechanics approach
    - Add fracture mechanics approach to the module
    - Include input parameters for fracture mechanics
    - Include possibility for inspection results as input
- Replace deterministic by probabilistic approach
    - Include probabilistic approach on fatigue resistance side as well
    - Include input parameters for probabilistic approach (pdf-functions)

5.4 Measurement system specifications

A measurement plan has been specifically written for a two years demonstration measurement campaign at the Gemini offshore wind farm. For this validation campaign, three wind turbines will be instrumented: two Fleet Leader wind turbines and one validator wind turbine.

A concept design “Gemini Field Demonstrator” has been used as input for this measurement plan, providing the type and number of sensors and their locations.

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[9] This is needed to account for distinctive properties (e.g. wall thickness, SCF, etc.) between measured and non-measured wind turbines in the Fleet Leader training process.

The measurement plan focuses on how the measurement system should look like based on this input, addressing the following items:

- description of the Gemini offshore wind farm;
- signal lists;
- the instrumentation to be installed, including specifications of sensors and their locations;
- calibration;
- description of the measurement network;
- description of the measurement system;

ECN Wind Energy is ISO17025 accredited and a recognized IECRE Test Laboratory among others for mechanical load measurements according to IEC 61400-13 [1]. The experiences with traceable, repeatable, etc. measurements following ECN's quality system are incorporated in the measurement plan.

6 WP 5: Structural Health Monitoring-tool demonstration

6.1 Introduction

The MONITOR SHM system is developed with a back-end and a front-end part. The SHM front-end includes the means to present the measured and processed results from the MONITOR methodology to a wider group of stakeholders. This stakeholders group (called 'users') is comprised of the wind farm operator, wind turbine- and support structure manufacturers, wind farm owner and researchers.

During the execution of the project multiple interviews have taken place to identify the needs and requirements from these future users. With the draft version of the front-end a remote web session has been organized to demonstrate the current state of the design.

In this section first the list of requirements is discussed. Next the current status of the design is presented, followed by an overview of the used development tools and potential tools for the final design. Finally the anticipated further development of the MONITOR SHM tool front-end is discussed.

6.2 List of requirements

The list of requirements for the frontend of the SHM tool has been established based on discussions during the project meetings and on a remote demonstration session with the MONITOR consortium partners.

1. Implementation
    a. Accessible to project partners with a web-interface
    b. Scalable to a larger number of sensors, instrumented wind turbines, or number of wind farms
    c. Instantaneous/Fast access of overview plots, for sampled data small delay is allowed
2. Design and presentation of output
    a. Plot accumulated fatigue damage or remaining lifetime of all 150 wind turbines
    b. Show anomalies in the data
    c. Plot accumulation of fatigue damage over time including lower and upper bound confidence interval and comparison to estimated fatigue consumption (based on either the design documentation or the recalculated values with the actuals)
    d. Plot the measured site conditions, compared with the assumed conditions for the design
    e. Present statistics overview
    f. Plot of statistics or raw data of selected signals as development over time, allow multiple plots for comparison
3. Accessibility of the data
    a. Graphical representation of the data in the front-end
    b. Export data of measured signals and output of analysis modules
    c. Provide periodic report

The following paragraphs contain more detailed specifications derived from the list of requirements.

6.2.1 *Design of the interface and presentation of output*

The interface design contains three different tabs to allow presentation of all relevant output at different levels:

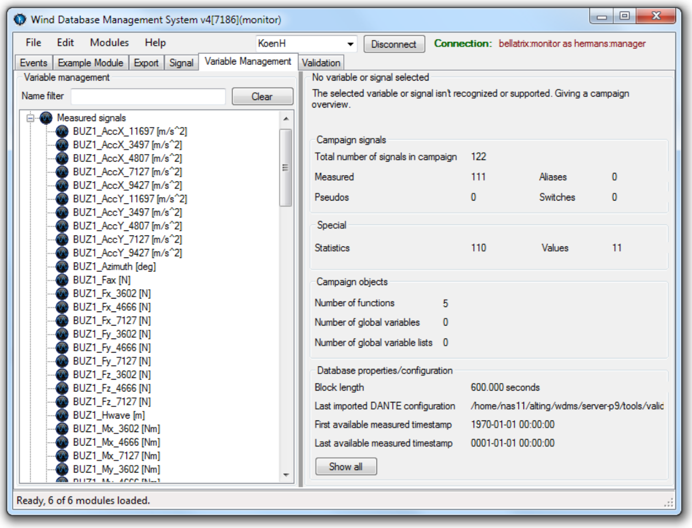
1. Map tab, which provides an overview of all the wind turbines in the wind farm. In this tab, colored circles will be used to indicate the selected property, such as fatigue life consumption or anomaly.
2. Plot tab, which shows the fatigue life, statistics or selected signals
3. Report tab, which can be used to produce periodic reports

Selection of the item of interest goes through a series of selection boxes, from ‘wind farm’ -> ‘wind turbine’ -> ‘signal’ and ‘location’.
Given the large number of wind turbines in a wind farm, the selection of the wind turbine can be two level (string and number). Alternatively, the Map tab can be made interactive to select the wind turbine of interest from there.

6.2.2 *Accessibility*

With the plot functionality, most of the measured and post-processed data stored in the central database will be accessible to the users from within the GUI. The user can export the selected signals to standard data format. An option is foreseen to generate a standard report for a specified (daily/weekly/monthly) period.

Developers will also get direct access to the data in the WDMS database by means of a set of log-in details and the latest WDMS client, shown in Figure 32.



KoenH

Connection: bellatrix:monitor as hermans:manager

Measured signals
- BUZ1_AccX_11697 [m/s^2]
- BUZ1_AccX_3497 [m/s^2]
- BUZ1_AccX_4807 [m/s^2]
- BUZ1_AccX_7127 [m/s^2]
- BUZ1_AccX_9427 [m/s^2]
- BUZ1_AccY_11697 [m/s^2]
- BUZ1_AccY_3497 [m/s^2]
- BUZ1_AccY_4807 [m/s^2]
- BUZ1_AccY_7127 [m/s^2]
- BUZ1_AccY_9427 [m/s^2]
- BUZ1_Azimuth [deg]
- BUZ1_Fax [N]
- BUZ1_Fx_3602 [N]
- BUZ1_Fx_4666 [N]
- BUZ1_Fx_7127 [N]
- BUZ1_Fy_3602 [N]
- BUZ1_Fy_4666 [N]
- BUZ1_Fy_7127 [N]
- BUZ1_Fz_3602 [N]
- BUZ1_Fz_4666 [N]
- BUZ1_Fz_7127 [N]
- BUZ1_Hwave [m]
- BUZ1_Mx_3602 [Nm]
- BUZ1_Mx_4666 [Nm]
- BUZ1_Mx_7127 [Nm]
- BUZ1_My_3602 [Nm]

No variable or signal selected

The selected variable or signal isn't recognized or supported. Giving a campaign overview.

Campaign signals

Total number of signals in campaign	122		
Measured	111	Aliases	0
Pseudos	0	Switches	0

Special

Statistics	110	Values	11

Campaign objects

Number of functions	5
Number of global variables	0
Number of global variable lists	0

Database properties/configuration

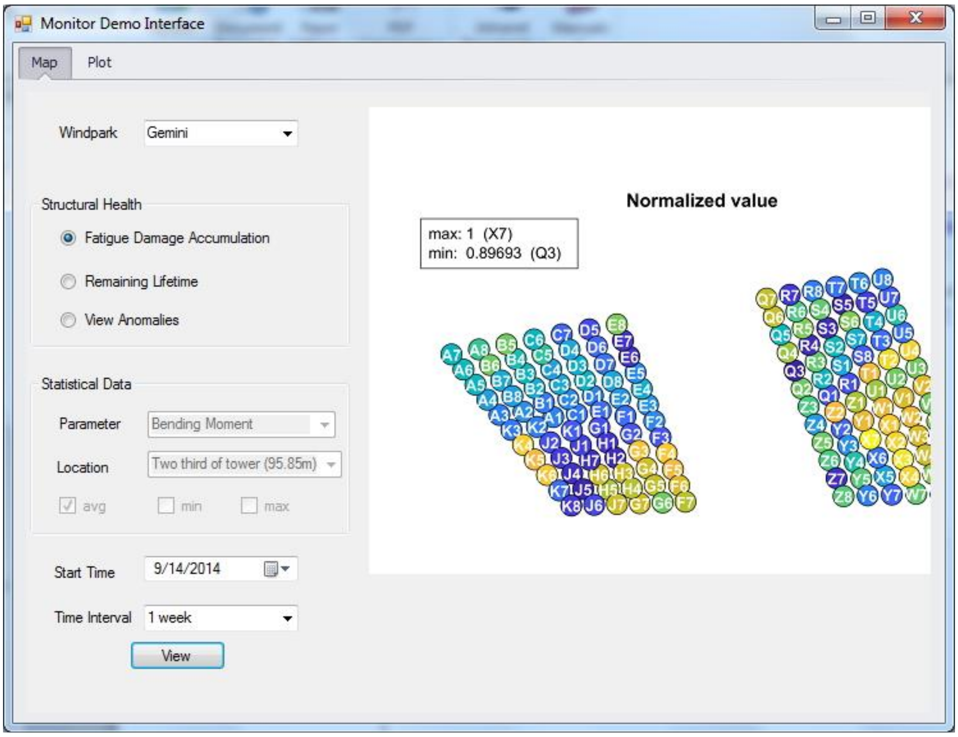
Block length	600.000 seconds
Last imported DANTE configuration	/home/nas11/alting/wdms/server-p9/tools/vali
First available measured timestamp	1970-01-01 00:00:00
Last available measured timestamp	0001-01-01 00:00:00

Ready, 6 of 6 modules loaded.

Figure 32: WDMS client (for access to back-end database)

6.3 Current status of the design

This section describes the current status of the design of the MONITOR tool front-end, reflectingon the list of requirements. This version has been created for the purpose of demonstration, feedback from the users and evaluation of different options.



Windpark: Gemini

Structural Health
- ● Fatigue Damage Accumulation
- ○ Remaining Lifetime
- ○ View Anomalies

Statistical Data
- Parameter: Bending Moment
- Location: Two third of tower (95.85m)
- ☑ avg ☐ min ☐ max

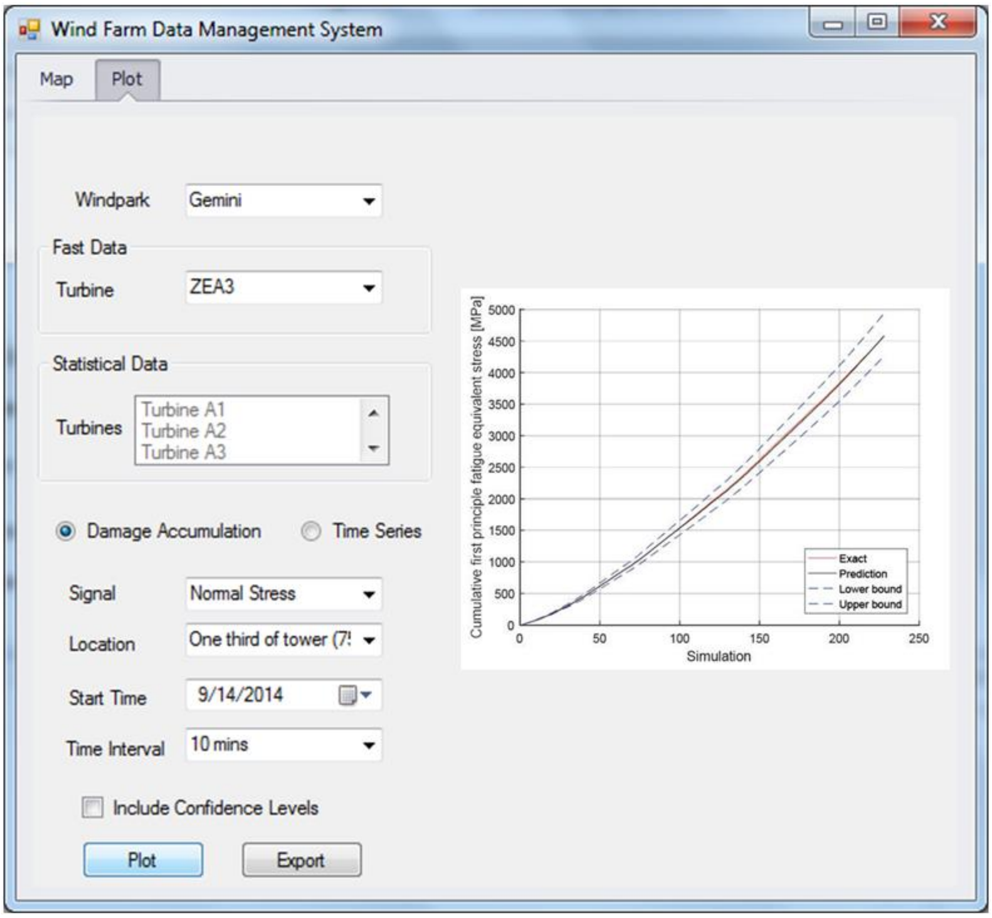
Start Time: 9/14/2014

Time Interval: 1 week

max: 1 (X7)
min: 0.89693 (Q3)

Figure 33 - Map tab of the front-end to give an overview of the complete wind farm

Figure 33 shows a print-screen of the start screen. This start screen provides an overview of the current status of the wind farm on the ‘Map’ tab. In the selection menu on the left several items can be chosen to be shown on the Map tab. Signal levels and anomalies are indicated with colored circles representing the individual wind turbines.



Windpark: Gemini

Turbine: ZEA3

Turbines: Turbine A1, Turbine A2, Turbine A3

● Damage Accumulation ○ Time Series

Signal: Normal Stress

Location: One third of tower (7!

Start Time: 9/14/2014

Time Interval: 10 mins

☐ Include Confidence Levels

Figure 34 - Plot tab of the front-end to show development of properties over time

Figure 34 shows a print screen of the ‘Plot’ tab. In this tab, time traces and statistics of measured signals (such as wind turbine rotor speed) and output data from the analysis modules (such as damage equivalent fatigue load in the transition piece) can be shown. Again on the left a menu can be found for selection of the property of interest.

The following items are listed for further improvement/development:

- Multiple plots, interactive legend to select statistics/signal type
- Interactive Map to select wind turbine of interest
- Statistics overview
- Specification of the periodic report generated by the ‘Report’ tab

The items not realized in the first phase of MONITOR will be documented as future work.

6.4 Tools for front-end development

The current demonstration version has been created with Microsoft Visual Basic. This tool is very useful to quickly get a graphical user interface running and test/show various options.

For the final MONITOR front-end, a web-based version is foreseen. From a brief survey on potential development tools, DevExpress has been selected to be a suitable tool for development of the web-based front-end. It has the required features and has been used in previous work. For now, it is taken as the preferred solution, but it is advised to reconsider this when starting the development of the production version.

6.5 Further development of the MONITOR SHM tool front-end

When considering the further development of the SHM tool front-end, two phases should to be distinguished:

1. Development
    - The basic features and design have been identified and partially implemented, no show stoppers are foreseen at the moment. The step to web-based version will reduce the complexity of data access of the individual users, although security needs to be addressed properly.
    - Taking the demonstration version as starting point, a first time usage (validation) campaign ready version of the front-end can be available within two months.
2. Usage
    - Some maintenance might be required during usage (e.g. when database properties change), but estimated effort is very limited.
    - The actual usage of the front-end as a web interface is relatively easy: a regular pc will be sufficient to access the front-end web application.

7 Overall project conclusions

The main goal of the MONITOR consortium, consisting of Gemini Windfarm, Van Oord, Mecal, Damen Verolme Rotterdam, ECN and TNO, was to develop and validate a robust and effective offshore wind farm support structure SHM system, including the underlying methodologies to interpret the collected data. Such a system enables a wind farm operator to know the structural health of all support structures within an offshore wind farm. The MONITOR project Phase 1 started in November 2015 and finished in March 2018. The project was a successful cooperation and has resulted in the initial design of the MONITOR SHM system including the underlying tools.

At the conclusion of the MONITOR project the OSE and MAC tools from TNO and the Fleet Leader tool from ECN have reached a Technology Readiness Level, such that they can be implemented in a demonstrator structural health monitoring system (TRL 6). The activities in the project have converged to a SHM demonstrator tool, including a functional SHM database and user-interface tool. The database consists of the raw measurement data, the processed measurement data, results of the OSE, Fleet Leader and MAC calculations and other relevant information that is required to know the structural health of all support structures within an offshore wind farm.

The combination of the OSE, Fleet Leader and MAC tools in one system provides not only data assimilation (via the OSE), but also a data extrapolation for monitoring structures in a cluster (Fleet Leader) and a calculation of the reliability and accuracy of the results (MAC). The three tools are comparable to the international state-of-the-art, and connect to existing research very well. In particular the Fleet Leader and MAC tool will distinguish the integrated system from market alternatives. The resulting MONITOR support structure monitoring system is a unique integrated system with demonstrated tools that will enable a wind farm operator to know the structural health of multiple support structures within an offshore wind farm, with a target reliability and accuracy.

For further enquiries regarding the MONITOR support structure monitoring system please contact TNO:

Koen Hermans
koen.hermans@tno.nl
+31 888 663 147

Sjoerd van der Putten
sjoerd.vanderputten@tno.nl
+31 888 662 081

8 List of reports and publications

8.1 Project Reports

Table 4: Project reports (not public)

Deliverable	**Authors**	**Report Title**	**Date**
WP1.D1: Report: ECN simulations results	K.W. Hermans	Phatas Model JIP Monitor wind turbine	March 2017
WP1.D2: Report: Mecal results part 1/2	Martin Gemen	FE modelling methodology specification for WP1 of the MONITOR JIP	May 2016
WP1.D2: Report: Mecal results part 2/2	Anoop Singh	MONITOR JIP WP1 FE modelling report	July 2016
WP1.D3: Report: OSE elaboration and analyses part 1/2	J.P. Pruiksma	Optimal State Estimator for Offshore Wind Turbines	June 2017
WP1.D3: Report: OSE elaboration and analyses part 2/2	E.C. Dillingh	Optimal State Estimator Stability, Robustness and Redundancy for the use in Offshore Wind Turbines	September 2017
WP1.D4: Damen Verolme Rotterdam results	Y. Salman	Structural dynamics phenomena, sensor reading sampling frequency and minimum number of modes used in OSE for jackets	January 2008
WP1.D5: Final Report: Effective and robust monitoring system design for a single wind turbine support structure	S. van der Putten, K.W. Hermans	MONITOR PROJECT PHASE 1 WP1-5 SUMMARY	October 2018
WP2.D1: Report: Validation of FL for sub-structures- Concept and results	K.W. Hermans, B. Hu	Fleet Leader extrapolation for wind farm load estimation	March 2017
WP2.D2: Report: FL model for local load indicators - Concept and results	K.W. Hermans, B. Hu	Fleet Leader extrapolation for wind farm load estimation	March 2017
WP2.D3: Final Report: Effective and robust sub-structure monitoring system design for a complete WF	S. van der Putten, K.W. Hermans	MONITOR PROJECT PHASE 1 WP1-5 SUMMARY	October 2018
WP2.D4: Report: TNO's Bayesian model for uncertainty quantification	Dr. Ir. D.L. Allaix, Dr. Ir. W.M.G. Courage	Monitoring the fatigue damage accumulation in the support structure of offshore wind farms by using Bayesian networks	June 2017
WP3.1 : Report: Structural Health Monitoring methodology	J.H. Paulissen	JIP MONITOR PHASE 1 - Structural Health Monitoring methodology MONITOR project - WP3.1	December 2017
WP3.2: Report: Concept design Gemini Field Demonstrator	J.H. Paulissen	JIP MONITOR PHASE 1 - WP3.2 Concept design Gemini demonstrator	December 2017

WP4.D1: Report: Data analysis methodology and technical requirements Gemini demonstrator	G. Bergman	Data analysis methodology and technical requirements Gemini demonstrator	December 2017
WP4.D2: Overall report: Data analysis methodology and technical requirements Gemini demonstrator	S. van der Putten	MONITOR Project WP4: Data analysis methodology and technical requirements Gemini demonstrator	February 2018
WP1-5: overall summary	S. van der Putten, K.W. Hermans	MONITOR PROJECT PHASE 1 WP1-5 SUMMARY	October 2018
Detailed workplan WP1-2	S. van der Putten	Detailed Work Plan for Phase 1 of the MONITOR JIP	January 2016
Detailed workplan WP3-5	J.H. Paulissen	JIP MONITOR WP3-5 detailed workplan v2017	December 2016

8.2 Project media attention and publications

- Monitoring fatigue accumulation of offshore wind support structures, K.W. Hermans, Offshore wind foundations IQPC conference, 4 - 6 July 2017, Bremen, Germany
- MONITOR JIP Begins Development of Structural Health Monitoring System for Offshore Wind Farms, S. van der Putten, TNO and ECN websites, 14 June 2016
- Monitor JIP Consortium Creating Structural Health Monitoring System for Offshore Wind Farms, http://www.offshorewind.biz/ and http://www.windtech-international.com/ among others, 15-25 June 2016

9 Signature

Delft, 11-10-2018

TNO

S. van der Putten, MSc.
Author

ECN part of TNO

Ing. P.M.J. Warnaar
Senior Business Developer - reviewer

TNO

Dr. T.G.H. Basten
Head of department Structural Dynamics