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Literature review on offshore substructure lifetime assessment and the potential of data-driven methodologies.

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1 Introduction

While the first offshore wind farms in Belgium are in the early phase of their design lifetime[1], the offshore wind industry is increasing its focus on the opportunities for lifetime extension.
The lifetime assessment of offshore wind farms based on supervisory control and data acquisition (SCADA) data has been subject of earlier research at OWI-lab. [1] The current research work is a continuation of this work within our recently approved Supersized 4.0 project.

The Supersized 4.0[2] project [2] will focus on monopile substructures for +7MW wind turbines and supplements the SCADA data with structural health monitoring (SHM) data, including the use of novel SHM technology such as IoT sensors and advanced data-analysis, supplemented with relevant project specific information from design, construction and operations and maintenance (O&M) phases. The present work, and one of the main deliverables of Supersized 4.0, has the objective to respond this increasing interest from the industry by developing a certifiable data-driven lifetime extension methodology and corresponding toolbox for the substructure.

While this research is based on a collaboration of the Belgian offshore wind industry and academic institutes, its relevance and application is industry wide.

A broad literature review has been initiated to explore current practices and ongoing research in the domain of lifetime assessment and monitoring of offshore foundations. The literature review allows to identify the opportunities for improvement to the current practices. These improvements can be taken into account as targets for the present research within Supersized 4.0.

2 Literature review

The nature of this research requires a thorough literature review. In the first 3 months of research, the literature review focused on the relevant offshore wind industry standards and guidelines, exploration of ongoing research projects and industry applications in view of lifetime.

[1] In Belgium the offshore wind has been operational since 2008, C-Power phase 1. The first wind farm with relevance for the current research has been commissioned in 2018.

[2] Supersized 4.0 research project concerning “Smart O&M for a fleet of supersized wind turbines in an industry 4.0 context”.

2.1 Literature in relation to the evaluation of lifetime for extension of lifetime.

First source of literature, when aiming for a certifiable method for the lifetime assessment of offshore structures, are the publications from regulatory institutes, also referred to as certification authorities, such as DNVGL, BV, UL, TÜV Süd [3-4,12, 13]. The referenced guidelines published by certification authorities provide in essence similar recommendations. The guidelines' approach for lifetime assessment is currently based on an analytical and practical part. The essence of the approach is to update the input – and design methods - of the analytical or numerical models in order to re-evaluate the (certified) design. The updated inputs are a result of in-depth design and as-built documentation reviews, updated environmental and operating conditions (EOC) and observations from periodic inspections. In relation to the subject of this research the guidelines lack a data-driven lifetime assessment approach, yet do not exclude the use of condition monitoring for the lifetime assessment. The legal obligations, market expectations and requirements for certification for extended lifetime are not conclusive.

The industry's focus concerning lifetime, has been mainly on the wind turbine generator and components (such as bearings, blades, generator components) to achieve optimization of power production and lifetime assessment of these turbine components. This includes the monitoring and assessment of performance and condition data (typically collected in the SCADA system). There is a potential spill-over between an industry-wide recognized data-driven lifetime assessment of turbine components and substructure and therefor this industry practice is – and will in the future be - consulted. A near future publication which could provide valuable insights in best-practices is the IEC61400-28 standard. [11-18-30]

In relation to the substructure, the existing model-driven engineering tools are being further exploited to find a response to the industry's requests in relation to lifetime. Examples of these tools are the use of detailed finite element analysis (FEA) and (true) digital twins of the structure. The supplementary use of structural health monitoring data in these model-driven approaches is getting increased attention. [6-7-8] While the data-driven approach as independent, yet complementary tool to model-driven approaches, remains an area for exploration and therefor the subject of this research.

In 2019 The Carbon Trust and its Offshore Wind Accelerator (OWA) partners ordered a desktop study which is collecting the state-of-the-art concerning structural health monitoring and lifetime assessment in view of lifetime extension of offshore wind substructures. The result is a comprehensive publication[3], including the review of current - and future innovative - technologies, applicable standards, analysis methods and concludes with a holistic lifetime extension framework. The framework – as is the entire document – is written from the perspective of the wind farm owner. Purpose is that it can be consulted by OWA partners' asset engineers and managers to support them in the process of data-collection, re-assessing the remaining lifetime of the substructure and the commercial evaluation thereof. [5] Important to note is that the publication is not linked to regulations or standards and thereby a non-binding document.

In comparison to the current practices and lifetime extension framework explained in [5], the research within Supersized 4.0 aims at truly data-driven approach, centralizing the use of measured EOC and structural conditions, with a reduction of the retrospective in-depth documentation review. The publication [5] is a valuable source of information. Especially to benchmark our data-driven lifetime assessment methodology within Supersized 4.0 - with the current industry perception of the topic - such our research is recognizable for the industry.

In parallel with The Carbon Trust, several research and development projects on the topic of lifetime assessment and research domains related to lifetime consumption such as corrosion, fatigue, soil conditions are ongoing. (see Table 1) To the knowledge of the author at time of writing this extended abstract the following research projects are considered relevant to follow, yet not coincidental nor

[3] The contents of this publication [5] may not be provided to any third parties. The author of this abstract could consult the publications since the Vrije Universiteit Brussel is one of the publishing contractors on behalf of The Carbon Trust.

conflicting, in relation to the subject of the research within Supersized 4.0. The below listed projects are in essence related to either optimizations in the operations and maintenance phase by a data-driven decision tool (short term), investigating the lifetime of wind turbine generator components or focusing on a supporting research domain related to lifetime consumption. Within Supersized the objective is to liaise with peer-research projects as listed below.

Table 1: Overview relevant peer R&D projects.
A further description of the below research projects can be consulted in the references.

Project name	Brief description	References
LifeWind	Focus of study is the wind turbine generator and components. Objective is to demonstrate procedures, relying on all available data incl. SHM, that can quantify the risk of failure, the remaining structural reliability and the maintenance costs upon extending the life of operational (in Denmark) wind turbines nearing their end of certified life. LifeWind has made recommendations for the IEC [11] technical specification on Lifetime extension which is expected in 2021. 2017-2020	[5] [18] [30]
IEA Task 42	The coordination of international research activities towards the assessment of remaining operational life of wind turbines near the end of the certified design life and identification of strategies for extending the useful life. No publications encountered. 2019-2022	[31]
H2020 AWESOME	Particular interest in workpackage 8 in relation to SHM for wind turbine extended life operation. Resulting in publication of the doctoral thesis by Ziegler. 2015-2018	[5] [14]
H2020 ROMEO	Research objective is to develop reliable O&M decision tools and strategies. Including the use of novel SHM technology such as an IoT platform, data-driven analysis for failure diagnosis. To the knowledge of the author, the focus is on short term (O&M) assessments and not on lifetime extension of substructures. 2017-2022	[5] [20] [24]
O&O Nobelwind	Research and development project in collaboration with a Belgian wind farm operator. Topics of the project included the use of optical stain gauges, validation of virtual sensing, monitoring of bolted connections, fleet wide assessments using SCADA data. 2016-2019	[5] [32]
MAXWind	Research with focus on fatigue and corrosion modelling with the goal to have an improved estimation of the remaining life of in-service wind turbines. 2020-2024	[28]
SoilTwin	Development of a soil model which allows for a more accurate frequency analysis. 2020-2022	[29]
C-FLO	Corrosion fatigue life optimization by development and calibration of corrosion fatigue models. The aim is an optimization of design and maintenance of monopiles. 2019-2022	[26]

Monitor JIP	Development and validation of an effective SHM system and data-analysis methods. 2016 – 2018	[5] [27]
SLIC	Fatigue and crack propagation curves have been re-evaluated based on experiments. Samples, in both in-air and seawater conditions, have been subjected to loads which are comparable to the loads experienced by offshore wind turbines. 2015-2020	[5] [37]

Lifetime assessment of monopiles has been subject of recent academic research activities. In 2018 the Ziegler's thesis has been published. Ziegler's research was part of the H2020 AWESOME project. The research involved a.o. a novel fatigue load monitoring concept which has been validated with real-life measurements. The damage equivalent fatigue loads along the entire monopile have been predicted based on the extrapolation of strain measurements at one level. [14]. Similar work, so called virtual sensing strategies, has been performed by researchers within OWI-lab [40] [41] and Aarhus University [42]. The lifetime assessment of offshore wind farms based on supervisory control and data acquisition (SCADA) data has been subject of earlier research at OWI-lab by Noppe [1] and ongoing research by Santos [43].

The topic of lifetime assessment is relying on several research domains. A provisional list of research domains which are of interest is given below. The in-depth review of academic publications has been limited to this day. For completeness and future reference, the to-date encountered publications are referenced.

- Fatigue capacity of steel offshore structures
  - Re-evaluation of the fatigue thickness effect for thick specimen [21]
  - Re-evaluation of fatigue and crack propagation performance [36] [37]
  - Measurement based fatigue damage extrapolation [38] [39]
- Corrosion
  - Performance of corrosion protection systems in relation to lifetime extension [23]
  - Corrosion fatigue behavior [19] [25] [26] [28]
- Soil – structure interaction [29]
  - Fatigue influence of pile head rotations [33]
  - Fatigue influence due to changes stiffness as a result of cyclic loading [33] [34]
- Scour protection influence to dynamics [35]
- Operational Modal Analysis techniques [22]
  - Damage identification [20] [24]
  - Virtual sensing [40]
- Structural reliability [44]
- Machine learning [24] and also subject of other work packages within Supersized 4.0.

2.2 Literature in relation to structural health monitoring technology

A focal point of reference for the structural health monitoring industry is the SAMCO Network (Structural Assessment, Monitoring and Control). A thematic network, funded by the European Commission, 2001-2005. Although the available SAMCO publications [15-17] date from 2006, these are still a reference for the industry. SAMCO publication [17] is referenced in the VDI 4551:2020 [10] and the methodologies are recognizable in the current regulations. The application of novel structural health monitoring technology in Supersized 4.0 is in accordance with the SAMCO vision towards and beyond 2020. [15]

The earlier referenced publications by The Carbon Trust [5] and the publicly available deliverables from ROMEO project provide a comprehensive overview of the current monitoring technology, including innovative techniques which are already (widely) applied in the industry and innovations which are incubating and expected to be market mature within the next years.

- Typical structural health monitoring setup consists of: Accelerometers (in WTG tower and foundation), strain gauges (incl. temperature measurement) typically at the interface level, inclinometers, supplemented with corrosion monitoring (e.g. ER probes or reference cells) and environmental monitoring equipment if required.
- Recent innovations applied in the industry involve amongst others: The use of strain gauges made out of fibre glass (such as fibre bragg grating, FBG), big data handling in cloud-based solutions, digitalization of inspection records.
- Innovations for the near future are amongst others: The further development of FBG, introduction of IoT sensors in the monitoring setup and advanced data-analysis and operational modal analysis techniques leading to virtual sensing, fleet-wide extrapolations, machine learning also referred to as artificial intelligence.

In 2020 the Verein Deutscher Ingenieure (VDI) published the updated standard VDI4551. [10] From the current set of regulations (codes, standards, guidelines), [10] is the most relevant standard in relation to good practice for structural health monitoring of offshore wind substructures. It contains recommended practices for the hardware, data-analysis and the roles of responsibilities for asset owners and measurement equipment providers. Important to note in relation to certification is that the VDI is a non-binding document as it is not (yet) linked to any regulation such as DNVGL or BSH. It is expected that the VDI 4551 will be integrated in the next version of the DIN 18088-6 (periodic inspections), which is expected in 2022-2023.

3 Conclusions and way forward

3.1 Opportunities for improvement to the current practices

The literature study allowed to determine a couple of opportunities for improvement to the current practices. This exercise is of added value for the determination and future evaluation of the research objectives for a data-driven approach within Supersized 4.0.

Table 2: Determined opportunities for improvement and corresponding ambition how to respond to them by the present research.

OFI to the current practice	Improvement in Supersized 4.0
Holistic approach subject to interpretation and without clear acceptance criteria	Development of a roadmap based on data-analysis techniques for various lifetime consuming elements and alignment on design-driven and data-driven alarm levels
Reactive approach for decision support	Proactive approach by planning the lifetime assessment evaluations as from development / design phase
Risk of pitfalls and “blackboxes” when relying on project documentation packages	Recording the actual behaviour of the structure as basis for the assessment, supplemented with relevant design and operational information which is agreed during the planning of the works
Gap of data-driven approach in regulations	Implementing state-of-the-art fundamental R&D know-how - with consideration of its relevance in offshore wind structures lifetime consumption – in the data-analysis toolboxes.

Improvements to the current definition and application of digital twin modelling. - Indirect approach to get the stain histories which are important for a fatigue and thus lifetime assessment - Extensive work to clarify uncertainties in digital twin model calibrations - Digital twin modelling expected to be a man-hour consuming activity	Using the recorded data to develop an empirical digital twin of the structures for lifetime assessment exercises. - SHM and data-analysis is a direct method to get to the required information for lifetime assessments - Bypass uncertainties by monitoring of the as-is configuration - Using mainly computer processors are used instead of human processors / man-hours - The structural model-driven assessment expected to be complementary with the empirical model.

3.2 Way forward

Based on the literature review, a framework and decision model for the data-driven lifetime analysis will be developed . The framework will be a gradual process going from specifying the needed information, ensuring the collection of this data, performing an initial assessment concerning the potential for lifetime extension, continuous follow-up, followed by a detailed assessment aiming for a quantification of the lifetime with certain probability.
The decision model will provide structure to investigate lifetime consuming elements and evaluate their impact towards a potential lifetime extension. Further advanced data-analysis work would be required to quantify this potential.

Continuation of the literature review in the domains on which the data-driven lifetime assessment framework is relying is necessary. Essential in this is to obtain mutual acquaintance – and collaboration - with researchers in these supporting domains.

Many of the technical solutions for the objective in this research are believed to be currently available or in research phase, one of the keys will be the collaboration to fit these into the process towards a data-driven lifetime extension methodology.

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