Inspection Techniques for Lifetime Extension of Offshore Wind Turbines

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# Abstract

Lifetime extension becomes increasingly crucial for research and industrial implementation, due to the fact that the first offshore wind farms face the end of their design lifetime. To this date, experiences with lifetime extension of offshore wind turbines are limited. Analyses about remaining useful lifetime depend on structure design and loadings on the turbine. The target of this thesis is to predict additional lifetime with regard to crack propagation and underwater crack detection. Fatigue crack growth in a weld at mudline is estimated by a fracture mechanics model which applies Paris’ Law. By means of Monte Carlo crack size distributions are simulated considering uncertainties in input parameters. In addition, underwater inspection techniques are evaluated with regard to their applicability. Detection results including probability of crack detection get linked with the simulated crack sizes. Therefore, a conditional probability model applying Bayes Theorem is implemented, resulting in modified crack size distributions. Stochastic estimations about remaining useful lifetime are evaluated for different cases; without and with inspection. Results without inspection are afflicted with poor representativeness, whereas remaining useful lifetime linked with inspection outcomes show reduction of uncertainty. Studies are made to indicate that lifetime predictions are mainly sensitive to variations in crack sizes. Large cracks reduce additional lifetime drastically. However, since the probability of detection increases with higher crack sizes, larger defects are more likely to be detected during inspection. Thus, this thesis emphasizes the increasing representativeness of resulting lifetime predictions after the implementation of underwater inspection and shows the added value of additional information about structural conditions.

**Keywords:** offshore wind energy, lifetime extension, remaining useful lifetime, fatigue crack propagation, inspection, probability of detection

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# Acronymos

ACFM Alternating current field measurement

ANST The American Society of Nondestructive Testing

COV Coefficient of variation

DNV *Det Norske Veritas* – international classification society

DoE Design of experiments

EC Eddy current

FEM Finite element model

GL *Germanischer Lloyd* – international classification society

IT Inspection technique

MC Monte Carlo

MPI Magnetic particle inspection

NDT Non-destructive testing

NREL *National Renewable Energy Laboratory*

OWT Offshore wind turbines

PoD Probability of detection

PoS Probability of sizing

ROV Remotely operated vehicle

RP Recommended Practice

RUL Remaining useful lifetime

UIT Underwater inspection technique

UT Ultrasonic testing

VI Visual inspection

WTG Wind turbine generator

# Nomenclature

|  |  |  |
| --- | --- | --- |
|  | Initial crack depth / initial crack size | [mm] |
|  | Crack depth / crack size | [mm] |
|  | Failure crack depth / critical crack size | [mm] |
|  | Crack size after n years | [mm] |
|  | Crack size after n years with the probability | [mm] |
|  | Crack size after n years with the probability | [mm] |
|  | Distribution parameter for inspections | [ - ] |
|  | Material constant / Crack growth parameter | [] |
|  | Monopile wall thickness | [mm] |
|  | Damage fraction |  |
|  | Calculated fatigue life | [years] |
|  | Weibull shape parameter | [ - ] |
|  | Number of simulation runs | [ - ] |
|  | Sequential number for sigma sign () | [ - ] |
|  | Maximum stress intensity factor | [MPa |
|  | Minimum stress intensity factor | [MPa |
|  |  | [MPa |
|  | Material constant / Crack growth exponent | [ - ] |
|  | Operating lifetime | [years] |
|  | Number of load cycles | [ - ] |
|  | Number of load cycles at | [ - ] |
|  | Probability | [%] |
|  | Probability of event X given that event V is true | [%] |
|  | Probability of detecting a crack | [%] |
|  | Probability of occurrence of crack size | [%] |
|  | Probability of detection | [%] |
|  | Probability of given that is true | [%] |
|  | =  Probability of detecting an existing crack | [%] |
|  | Probability of not detecting an existing crack | [%] |
|  | Remaining useful lifetime | [years] |
|  | Hot spot stress range | [MPa] |
|  | Time | [years] |
|  | Crack length | [mm] |
|  | Distribution parameter for inspections | [ - ] |
|  | Geometry factor | [ - ] |
|  | Mean value |  |
|  | Standard deviation |  |
|  | Integration of Paris’ Law |  |
|  | Event of detection |  |

|  |  |  |
| --- | --- | --- |
|  | pi |  |
| , | delta |  |
|  | sum |  |
|  | integral |  |

# Definitions

Crack size crack depth

Environmental conditions surrounding factors, which may have influence on turbine parts

Design lifetime planned time, the wind turbine is able to operate

Lifetime extension additional lifetime after design lifetime is exceeded

Operating time time, the turbine produces energy or is ready to produce energy

Remaining useful lifetime estimated time, the turbine is able for further operation

Repowering replacement of wind turbine components after exceeding the end of their design lifetime

State-of-the-art the current status of techniques, guidelines, standards, etc.

Wind turbine energy plant, which converts kinetic energy from the wind into electrical energy

# Introduction

The operating life of offshore wind turbines (OWT) is limited to 20 years [1]. In the next years the first wind farms reach the end of their planned service time. Lifetime extension of OWT is an option to save on investment and planning of new wind farms. The process of the early decommissioning of wind turbines which may still be capable of operating [2, 3] would be avoided and would not only reduce costs and economize resources, but would also keep the environmental balance.

To the knowledge of the author there is no information about practical implementation of lifetime extension in the industrial sector of OWTs public. To this date no experiences or test data are available. In 2015 the international classification society *Det Norske Veritas* and *Germanischer Lloyd* (DNV GL) [4] published a recommended practice (RP) of ‘Probabilistic methods for planning inspection for fatigue cracks in offshore structures’. This guideline recommends ‘the use of probabilistic methods for inspection planning of fatigue cracks in jacket structures, semisubmersibles and floating production vessels’ [4]. Not included are recommendations for crack inspection of offshore monopiles, but since the RP is formulated in a general matter, analogies to monopiles can be assumed. In reference to DNV GL [4], Lotsberg et al. [5] follow up with a publication about ‘Methods of planning inspection of fatigue cracks in offshore structures’. This paper points out ‘the essential features of the probabilistic methods’ [5]. In March 2016 DNV GL [1, 6] released a standard for lifetime extension of wind turbines and the related certification process. This standard substitutes the ‘Guideline for Continued Operation of Wind Turbines’ [7] from 2009. DNV GL [1] recommends a twofold approach including an analytical part and a practical part and defines criteria to decide about permission of continued operating of wind turbines provided visual inspections when reaching the design lifetime. Underwater inspection techniques (UIT) are presented by the *American Society of Non-destructive Testing* (ASNT) [8] and the *Non-destructive Testing* (NDT) *Education Research Centre* [9]. DNV GL [4] and May et al. [10] provide an overview about feasible ITs for crack detection pointing out requirements and advantages.

Based on those references studies are required to analyse the suitability of approaches to structural reassessment. Practical considerations about fatigue and extreme loads are mandatory as well as information from design assumptions. In addition current monitoring data to estimate environmental loadings, material resistance, and the structural integrity are necessary. Thus, evaluations about remaining useful lifetime (RUL) and the practical feasibility of lifetime extension can be carried out, including uncertain outputs of underwater inspection.

The focus of this work is on estimations about RUL considering fatigue crack propagation. Fracture mechanic models and the implementation of Paris’ Law to estimate fatigue failures are presented by Kirkemo [11]. Ziegler et al. [3] published ‘Comparing a fracture mechanics model to the SN-curve approach for jacket-supported offshore wind turbines: Challenges and opportunities for lifetime prediction’ to make fatigue life predictions with regard to crack propagation in welded details. Effects of weather seasonality on fatigue crack growth for monopile-based offshore structures are also discussed by Ziegler [2].

The target of the presented thesis indicates to demonstrate the added value of offshore inspections for lifetime extension. Crack propagation due to fatigue loads is simulated with a fracture mechanics model applying Paris’ Law. This approach was already recommended by Ziegler [2, 3] and Kirkemo [11]. The simulation basis is provided by Ziegler et al. [2, 3]. Calculations of RUL are performed with crack growth simulation results and are linked with generic results of underwater inspections. Moan [12] established the connection between crack occurrence and inspection results by means of Bayes’ Theorem, which is used to solve conditional probability problems.

The presented thesis is sectioned in the following chapters:

* First **chapter 2** provides a brief overview in the ‘State-of-the-art’, which includes mathematical basics of fatigue crack propagation and an introduction in the simulation model. An overview about possible UITs and their applications for OWTs is outlined as well as the probability of detection (PoD) for the ITs.
* In **chapter 3** the ‘Methodological approach’ is explained containing the assessment and selection of ITs and further development of the crack propagation model. The procedure of developing a stochastic model, which includes results from inspection, is discussed here in detail. Chapter 3 also contains the definition of the input parameters.
* ‘Sensitivity study and discussion of the results is outlined in **chapter 4**. Estimations about RUL before and after inspection are presented and discussed as well as the influence of input parameters by means of the design of experiments (DoE) method.
* A conclusion and recommendations for future works are given in **chapter 5**.
* In the **appendix** flow diagrams of the implemented simulation models are illustrated.

# State-of-the-art

Monopile-based offshore structures are steel constructions consisting of several tubular segments welded together with butt welds from two sides (X-groove welds) [13]. OWTs are susceptible for fatigue loads, due to wind and wave excitation of the structure, which endangers the structural integrity. Exceptionally locations with welded details are prone to fatigue cracks due to small material defects. Therefore, critical parts (so called hot spots) must be inspected, if it comes to the question of lifetime extension of OWTs [14]. ITs considered in the presented study are focused on crack detection and sizing. The practical method of inspections is supplemented with an analytical approach of using a simulation model to calculate fatigue crack growth and RULs considering reliability and feasibility of underwater ITs.

Inspections are mandatory for renewed certification of existing wind turbines in order to extend their lifetime according to DNV GL [1, 6]. In addition condition monitoring of the structure can be profitable to support periodic inspection. More information about condition monitoring is given by Friedmann et al. [15, 16].

## SN-curve analysis

The SN-curve calculation post-processes fatigue loads in the structure to calculate structural failures. The fatigue damage can be calculated with the Palmgren-Miner theorem, which says that a structure can only tolerate a specific number of damage cycles until a failure due to fatigue load effects occurs [11].

The Miner’s Rule calibrates the fatigue damage and results from SN-curve material test data as follows [3]:

(2‑1)

The number of cycle to failure is given by the SN-curves, which results from material tests. No physically measurable parameters are included in the Miner’s Rule [11]. On that score an implementation of inspection results is not possible. Therefore, crack size measurement is requested to analyse the changes from initial to failure conditions [11].

## Fatigue crack growth

The fatigue life of a structure consists of crack initiation, crack propagation and finally ends in brittle failures [3]. In the crack initiation phase microstructural changes cause small cracks, which result in one or more measurable initial cracks in [mm] [11]. During crack propagation the initial crack size growths depending on the crack growth parameter , material parameter and on the stresses intensity factor [11]. A crucial factor for lifetime extension is the structural integrity of the construction, which is mainly depending on fatigue loads. The focus on this work is on fatigue crack propagation. Brittle failures occur at the end of the propagation phase [11], but are not considered in the presented thesis.

To analyse crack propagation due to fatigue loads linear-elastic fracture mechanics models are used. The Paris’ Law is an equation to describe the exponential change of crack size per load cycle [11]:

(2‑2)

The slope is a given material constant (here: [17]. The crack growth parameter (here: ) is calibrated by Ziegler et al. [2] “to yield the identical lifetime as with SN-curve analysis” [3].

The stress intensity factoris calculated with the following equation [11]:

(2‑3)

is a geometry parameter (here: ) [11], which accounts for structural and crack geometry. Hot spot stresses are given from simulations with finite element modelling (FEM) with reference to weather data. They represent the aero and hydro dynamic loads on the structure and are equal to the maximum principle stresses according to DNV  GL [18] depending on the crack propagation mode [2].

## Other failure modes

When it comes to the final question of lifetime extension, for a complete prediction of lifetime extension not only crack propagation has to be considered. Fatigue loads occurring from corrosion and scour as well as extreme loads due to extreme weather conditions or external forces are crucial aspects on the strength of the structure. Thus, first predictions about RULS are made, which can be used as a basis for further analyses about lifetime extension.

The focus of the presented work is on fatigue load. Extreme loads are not needed to look at closely, due to the fact, that “environmental conditions at the site are more benign than the original design conditions” [1].

## Description of the current existing model

The existing Matlab tool, written by Ziegler et al. [2, 3], is based on a fracture mechanics model to calculate fatigue crack propagation with the Paris’ law equation (cf. chapter 2.2). The reference wind turbine is a 5 MW offshore wind turbine provided by *National Renewable Energy Laboratory* (NREL) located in 20 m water depth [2]. The foundation is an OC3 monopile from the OC3 project [19]. The diameter at tower bottom and mudline is 6 m [2]. Wall thicknesses in these areas come to 0.06 m [2]. For the presented work the welded parts at the mudline are regarded as the analysed and inspected hot spot. This is where one of the critical parts for crack initiation is assumed. In practice other hot spots must be evaluated and analysed, e.g. the tower bottom. The weather data, measured in the North Sea near the UK, are originally provided by the *European Center for Medium-Range Weather Forecasts* and processed by Ziegler [2]. The wind speed is shown in Figure 1 [2].



Figure 1: Probability of occurrence of wind speed

regarding to Ziegler et al. [2]

Figure 1 illustrates the Weibull distribution of occurring wind speeds from zero to 30 m/s, divided in steps size 2 m/s. The highest probability of occurrence is a wind speed of 8 m/s. Wind speeds higher than 25 m/s occur rarely.

Environmental conditions used by Ziegler et al. [2, 3], are based on data from *UpWind Design Basis*. Wind and wave loadings as a generated aero and hydrodynamic load field affect all turbine segments by means of simulation. To analyse the structural response a FEM is used. The stress ranges results from the problem-specific modelling with FE simulation and depend on the occurring wind speeds (cf. Figure 1Figure 3). Stresses ranges are defined as model input data depending on fatigue loads and weather time series with 6 h duration. Ziegler [2, 3] demonstrated that a 1 h time window of simulation can represents all occurring stress ranges, if the wind speed distribution get linked with the stress ranges from the design. This results in the design lifetime of 32.88 years and gives the input value for (here: ) for lifetime calculation. The initial crack depth , and the parameters and are individual input parameters. The critical crack depth can be chose by the user to a fraction of the wall thickness of the monopile (here: ) [2]. If the calculated crack size reaches the critical crack depth the simulation stops. The following graph shows the crack progress as well as the resulting lifetime (32.88 years) depending on the chosen input parameters (cf. chapter 3.2.).



Figure 2: Crack growth curve

over the time (x-axis) until crack size crack size (y-axis) reaches the critical crack depth [2]

Figure 2 shows the crack propagation progress. Crack size increases slightly between 20 and 30 years, and grow strongly after 30 years of operating time. At 32.88 years the crack size reaches 60 mm. For the given crack growth model the additional lifetime can be assumed to 12.88 years.

A flow diagram of the existing tool is shown in Appendix A (cf. Figure 22, page 51).

## Underwater inspection techniques

Several ITs exist for detecting cracks in any kind of structures, but only a few are feasible under offshore conditions. Methods used in the offshore oil and gas industry are feasible methods for inspections for wind turbines, although OWTs are exposed to higher dynamic loads [8].

For lifetime extension of installed and operating OWTs only non‑destructive testing (NDT) methods are feasible. Non-destructive means that the structure can under no circumstances get influenced in its strengths and stability due to the inspection process. Inspection methods for underwater inspections are listed in the RP from DNV GL [4] and health and safety reports from May et al. [10]. The following section gives an overview about commonly used ITs based on [4, 10]:[[1]](#footnote-1)

* eddy current (EC),
* ultrasonic testing (UT),
* magnetic particle inspection (MPI),
* alternating current field measurement (ACFM), and
* visual inspection (VI)

The inspection process can either be done by divers or by remotely operated vehicles (ROV). For some ITs a coating removal is necessary, while some methods conduct the inspection above the coating. For each of the listed techniques the marine growth must be taken off. To provide a quality workmanship some ITs special require special trainings.

**Eddy current**

EC inspection is a technique based on electromagnetic testing, which uses the effect of electromagnetic field changes [8]. The change of the currents can be measured, where defects in the surface structure interrupt the current flow [9]. The EC method can be done without coating removal by ROVs or divers supported by a trained inspector above water [4, 10].

**Ultrasonic testing**

For an UT high-frequency sound waves, like pulse echoes, are transmitted to the structure and are received. Imperfections in the structure are detected from measures of time and energy chances due to changes in material thickness and properties [8, 9]. For UT inspection a special training for diver is needed. The use of ROVs is not possible [10].

**Magnetic particle inspection**

A ferromagnetic material is used to create one or more magnetic fields. An interruption in the structure deflects the flux lines of the magnetic flow and forces some of the flux at sides of flux leakage [8, 9]. Magnetic particles spread over the surface produce a visible indication of a defect or damage in the material. According to May et al. [10] for a MPI the surface must be cleaned and the coating should be removed slightly. Divers or trained inspectors guiding a ROV are employed for this inspection.

**Alternating current field measurement**

The ACFM method is based on electromagnetic techniques. A sensor probe creates an alternating current on the inspected surface [4, 8]. Defects in the structure interrupt the uniform currents from the magnetic field, which are measured by the sensor probe. A minimal cleaning of the surface is required as well as trained inspection divers [10].

**Visual inspection**

VI is a simple method to inspect underwater structures by looking at the surface and check if damages or failures are visible [8]. Both, a direct inspection of the surface is possible or an inspection with optical instruments and cameras by divers or ROV [10]. For the visual inspection the surface must be cleaned from marine growth. Most other underwater inspections include VIs [10].

### Probability of detection

The PoD is defined by the percentage of detecting a crack during inspection. In the presented work the crack, which is detected/is not detected is a crack resulting from the crack simulation model. PoD depends on the inspection performance [4]. Factors that affect the inspection performance, and therefore PoD, are e.g. inspectors’ qualifications, the implemented IT, environmental conditions and the design of the structure [20]. The probability of not detecting a crack is the complement of PoD: PoD. The Probability of Sizing (PoS) is defined by the percentage of exact measurements of the size of the detected crack, but is not further considered in the presented model.

PoD functions vary for different inspection methods [4]. For EC, MPI, ACFM, and UT the equation is defined by DNV GL [4] as follows:

(2‑4)

The distribution parameters for underwater inspections with EC, MPI, and ACFM and UT are given in Table 1, according to DNV GL [4].

Table 1: Distribution parameters and for PoD of EC, MPI, ACFM, and UT

[4]

|  |  |  |
| --- | --- | --- |
| IT |  |  |
| EC, MPI, ACFM | 1.16 | 0.9 |
| UT | 0.41 | 0.642 |

With the distribution parameters in Table 1 the PoD curves are plotted as shown in the following figure.



Figure 3: Probability of detection for ITs

: EC, MPI, and ACFM (solid line) and UT (dashed line) depending on crack size with the distribution parameters given in Table 1

In Figure 3 the PoD curve for inspection with EC, MPI, and ACFM (solid line) as well as UT (dashed line) are plotted. This plot clarifies the increasing probability of detection for larger cracks. The PoD strongly increases until a crack depth of approximately 20 mm. After a crack size of 20 mm the PoD stays almost consistent above 90%. It is shown, that the PoD progression for UT increases stronger than the curve of the EC method. UT has a higher PoD for smaller cracks () and a lower PoD for larger cracks ().

For VI a very good cleaning of the inspected surface is necessary [4]. The PoD is depending on the location and the access of the crack. The PoD function for VI is modelled as a function for crack length instead of crack depth. Therefore, instead of the crack depth the crack length is measured. The PoD of VIs is also depending on the type of fatigue crack. “If the fatigue crack is along a weld toe without going through the plate thickness, it is considered to be more difficult to detect than a crack going through the thickness” [4]. PoD curves for VIs are based on judgments – data tests are less available [4]. The following equation defines the PoD for crack length detection by means of VIs [4]:

(2‑5)

To compare the VI method with the other inspection methods, an adaption with the aspect ratio is made. The initial aspect ratio for crack propagation is according to DNV GL [4]:

(2‑6)

stands for the initial crack depth and for the initial crack length. Table 2 gives an overview of the distribution parameter for VI, according to DNV GL [4]. Those values are depended on the access of the inspected part and taking also into account the inspectors’ workmanship and the sea water conditions.

Table 2: Distribution parameters and for PoD of VI

with easy and difficult access [4]

|  |  |  |
| --- | --- | --- |
| access |  |  |
| easy | 15.78 | 1.079 |
| difficult | 83.03 | 1.079 |

In the following plot PoD curves for VI with easy and difficult access are illustrated.



Figure 4: Probability of detection for VI

for easy and difficult access depending on crack size

For VI the PoD curve is below the PoD curves from other ITs. The PoD for VI with difficult access (dashed line) growths weakly compared to VI with easy access (solid line), shown in Figure 4. The PoD for VI approximates the PoD curve for UT at a crack size of 50 mm and never reaches the PoD for EC inspection in the considered case, since the monopile wall thickness is 60 mm.

### Overview of requirements on inspection techniques

In Table 3 an overview of the five mentioned ITs is given in respect of the requirements, if it comes to practical implementation. Requirements are the application with divers and/or ROVs as well as the cleaning of the surface and/or coating removal.

Table 3: Overview of ITs

with: fulfilled requirements (✓) and not fulfilled requirements (🗶); high PoD (**↑**), medium PoD (↔), and low PoD (↓)

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | EC | | UT | | MPI | | ACFM | | VI | |
| Diver | | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | |
| ROV | | ✓ | | 🗶 | | ✓ | | 🗶 | | ✓ | |
| Surface cleaning | | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | |
| Coating removal | | 🗶 | | ✓ | | ✓ | | 🗶 | | 🗶 | |
| PoD | | **↑** | | **↔** | | **↑** | | **↑** | | **↓** | |

# Methodological approach

To achieve an extension of lifetime after the service lifetime is expired, some requirements must be considered. Examples for requirements are feasibility of the IT, reliability of the results, and economic aspects. In this work RUL will be evaluated based on failure due to fatigue crack propagation at one specified hot spot (here: mudline). The approach of the presented work is sectioned in the following issues:

* Selection of ITs for underwater crack detection,
* Definition of distributed input parameters for the crack calculation model,
* Further development of the simulation model for crack growth linked with the inspection results, and
* RUL evaluation.

If it comes to the term “RUL” in further section, the RUL only based on fatigue crack propagation is meant. For a practical implementation of lifetime extension all aspects, which can influence the structural integrity, safety and health and environmental conditions have to be considered. The wind farm operator has to adhere to guidelines and standards.

## Assessment and selection of inspection techniques

The application of ITs depends on different aspects, e.g. location, environmental conditions, foundation of the OWT, part and type of an expected damage, available resources. As mentioned above, besides the mentioned factors the IT for lifetime extension of offshore monopiles must be mandatory non-destructive.

A decision matrix helps to evaluate the suitability of ITs for lifetime extension. Possible criteria for the decision matrix are PoD, costs, environmental and safety risk, limitations, ease of installation and use, accuracy, and maintenance [10]. According to DNV GL [4] the capability of the used IT, the degree of reliance on operator skill and the auditability have also an influence on the reliability of an IT. For the presented work three () of the mentioned criteria will be evaluated exemplarily:

* **PoD**: cf. chapter 2.5.1,
* **Limitation / ease of installation and practical implementation**: universal applicability with regard to the inspected part of the structure, water deep and required coating removal or cleaning, and
* **Reliance on operator skills**: required diver, need of special trainings for operator.

Nevertheless, for a practical implementation it is recommended to take into account all criteria and aspects. Costs must be considered individually for each application. The award of the scoring system is just an indication from the author based on the named references May et al. [10] and DNV GL [4]. It might be specified due to the present circumstances and depending on the application and aims.

The applied decision matrix (cf. Table 5) is based on a scoring system of one to three points. This scoring system is chosen by the author. An evaluation with one point means that the use of this method is not fully recommended under the current conditions (worse conditions compared to the other methods). Whereas the award of three points recommends the implementation of this technique under the current aspects (much better conditions compared to the other methods). The award of two points is in the middle of one and three points and only possibly recommended. Methods and criteria with an information deficit will be marked with an asterisk (\*). If a method has missing data it will be excluded and not further considered as a possible inspection method in this work. The reason is an information deficit to make a conclusive decision.

The criteria are weighted with a defined importance by means of a symmetric pair-wise comparison matrix, cf. Table 4. Therefore, each criterion is line by line compared with the remaining criteria in the columns. Is the criterion in the line more relevant than to one in the header, the cell is scored with two points, less importance is scored with zero and if both criteria are defined with the same importance the cell input is one. The points are added line by line and the criterion with the highest sum is on the leading position and gets the highest weighting value three. The weighting may differ for practical implementation and works with other focus.

Table 4: Pair-wise comparison matrix:

Criteria for the assessment of the ITs

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | PoD | Limitation | Reliance on operator skills | Sum ∑ | Ranking | Weight |
| PoD | - | 2 | 2 | **4** | **1** | **3** |
| Limitation | 0 | - | 2 | **2** | **2** | **2** |
| Reliance on operator skills | 0 | 0 | - | **0** | **3** | **1** |

Table 5: Decision matrix for ITs

with weighted criteria

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | | | Inspection technique | | | | |
| i | **Criteria** | **Weight** | **EC** | **UT** | **MPI** | **ACFM** | **V** |
| 1 | PoD | 3 | 3 | 3 | 2 | 2 | 1 |
| 2 | Limitation | 2 | 3 | (\*) | 1 | 2 | 2 |
| 3 | Reliance on operator skills | 1 | 2 | 1 | 2 | 1 | 3 |
|  | | | **2.83** | (2.5) | 1.67 | 1.83 | 1.67 |

The points for criterion **‘PoD’** are based on information from DNV GL [4]. Three points stand for relative high PoD values compared to the PoD of other ITs, whereas one point means lower PoDs. A method with only less or uncertain PoD data is scored with one point. The information for evaluation of criteria 2 and 3 are based on statements from May et al. [10]. Techniques which need no removal of the coating and only minimal or no cleaning of the surface are valued with three points in criterion **‘limitation / ease of installation and practical implementation’**. In contrast methods with required coating removal and cleaning are evaluated with one point. The award of two points in this criterion stands for cleaning but no coating removal. The criterion **‘reliance on operator skills’** is based on the deployment of a diver or a ROV, according to May et al. [10]. If a diver is mandatory needed, the IT is scored with one and if a ROV can be used instead of a trained diver three points are given. Techniques which can be implemented by both, ROV or divers are scored with two points. For further cost evaluations this criterion might be of crucial importance, since divers are very costly due to high risks.

For the presented decision matrix and under consideration of the chosen criteria an implementation of the EC technique is recommended with nearly three points (2.83), followed by ACFM technique. Absolutely not recommended are the MPI and VI with less than two points. The UT method is not taken into account due to an information deficit of one criterion. Visual inspection often supplements other ITs [8].

In the following the PoD is always calculated for the EC method by means of equation (2-4) and the distribution parameters and (cf. Table 1).

## Definition of input parameters

Input parameters used in this thesis are based on literature values, according to DNV GL [4], Lotsberg et al. [5], Kirkemo [11], and Ziegler et al. [2, 3] The crack propagation model, described in chapter 2.4, works with the following deterministic input parameters:

* Initial crack size ,
* Material parameter and ,
* Geometry parameter ,
* Design lifetime in years,
* Stress ranges and number of cycles from aero-hydro-elastic simulations, and
* Critical crack size ,

Due to uncertainties in the occurrence of input parameters, , , and are no longer come as deterministic values, but as stochastic ones. Thus, the expected outputs ( and RUL) are distributions, taking into account randomness in crack propagation.

The following section gives recommendations for the distributions of , and according to DNV GL [4] and Lotsberg et al. [5].

### Initial crack size

The initial crack size defines the crack size at the beginning of the simulation. According to DNV GL [4] and Lotsberg et al. [5] is exponential distributed.

Exponential distribution function [21]: (3‑1)

The mean value as well as the standard deviation are [4, 5]. The median value for crack size is [4, 5]. Initial cracks larger than are improbable, 90-percentile is about according to DNV GL [4] and Lotsberg et al. [5].



Figure 5: Exponential distribution of the input parameter initial crack size

with mean value of

Figure 5 shows the exponential distribution of initial crack size from 0 to 0.4 mm (x-axis). After 0.25 mm the probability approaches zero.

### Crack growth parameter

The crack growth parameter influences the crack propagation and is dependent on the material obtaining from experiments [22]. Crack growth parameter grows with decreasing material parameter clarified by the unit of , where is the exponent of () in the denominator of the fraction. Due to the dependence from the material constant on the parameter (), it is useful to vary only one of those values. Therefore, in this thesis stays as a deterministic input parameter [3]. The distribution of *C* is assumed as a normal distribution [11].

Normal distribution function [21]: (3‑2)

The mean value is calculated by the following equation [4]:

(3‑3)

with

The calculated fatigue life based on the SN-curve data is defined by 32.88 years, according to Ziegler [3]. is used to calculate the mean crack growth parameter . Therefore the Weibull shape parameter is needed, which is defined between 0.7 and 1.1, according to DNV GL [4].

In Table 6 the resulting mean values for crack growth parameter are listed.

Table 6: Mean values for crack growth parameter

, depending on different Weibull shape parameters for calculated fatigue life time of 32.8 years

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Weibull shape parameter | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 |
|  | 1.815 | 1.717 | 1.624 | 1.537 | 1.454 |
| Median value | 3.322 | 3.143 | 2.973 | 2.812 | 2.660 |

For the presented work the Weibull parameter is used, which results in the most conservative results for the mean crack growth parameter. The standard deviations for welded metal and basic materials are listed in the following table [4].

Table 7: Standard deviation for welded and basic materials

|  |  |  |
| --- | --- | --- |
|  | welded materials | basic materials |
| Standard deviation |  |  |

Thus, the mean value is defined by with in . The following figure shows the normal distribution of .



Figure 6: Normal distribution of the input parameter crack growth parameter

with mean value and standard deviation in .

The x-axis in Figure 6 shows the crack growth parameter C in [], with the mean value at . The probability of values before and after 4.5 approaches zero.

The crack growth parameter calculated by Ziegler et al. [2] is , cf. chapter 2.4. This value is 45% higher than the chosen mean value in this chapter and would result in even more conservative results.

### Geometry factor

The geometry factor for small cracks in infinite bodies is assumed as a normal distribution with a mean value [4].

Normal distribution function [21]: (3‑4)

The coefficient of variance (COV) is [11]. With the following equation the standard deviation can be calculated [21]:

(3‑5)

The standard deviation results into .



Figure 7: Normal distribution of the input parameter geometry factor

with mean value and standard deviation

The normal distribution of the geometry factor is shown in Figure 7. Mean value is 1. Values smaller than and higher 1.5 have a probability approaching zero.

## Further development of existing model

The deterministic simulation tool, described in chapter 2.4, should now convert into a stochastic one. Therefore the parameters as defined in chapter 3.2 afflicted with uncertainties are defined as distributions. A Monte Carlo (MC) simulation is implemented to choose random input values out of the distributions.

The distribution of crack size after years (here: 20 years, design lifetime [3]) is the expected output, depending on the number of runs and the input values. Fixed inputs, like weather data are mentioned in chapter 2.4. , , and as well as the deterministic values , , and can be chosen by the models user. Recommendations are given in chapter 2.2 and chapter 3.2. A flow chart of the simulation model is shown in Appendix A (cf. Figure 23, page 52).

### Monte Carlo simulation

With the existing model and the provided processing power one simulation takes around four minutes, which limits the number of simulations. By using an integrated solution of the Paris’ Law according to Kirkemo [11] the simulation time for one simulation can be drastically shorten to less than 0.2 second. Therefore and to reduce complexity the stress ranges get divided in so called “bins” with a defined size of 1 MPa. In each bin a mean value of the stress ranges is calculated. Results might slightly deviate from exact solution of Paris’ Law.

Thus, the Paris’ Law can be solved by the following integral [11]:

(3‑6)

The input equation for calculating crack size after years can be modified by [11]:

(3‑7)

Crack size after years now results in the following equation:

(3‑8)

[mm]

For a MC simulation the variable input parameters must be independent from each other. The probabilistic input parameters, , and are chosen randomly from their distributions. The material constant is chosen as a deterministic value due to the dependency on , see chapter 2.2 and 3.2.2. DNV [17] recommends for welded materials in seawater conditions with corrosion protection. The stress ranges , now divided in bins width 1 MPa, are given by Ziegler et al. [2] from the simulated wind and wave loads acting on the turbine. , which results from stress range bins and the wind speed distribution, defines the number of load cycles per stress range for one hour [3].

A loop is used to sum the binned stress ranges with their number of cycles . chances every loop, starting with one initial crack size from the distribution. The next value results from the sum of the fraction + (cf. equation (3-8)). The loop ends, when all stress range bins are added up. This results in after one hour, due to the fact that loadings, and with that the stress ranges are given for one hour [3]. The number of loop runs is equal to the number of bins. For estimating the crack size after operation lifetime of years, 24 hours/day and 365 days/year must be multiplied in the equation. Thus, results into:

(3‑9)

**Comparison of crack size calculated by integrated and by cycle-by-cycle solution of Paris’ Law**

A comparison of the resulting -values proves the similarity of the integrated solutions of the Paris’ Law with the cycle by cycle solution ( as mentioned in the original model (cf. chapter 2.4). is calculated new (cf. equation (2-3) in chapter 2.2) after each stress cycle adding on the crack depth from the last cycle [2, 3]:

(3‑10)

With the same input parameters the resulting values differ by a few percent (for 20 years the deviation is smaller than 0.1% and for 40 years smaller than 0.6%), which may result from averaging the stress ranges in each bin. With smaller bins the deviation is reduced slightly, but the time for one simulation run increases strongly. Bins with 0.01 MPa deviate from bins with 1 MPa with a maximum value of 2%. For the mean value for each input parameter the deviation is 0.4%. The advantage of the time gain due to bigger bins compensate the slightly deviating results – for bins with 0.01 MPa the simulation time is between 10 and 30 seconds per run, whereas the simulation time for a run with 1 MPa‑bins takes 0.2 seconds. Thus, a simplification by means of integration with bins size 1 MPa is suitable.

**Convergence study**

A convergence study for Monte Carlo simulation is made to check how many runs can represent exact results with only a small deviation. As more simulations are made, the more exact is the outcome – infinity runs would represent most exact results. With a so called bootstrap sampling, comparable with convergent studies, a closer examination of the minimum runs can be used, but due to the short simulation time this is not necessary for the presented work. Table 8 lists the mean values for and the standard deviation for an independent number of runs.

Table 8: Mean values and standard deviation for crack size

for various numbers of MC simulations

|  |  |
| --- | --- |
| MC simulations | Mean value [mm] |
| 30,000 | 0.28 |
| 20,000 | 0.29 |
| 10,000 | 0.28 |
| 5,000 | 0.27 |
| 1,000 | 0.23 |
| 500 | 0.24 |
| 50 | 0.12 |

The table results in the following plot, where convergence between 5,000 and 30,000 runs is clarified.



Figure 8: Mean values of crack size

depending on the number of runs from MC simulation

Figure 8 shows the mean values depending on the runs of simulation. After 5,000 runs the mean values begin to converge. Here, the mean value deviates with 1% from the mean value out of 30,000 simulations. The mean value of 10,000 runs is only deviating about 0.9% from the mean value of 30,000 runs. To save time 5,000 simulations are recommended, fewer simulations can show gaps due to missing data and data combinations and distort the expected results. If time is not crucial, more simulations are always recommended, but more simulations results only in slightly decreasing deviation.

### Bayes Theorem

After inspection the probability of occurrence of crack size changes depending on the event of detection. Even if no crack is detected the information about crack occurrence increases [23]. To link the probability of detecting cracks with occurring crack distributions (resulting from simulation) conditional probability analyses is used. The Bayes Theorem [12] describes an equation for conditional probabilities, which gives the probability of event X given that event is true [24]:

(3‑11)

with.

probability of event X

probability of event Y

probability of observing Z after X is occurred

The probability, that a detected crack is a real one is defined by . In other words, is the probability of given that the probability of detection is true. With equation (3‑11) is defined as:

(3‑12)

crack size (simulated) [mm]

probability of occurrence of crack size

probability of no detection

is the probability of the occurrence of crack size after years. is the event of detection and the probability of detection. the already known probability of detection an existing crack (cf. chapter 2.5.1) [12].

The following tree diagram shows the different combinations of inspection, detection and crack existence.

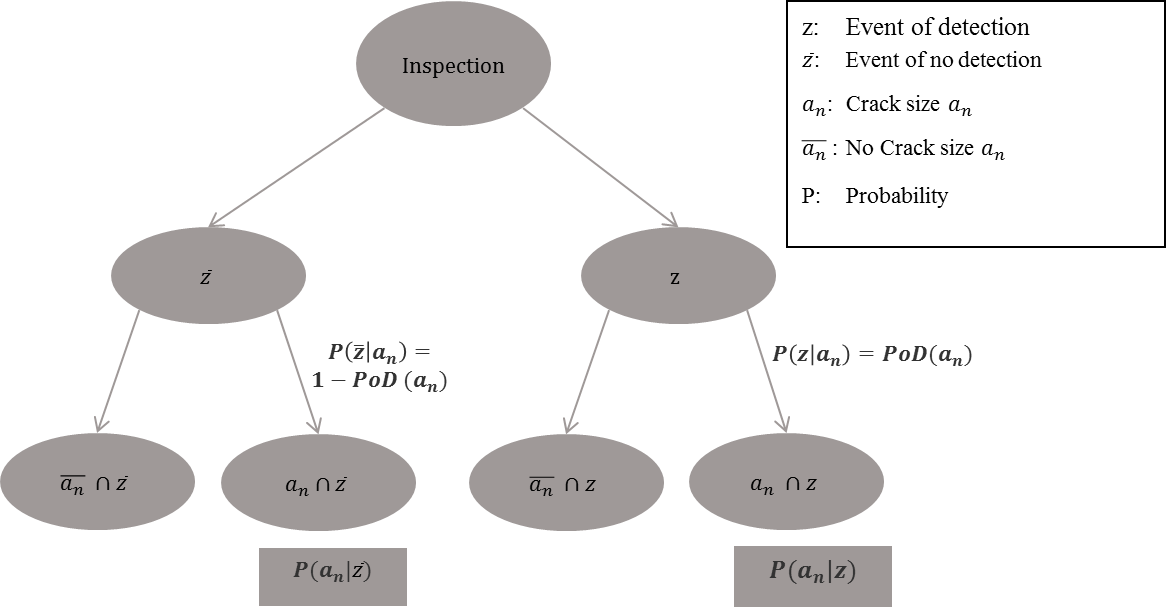


Figure 9: Tree diagram

illustrating the procedure of inspection with regard to the event of crack existence depending on the event of detection

The tree diagram in Figure 9 illustrates the event of crack existence depending on the event of detection. The first row is the event of detection . On the right sector event is true. If detection is true, there are two possibilities:

* detecting a crack, which does not exist (wrong detecting) on the left or
* detecting an existing crack on the right.

The last point finally results in the probability , which defines the probability of the existence of a crack given that the event detection is true. The event of detecting a crack if no crack exists () can happens due to inspecting failures or poor workman ship and is also not considered here.

On the left site, the event of detection is false (), which means that nothing is detected:

* not detecting anything, if no crack exists on the left and
* not detecting an existing crack on the right.

If a crack exists, but is not detected , the complement of PoD is used: [12]. The output of this sector is the probability of the existence of a crack given that the event of detection is false. The sector on the left-left side is the event of no crack existence given the event of no detection. This sector is not further discussed in the presented work.

The event z ‘detection’ with the probability of detection is previously unknown, but can be calculated with the following equation [12]:

(3‑13)

The integral in equation (3-13) includes all occurring crack sizes and their PoDs. is the smallest crack size (smallest -value) during a defined number of simulations, the largest.

Since the probability events are given as conditional probability distributions the Bayes’ Theorem is written as [12]:

(3‑14)

With and as distributed values and equation (3-13) the probability of the existence of a detected crack comes to [12]:

(3‑15)

The probability of the existence of a non-detected crack is defined as follows [12]:

(3‑16)

crack size (simulated) [mm]

probability of occurrence of crack size

probability of no detection

With equations (3-15) and (3-16) the probabilities of occurrence of the crack size after years are determined The new distributions are results from the added information from inspections. is distributed with for crack detected and for no crack detected.

### Calculation of RUL

The RUL can be calculated with the integrated solution of Paris’ Law (cf. chapter 3.3.1) and is dependent on the crack size after years (here: ). is now defined by three different distributions for RUL calculations:

* Case 1: without inspection (crack size ),
* Case 2: with inspection and with detection of a crack size , and
* Case 3: with inspection and no detection of a crack size .

A rearrangement of equation (3-9) is needed to calculate RUL after years of operating. The input ‘design lifetime ’ is not further needed for RUL calculations, since is the new input distribution for crack size at the end of design lifetime and it is searched for RUL in years.

Thus, the equation for RUL calculation is defined by:

(3‑17)

where

are replaced by the results of Bayes Theorem (cf. chapter 3.3.2) to analyse RUL after inspection. In case 2 is used to calculate RUL with inspection and detecting a crack and in case 3 for the event ‘inspection and not detecting a crack’. and are distributed as mentioned in chapter 3.2. and weather input data are not modified (cf. chapter 2.2 and 3.3.1). The maximum possible crack depth , before a structure fails, can be assumed equal to the monopile wall thickness or to a fraction of the wall thickness, when the crack depth reaches a critical state for the structural integrity.

The results are distributions for RUL, which are dependent on crack size and the event of detection. The three output distributions of RUL as well as their median values and standard deviations will be evaluated and discussed in chapter 4.

### Design of experiments

Crack size and with that RUL calculation is depending on different input parameters. To analyze which of the distributed input parameters have the main influence on the results, the DoE method is suggested. The parameters ,, and influence crack size . For the influence on RULs is replaced by . Three characteristic values from each distribution are defined. The simulation runs times (three input parameters per analysis with three different values each) with only one parameter variating. The not varying parameters are assumed at their median values. For the DoE study in the presented work a minimum, median, and maximum value for each input parameter is defined. The minimum and maximum values are defined by the 10-/ 90-percentile (10P / 90P) method. This is a statistic measure of location defining a limit at which 10% / 90% of the distributed values are smaller than the limit. Median is the 50P value. In the following table the values for variating input parameters ,, and are listed.

Table 9: Minimum, median, and maximum value for input parameter

: , , and

|  |  |  |  |
| --- | --- | --- | --- |
|  | Minimum  Percentile 10P | Median  Percentile 50P | Maximum  Percentile 90P |
| Initial crack size |  |  |  |
| Crack growth parameter |  |  |  |
| Geometry factor |  |  |  |

# Sensitivity study and discussion of the results

In consideration of the presented methodological approach (cf. chapter 3) three different cases for RUL results are now evaluated:

* Case 1: without inspection (crack size ),
* Case 2: with inspection and with detection of a crack size , and
* Case 3: with inspection and no detection of a crack size .

For each case the crack size distributions are presented, which are crucial inputs for the following RUL preconditions. This chapter contains the discussion of the results including consideration of added value of underwater inspection in regard to lifetime extension. At last limitations are mentioned followed by practical application and scientific values.

## Resulting crack sizes and RULs

Result plots are outputs from the crack propagation and RUL model. Distributions are illustrated as histograms divided in bins. In the following plots y-axis always shows the probability of occurrence between zero and one. On the x-axis the outcomes – crack size or RUL – are displayed.

Crack sizes , , and are divided in bins of width 0.01 mm and are plotted from zero to 0.5 mm. Cracks higher than 0.5 mm are not displayed, since they result from outliers from MC simulation for high input values and have very low probabilities. RULs are divided in bins of 10 years width and are plotted from zero to 500 years. Outliers higher than 500 years result from very small input values (mainly small crack sizes). Since they are more than 25 times higher than design lifetime and RUL for the whole wind turbine is assumed to 5 years[[2]](#footnote-2) [25], they have no significant relevance for practical implementation.

The next section presents crack size results and RUL outputs in case of no inspection, followed by the outcomes including inspection (Bayes Theorem), distinguished between crack detection and no crack detection.

**Case 1: Without inspection**

The following plot shows the crack size distribution from crack simulation model without consideration of inspection. The distribution is calculated based on literature data and assumptions for input values, cf. chapter 3.2.



Figure 10: Distribution of crack size without inspection.

The solid line illustrates median crack size, dotted line (left) 10P, dotted line (right) 90P

Crack size after 20 years of operating time appears to be exponential distributed, shown in Figure 10. The highest probability of occurring crack sizes after 20 years is between zero and 0.01 mm with 17%. With 13% occurrence cracks sizes 0.01 to 0.02 mm follow, than with 9% cracks sizes from 0.02 to 0.03 mm. The probability of occurring is strongly decreasing with larger crack sizes. This exponential decrease might result from exponential initial crack size , which has a significant influence on the crack propagation (cf. chapter 4.2).

The median value of is 0.05 mm, which clarifies that 50% of occurring crack sizes are smaller than 0.05 mm. The median is illustrated with a solid line. 10% of crack sizes are smaller than 0.01 mm, which is defined by the P10 (left dotted line). The 90P results in 0.27 mm (right dotted line).

RUL resulting from crack size and input parameters mentioned in chapter 3.2 is illustrated in the following figure.



Figure 11: Distribution of RUL after without inspection.

The solid line illustrates median RUL, dotted line (left) 10P, dotted line (right) 90P

Figure 11 shows the probability of occurrence (y-axis) for RUL (x-axis) without inspection from zero to 500 years. A strong increase of probability until 40 years of RUL is shown, followed by a slow decrease from 40 years to 500 years. The plot illustrates that the most likely RULs are between 30 and 40 years with 10%, followed by the time frame from 40 to 50 years with 8%, and 20 to 30 years with 7%. Outliers higher than 500 years of RUL are not considered, since they occur with very low probabilities and have no relevance for the regarded lifetime extension as mentioned before.

The solid line in Figure 11 shows the median value for RUL at 75.95 years. At least 90% of occurring RULs are higher than 24.64 years (P10, left dotted line) whereas 10% of the values are above 281.47 years (P90, right dotted line).

Assumed RULs of the whole OWT are 5 years. Since the regarded OC3 research monopile has a very conservative design, RULs resulting on fatigue crack propagation at mudline weld toe are expected much higher than 5 years. The 10P of RUL is about 5 times higher than the assumed RUL of 5 years. The high value of P90 indicates large distances from RUL values above 281.47 years to the most occurring RUL values between 30 and 50 years. Those large distances as well as outliers imply poor representativeness of the results.

With inspection increasing expressiveness of RUL outputs are expected. Therefore, the results presented above are linked with the inspection outcomes by means of Bayes Theorem (cf. chapter 3.3.2). In case 2 and 3 the events of detecting a crack or not detecting a crack during inspection are discussed.

**Case 2 & 3: With inspection**

**2) With detection of a crack size / 3) without detection of crack size**

After inspection crack size distribution changes depending on the event of detecting a crack size (case 2) or not detecting a crack size (case 3). This effect is shown in the following figure, where case 2 is plotted as a bright line (upper plot) and case 3 as a dark line (lower plot).



Figure 12: Distribution of crack size and with inspection

in both cases: 2) with detection, and 3) without detection. The solid lines illustrate median crack size, dotted lines (left) 10P, dotted line (right, only in lower plot) 90P

In Figure 12 the probability of occurrence of crack sizes after inspection is illustrated.

**Case 2:** In this case the most likely bin is of 0.05 and 0.06 mm crack size with 3.5%, closely followed by bins from 0.03 to 0.05 mm and 0.06 to 0.08 mm, each with approximately 3%. The distribution changes from exponential shape (case 1) to a wide covered spectrum, where a high number of crack sizes with small probabilities of occurrence are considered. The median value increases to = 0.20 mm and 10P is shown at 0.03 mm. 90P (1.59 mm) is not illustrated in the figure. The change in the distribution compared to the distribution in case 1 results from the combination of crack occurrence with PoD. Since larger cracks are easier to detect, the probability that a (large) crack size exists after a positive detection increases. Therefore, the curve moves to higher crack sizes.

**Case 3:** Here, the distribution slightly moves to smaller crack sizes. The highest probability of occurrence with 18% is given for cracks smaller than 0.01 mm. Crack sizes in bin 0.01 to 0.02 mm occur with 13%. Larger crack size bins have strongly decreasing probabilities of occurrence. The exponential shape of the distribution from case 1 is still given. This effect can be explained by the low influence of the event of no detection, which implies the complement of PoD (1-PoD). If no crack is detected, it can be assumed that larger cracks do not exist in the inspected region, because larger cracks would have been likely to be detected. But there is still the risk of the existence of small cracks. Median value variates slightly to 0.04 mm compared to median of case 1. 10% of crack sizes are nearly zero millimeters, whereas 90% are smaller than 0.21 mm

The crack size distributions with inspection (cf. Figure 12) result in the following RULs plots.



Figure 13: Distribution of RUL with inspection

in the cases: 2) with detection and 3) without detection. The solid lines illustrate median RUL, dotted lines (left) 10P, dotted lines (right) 90P

In Figure 13 the probabilities of occurrence (y-axis) of RULs (x-axis) with inspection are shown. The upper plot shows RULs in case 2) with crack detection, the lower plot illustrates RULs in case 3) without crack detection.

**Case 2**: With 17% the most likely RUL values occur between 30 and 40 years. With 16% of occurrence the bin from 20 to 30 years occurs, followed by 40 to 50 years with 13%. The distribution increases strongly from zero to 40 years and decreases after 40% exponential. RULs longer than 170 years occur with a probability approaching zero. If a crack is detected the median RUL value is approximately 33.46 years. 10% of occurring RULs are shorter than 8.93 years. This value is a little higher than assumed RUL of 5 years. The curve tail is very flat, which explains the smaller RULs at 90P (94.53 years) compared to case 1.

**Case 3**: RUL values between 40 and 50 years occur most frequently, with 7%, followed by the bin of 30 to 40 years and 50 to 60 years. The distribution increases from zero to 50 years and slowly decreases after 50 years. RULs after 400 years occur rarely. Here, the probability of occurrence approaches zero percent. Median RUL value is 81.91 years. 10P is 28.71 years, 90P results in 263.32 years. The high 90P confirm the fatter tail of the curve after detection results is negative. The curve progression varies slightly from the shape in case 1. This effect can be explained analogically to the similarity in crack size distributions. If no crack is detected, there might be still the risk of the existence of a small crack. But it is likely that large cracks not exist, since they have high PoDs.

**Comparison and discussion**

Lifetime extension based on fatigue crack propagation and inspection delivers the crack size results listed in the following tables and figures.

Table 10: Comparison of percentile values of crack size

in case: 1) without inspection, 2) with inspection and detection, and 3) with inspection and no detection

|  |  |  |  |
| --- | --- | --- | --- |
|  | [mm] | [mm] | [mm] |
| Case 1:  Without inspection | 0.05 | 0.01 | 0.27 |
| Case 2:  With inspection with crack detection | 0.20 | 0.03 | 1.59 |
| Case 3:  With inspection without crack detection | 0.04 | 0 | 0.21 |

The percentile values for crack size increase with the event of crack detection and decrease for the event of no detection. This is a result of the fact that larger cracks have a higher PoD than smaller cracks. The probability that smaller cracks might not found during inspection is higher.

In Figure 14 a comparison of crack size of all three cases is illustrated.



Figure 14: Comparison of crack size distributions and median values

(vertical lines) in case: 1) without inspection (dotted line), 2) with inspection and detection (bright solid line), and 3) with inspection and no detection (dark solid line)

The red dotted line in the figure above shows the distribution without any inspection, the grey lines are the events with inspection (bright: with detection, dark: without detection). The lower effect of inspection without detection (case 3) compared to the clear shift to higher crack sizes for case 2 with detection is emphasized. For a positive event of detection, it is likely that a crack size exists. Therefore, the crack size curve moves to higher crack sizes. Crack detection increases the information about the condition of the inspected part of the structure. Whereas the event of no detection still contains the risk of an existing crack, which is not found during inspection. If no crack is detected, it is likely that no large cracks are presented. But here, large cracks do likely not exist, because they should have been detected during inspection due to their higher PoD. This explains the slight move to smaller crack sizes.

With the results of crack size distributions, presented in Table 10 and Figure 14, RULs are calculated and for a comparison listed in the following table. For a conservative inspection planning the RULs are rounded down to whole years. In Figure 15 the three distributions are compared to each other.

Table 11: Comparison of percentile RUL values

in the cases: 1) without inspection, 2) with inspection and detection, and 3) with inspection and no detection

|  |  |  |  |
| --- | --- | --- | --- |
|  | [years] | [years] | [years] |
| Case 1:  Without inspection | 75 | 24 | 281 |
| Case 2:  With inspection with crack detection | 33 | 8 | 94 |
| Case 3:  With inspection without crack detection | 81 | 28 | 263 |

If a crack is detected, the median value for RUL decreases compared to the event of no inspection, but increases for no crack detection. This de-/increase stems from the distributions of after inspection, which move to larger/smaller crack sizes. It is shown, that 90P values increases after inspection independent of the detection result. The 90P for case 2 is reduced by 67%, whereas the case of no detecting during inspection implies a reduction by 7%. values are much higher than expected RULs and are not suitable for predictions about lifetime extensions. Those values might be results of outliers and model uncertainties. Whereas the values or even less percentile values might be used for realistic estimations about practical implementation of lifetime extension, since they show results in the expected ranges of RULs.



Figure 15: Comparison of RUL distributions and median values

(vertical lines) in the cases: 1) without inspection (dotted line), 2) with inspection and detection (bright solid line), and 3) with inspection and no detection (dark solid line)

The dotted line in Figure 15 illustrates RUL without inspection. With inspection and the event of detecting a crack size the distribution moves to smaller RUL values (bright line). For the event of not detecting a crack, a slight move to higher RUL values is shown (dark line). This effect is similar to the slight change of crack size curve after inspection with no detection, explained above. The comparison of the 90Ps of all three cases shows, that inspection lowers 90P values, independent of detection result. This means in turn, that the distribution curve has a flatter tail, compared to curves with higher 90P values. The flatter tail of the bright curve for inspection with detection is illustrated in Figure 15.

A box plot clarifies the uncertainties illustrating the 25P and 75P as well as upper and lower whiskers and outliers. The defined limit of RUL is 500 years.



Figure 16: Box plot

illustrating median (line in the box), 25P (left box end), and 75P (right box end), whiskers (vertical dark lines), and outliers (tiny bright lines) for the cases: 1) without inspection, 2) with inspection and detection, and 3) with inspection and no detection

In Figure 16 a box plot is used to clearly illustrate outliers. Outliers occur before and after the defined limit of 500 years (bright dotted line). The boxes show the median values (dark line in the box) and frame the 25P and 75P (which are not further discussed here). The outliers are plotted as tiny bright lines behind the upper whisker, which is illustrated as a dashed bright line ending in a dark vertical line. Lower whisker is seen very close to the zero year line (y-axis). The upper whisker length is defined by 1.5 times the interquartile ranges, which is the 75P minus median value. The upper whisker ends at the maximum data point in this range. Analogy the length of the lower whisker is 1.5 times the difference between median and 25P and ends at the minimum data value in this range. The outliers behind the upper whisker might be result of very small input crack sizes.

In the following table the values displayed in the box plot in Figure 16 are listed. Here is equal to lower whisker.

Table 12: Values for RUL used in boxplots

for case: 1) without inspection, 2) with inspection and detection, and 3) with inspection and no detection

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Upper whisker [years] | Number of outliers | [years] | [years] |
| Case 1:  Without inspection | 339 | 375 | 8085 | 0 |
| Case 2:  With inspection with crack detection | 130 | 214 | 792 | 0 |
| Case 3:  With inspection without crack detection | 337 | 240 | 1098 | 5 |

To discuss the results before and after inspection the values in Table 12 are used. Case 2 (with crack detection) and case 3 (without crack detection) are presented compared to case 1 without inspection. Noticeable are the high values for maximum RUL in all three cases. Case 1 reaches 8085 years, which is not a realistic value for practicable lifetime extension, as mentioned before.

**Case 2**: The upper whisker is no more than half the size of those in case 1 and 3. The number of outliers is reduced by 43%. It is illustrated that the maximum value for RUL is strongly reduced by 90%. This can be explained by the flatter tail of the distribution curve in case 2 (cf. Figure 15). For detecting large cracks the estimation can result in zero years of RUL (lower whisker).

**Case 3**: The upper whisker is about 2 years smaller than the whisker in case 1. The number of outliers is reduced by 36% compared to the number of outliers in case 1. Maximum RUL shows a reduction by 87%. The minimum RUL is 5 years. This is a result of the event of no detection, which contains the possibility of ‘no crack existence’.

Outliers in RUL distribution mainly result from very small crack size values. The presented reductions in whiskers, outliers and maximum RULs clarify lower uncertainties after an underwater inspection. Expressiveness for case 2 is higher compared to case 3, which shows only slight decreases of uncertainties.

Conclusive it can be said, that inspection independent of the detection result lowers uncertainties in the evaluation of RULs. This effect illustrated in the box plot comparison. Additional inspections would lower uncertainties even more, but this is not considered in the presented thesis.

## Sensitivity study by means of DoE study

In the following section a sensitivity study is made, to discuss the influence of input parameter on the results. With DoE studies effects on crack size and RUL due to variations in ,, and can be analyzed. As mentioned before for , , and the 10P, median and 90P values are chosen to calculate variating only one input parameter (cf. chapter 3.3.4).

**Influence of input parameters on crack size**

The following figure shows effects of variating input values on crack size after 20 years of operating. The y-axis illustrates the crack size from zero to 0.3 mm. The x-axis show , and in each case for 10P, median and 90P.



Figure 17: Influence of distributed parameters ,, and on crack size

. The figure shows fitted curves through the -values for 10P, median, and 90P for the parameters: (left plot), (middle plot), (right plot)

In Figure 17 the deviation of the three input parameters ,, and is shown around the median value (0.046 mm). Fitted curves run through the -values for 10P, median and 90P for each variating parameter.

**Influence of** : Here the variation of initial crack size is demonstrate, which is around 0.25 mm (from 0.005 mm for and 0.26 for ). The high impact of increasing crack sizes becomes significantly clear.

**Influence of** : The influence of geometry parameter on crack size is about 0.02 mm. With crack size results in 0.04 mm and with .in 0.06 mm.

**Influence of** : The crack growth parameter has a slight influence of only 0.01 mm. The crack size is 0.04 mm for and comes to 0.05 mm for .

The influences of and are more than ten times smaller compared to the effect of initial crack size .

**Indirect influence of input parameters on RUL**

Crack sizes from the DoE study above result in the following RULs. RUL is shown on the y-axis from zero to 260 years. The x-axis illustrates 10P, median, and 90P of the variating input parameter. The influence of ,, and discussed now, is called ‘indirect influence’. Input parameters effect , which is used to calculated RULs, but not directly influence RUL estimations.



Figure 18: Indirect influence of distributed parameters ,, and on RUL

with from DoE study (without inspection). Fitted curves go through the RUL values for 10P, median, and 90P for the parameters: (left plot), (middle plot), (right plot)

The median value for RUL in Figure 18 is in each case 74.42 years. Though the RULs values fitted curves are plotted to show the curve progression from 10P to 90P in each parameter variation.

**Influence of** : RUL maximum results in 250.73 years for initial crack size and minimum in 27.98 years for .

**Influence of** : The influence of geometry parameter on RUL is about 16 years. With RUL results in 81.27 years and with .in 65.28 years.

**Influence of** : The crack growth parameter has a slight influence of only 3 years. The RUL comes to 76.12 years and to 72.75 years for .

**Direct influence of input parameters on RUL**

In the next section the ‘direct influence’ of input parameters on RUL is discussed. Therefore, for crack size a minimum (10P), median (50P), and maximum (90P) value are chosen. Material and geometry parameter and stay as mentioned before. The following table presents crack size values after 20 years.

Table 13: Minimum, median, and maximum value for crack size

for case 1) without inspection

|  |  |  |  |
| --- | --- | --- | --- |
|  | Minimum  Percentile 10P | Median 50  Percentile 50P | Maximum  Percentile 90P |
| Crack size |  |  |  |

In this evaluation the crack size values in Table 13 are already influenced by and . The following figure illustrates the direct effect on RULs of variating input values , , and .



Figure 19: Direct influence of distributed parameters ,, and on the RUL

(case 1). Fitted curves go through the RUL values for 10P, median, and 90P for the parameters: (left plot), (middle plot), (right plot)

In Figure 19 the effect of the three input parameters ,, and is shown by means of fitted curves around the median RUL value, which is 74.24 years.

**Influence of** : Here the variation of crack size is demonstrated, which is around 240 years (from 9.35 years for and 249.93 years for ). The high impact of increasing crack sizes becomes significantly clear. The variance is about 17 years higher compared to the influence of initial crack size .

**Influence of** : The influence of geometry parameter on RUL is about +38/‑24 years from 112.94 years for and 50.95 years for . With the direct influence of the variance increases from 16 years to 62 years.

**Influence of** : The crack growth parameter shows a variation of only four years. The RUL is 81.15 years for and comes to 68.54 years for . The variance is here 10 years higher than in the case of indirect influence.

Compared with the effect of the crack sizes and , the influences of and are much lower. Figure 18 and Figure 19 also illustrate the decrease of RUL with higher percentile of input parameter values. Direct influences of variating input parameters affect RULs more than indirect influences.

**Qualitative direct influence of input parameter in case 2 & 3**

To show qualitatively the influence of variating input parameters in case 2 and 3 the following figures are used. Here only the direct influence on RULs is presented.



Figure 20: Direct influence of distributed parameters ,, and on the RUL

(case 2). Fitted curves go through RUL values for 10P, median, and 90P for the parameters: (left plot), (middle plot), (right plot)

In case 2 (cf. Figure 20) the range between 10P and 90P values around median (33 years) is smaller compared to the ranges in case 1. This implies that 10P and 90P of the parameters have lower influences on RULs. The effect of and on RULs is still smaller than the influence of crack size . But the relation of the influence of crack size to geometry parameter decreases compared to the relation in case 1 – analogously for the relation of the influence of crack size to crack growth parameter. Therefore, it can be said, that variations in and are more significant for predictions of RUL.



Figure 21: Direct influence of distributed parameters ,, and on the RUL

(case 3). Fitted curves go through the RUL values for 10P, median, and 90P for the parameters: (left plot), (middle plot), (right plot)

Case 3 shows the same trend as case 1: variations in crack size have a high influence on RUL results, whereas and show a smaller effect on RULs.

**Uncertainties of other input parameters**

Input values are recommendations from literature. Some input parameters are implemented with distributions, whereas others come as deterministic values. Uncertainties from deterministic parameters are not considered but might also have influences on the results. As soon as experimental or measurement data are available parameters should be adapted to optimize RUL estimations.

Due to the dependency of **material parameter**  and , is defined as a deterministic value without uncertainties. The influence on RUL due to variating values can be assumed proportional to the influence of, since the unit of is [].

Variations in **weather data** influences the aero- and hydrodynamic loads, these uncertainties are not considered in the presented work.

For longer **design lifetimes** (n > 20 years) the RULs are reduced one-to-one by the remaining years. For design lifetimes shorter than 20 years the RULs are extended by the years, which design lifetime is shorter. For example if design lifetime is 18 years, which is 2 years ( years) shorter than the assumed and RUL is 75 years, RUL would be 2 years longer (77 years). This also applies for design lifetimes longer than :  years results in RUL years.

Another impact on RUL has the **critical crack size** . With smaller failure crack sizes RULs decrease.

Crack growth and RUL model does not represent reality exactly. **Model uncertainties** influence the results and cannot be predicted with accuracy. In the following chapter limitations and simplifications for the simulation model are mentioned.

## Limitations

The presented results in this work reflect only estimations due to fatigue crack growth based on literature values. Nevertheless, the evaluated outputs give a proficient review of possible lifetime extension due to inspection linked with fracture mechanics simulation tools. In this thesis analysis are made only for the reference wind turbine (NREL 5MW) in water depth of 20 m. Results can not applied one-to-one to other turbines, structures and water depths. For practical implementation each case must be considered in particular, depending on external conditions and influences. Moreover, all possible occurring load cases must be considered.

Simplifications and assumptions are made for the RUL estimation model. Some are not unavoidable due to missing data or experiences. Some are just simplifications to provide an efficient implementation of the thesis’ scope and requirements. In the following the main limitations are mentioned:

1. **Aero- and hydrodynamic loads simulated by FEM**

As mentioned in chapter 2.4 the weather data are provided by the *European Center for Medium-Range Weather Forecasts* to simulate aero- and hydrodynamic loads acting on the turbine by means of FEM simulation. Simulated loadings in general do not represent real loads.

1. **Load case: Fatigue crack propagation**

Failures from other than fatigue loads resulting in crack propagation are not considered in this thesis. Extreme loads are neglected, because the assumption that environmental conditions are more benign than original design [1].

1. **Hot spot: mudline**

In the presented work the weld seam at the mudline is assumend as the critical hot spot, where critical fatigue cracks occure. This might not result in the most conservative solution. Nevertheless, it can be assumed that the welding toe at the mudline is in the regarded case one of the crucial hot spots [2].

1. **Monte Carlo simulation with a finite number of runs**

Due to time and computational limits Monte Carlo simulation can only run with a finte number. For this thesis the runs for crack size distribution is limited to 30,000 whereas the number of runs for RUL calcultion is limited to 5,000.

1. **Integrated solution of Paris’ Law**

To save simulation time Paris’ Law is solved by integration. Herefore, the provided weather data is sorted in bins and a mean value per bin is appraised. The error deviation changes depending on the bin size. The higher the bin width the greater the deviation. With the chosen bin width of 1 MPa deviation is lower than 1%.

1. **Simplifications in benefit analysis for ITs**

The decision matrix is defined by three exemplary criteria and weighted with a scoring system of three step ranges to illustrate the procedure of selecting one convenient IT for the considered case. In this thesis only the EC technique is mentioned.

1. **Assumptions in time and result of inspection**

In the considered case one inspection is made after 20 years of lifetime. Many inspections (with different ITs) result in more conclusive statements about the current status of OWTs. The PoD is assumed by an equation, which does not reflect real inspection results exactly.

## Industrial implementation and scientific value

Lifetime extension becomes very appealing for industrial implementation, since the first offshore windfarms exceed the end of their design lifetimes. Estimations of RULs based on fatigue crack inspection and uncertainties in various input parameters cannot provide complete reliable recommendations for practical implementation. Nonetheless, windfarm operators profit of additional information about structure conditions due to inspection results. Those outcomes supplement the theoretical assumptions and approaches about crack propagation and RUL estimations. The theoretical approach to estimate RULs after inspection can be further developed by means of test and measurement data. Percentile statements can be used for further decisions about inspection planning and thus, in turn about lifetime extension or repowering.

The scientific advantage of the thesis is given in linking a stochastic crack propagation model with uncertain outcomes of underwater inspection to show the reduction of uncertainties. The implementation of the Bayes Theorem to link a crack propagation model with uncertain underwater inspection outcomes to estimate RULs of monopile-based OWTs is the novelity of this work.

# Conclusion and recommendations

To pick up the crucial question concerning lifetime extension of OWTs a recapping conclusion of the thesis is given in this chapter. Statements about RULs with regard to **fatigue crack failure** are presented in this work. Feasibility of **inspection techniques** under seawater conditions are discussed, resulting in several ITs like EC, UT, and VI.

With defined input values a provided crack simulation model is further developed to a stochastic analysis tool. By saving simulation time with the integrated solution of Paris’ Law a MC simulation can easily implemented to realize distributed results containing uncertainties. Conditional probabilities are used to link theoretical results with the PoD after inspection. With the **stochastic crack simulation model** RULs are calculated and estimated under consideration of inspection. By means of the Bayes Theorem crack growth distribution is linked with inspection outputs to update RULs calculation.

The results meet the expectations that with inspection crack size distribution changes depending on the event of detection. For crack detection during inspection RUL decreases to a median value of 33 years and P90 is reduced by 67%. For no crack detection during inspection RUL increases to a median value of 81 years and P90 is reduced by 7%. Decreasing uncertainties are also clarified by the reduced number of outliers. The reduction is 43% for crack detection and 36% for no crack detection compared to the number of outliers without inspection.

Conclusive, the additional information from inspection outcomes, indicating **reduced uncertainties** and **higher representativeness of RULs,** are presented in this thesis. Predictions about lifetime extension of monopile-based OWTs are made with regard to fatigue crack growth at mudline welding toes and underwater inspection. It is shown, that RUL reacts very sensitive to variations in crack sizes. However, during inspection larger cracks are more likely to be detected, since their PoD is higher. This in turn, delivers enhanced expressiveness of RUL predictions.

As a key result, the thesis emphasizes the added value of inspection by increasing representativeness of additional lifetime predictions after inspection. For operators of offshore windfarms inspection is inevitable if lifetime extension is planned.

**Recommendations**

The following further perspectives could supply the examined approaches. In the following four recommendations are given for future works:

1. **Consideration of other fatigue load cases and hot spots including variation of other parameters**

In the presented thesis only RUL based on fatigue growth is considered. A first step in further works is the implementation of all possible fatigue load cases. Recommended is the evaluation of all critical hot spots. The input parameters for the calculation model should be adapted depending on environmental conditions, turbine type or empirical data, if tests or practical implementation are available.

1. **Comparison with all ITs and implementation of PoS**

For a qualitative statement of feasibility and reliability of ITs, the methods have to be evaluated individually depending on the examined case. Assessment criteria and the benefit-analyses by means of a decision matrix must be adapted. The recommended next step is the implementation of PoS as well as the consequences of a second or more under water inspections after the results of first inspections are known.

1. **Additional structural monitoring**

A review of monitoring methods for offshore monopiles as an alternative or as an additional requirement for inspections techniques is recommended. Friedmann et al. [15, 16] shows technologies for underwater inspection by means of condition or structural health monitoring.

1. **Cost evaluation (reliability)**

Cost evaluation of the mentioned ITs and a development of an economic model that allows to link ITs to costs of lifetime extension is strongly advised, if it comes to practical implementation. This model should allow the link of ITs to costs of lifetime extension and should help in deciding on optimal methods for structural reassessment.

At last, for comprehensive predictions the economic and safety aspects has to be considered individually to assess lifetime extension. The economic and safety part is left for future work.

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|  |  |
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# Appendix

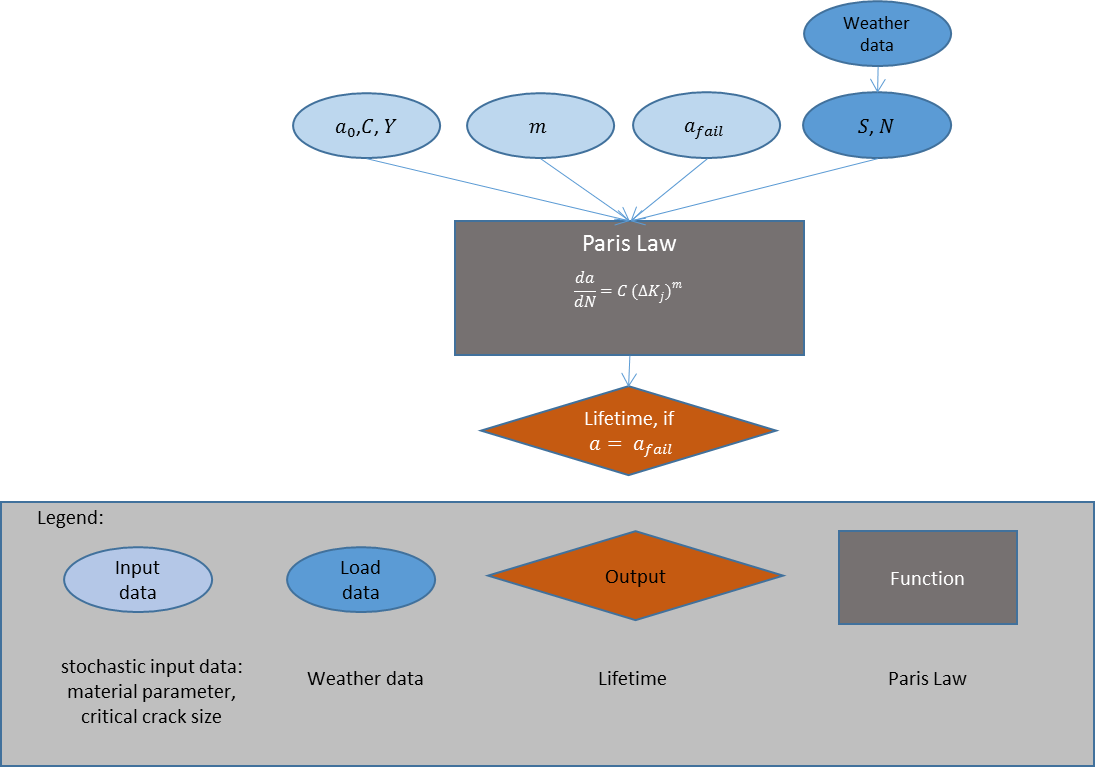


Figure 22: Flow diagram of the existing simulation tool

to analyze lifetime if crack size reaches

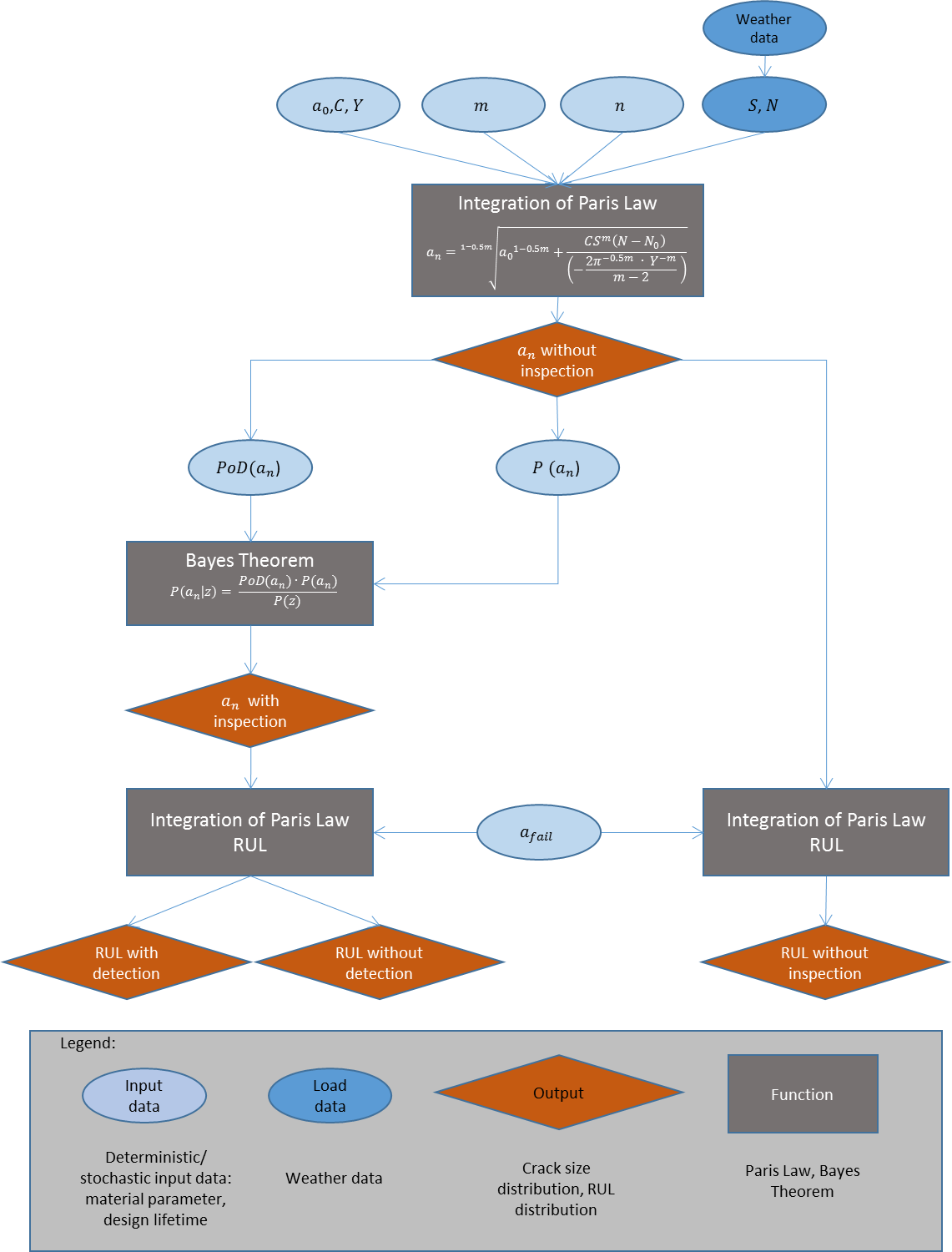


Figure 23: Flow diagram of the further developed simulation tool

to analyze crack size distribution after years and RUL distribution depending on inspection outcomes

# Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

This thesis was not previously presented to another examination board and has not been published.

Stuttgart, 08/15/2016

Date Jutta Stutzmann

1. For a practical implementation all methods on the current market should be considered. See more details about inspection techniques at [4, 8, 9, 10]. [↑](#footnote-ref-1)
2. Holzmüller [25] presented 2015 an expert varification management to estimate RULs for onshore wind turbines based on design strength calculations. Here, Holzmüller [25] estimate RULs for onshore wind turbines of 5 to 9 years. Based on this reference, lifetime extension of 5 years for OWT is assumed. [↑](#footnote-ref-2)