Simon Ambühl

Reliability of Wave Energy Converters

Revised Version

PhD Thesis defended at Aalborg University,
Department of Civil Engineering

River Publishers

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Preface

The work presented in this dissertation is part of the 'Structural Design of Wave Energy Devices (SDWED)' project supported by the Danish Council for Strategic Research (Contract 09-67257). The financial support was greatly appreciated. The work was carried out at the Department of Civil Engineering, Aalborg University, Denmark.

When I finished my master studies about Fluid Dynamics and Renewable Energy Technologies at ETH Zurich in 2011, I started to look for PhD opportunities abroad in order to join another university and to get new personal as well as professional experience. Professor John Dalsgaard Sørensen and Associate Professor Jens Peter Kofoed offered me a PhD position at Aalborg University in the field of structural reliability in connection with wave energy converters. With that opportunity I trod new ground.

The three years of PhD passed quickly and they did not leave a lot of time for excursions. The limited time forced me to stay firmly to the study plan and to the agreements we made at the beginning of my PhD. But after these intensive three years I can say that personally as well as professionally I have made large steps forward and my expectations before starting the PhD have been achieved. The time during this PhD was very interesting and inspiring for me.

Acknowledgements

This work would not have been possible without the support of many people.

First I would like to thank my supervisor Professor John Dalsgaard Sørensen for his advice, encouragement and guidance during my work. His knowledge has been a great inspiration to me. Thanks also go to Associate Professor Jens Peter Kofoed for the support concerning the wave energy sector. Furthermore, I would like to thank Associate Professor Morten Kramer for organising the collaboration with Wavestar A/S and for the helpful discussions about the technical background of this kind of device. Also, thanks to our contacts from DNV-GL, especially Claudio F. Bittencourt, for sharing their knowledge about wave energy devices and for showing the problems from an industrial perspective.

Thanks to my colleagues at the Department of Civil Engineering for the fruitful discussions we had during the 10 o'clock break and the time we spent together during our spare time. Also, many thanks to the secretary staff at the department, who made it a warm welcome when starting the PhD and helped me a lot with different paperwork.

Last, but not least, I would like to thank my wife, Lea, who supported me whenever needed, and my family, who always made me feel home when I was back in Switzerland.

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Simon Ambühl

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John Dalsgaard Sørensen

List of published papers:

Papers included in the appendix of the thesis :

1. Ambühl, S., Kofoed, J.P. and J.D. Sørensen. 2014. ”Stochastic Modeling of Long-term and Extreme Value Estimation of Wind and Sea Conditions for Probabilistic Reliability Assessments of Wave Energy Devices.” *Ocean Engineering.* 89 (2014): 243-255. DOI: 10.1016/j.oceaneng.2014.08.010.
2. Ambühl, S., Kramer, M., Kofoed, J.P., Bittencourt Ferreira, C. and J.D. Sørensen. 2013. ”Reliability Assessment of Wave Energy Devices.” 11th International Conference on Structural Safety and Reliability (ICOSSAR) 2013, New York, USA.
3. Ambühl, S., Ferri, F., Kofoed, J.P. and J.D. Sørensen. 2015. ”Fatigue Reliability and Calibration of Fatigue Design Factors of Wave Energy Converters.” *International Journal of Marine Energy.* 10 (2015): 17-38. DOI: 10.1016/j.ijome.2015.01.004.
4. Ambühl, S., Sterndorff, M. and J.D. Sørensen. 2014. ”Extrapolation of Extreme Response for Different Mooring Line Systems of Floating Wave Energy Converters.” *International Journal of Marine Energy.* 7 (2014): 1-19. DOI: 10.1016/j.ijome.2014.09.003.
5. Ambühl, S., Marquis, L., Kofoed, J.P. and J.D. Sørensen. 2015. ”Operation and Maintenance Strategies for Wave Energy Converters.” *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability.* Published online. DOI: 10.1177/1748006X15577877.
6. Ambühl, S., Kramer, M. and J.D. Sørensen. 2014. ”Reliability-based Structural Optimization of Wave Energy Converters.” *Energies.* 7 (12): 8178-8200. DOI: 10.3390/en7128178.

Other papers:

7. Ambühl, S., Kramer, M., Kofoed, J.P. and J.D. Sørensen. 2012. ”Reliability Assessment of Wave Energy Devices.” 4th International Conference on Ocean Energy (ICOE), Dublin, Ireland.
8. Ferri, F., Ambühl, S., Fischer, B. and J.P. Kofoed. 2014. ”Balancing Power Output and Structural Fatigue of Wave Energy Converters by Means of Control Strategies.” *Energies.* 7 (4): 2246-2273. DOI: 10.3390/en7042246.
9. Ambühl, S., Kofoed, J.P. and J.D. Sørensen. 2013. ”Influence of Wave State Uncertainties on Probabilistic Reliability Assessments of Wave Energy Devices.” 10th European Wave and Tidal Energy Conference (EWTEC) 2013, Aalborg, Denmark.
10. Ambühl, S., Kofoed, J.P. and J.D. Sørensen. 2014. ”Determination of Wave Model Uncertainties used for Probabilistic Reliability Assessments of Wave Energy Devices.” 23rd International Society of Offshore and Polar Engineers (ISOPE) Conference, Busan, South Korea.
11. Ambühl, S., Kofoed, J.P. and J.D. Sørensen. 2015. ”Quantification of Wave Model Uncertainties used for Probabilistic Reliability Assessments of Wave Energy Converters.” *Journal of Ocean and Wind Energy (JOWE).* 2(2): 98-106. DOI: 10.17736/jowe.2015.ilr03.

This thesis has been submitted for assessment in partial fulfillment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available at the faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

Summary

There are many different working principles for wave energy converters (WECs) which are used to produce electricity from waves. In order for WECs to become successful and more competitive to other renewable electricity sources, the consideration of the structural reliability of WECs is essential. Structural reliability considerations and optimizations impact operation and maintenance (O&M) costs as well as the initial investment costs. Furthermore, there is a control system for WEC applications which defines the harvested energy but also the loads onto the structure. Therefore, extreme loads but also fatigue loads are important to the structural designs of WEC devices. The extreme loads on WEC structures during extreme environmental conditions can be limited by moving the device in storm protection/idle mode where no electricity is produced.

Structural reliability assessments use a probabilistic approach that includes uncertainties related to the limited amount of data and the considered models used to calculate the loads/stresses as well as uncertainties given by Mother Nature (e.g. inter-annual variation of extreme values) and measurement uncertainties.

Due to limited amount of knowledge, reliability considerations for WEC structures are mainly based on experiences from offshore wind turbines as well as structures used in oil and gas industry. But nevertheless, WEC-specific uncertainties need to be quantified, and the required structural reliability levels, which are important to e.g. the calibration of safety factors, need to be defined for WEC applications.

O&M operations can be performed preventively or correctively. Access to the device can be by boat, which is cheaper, but takes longer and is limited by the wave characteristics or by helicopter, which is more expensive but faster than by boat, and is also constricted to small cargo and its operation is limited by the wind speed.

Many WECs have a storm protection mode/idle mode where the extreme loads during extreme environmental conditions are minimized. Therefore, extreme loads may occur during operation where electricity is produced. Hence, loads during operation can be extrapolated to extreme loads during operation. The control system mainly drives fatigue loads during operational mode. Since WEC devices are unmanned and have limited access (mainly during winter months) due to strong environmental conditions, failure modes where electrical/mechanical components as well as the control system fail and lead to abnormal loads onto the structure should also be accounted for in the structural design.

Before using a probabilistic reliability approach to start optimizing WEC structures, WEC-specific uncertainties need to be found and quantified. This thesis quantifies the uncertainties related to the wave and wind condition assessments as well as the uncertainties linked to long-term and extreme environmental modeling. Different ultimate limit states as well as fatigue limit states are considered in various papers. The study will estimate the influence of system failure (failure of electrical/mechanical components or the control system) in structural design considering the most critical system failure modes of the Wavestar device. Furthermore, extreme mooring loads are extrapolated from measurements of the lab-scaled floating WEC WEPTOS. Calibration of safety factors are performed for welded structures at the Wavestar device including different control systems for harvesting energy from waves. In addition, a case study of different O&M strategies for WECs is discussed, and an example of reliability-based structural optimization of the Wavestar foundation is presented.

The work performed in this thesis focuses on the Wavestar and WEPTOS WEC devices which are only two working principles out of a large diversity. Therefore, in order to gain general statements and give advice for standards for structural WEC designs, more working principles should be investigated using the methodologies presented in this thesis.

Summary in Danish

Der findes mange forskellige funktionsprincipper for bølgekraftanlæg, som producerer strøm fra bølgerne. For at anlæggene kan få succes og blive mere konkurrencedygtige med andre vedvarende elektricitetskilder, er overvejelsen af bølgekraftanlægges strukturelle pålidelighed meget vigtigt. Overvejelsen af den strukturelle pålidelighed og optimering påvirker drift og vedligeholdelsesomkostningerne samt de initiale investeringsomkostninger. Desuden er der et kontrolsystem for bølgekraftanlæg, som definerer høstet energi men også strukturelle belastninger. Derfor er ekstreme belastninger men også udmattelseslaster vigtige for det strukturelle design af bølgekraftanlægget. Ekstreme belastninger på strukturen i stormvejr kan begrænses når anlægget sættes i stormbeskyttelse/tomgang modus hvor der ikke produceres strøm.

Strukturelle pålidelighedsevalueringer bruger en probabilistisk tilgang der typisk inkluderer usikkerheder der er relateret til en begrænsede datamængde og modellerne der bruges til at beregne belastninger/spændinger samt usikkerheder givet ved moder natur (f.eks. årlige variation af ekstreme værdier) og måleusikkerheder.

På grund af begrænset viden er pålidelighedsbetragtninger af bølgekraftanlægs strukturer primært baseret på erfaringer fra havvindmøller og olie- og gasindustrien. Men specifikke bølgekraftanlægs usikkerheder skal kvantificeres, og de krævede pålidelighedsniveauer af strukturen, som f.eks. er vigtige for kalibrering af sikkerhedsfaktorerne, skal fastlægges for anvendelse af bølgekraftanlæg.

Beslutninger omkring drift og vedligehold kan være præventiv eller korrektiv. Adgang til anlægget kan være med båd som er billigere men tager længere tid og er begrænset til bølgekarakteristika, eller med helikopter som er dyrere men hurtigere end med båden men begrænset af vindhastigheden.

Mange bølgekraftanlæg har en stormbeskyttelse/tomgang modus hvor de ekstreme belastninger under ekstreme stormbetingelser bliver minimeret. Derfor kan ekstreme belastninger forekomme under driften, hvor ekstreme belastninger under drift kan estimeres ved extrapolation fra almindelige belastninger under drift. Kontrolsystemet påvirker primært udmattelseslaster under drift hvor anlægget producerer strøm. Da bølgekraftanlæg er ubemandede og adgangen er begrænset (især i vintermånederne) på grund af for høje vindhastigheder eller høje bølger, bør man tage hensyn til fejl situationer hvor elektriske/mekaniske komponenter og kontrolsystemet fejler og fører til store belastninger på strukturen i betragtning i det strukturelle design.

Før man starter med en probabilistisk tilgang på de strukturelle optimeringer af bølgekraftanlæg, skal de specifikke usikkerheder for bølgekraftanlæg findes og kvantificeres. Denne afhandling kvantificerer usikkerhederne relateret til bølge- og vindbetingelser og usikkerheder forbundet med modellering af langtids og ekstreme betingelser. Forskellige brudgrænsetilstande knyttet til ekstreme belastninger eller udmattelseslaster er betragtet i forskellige artikler. Der gives et skøn på indflydelsen af systemfejl (fejl af elektrisk/mekanisk komponent eller kontrolsystemet) på strukturelt design ved betragtning af de mest kritiske systemfejl for Wavestar-anlægget. Desuden er ekstrem fortøjningsbelastninger ekstrapoleret fra målte data fra WEPTOS-anlægget i laboratoriet. Kalibrering af sikkerhedsfaktorer er udført for svejste stål konstruktioner på Wavestar-anlægget for forskellige kontrolalgoritmer som definerer høstede energi fra bølgerne. Endvidere diskuteres et studie af forskellige drift og vedligeholdelses aktioner/muligheder for bølgekraftværker og et eksempel af pålidelighedsbaseret strukturel optimering af Wavestars fundering beskrives.

Arbejdet i denne Ph.D.-afhandling fokuserer på Wavestar og WEPTOS bølgekraftværkerne som er kun to funktionsprincipper ud af en stor diversitet. For at opnå mere generelle erfaringer, der kan implementeres i standarder for design af strukturelle bølgekraftværkskonstruktioner, bør flere funktionsprincipper undersøges ved hjælp med metoderne, der er præsenteret i denne afhandling.

Contents

Chapter 1

Introduction

The living standards are getting higher in developed countries. With higher living standards, the energy demand is also expected to increase. Furthermore, developing countries like China and India are asking for more energy leading to a very high growth in energy consumption. The primary energy demand is expected to increase by 41 % between 2012 and 2035 based on [17]. Primary energy covers the energy form that is found in nature and not subjected to any conversion or transmission process.

Nowadays, most of the energy demand is covered by fossil fuels. But in the far future, fossil fuels might be depleted, and political discussions are ongoing about reducing pollution linked to the burning of fossil fuels. Different studies and investigations [17, 119, 51] show that electricity, which contributes to transportation, power supply in households and the industry, will become an important energy form in the future. In 2012, 42 % of the primary energy is converted into electricity and, according to [17], this number is expected to rise to 46 % by 2035.

Today, electricity is mainly produced from coal, hydro, natural gas and nuclear sources. Figure 1.1 shows the trends of how the sources for power production are expected to be in the future. It is expected that the use of coal as well as nuclear power plants will lessen in the future due to high pollution (coal) as well as the severe consequences in case of failures (nuclear). In order to cover the increasing demand and decreased power production of today's large electricity sources, renewable energy sources are expected to increase. The global power production from renewables is expected to reach 13 % in 2035 [17].

Renewable electricity sources used today are wind, solar, geothermal and biomass. Other renewable electricity sources which are not used today on a grand scale include waves and tides. The challenge when using renewables for electricity supply is their unsteady electricity production rate, which is not easy to adapt to the varying electricity demand. Electricity from wind can only be produced when the wind is blowing, and waves can only be used for electricity production when there are waves. But with the use of different renewable sources and their combination, coverage of the electricity demand at any time can to a higher degree be guaranteed.

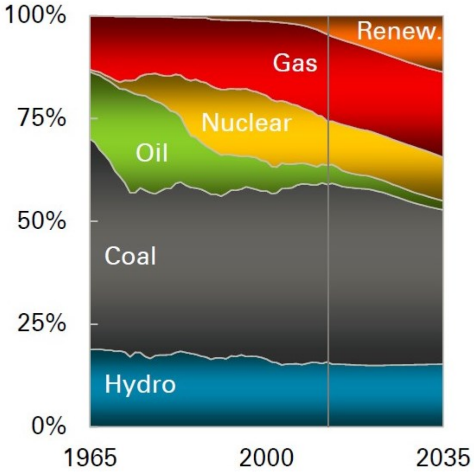


Figure 1.1: Expected development of primary energy sources.
[17]

Wave energy is a large source for harvesting power. According to [46], the total wave energy resource is equal to 32,000 TWh/y, which is more than the annual electricity consumption in 2012 (19,090 TWh/y, [21]). A more detailed wave resource assessment is given in [82] where locations with low energy resources (lower than 5 kW/m) and areas impacted by ice are removed from the wave power resource. This assessment leads to a theoretically useable wave energy resource of 26,150 TWh/y. The amount of electricity produced from waves is negligible so far, but it is expected to increase in the future due to the large source potential, which is according to [23] around 2 TW.

The following section will give a short introduction into existing WEC technologies (section 1.1) as well as general structural designs (section 1.2) which are the two topics combined in this PhD thesis.

1.1 Wave Energy Converter Technology

Wave Energy Converters (WECs), which are also called Wave Energy Devices (WEDs), are used to harvest kinetic and potential energy from waves and transfer them to electricity. Research on how to harvest electricity from waves goes back to the nineteen seventies where the energy sector sought for alternative energy sources during the oil crisis. One of the first wave energy converters was the so-called Salter's Duck [100] developed by Stephen Salter from University of Edinburgh.

Up to now, a large diversity of different working principles were developed. Details about different devices and their actual status are given in [85, 126]. The different devices can e.g. be distinguished by their position as well as the working principle. When talking about different positions, the distance to shore is considered. WECs can be placed:

- onshore (at the coast),
- nearshore, or
- offshore.

It needs to be mentioned that prototypes are often located nearshore in order to have a high accessibility and avoid failure due to extreme loads (minimize risk due to limited knowledge). When it comes to the developed stage, the same working principle might be placed further offshore, where higher wave energy resources can be expected. When considering the different working principles, the most common types of WECs are:

- Wave Activated Body (WAB),
- Oscillating Water Column (OWC), and
- Overtopping systems.

Fig. 1.2 gives examples of the different working principles. WABs contain moving parts, which are directly activated by the cyclic movement of the waves. The kinetic movement of the waves is converted into electric energy. An OWC device uses the heave motion of the waves in order to produce fluctuating air pressure in an air chamber above the water surface. An air turbine is driven by the air flow, which balances the pressure inside the chamber and ambient pressure outside the chamber. Overtopping systems use the kinetic energy of the waves, which is transferred to potential energy when the water moves up a slope and is stored in a reservoir. The stored potential energy can then be released and transferred to electricity using e.g. a turbine.

Furthermore, different configurations of how the WEC is arranged relative to the incoming wave direction can be used for distinction (type specification). The common configurations are:

- Point absorber,
- Attenuators, and
- Terminating devices.

Fig. 1.3 shows how the three different configurations look like in connection with the incoming wave direction. Point absorbers look similar to buoys and make it possible to harvest energy from all different directions. Their heave, surge and pitch movement can be transferred to electricity. Attenuators are arranged parallel to the wave direction and terminators are elongated bodies, which lie perpendicular to the incoming wave direction. Attenuators and terminators need to be adjustable to the wave direction whereas the wave direction is often of minor importance for point absorbers.

So far, no WEC concept has reached the commercial stage. Some devices like Pelamis [91], Wavestar [125], Aquamarine [9] or CETO [20] exist at prototype level. Others (e.g. WEPTOS [128] or Wave Dragon [124]) are

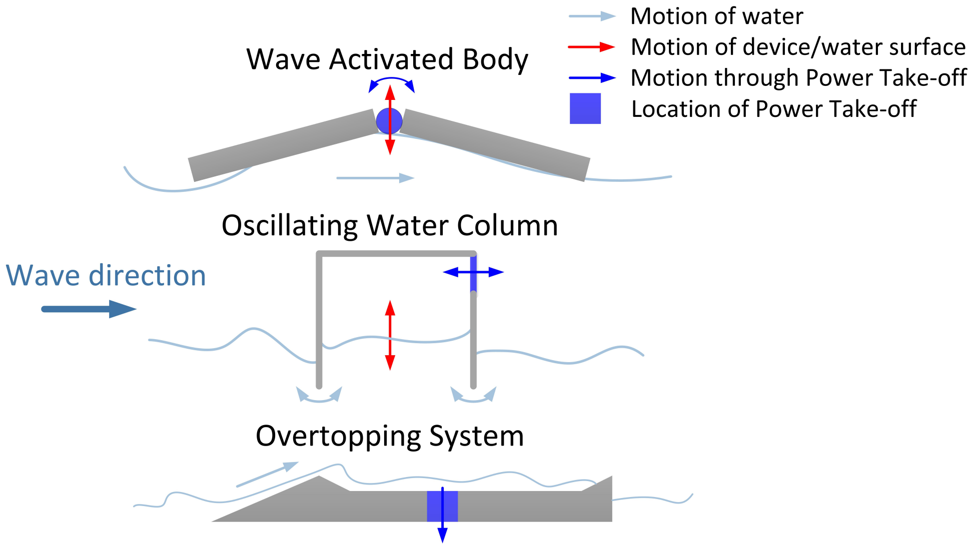


Figure 1.2: Sketch of different working principles of WECs.

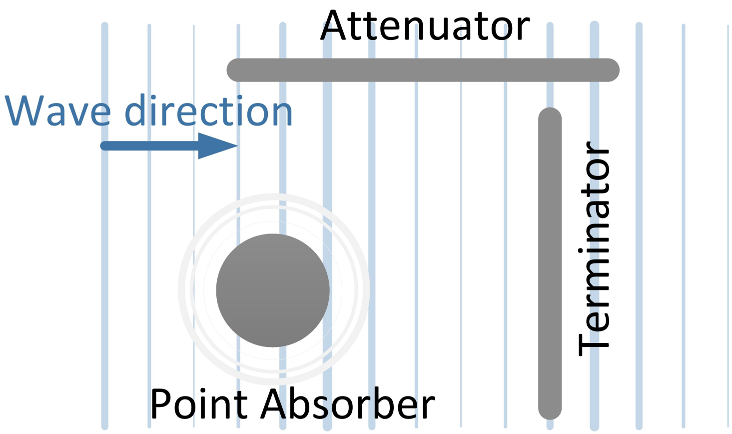


Figure 1.3: Different configurations of WECs according to [23].

developing a real-scale prototype. And there are many devices on lab-scale or even just on paper. An overview about different development stages of Danish WECs as well as WECs from all over the world are summarized in [85]. The huge diversity of different devices makes it a big challenge from a structural standardization point-of-view.
The focus of this PhD thesis is the Wavestar and the WEPTOS devices. The Wavestar device is a WAB point absorber WEC, and the WEPTOS is a WAB attenuator/terminating WEC. Fig. 1.4 shows pictures of the two devices. The Wavestar device exists on prototype level and is placed at Hanstholm (DK). It was installed in September 2009 and was feeding electricity into the grid between January 2010 and September 2013. At the moment, remodelling work on the PTO system is going on. The prototype consists of two floaters, which drive a hydraulic cycle. The hydraulic cycle impels a turbine and a generator. Four piles with gravity-based foundations are used. The piles and the floaters are connected with a platform on which the turbines/generators and safety equipment are located. There is also a control system activated during operation defining the amount of harvested energy from the waves as well as the loads onto the structure. When the wave height is large, the floaters can be taken out of the water in order to reduce the loads onto the structure. This prototype is a two-float section of a planned 20-float device. More information about the Wavestar device can be found in [68, 76].
The WEPTOS device consists of two legs, each holding a certain amount of Salter's Ducks, which drive a common axle and impel a generator located in the front compartments. The lab-scaled prototype had 20 rotors at each leg whereas the updated device consists of 10 rotors at each leg. The WEPTOS device is floating because it needs to weathervane. In order to reduce extreme loads, the opening angle (angle between the two legs) can be adapted between 30 and 120 degrees. More information about the WEPTOS device can be found in [89, 88].

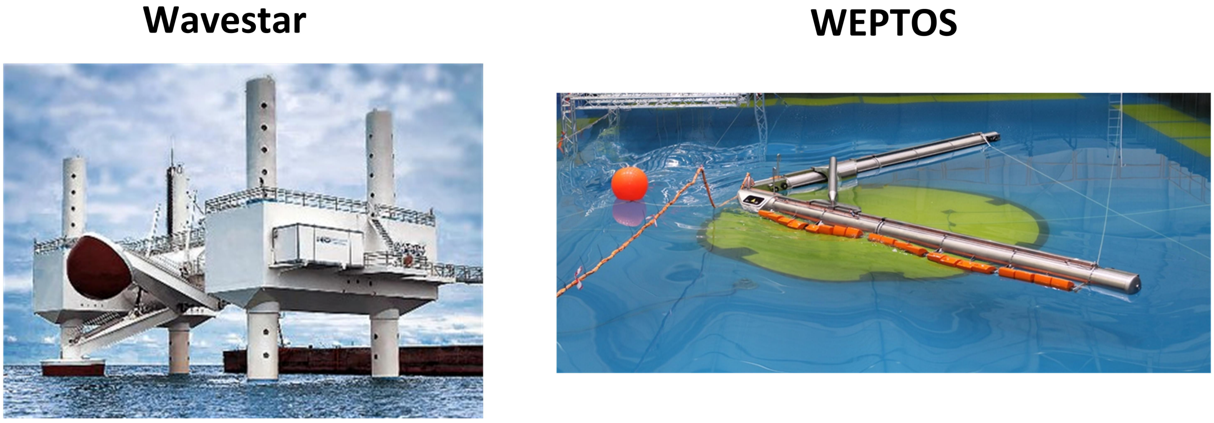


Figure 1.4: Picture of the Wavestar prototype located at Hanstholm (DK) and the lab-scaled WEPTOS WEC.

1.2 Structural Design Criteria

When designing structures, there are generally two different kinds of loads, which may drive the design. There are extreme loads (e.g. from wind or waves), which may lead to failure. But there are also fatigue loads, which may lead to failure of the structure over time. Fatigue loads are of importance for structural parts, which are under cyclic loading and inspections may highly impact its design recommendations. The design of some components of a WEC may be driven by extreme loads and other by fatigue. Fig. 1.5 shows an example of structural parts where the design is driven either by fatigue or extreme loads with focus on the Wavestar device.
What is driven by fatigue and extreme loads depends on the working principle of the WEC. The large diversity of devices makes it difficult to give general recommendations and make it difficult to standardize the structural design.

1.3 Objectives of Thesis

Developing a new technology also makes it necessary to consider the structural reliability related with the new technology. Probabilistic structural reliability assessments of WECs which are considered in this PhD thesis are not performed by the WEC community so far, but are fundamental for driving the development of WECs further and for decreasing the overall costs as well as to be used as basis for safety factors in design standards.

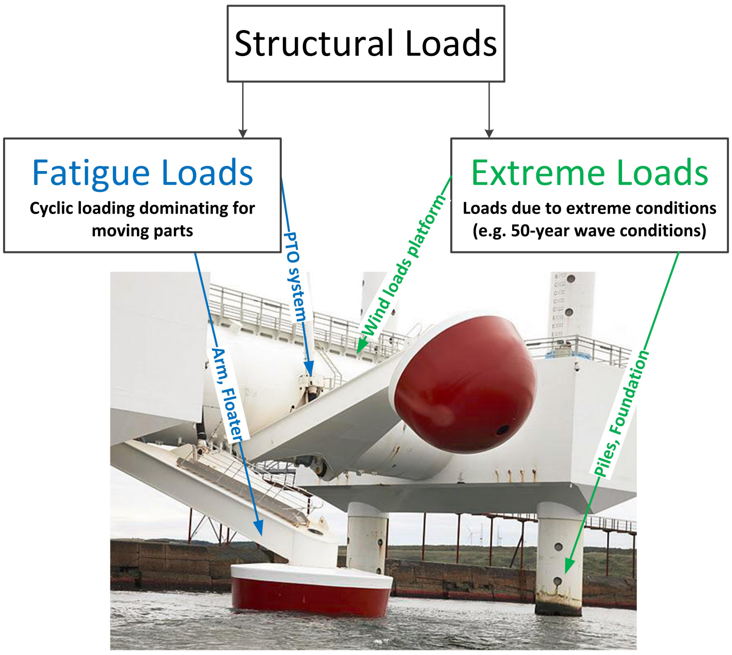


Figure 1.5: Example of Wavestar's structural components, which are either more exposed to fatigue or extreme loads.

This PhD thesis focuses on structural reliability of WECs, where methodologies used in nearby industries like offshore wind turbines or oil and gas steel structures are transferred and adapted to WECs. Furthermore, this work quantifies and focuses on WEC-specific topics and challenges related to probabilistic reliability assessments of WECs. The following objectives are considered in this thesis:

- Formulation of a probabilistic basis for assessment of the reliability of WECs including stochastic modeling of uncertainties.
- Identification and development of methods for estimating the reliability of WECs including the effect of inspections as well as operation and maintenance considerations.
- Discussion of target reliability levels applicable to WEC components.
- Consideration of different limit states like ultimate limit states, fatigue limit states and accidental limit states.
- Approach to calibrate structural safety factors (can be included in structural standards of WECs) on the basis of probabilistic reliability assessments.
- Presentation of a method to extrapolate extreme loads.
- Method to optimize the structure of a WEC using a reliability-based approach.

The thesis only focuses on two different WEC devices. Therefore, the transfer of the results to other working principles is limited. But the presented methodologies can directly be overtaken and be applied to every kind of existing WEC device.

1.4 Thesis Outline

The thesis is organized as a collection of papers, which are presented in the appendices. Fig. 1.6 gives a graphical overview about the entire thesis including to which chapter the different appendices (Papers) belong.
Chapter 1 gives the introduction of the thesis. Chapter 2 provides the theoretical background about probabilistic reliability assessments. Chapter 3 gives an overview about the different types of uncertainties and how they can be quantified. Uncertainties need to be quantified for probabilistic reliability assessments of WEC structures. Together with models for fatigue (Chapter 4), extreme loads or extreme environmental conditions (Chapter 5) as well as different failure modes of WECs (Chapter 6), the quantified uncertainties are used as input for probabilistic reliability assessments of WEC structures. Chapter 7 gives a discussion about target reliability indices, which result

from probabilistic reliability assessments for WEC applications. A further step when optimizing WEC structures is not only focusing on target reliability levels, but using them as a boundary condition and focus on minimizing the overall costs e.g. for maintenance and operation actions as well as the resulting cost of energy, as discussed in Chapter 8. Chapter 9 presents the conclusions and outlook.
The following points are considered in the different papers written by the author during his PhD:

- Uncertainty quantification which are of importance and unique for structural reliability assessments of WECs (Papers 1, 3, 9, 10 and 11).
- Examples of probabilistic structural reliability assessments of WECs (Papers 1, 2, 3, 6, 7, 9, 10 and 11).
- Methodology for including failure of electrical/mechanical components and control system in probabilistic structural reliability assessments (Paper 2).
- Calibration of partial safety factors (Fatigue Design Factor) (Paper 3).
- Method to extrapolate structural extreme loads of WECs (Paper 4).
- Consideration of different operation and maintenance (O&M) strategies for WECs (Paper 5).
- Example of reliability-based structural optimized designs for WEC applications (Paper 6).

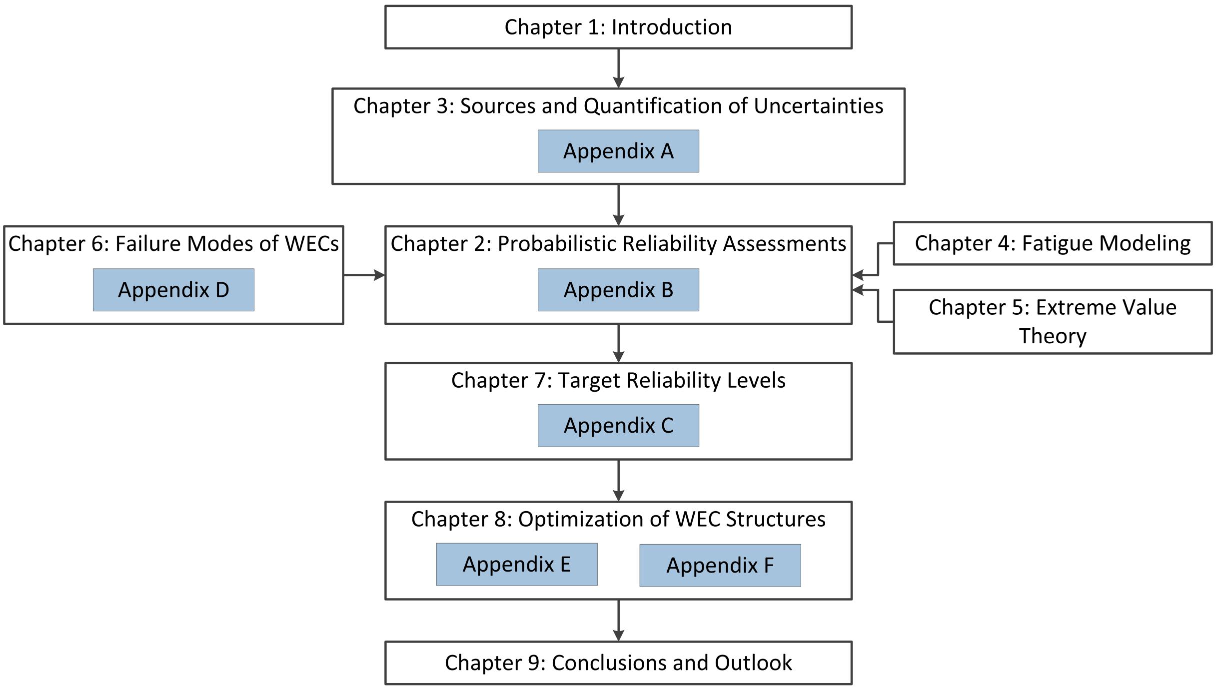


Figure 1.6: Graphical outline of the thesis.

Chapter 2

Probabilistic Reliability Assessment

Engineering designs might be formulated based on the worst conditions (e.g. highest possible wave or smallest expected fatigue life) and other conservative assumptions. Indeed this kind of approach has been the basis for many structural designs. But this approach contains neither information about the related risk nor a measure about the degree of conservativeness. Thus, the resulting design may be excessively costly. Information about the related risk of a certain design as well as a degree of conservativeness can be gained when applying probabilistic reliability assessments [5].

When performing a structural design, one can follow two approaches as shown in Fig. 2.1. One strategy uses a deterministic (semi-probabilistic) approach, where so-called partial safety factors are considered. Deterministic approaches are often proposed by standards in order to simplify the design procedure. The safety factors account for uncertainties, which are not explicitly considered when focusing on deterministic values.

Another design approach, which is used in this thesis and necessary when calibrating safety factors to be used in deterministic structural approaches, is called probabilistic design approach. Probabilistic reliability assessments make it possible to consider parameters as stochastic variables and not as fixed (deterministic) values as well as determination of the probability of failure of a certain structural detail for a certain structural limit state. Stochastic variables make it possible to implement uncertainties related to a certain parameter.

Whether or not a certain probability of failure resulting from a probabilistic reliability assessment of a structural detail can be accepted is based on a risk-based design approach. The risk-based design takes into considerations the consequences in case of failure and is used to define target reliability levels (see section 7).

A general overview about probabilistic reliability assessments is given in [75, 69]. Fig. 2.2 shows the different steps of a probabilistic reliability assessment. The first step considers quantification of uncertainties, which in a

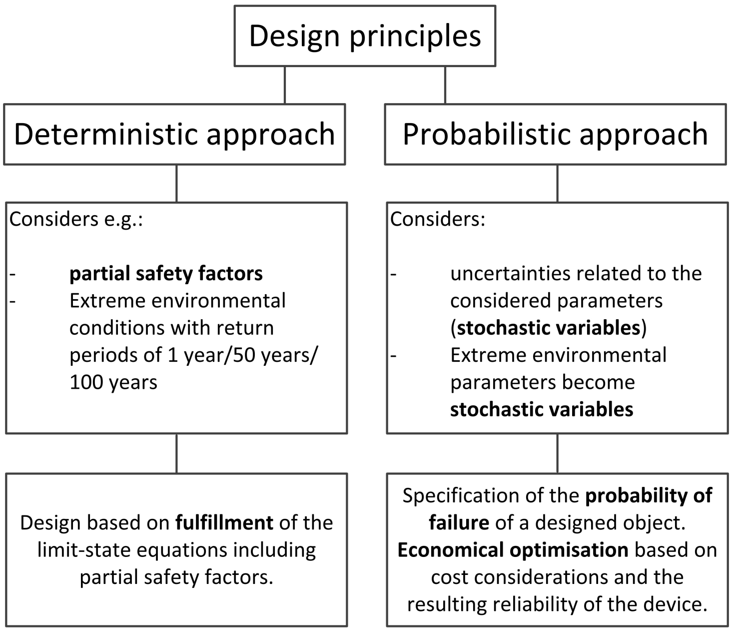


Figure 2.1: Different approaches in order to design a structural component.

second step are used as input for the creation of stochastic variables $\mathbf{X} = \{X_1, X_2, ...\}$. These stochastic variables are used for a certain limit state equation, $g(\mathbf{x})$, which is generally defined as:

$$g(\mathbf{x}) = R(\mathbf{x}) - S(\mathbf{x}) \tag{2.1}$$

where $R(\mathbf{x})$ indicates the resistance and $S(\mathbf{x})$ the load effects (e.g. forces or moments). Failure occurs if the limit state equation is smaller or equal to zero. The vector **x** shows realizations of the stochastic variables **X**.
In order to estimate the probability of failure, P_F, of a structural detail's failure mode one can use Monte Carlo simulations or approximate the probability of failure based on the so-called reliability index β. The reliability index can be transferred to the probability of failure in the following way:

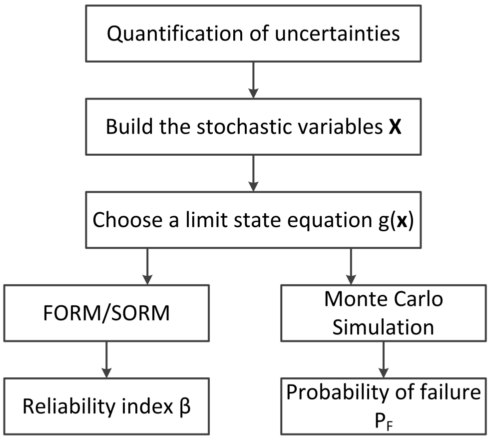


Figure 2.2: Procedure about how to perform a probabilistic reliability assessment. FORM: First Order Reliability Method, SORM: Second Order Reliability Method.

$$P_F(\mathbf{X}) \approx \Phi(-\beta(\mathbf{X})) \tag{2.2}$$

where $\Phi()$ is the standardized normal distribution. Table 2.1 shows the relation between the probability of failure, P_F, and the reliability index β.
First Order Reliability Methods (FORM) as well as Second Order Reliability Methods (SORM) are used to estimate β and are based on a transformation from the real space 'x' to the standard normalized space 'u', where all stochastic variables become normalized and independent. The Rosenblatt transformation [99] or Nataf transformation [83] can be used. Fig. 2.3 shows a sketch of how the probability of failure as well as the reliability index can be estimated in the standardized normal space 'u'. The reliability index β is equal to the distance between the origin and the most probable failure point u^* in the standardized normal space. The direction vector α of the β value indicates the importance of the different stochastic variables.

Table 2.1: Relation between failure probability P_F and the resulting reliability index.

P_F	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}
β	4.7	4.3	3.7	3.1	2.3

Crude Monte Carlo simulations (see e.g. [5]) are based on many random realizations of the limit state equation $g(\mathbf{x})$ and the count of number of realizations with structural failure lead to the probability of failure P_F. The probability of failure from results of a Monte Carlo simulation can be calculated as:

$$P_F = \frac{\text{Number of realizations leading to failure}}{\text{Total number of realizations}} \tag{2.3}$$

A more advanced simulation technique is called Directional Sampling (see e.g. [25, 15]) where a limit state equation is formulated in polar coordinates in the 'u'-space. When some information about the most probable failure point u^* is available, different more effective sampling methods exist, like e.g. Importance Sampling [77]. Other simulation techniques are Conditional Sampling [13], Asymptotic Sampling [19] or Subset Simulation [11].
Probabilistic reliability approaches can be used when the failure mode can be written in a formula, representing the

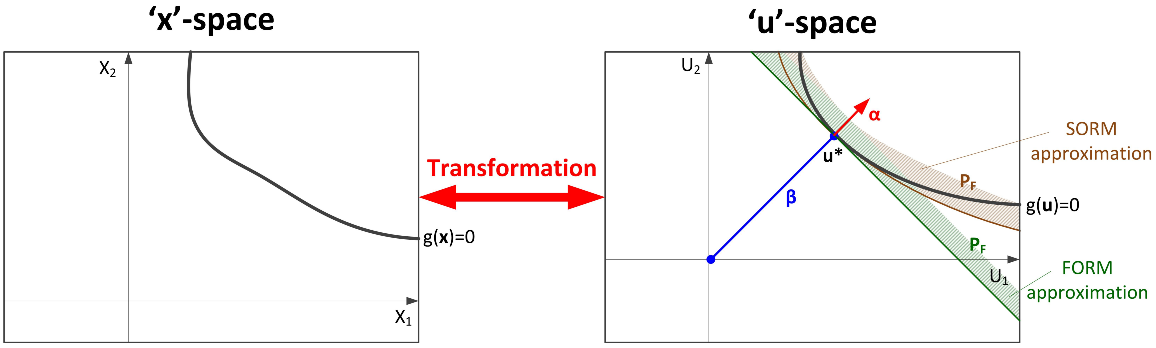


Figure 2.3: Sketch of how the probability of failure is estimated based on FORM and SORM approximations. β: reliability index, P_F: Probability of failure estimated from FORM/SORM approximation, u^*: most probable failure point.

physical reason for failure and the critical failure modes can be identified. For complex systems like e.g an airplane engine which consists of many thousand components, probabilistic reliability approaches will be too complex because there are too many failure modes and often the physical reason for failure is too complex to be written in formulas. Therefore, constant (time-independent) failure rates for the different components are estimated based on observations and testings instead. Furthermore, for off-the-shelf articles, failure rates can be collected and failure databases can be elaborated due to the fact that the product exists many times. The reliability of a certain component can be calculated from the counted failures and is the basis for the so-called classical reliability theory.

There are reliability studies available about WECs [24, 131, 116, 117]. These reliability assessments are performed by assuming a constant/deterministic failure rate of a certain component. Probabilistic design methods are not yet accomplished in the design of WEC structures. A generic outline about how to deal with probabilistic design methods for WECs is given in [109]. Probabilistic reliability assessments are to some extent established in nearby industries like (offshore) wind turbines (see e.g. [108, 118, 111]) or offshore steel structures (see e.g. [52, 80]). There are also some probabilistic reliability studies for tidal turbines [121, 122, 120]. A general guideline for structural reliability assessments is given in [66]. The prevailed methodologies in probabilistic reliability assessments of offshore wind turbines and oil and gas platforms can be transferred to and also be used for probabilistic reliability assessments of WECs.

Probabilistic reliability assessments can be performed using software packages like the Fortran-based PRADSS [105], open-access Matlab-based FERUM [54] and other commercial available softwares like STRUREL [97] or Proban [28].

Probabilistic reliability assessments can be performed for fatigue limit states and limit states due to extreme loads. Section 4 shows how fatigue is modeled and section 5 gives background information about extreme load assessments. The next section shows the different sources of uncertainties as well as how they can be modeled and quantified.

Chapter 3

Sources and Quantification of Uncertainties

When solving engineering problems, uncertainties are unavoidable and it is essential to recognize all major sources of uncertainties.

Before starting probabilistic reliability assessments, the uncertainties related to the considered limit state need to be found and quantified. There are different types of uncertainties, which should be quantified and considered when performing probabilistic structural designs:

- Physical uncertainties
- Modeling uncertainties
- Statistical uncertainties
- Measurement uncertainties

Another distinction of uncertainties is related to the ability to reduce them. There are epistemic (knowledge-based) and aleatory (data-based) uncertainties. Epistemic uncertainties include uncertainties related to limited amount of data (statistical uncertainties), measurements (measurement uncertainties) as well as to idealization/imperfect knowledge of mathematical model and distribution types used for the stochastic variables (model uncertainties). This kind of uncertainty can be reduced when a larger dataset, a better measurement device as well as more knowledge about the used models are gained. Aleatory uncertainties include the physical uncertainties, which exist due to natural randomness of a certain quantity (e.g. change in annual maximum significant wave heights, different water conditions like salinity or pollution) and cannot be reduced when more information is available. More examples of uncertainty sources for different engineering applications are given in [5].

In the following the mentioned types of uncertainties are discussed and it is shown how to quantify them in relation to structural designs of wave energy converters. Often not only one type of uncertainty is present but a combination of different uncertainty types. Therefore, it might not always be possible to uniquely separate or classify the different uncertainty types for a certain considered quantity.

An example of how the different uncertainty types are inter-connected is shown based on a minimal list presented by [62] (see Table 3.1) where uncertainty components to be considered when performing a wave resource assessment for WECs are presented. The uncertainties are divided in two categories, where uncertainties of category A can be estimated from wave state measurements whereas uncertainties of category B need to be estimated from other means. The author added the last row in Table 3.1 where the uncertainty source is mentioned.

Fig. 3.1 shows another example of different uncertainty sources used to model environmental conditions for extreme and long-term environmental conditions. This flow chart is in accordance to the modeling procedure presented in Paper 1 for stochastic modeling of wind and sea conditions.

3.1 Physical Uncertainties

Physical uncertainties are given by Mother Nature and cannot be reduced or controlled even though we would have an infinite long data set and perfect knowledge. This kind of uncertainty is always present and occurs due to inherent physical variability. Physical uncertainties can simply be represented by a stochastic variable instead of

Table 3.1: Minimal list of uncertainty components to be considered according to [62] including (possible) uncertainty sources added by the author. Uncertainty category A indicates uncertainty sources that can be described based on the available measured data from wave buoys whereas category B needs other sources (e.g. based on information from a measurement device). Unc.: uncertainty, cat.: category.

Measured/ model parameter	Unc. component	Unc. cat.	Unc. sources
Significant wave height	Wave measuring instrument/model calibration	B	Modeling and measurement uncertainty
	Annual maximum extreme significant wave height	A	Physical/modeling uncertainty
	Influence of moorings and/or other local effects	B	Modeling uncertainty
	Data acquisition system	B	Statistical and measurement uncertainty
Wave period	Wave measuring instrument/model calibration	B	Model and measuring uncertainty
	Influence of moorings and/or other local effects	B	Model and measurement uncertainty
	Data acquisition system	B	Statistical and measurement uncertainty
	Strength of marine currents	B	Statistical, modeling measurement uncertainty
Annual mean wave power	Water depth	A/B	Measurement and modeling uncertainty
	Water density	A/B	Measurement uncertainty
	Inter-annual variability of significant wave height/wave period	A	Physical, measurement and modeling uncertainty

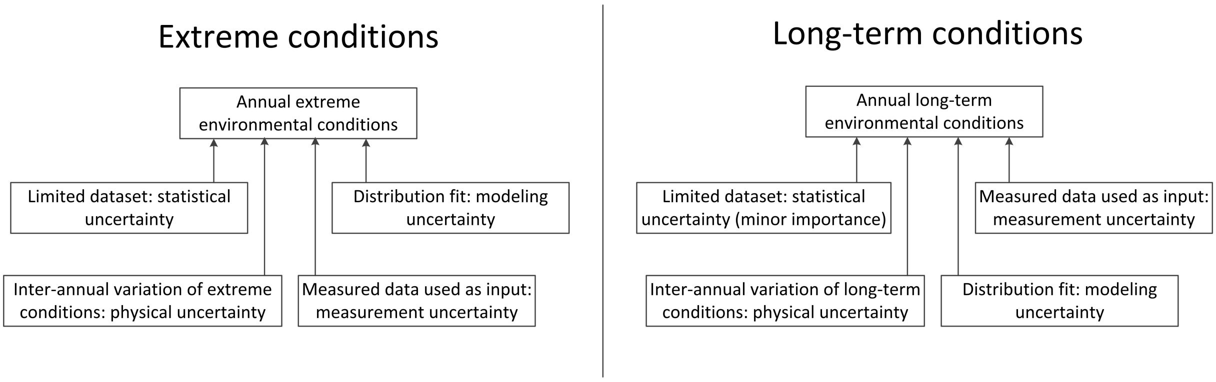


Figure 3.1: Different uncertainty sources for extreme and long-term environmental conditions. The presented uncertainty sources are in accordance with the strategy shown in Paper 1.

a deterministic value. The distribution parameters can be found based on e.g. a Maximum Likelihood approach, as explained in section 5.1. Examples of physical uncertainty sources with focus on wave energy converters are parameters related to:

- Environmental conditions and parameters,
- Material properties and
- Geometry of structure.

Physical uncertainties are present when considering extreme events as well as load cases which drive fatigue. Physical uncertainties considered for extreme or fatigue load assessments can be different.

This type of uncertainty will propagate through the whole structural design process. Its influences on load estimations can e.g. be determined by Monte Carlo simulations, which repeat a certain limit state multiple times with randomly chosen realizations of stochastic parameters.

For environmental conditions, physical uncertainties are often treated as inter-annual variations of a certain environmental parameters (e.g. wave height or wind and current speed) as performed in Paper 1. Table 3.2 shows the importance of inter-annual variations for fatigue assessments.

Table 3.2: Importance of inter-annual variations of wind and wave conditions for fatigue assessments determined in this work. Low importance: Uncertainty range leads to $\Delta\beta$ variation equal to or less than 0.1; Medium importance: Uncertainty range leads to $\Delta\beta$ values between 3.1 and 3.7.

Description	Importance	Source
Wave - Fatigue (long-term distribution)	medium-low	Paper 1
Wind - Fatigue (long-term distribution)	low	Paper 1

3.2 Model Uncertainties

Model uncertainties consider uncertainties related to physical models in order to estimate e.g. environmental conditions, loads or stresses. In the following, examples where modeling uncertainties should be considered for WEC applications are given:

- Wave conditions modeled with wave models,
- Load calculation models,
- Stress estimations based on loads onto the structure (structural analysis) and
- Models to assess damage/fatigue.

Model uncertainties are often application-specific and WEC model-type specific due to the fact that the same resistance and load models are not always considered or the environmental conditions are different. In order to determine modeling uncertainties, validation of the model is necessary. Validations assesses the accuracy of the model. There are different guidelines/standards of how to perform and define validation dependent on the application. When focusing on resistance models, their modeling uncertainty can be determined using the approach proposed in [48] (Annex D), where an experimental value , r_{exp}, is calculated from a theoretical value, r_{th}, in the following way:

$$r_{exp} = b \cdot \Delta \cdot r_{th} \tag{3.1}$$

where b is the mean value correction factor and Δ the error (scatter) distribution, which is assumed to be LogNormal distributed with mean value equal to 1.

Focusing on WECs, there are two different types of model uncertainties:

- Type I: Modeling uncertainties different for WEC and other offshore applications (WEC-specific).
- Type II: generally valid modeling uncertainties (independent on the specific application).

Type I includes e.g. uncertainties related to control system modeling as well as wave models used to estimate wave conditions. Type II modeling uncertainties consider many resistance uncertainties like e.g. soil property uncertainties or uncertainties related to material characteristics. A general overview and guidelines for different model uncertainties (mainly for Type II) are given in [67].

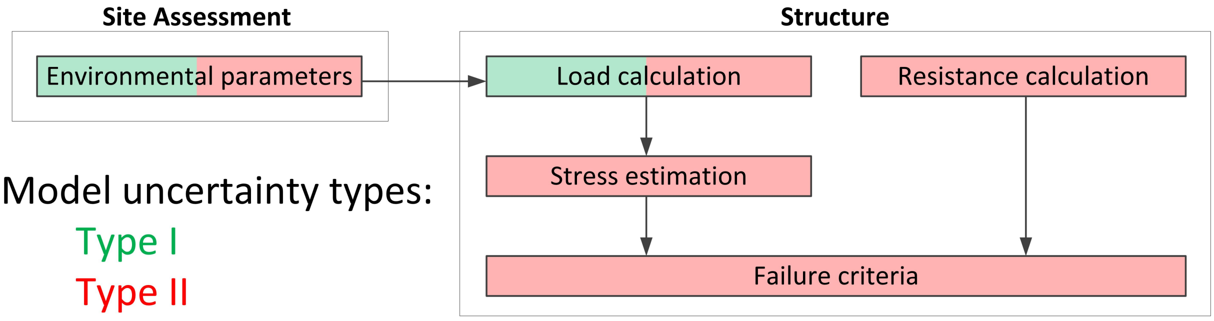


Figure 3.2: Sources and types of model uncertainties when doing a structural design of a WEC component. Type I: WEC-specific uncertainty, Type II: Application independent uncertainty.

Fig. 3.2 gives a broad overview about the different model uncertainties and types (WEC-specific or application independent uncertainties) when designing a structural part. The different parts in Fig. 3.2 can be further divided and their modeling uncertainties can be described in more detail. Fig. 3.3 presents an example of detailed sources of modeling uncertainties for a site assessment performed using wave models. Uncertainties about wave models are quantified in Paper 10.
Established methods like Palmgren-Miner rule as well as stress concentration factor uncertainties and SN-curves as well as Fracture mechanics models can be taken from a general research, see e.g. [103] or specific research in offshore engineering [129, 112, 55, 107]. Uncertainties about these well-established methods can be used independent on the application, the specified and commonly used uncertainties can also be used for WEC applications. For probabilistic fatigue reliability assessments the failure model criterion Δ (see Equation 4.4) reference [129] proposes a LogNormal distribution with mean value equal to 1 and a COV equal to 0.3. This stochastic model has become the general accepted model for Δ and used in many reliability assessments if explicitly no specific data is available. Fatigue modeling tools like SN-curves are related to uncertainties. Uncertainties related to SN-curves are often treated by making the parameter K (see Equation 4.1) a stochastic variable. The parameter m often remains a deterministic value. When using a Fracture mechanics approach to model crack evolution (see Equation 4.7), the initial crack size a_0 as well as the parameter C are often chosen to be random variables. The parameter m in Equation 4.7 often remains a deterministic value. The stochastic models to be chosen for a_0 and C depend on the application, the used material, the manufacturing process/quality and the environmental/operational conditions. Therefore it is difficult to give general guidelines, but [114] presents an overview about different used/proposed stochastic models for a_0.

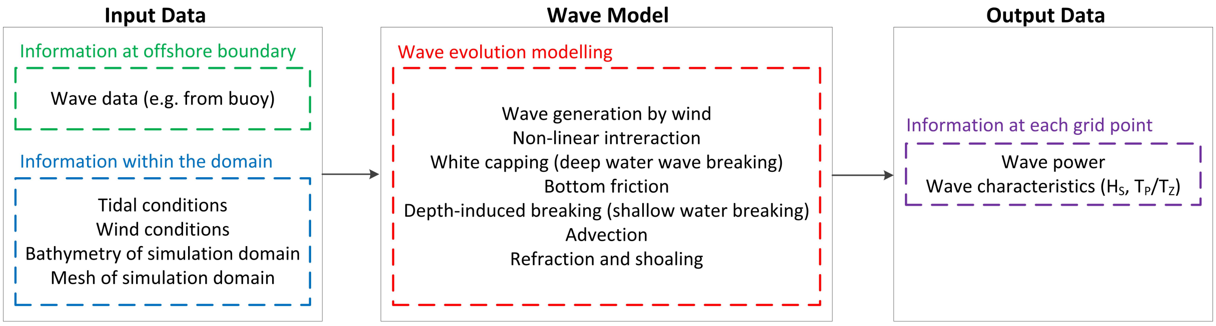


Figure 3.3: Sources of uncertainties when doing a site assessment using wave models.

When performing load calculations, stress concentrations are of importance for structural failure considerations. Stress concentrations should be accounted for, which can be done by introducing a stochastic variable called X_{SCF} (uncertainty about stress concentration factor), which is most often assumed to be LogNormal distributed. A discussion which values for X_{SCF} to be chosen for structural WEC designs and their effect on fatigue reliability is assessed in Paper 3. Reference [114] shows a summary of published and proposed uncertainty ranges for stress concentrations for offshore applications and [107] presents a range of stress concentration factor uncertainties dependent on the effort on estimating the hot spots (e.g. use of Finite-element modeling or just parametric stress concentration factors).
Quantification of Type I model uncertainties is important for WEC designs due to the fact that compared with

nearby industries the control system influences the wave-dominated loads and different design tools (like e.g. wave models) are uniquely used for WEC applications. The following modeling uncertainties are quantified in this thesis in relation with structural designs of WECs:

- Environmental parameter uncertainties, which are of importance for WECs (Paper 1).
- Model uncertainty for fatigue assessment (Papers 3 and 7).
- Wave modeling uncertainty (Papers 10 and 11).
- Model uncertainties of different control strategies/systems (Paper 3).
- Uncertainty of scatter diagram discretization (Paper 9).
- Uncertainties related to wave state approximations (Paper 9).

Tables 3.3 and 3.4 show the importance of modeling uncertainties determined in this work with focus on environmental parameter assessments as well as structural load/stress estimations. Of large importance are uncertainties related to stress concentration assessments, wave load estimations, inspection considerations as well as loads occurring during system failure (e.g. load due to failure of mechanical or electrical components).

Table 3.3: Importance of different modeling uncertainties related to environmental assessments determined in this work. Low importance: Uncertainty range leads to $\Delta\beta$ variation equal to or less than 0.1; Medium importance: Uncertainty range leads to $\Delta\beta$ values between 3.1 and 3.7.

Description	Importance	Source
Discretization of wave states in scatter diagrams	low	Paper 9
Considered peak enhancement factor of JONSWAP spectrum	medium	Paper 9
Extreme wave height during certain wave state	medium	Paper 9
Data from wave models	medium	Papers 10 and 11

Table 3.4: Importance of different modeling uncertainties related to load/stress assessments determined in this work. Low importance: Uncertainty range leads to $\Delta\beta$ variation equal to or less than 0.1; Medium importance: Uncertainty range leads to $\Delta\beta$ values between 3.1 and 3.7; High importance: Uncertainty range leads to $\Delta\beta$ values larger than 3.7 or smaller than 3.1.

Description	Importance	Source
Wave load assessments	high	Papers 1, 2, 10 and 11
Wind load assessment	medium-low	Paper 1
Load characteristics among different control systems	high	Paper 2
Stress concentration	high	Paper 3
Whether or not inspections are performed	high	Paper 3
Inspection modeling and technique	medium	Paper 3
Load extrapolation	medium	Paper 4
Loads given failure of the system (abnormal loads)	high	Papers 2 and 4

3.3 Statistical Uncertainties

Statistical uncertainties are present due to the fact that weather data sets used to estimate environmental conditions or test runs necessary to detect the material properties are limited.

Since distribution parameters $\boldsymbol{\alpha} = [\alpha_1, ..., \alpha_m]$ of a certain distribution $F(x|\boldsymbol{\alpha})$ can be estimated by the Maximum Likelihood method (see section 5.1), these parameters become asymptotically (if the number of considered data point is larger than 25-30) Normal distributed stochastic values with mean values equal to the Maximum Likelihood estimation and covariance matrix equal to [70]:

$$\mathbf{C}_{\boldsymbol{\alpha}} = [\mathbf{H}]^{-1} = \begin{bmatrix} \sigma_{\alpha_1}^2 & \rho_{\alpha_1,\alpha_2}\sigma_{\alpha_1}\sigma_{\alpha_2} & \cdots & \rho_{\alpha_1,\alpha_m}\sigma_{\alpha_1}\sigma_{\alpha_m} \\ \rho_{\alpha_1,\alpha_2}\sigma_{\alpha_1}\sigma_{\alpha_2} & \sigma_{\alpha_2}^2 & \cdots & \rho_{\alpha_2,\alpha_m}\sigma_{\alpha_2}\sigma_{\alpha_m} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{\alpha_1,\alpha_m}\sigma_{\alpha_1}\sigma_{\alpha_m} & \rho_{\alpha_2,\alpha_m}\sigma_{\alpha_2}\sigma_{\alpha_m} & \cdots & \sigma_{\alpha_m}^2 \end{bmatrix} \tag{3.2}$$

where $\mathbf{H}$ is the Hessian matrix, which is calculated from second derivatives of the Log-Likelihood function $\ln(L)$ (see Equation 5.9). An element (i, j) in $\mathbf{H}$ is obtained from:

$$\mathbf{H}_{i,j} = \frac{\partial^2}{\partial \alpha_i \partial \alpha_j} \ln(L) \tag{3.3}$$

The Hessian matrix estimates the standard deviation, σ_{α_i}, of a certain distribution parameter α_i and the correlation coefficient ρ_{α_i,α_j} between α_i and α_j. The Hessian matrix is estimated by numerical differentiation. An example for including statistical uncertainties based on the Hessian matrix is shown in Paper 1, where statistical uncertainties of extreme and long-term distribution parameters for wind and wave conditions are considered.

Table 3.5 shows the different statistical uncertainties and their importance determined in the attached papers in the appendix. Care should be taken due to limited data points when short time-series are used for load assessments as well as a small environmental data set is used for extreme load assessments or to estimate extreme environmental conditions. The considered data should be representative and should come from a statistically homogeneous independent population. An independent population means that each data point is independent of each other (e.g. extreme wave height data points do not result from the same storm).

Table 3.5: Importance of different statistical uncertainties determined in this work. Low importance: Uncertainty range leads to $\Delta\beta$ variation equal to or less than 0.1; Medium importance: Uncertainty range leads to $\Delta\beta$ values between 3.1 and 3.7; High importance: Uncertainty range leads to $\Delta\beta$ values larger than 3.7 or smaller than 3.1.

Description	Importance	Source
Wave load/elevation time-series	low (time $>$ 60 mins) high (time $<$ 60 mins)	Paper 9
Environmental conditions for fatigue loads	low	Paper 1
Environmental conditions for extreme loads	medium-high	Paper 1

3.4 Measurement Uncertainties

For wave energy converters, measurement uncertainties related to wave/wind/current characteristics measurements are of importance. Furthermore, also measurement uncertainties are present when measuring loads at a prototype or a lab-scaled device during tank tests or when performing material tests (e.g. tensile tests) in order to detect the characteristics of the considered material. Load and material characteristics measurement uncertainties might be provided by the manufacturer of the devices used to measure. The measurement uncertainty can be reduced by calibration and quantified by validation.

Measurement errors can be divided into bias (systematic) errors as well as random (precision) errors. For a good overview about the range of measurement uncertainties for different offshore environmental measurement devices, see [14]. For wind speed measurements, reference [90] gives information about different wind measurement devices and reference [4] for wave measurement devices. Reference [67] gives general measurement uncertainties if no specific measurement uncertainties are available. Environmental condition measurements, which might be of importance for WECs, are:

- Wave conditions
  - Significant wave height
  - Peak/mean zero-crossing wave period
  - extreme instantaneous wave height during certain time interval
  - corresponding wave period of extreme instantaneous wave height
  - wave direction
- Wind conditions
  - (10 - mean) wind speed
  - peak wind speed during 10 minutes
  - wind direction
- Current conditions

  - current speed
  - current direction

Furthermore, the position where the wind and current measurements are performed is important in order to be able to account for boundary conditions and adjust the conditions for other heights and locations.

Chapter 4

Fatigue Modeling

This section describes the theoretical background about modeling of fatigue. Fatigue, which is characterized by cyclic loading, is important in structural details with high stress concentrations like e.g. at welded details and bolted or notched connections. To describe fatigue, three different models are used in structural engineering sciences. One model focuses on an empirical approach using SN (stress versus life) curves and the Palmgren-Miner rule, which assumes linear damage accumulation. This model is widely used for bolted or welded structures. The second fatigue model is based on fracture mechanics and considers crack evolution, which is the physical reason for fatigue failure. Another way to describe fatigue is by using the so-called strain-life (ε - N) approach, which is of importance for notched structural details and often used in practice due to the fact that strain can easily be measured. The SN-curve model as well as the fracture mechanics model are described in the following due to the fact that these two models are applied in this thesis. Readers interested in fatigue modeling are referred to e.g. [113, 92, 101], on which this section is based.

4.1 SN-curves and Palmgren-Miner Rule

Fatigue failure depends on the number of load cycles of a certain load amplitude. Larger load amplitudes need lower number of cycles, leading to fatigue failure. The number of constant cycles leading to failure is dependent on the load amplitude. The relationship between the number of cycles, N_F, of a certain stress range ΔS, leading to failure can be expressed by so-called SN-curves, which are also called Wöehler curves and named after August Wöehler who did the first systematic strength tests of steel and iron [130]. These curves can in their simplest form be described by the Basquin Equation [12], which assumes a linear relationship between $\log N_F$ and $\log \Delta S$:

$$N_F = K \cdot \Delta S^{-m} \tag{4.1}$$

where K and m are parameters, which are estimated from experiments. SN-curves depend among others on the environmental conditions (e.g. above water surface or submerged) and the considered corrosion protection (e.g. cathodic protection or no corrosion protection). There are linear and multi-linear SN-curves where the slope m is not constant over the whole stress range. Figure 4.1 shows examples for different SN-curves. SN-curves can be found in [43] or [65] for offshore structures.

In order to estimate the number of stress cycles with a certain stress amplitude, one can use Rainflow counting (see e.g. [10]), which transfers load time-series into number of cycles of a certain stress range and a given time period. Instead of Rainflow counting, one can apply other cycle counting methods like Range-Pair Method, Racetrack counting, Level-Crossing Method or Peak Counting Method. An overview about the different cycle counting methods is given in [10, 113]. The result of the cycle counting method is a so-called load/stress spectrum, which shows the number of cycles at a specific load/stress range during a certain time duration. The considered time duration is normally the expected lifetime. Fig. 4.2 shows an example of a load spectrum considered in Paper 3.

The Palmgren-Miner rule [79], which assumes linear damage accumulation and independence on the order of cycle occurrence on the total damage, can be used to estimate the damage increment, ΔD_i, resulting from a certain load cycle:

$$\Delta D_i = \frac{1}{N_{F,i}} \tag{4.2}$$

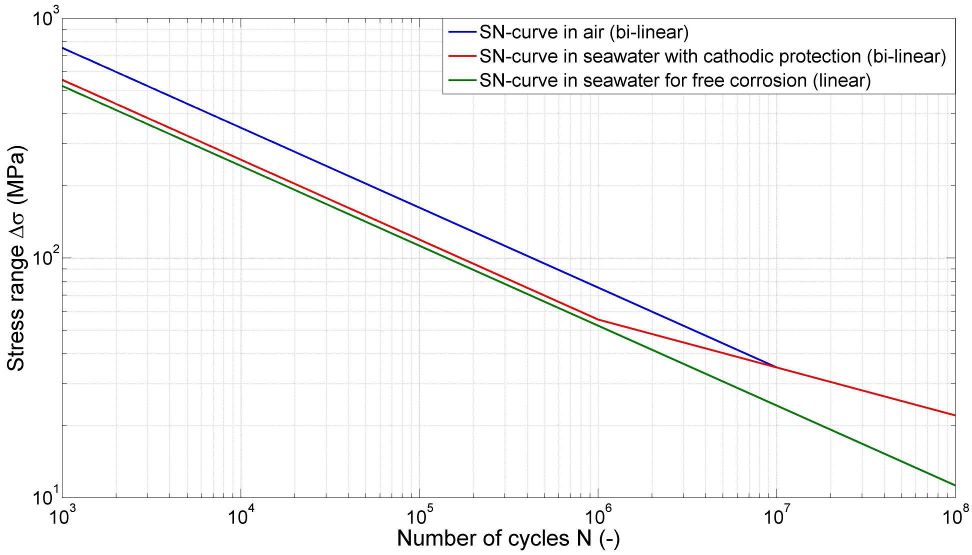


Figure 4.1: Example of linear and multi-linear SN-curves according to [43] considering a so-called 'F'-detail.

where $N_{F,i}$ is the number of cycles until failure for the load amplitude ΔF_i. The total damage, D_{tot}, after n cycles is equal to:

$$D_{tot} = \sum_{i=1}^{n} \Delta D_i = \sum_{i=1}^{n} \frac{1}{N_{F,i}} \tag{4.3}$$

The limit state equation for fatigue failure can be formulated to be:

$$g(t) = \Delta - D_{tot}(t) \tag{4.4}$$

where t is the time and corresponds with the number of cycles n. The variable Δ corresponds to the failure criteria. For deterministic design purposes it is assumed that fatigue failure of the structure happens when the failure criterion Δ is equal to one.

When performing a deterministic structural design, a fatigue safety factor needs to be considered, which accounts for the uncertainties that are considered by the use of partial safety factors. The fatigue safety factor 'Fatigue Design Factor' (FDF) is defined as:

$$FDF = \frac{T_{FAT}}{T_L} \tag{4.5}$$

where T_L is the expected lifetime of the structural detail and T_{FAT} the fatigue lifetime considered in the design. The FDF is also called DDF (Design Fatigue Factor) and used in common deterministic fatigue assessments for e.g. offshore platforms [65] or offshore wind turbines [39, 40]. It needs to be mentioned that for a linear SN-curve, the FDF value is directly connected to the partial safety factors for fatigue load (γ_f) and fatigue strength (γ_m):

$$FDF = (\gamma_m \gamma_f)^m \tag{4.6}$$

where m represents the slope of the SN-curve. A calibration of required FDF values for WECs is performed in Paper 3 and more background information about calibration of safety factors is given in section 7.2.

4.2 Fracture Mechanics

The foundation of fracture mechanics was laid in 1920, where Griffith [57] found out based on theoretical and experimental investigations on brittle glass fracture that the nominal stress S at fracture multiplied with the square root of the fracture crack size a is constant for different crack sizes.

Fatigue failure occurs due to evolution of cracks, which can be modeled using a fracture mechanics approach. Crack evolution consists of three stages as shown in Fig. 4.3. The crack needs to be initiated first (initiation period). Then the crack is growing (crack growth period) and at the end failure happens (structural failure).

Crack initiation, which depends on fabrication or maintenance defects, has different causes and is therefore difficult to model. On a microscale large local shear stresses, which lead to cyclic slip, may occur. Such slips lead to

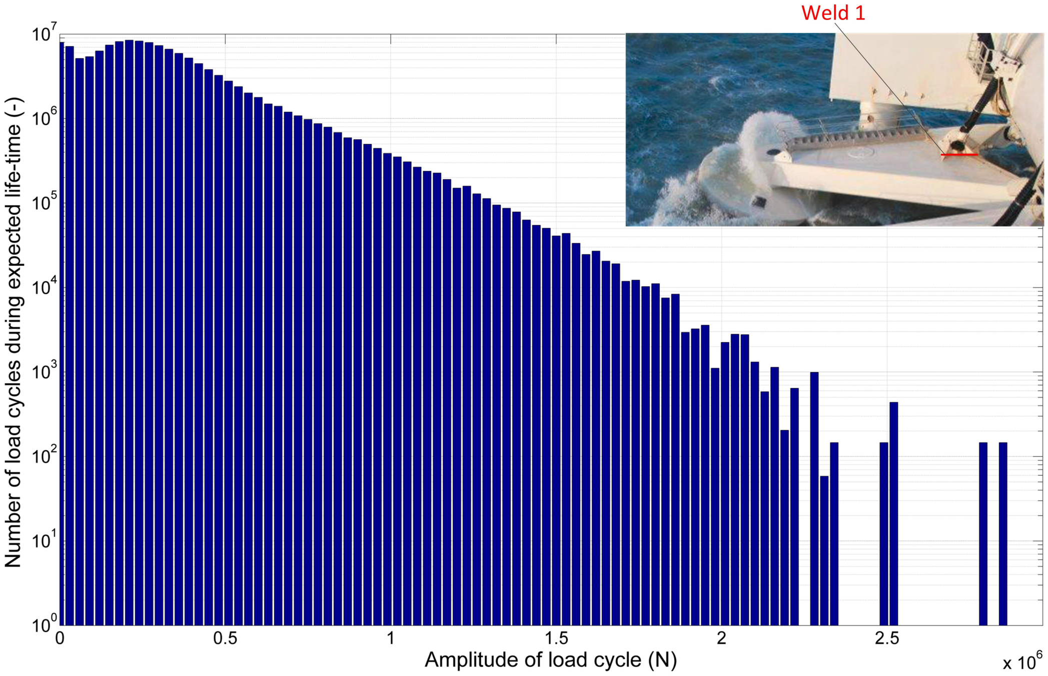


Figure 4.2: Example of load spectrum for an expected lifetime of 20 years at location of Weld 1 of the Wavestar device, see Paper 3.

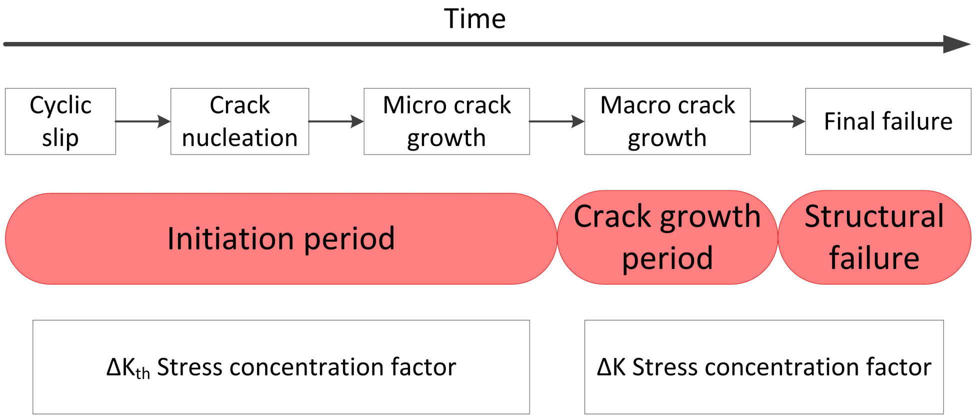


Figure 4.3: Different phases of the fatigue life and relevant factors like time and different stress concentration factors. This sketch is reproduced from a sketch shown in [101].

plastic deformation and nucleation of cracks. For many applications an initial crack size a_0 or a number of cycles to initiation, N_0, is assumed. An overview about initial crack models and their applications is given in [114]. When modeling the second stage, where crack evolution happens, the Paris Law [87] can be applied:

$$\frac{da}{dN} = C \cdot \Delta K^m \tag{4.7}$$

where da/dN is the crack growth rate and ΔK the stress intensity range. The parameters m and C can be found from experiments. Fig. 4.4 shows a typical crack growth behavior in metals. The crack growth can be divided into three regions (A, B and C). Paris Law is valid in Region B, where there is a linear relation between $\log(\Delta K)$ and $\log(da/dN)$. In region A, Paris Law overestimates the crack growth rate whereas in region C the crack growth rate is underestimated when using Paris Law. The stress intensity range ΔK for a one-dimensional fracture mechanics model can be calculated by the use of a geometry function and the equivalent stress range ΔS_e (stress assuming that the crack does not exist):

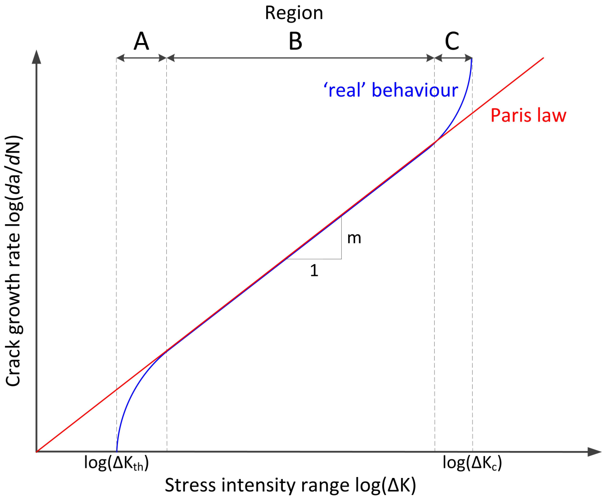


Figure 4.4: Typical fatigue crack growth behavior in metals. The red line indicates the approximation based on Paris Law. ΔK_{th} indicates the threshold values below which no observable crack growth takes place and ΔK_c is the critical stress intensity factor, which leads to instability/structural failure.

$$\Delta K = Y \Delta S_e \sqrt{\pi a} \tag{4.8}$$

where Y is a dimensionless parameter accounting for different crack forms (e.g. circular or elliptical shape) and different locations (e.g central or edge cracks). An overview about different Y models available is given in [113]. Structural detail-specific one- and two-dimensional fracture mechanics models are given in [18]. The limit state equation using a fracture mechanics approach focusing on the time-dependent crack size $a(t)$ is equal to:

$$g(t) = a_c - a(t) \tag{4.9}$$

where a_c is the critical crack size, which could be e.g. the considered thickness. The fracture mechanics approach can be used for fatigue reliability assessments when inspections should be included and considered. The implementation of inspections is related to some characteristics, which are described in the following section.

4.3 Implementation of Inspections

When performing inspections, uncertainties about the detection of a defect needs to be accounted for. This can be done by using so-called probability of detection (P_D) curves, which are dependent on the used inspection technology as well as the crack size. Different P_D models are presented e.g. in [114, 29]. Figure 4.5 shows the P_D models considered in Paper 3.

For inspections often so-called semi-empirical fracture mechanics models are used. Semi-empirical fracture mechanics models contain m and C parameters, which are chosen from fitting the fracture mechanics annual/cumulative reliability index results (considering no inspections) to the reliability index results from the SN approach. This application has been performed for nearby offshore industries like offshore wind turbines or oil and gas steel

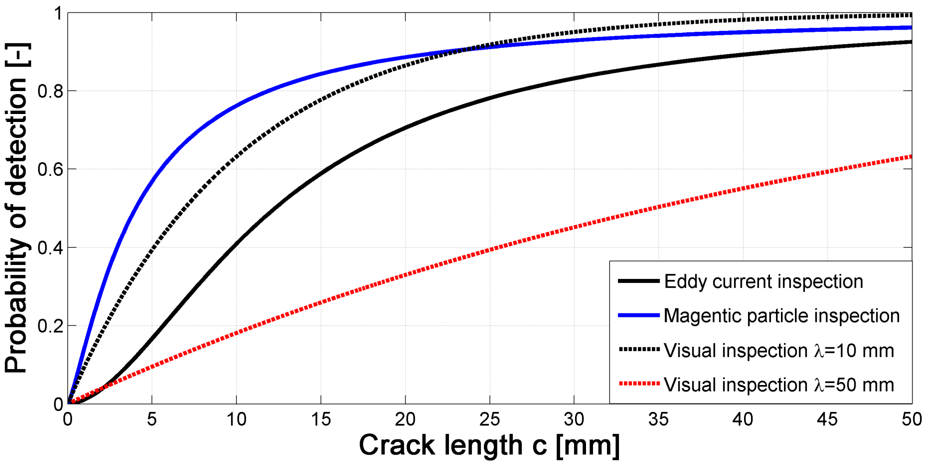


Figure 4.5: Example of P_D curves used in Paper 3.

structures, (see e.g. [44, 107, 52]) and is also proposed in standards (see e.g. [2]) for fatigue assessments. The same approach is used in Paper 3 in order to model the effect of inspection on structural safety factors. Figure 4.6 shows an example from Paper 3 where the resulting cumulative reliability curve of the fracture mechanics model (considering no inspections) is fitted to the SN approach.

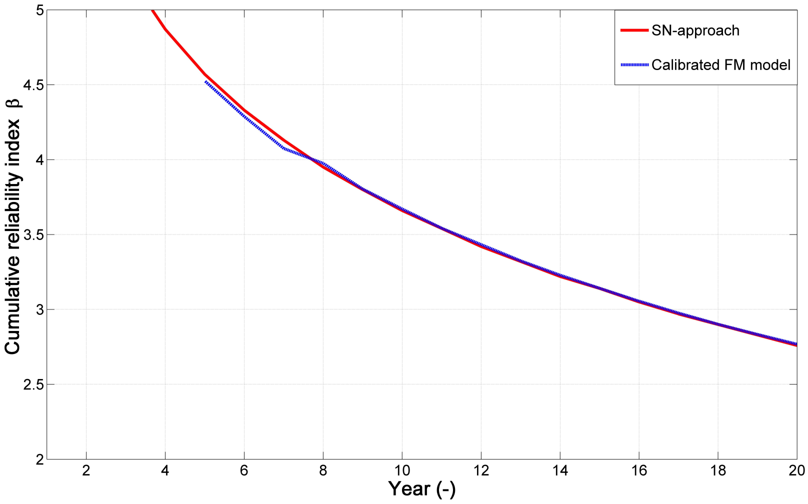


Figure 4.6: Example of cumulative reliability curves obtained for the (fitted) fracture mechanics model with no inspections as well as the SN-curve model. [Paper 3]

Chapter 5

Extreme Value Theory

Extreme value theory is of importance when focusing on extreme and rare events. Extreme values in a structural design context can be either extreme environmental conditions (see e.g. Paper 1) or directly extreme load effects (see e.g. Paper 4) from load time-series. For both cases mentioned, the same theory, which will be explained in the following, can be applied. For further details, the reader should contact e.g. [22, 5]. Extreme loads are needed for structural ultimate limit states.

Before estimating long-term extremes (e.g. annual extreme values), short-term extreme values need to be found from the available time-series. Extreme values given a certain data set can be estimated using the so-called peaks-over-threshold method, where only extreme values above a certain threshold u are considered. In order to guarantee that the different extreme values are independent (result from different storms), a minimal temporal separation should be considered between two extreme values. The choice of a threshold value is not straightforward. The number of resulting peak values should not be too low, otherwise their extreme values have high (statistical) uncertainties, and if there are too many peak values, the estimation (extrapolation) of extreme values becomes too uncertain (high modeling uncertainty). Therefore, a sensitivity analysis of different threshold values is of importance, and the resulting extreme value/distribution parameters should not vary significantly when changing the threshold value.

If a large data set is available like H_S values over many years, annual extreme values can be directly detected using the annual extreme value as a block maximum. But due to the fact that long-term measurements/simulations are costly and time-consuming, short-term data is often available. Short-term data means structural load-time series over several hours or environmental data sets over several months or years.

Extreme loads are of importance for WECs, but it needs to be stated that extreme loads may not occur simultaneously with extreme environmental conditions. WECs often have a storm protection mode and in some cases a control system which can 'minimize' loads and at the same time secure a reasonable power production with the aim of reducing the extreme loads during extreme environmental conditions. Extreme loads can occur during operation with/without failure of electrical/mechanical components as well as malfunction of the control system. Paper 2 shows an example of how system failures can be included in structural reliability assessments for WECs.

The generalized extreme value (GEV) distribution can be used for estimating and modeling extreme values. The GEV distribution contains a scale parameter B, a location parameter l and a shape parameter k. Its general form is:

$$F_{GEV}(x, l, B, k) = \exp\left(-\left[1 + k\left(\frac{x-l}{B}\right)\right]^{-1/k}\right) \tag{5.1}$$

The GEV distribution can be divided into three types depending on the shape parameter k, which defines the upper tail behavior of the distribution:

- $k = 0$ Gumbel distribution (Type I)

$$F_I(x, l, B) = \exp\left(-\exp\left[-\frac{x-l}{B}\right]\right) \tag{5.2}$$

- $k = 1/\alpha < 0$ Fréchet distribution (Type II)

$$F_{II}(x, l, B, \alpha) = \begin{cases} 0 & x \leq l - \alpha B \\ \exp\left(-\left[1 + \frac{1}{\alpha}\left(\frac{x-l}{B}\right)\right]^{-\alpha}\right) & x > l - \alpha B \end{cases} \tag{5.3}$$

- $k = -1/\alpha < 0$ (Reversed) Weibull distribution (Type III)

$$F_{III}(x,l,B,\alpha) = \begin{cases} \exp\left(-\left[1-\frac{1}{\alpha}\left(\frac{x-l}{B}\right)\right]^{\alpha}\right) & x \leq l+\alpha B \\ 1 & x > l+\alpha B \end{cases} \tag{5.4}$$

Distribution Type I shows double exponential form whereas Type II and III have single exponential forms. Distribution Equations 5.2 and 5.3 focus on maximum values of a data set, whereas Equation 5.4 focuses on the minima values. When dealing with maxima values and Weibull distributions, Equation 5.4 can be adjusted by replacing x by $-x$ and subtracting 1 from F_{III}. This leads to the following Weibull distribution that focuses on maxima values:

$$F_{III}(x,l,B,\alpha) = \begin{cases} 0 & x \leq l \\ 1-\exp\left(-\left[\frac{x-l}{B}\right]^{\alpha}\right) & x > l \end{cases} \tag{5.5}$$

When extracting extreme values from a given data set, e.g by the use of the peak-over-threshold method, extreme (maximum) values are already chosen and instead of a so-called 3-parameter Weibull distribution, a 2-parameter Weibull distribution can be used:

$$F_{III}(x,B,\alpha) = 1-\exp\left(-\left[\frac{x}{B}\right]^{\alpha}\right) \tag{5.6}$$

with scale parameter B and shape parameter α.

Another important distribution when focusing on extreme values is the generalized Pareto distribution (GPD), which directly includes the threshold value u in the distribution:

$$F_{GPD} = 1-\left(1+\frac{\xi}{\sigma}(h-u)\right)^{-1/\xi} \tag{5.7}$$

where ξ is the shape parameter and σ the scale parameter.

Which distribution type fits best to the considered data set needs to be checked by a Q-Q plot (Quantile-Quantile plot) where the theoretical (fitted) value and the sample values are compared or by a P-P plot (Probability-Probability plot) where the two cumulative distributions are compared against each other. It needs to be mentioned that for extreme value theory the tail fit is of importance due to the fact that extreme/rare events are of importance. In order to estimate the distribution parameters from the available data set, different approaches like:

- Moment method,
- Least Square method,
- Maximum Likelihood method or
- Bayesian Statistics

can be used. The simplest method is using the moment method, where the standard deviation and mean value are calculated directly from the data set. This approach is not appropriate for small data sets due to the fact that an estimate about statistical uncertainties is not given. The Least Square method finds the distribution values, which minimize the squared sum of the residuals (difference between the model and the measured values). Another and more appropriate way when small data sets are available is the Maximum Likelihood estimation, which is based on a likelihood estimation of the distribution parameters. The Bayesian approach enables to update a certain distribution when new data becomes available as well as prior knowledge can be used. In general Maximum Likelihood and Bayesian statistics are recommended for parameter distribution fitting because they account for statistical uncertainties (limited data sets) and are used in this thesis. Therefore, these two approaches are explained in more detail in the following.

5.1 Maximum Likelihood Estimation

When data is available and a distribution or rather distribution parameters need to be fitted, the so-called Maximum Likelihood estimation can be used. The Maximum Likelihood method estimates the distribution parameters α_1 and α_2 of a distribution density function $f_X(x|\alpha_1,\alpha_2)$. When n data values are available, the Maximum Likelihood L can be calculated as:

$$L(\alpha_1,\alpha_2) = \prod_{i=1}^{n} f_X(x_i|\alpha_1,\alpha_2) \tag{5.8}$$

Due to the fact that the maximum Likelihood is equal to the parameter distribution values where the value L is maximized, often the logarithmic Maximum Likelihood is considered where multiplications become summations. That makes it easier for partial differentiations when looking for the resulting maximum likelihood value. The Log-Likelihood function becomes:

$$\ln\left(L(\alpha_1,\alpha_2)\right) = \ln\left(\prod_{i=1}^{n} f_X(x_i|\alpha_1,\alpha_2)\right) = \sum_{i=1}^{n} \ln\left(f_X(x_i|\alpha_1,\alpha_2)\right) \tag{5.9}$$

The Log-Likelihood function needs to be maximized in order to estimate the most probable distribution values:

$$\max_{\alpha_1,\alpha_2} \quad \ln\left(L(\alpha_1,\alpha_2)\right) \tag{5.10}$$

Maximation of the Log-likelihood function may be obtained from the solution of the following set of equations:

$$\begin{aligned} \frac{\partial \ln\left(L(\alpha_1,\alpha_2)\right)}{\partial \alpha_1} &= 0 \\ \frac{\partial \ln\left(L(\alpha_1,\alpha_2)\right)}{\partial \alpha_2} &= 0 \end{aligned} \tag{5.11}$$

Information about different algorithms for Equation 5.10 are shown in [102]. The Maximum Likelihood method can also be used for parameter estimation of regression lines or other estimations of statistical values. How to estimate the statistical uncertainty of the parameters α_1 and α_2 is given in section 3.3.

5.2 Bayesian Updating

When new data, B, becomes available the prior estimated probability, $P(A)$, including the old data set A can be updated including the new available data and using Bayes' theorem:

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)} \tag{5.12}$$

where $P(B|A)$ is the likelihood of B given A, $P(B)$ the probability of B and $P(A|B)$ the posterior probability of A given B. Bayes' theorem gives a relationship between the probabilities of the data sets A and B as well as their conditional probabilities $P(B|A)$ and $P(A|B)$.

Bayes' rule can also be used if probability distributions should be updated because new data y becomes available. Due to the fact that the probability distribution $p(y)$ is constant for a given data set y, according to Equation 5.13 the following relationship for Bayes inference can be found:

$$p(\theta|y) = \frac{p(y|\theta) \cdot p(\theta)}{p(y)} = \frac{p(y,\theta)}{p(y)} \propto p(y|\theta) \cdot p(\theta) \tag{5.13}$$

where $p(\theta)$ is the prior (initial) distribution of quantity θ (e.g. distribution parameters) estimated by a Maximum Likelihood approach, $p(y|\theta)$ is the likelihood function (conditional distribution of y given the quantity θ), $p(y,\theta)$ is the joint distribution of y and θ and $p(\theta|y)$ is the updated/posterior distribution of quantity θ including the new data set y.

More information about Bayesian updating is available e.g. in [96, 16, 70]. The prior as well as posterior distribution type are chosen to be the same type (conjugate distributions). In the literature, a number of prior and posterior distribution functions can be found, see e.g. [96, 95].

Paper 1 provides an example how updating can be performed for environmental parameters like the significant wave height, the wind speed as well as the mean zero-crossing wave period. Another important application field of Bayesian updating is inspection and detection of material defects. Inspection methods are imperfect and periodic inspection can be used to gain additional knowledge and update the number of necessary inspections as well as the condition of the structure. Bayesian methods can also be used for other civil engineering applications. An overview about different applications is given e.g. in [132].

Chapter 6

Failure Modes of WECs

Structural failure, which means complete or partial loss of load-carrying capacity, of components or structural systems may occur due to different failure modes. Failure modes are used to describe a certain type of structural failure and are also considered as limit state conditions when designing structural parts. Commonly, failure modes are divided into the following categories:

- Ultimate Limit States (ULS), which contain structural failures due to excess of maximum load carrying load capacity.
- Fatigue Limit States (FLS) focus on failure modes due to cyclic loading and structural damage accumulation.
- Accidental Limit States (ALS) are failure modes resulting from accidental loads caused by e.g. collisions, floods, explosions or fire.
- Serviceability Limit States (SLS) occur when excessive vibrations, leakages, deflections or drainage, which disable the function for which the structural part was built.

Examples of limit states are given in [30] and presented here:

- Ultimate Limit States (ULS):
  - loss of structural resistance (excessive yielding and buckling)
  - failure of components due to brittle fracture
  - loss of static equilibrium of the structure, or of a part of the structure, considered as a rigid body, e.g. overturning or capsizing
  - failure of critical components of the structure caused by exceeding the ultimate resistance (in some cases reduced by repeated loads) or the ultimate deformation of the components
  - transformation of the structure into a mechanism (collapse or excessive deformation)
- Fatigue Limit States (FLS):
  - cumulative damage due to repeated loads
- Accidental Limit States (ALS):
  - ultimate resistance of damaged structures
  - maintain structural integrity after local damage or flooding
  - loss of station keeping (free drifting)
- Serviceability Limit States (SLS):
  - deflections that may alter the effect of acting forces
  - deformations that may change the distribution of loads between supported rigid objects and the supporting structure
  - excessive vibrations producing discomfort or affecting non-structural components
  - motion that exceeds the limitation of equipment

  - temperature induced deformations

This thesis considers ULS (see Papers 1, 2, 5, 6, 9, 10 and 11) and FLS (see Papers 1, 3, 7, 8 and 9) with focus on welded and bolted steel structures. A certain failure mode is modelled by a limit state equation (probabilistic approach) or design equation (deterministic approach).
In this PhD thesis, the following specific failure modes are considered:

- Fatigue failure of steel structures at Wavestar device: Papers 1, 3, 7, 8 and 9
- Fatigue failure of Wavestar system: Paper 2
- Sliding of gravity-based foundation of Wavestar device: Papers 1, 2, 6 and 9,
- Bending failure of Wavestar pile: Papers 6, 10 and 11
- Failure of mooring line of the WEPTOS device: Paper 4
- Bearing capacity failure of Wavestar foundation: Paper 6
- Loss of mooring line due to extreme tension loads: Paper 5
- Overturning of Wavestar device: Paper 6

Structural failures might occur during or be driven by different modes (e.g production mode or storm protection mode) of the device. Therefore, different design situations, which are called 'Load Cases' in deterministic approaches including different load combinations, need to be considered when focusing on a certain structural failure mode. For offshore wind turbines, the following design situations are considered [60, 39]:

- Power production
- Power production plus occurrence of fault
- Start-up
- Normal shutdown
- Emergency shutdown
- Parked (standing or idling position)
- Parked and fault conditions
- Transport, assembly (installation), maintenance and repair

Not all of the above mentioned design situations are relevant for all WEC types. A fault in the list above references to faults of an electrical and mechanical component as well as software failure (e.g. failure of control system). When focusing on the structure of WECs and 'abnormal' loads (loads occurring during system failures) due impacts from outside or partial failure of the structure, the following failure modes might be of importance according to [27] and [47]:

- Foundation failure
- Vessel impact and loads to other marine activities
- Loss of station keeping (mooring line or anchor system failure)
- Loss of stability (leakage)
- Fire
- Interference floating device with debris
- Seismic events

It is important to include the whole system and its working principle (including its failure modes) when designing structures for WECs. Therefore, loads resulting from failures of electrical/mechanical components and the control system in the structural design should be considered.
Also for probabilistic structural reliability assessments, failure of the system should be considered. An example of how the working system principle can be included in probabilistic reliability assessments is shown in Paper 2 for an ultimate limit state. Additionally for WECs, system failure might also impact the fatigue behavior due to WEC devices are most probably placed at locations where there are strong wave conditions in order to harvest much wave energy. A study performed in this thesis (see Paper 5) showed that the device might be unaccessible during a certain period of time (mainly during winter months) when the wave conditions are too strong for safe access. Malfunction over a long period of time due to inaccessibility also influences the fatigue behavior of the structural components of WECs. Fig. 6.1 gives a general overview about possible sources, which might influence the downtime of a broken system component.
Furthermore, structural robustness considerations are important when analyzing the system and its impact on the structure in case of failure. Failure of structural details may directly lead to total collapse of the structure or to large loads on the remaining intact structural parts. Fig. 6.2 shows an example taken from Paper 4 where extreme mooring tension loads with a recurrence period of 50 years are extrapolated. In general the failure of one mooring line increases the extreme loads onto the remaining mooring lines. But the load increase decreases the more mooring lines are installed. These increased tension loads will increase the probability that other mooring lines will also fail due to large loads. Furthermore, subsequent damage given a structural failure of a mooring line can occur due to larger movements of the floating device when a mooring line is broken. This may lead to collisions with other naval structures like ships.

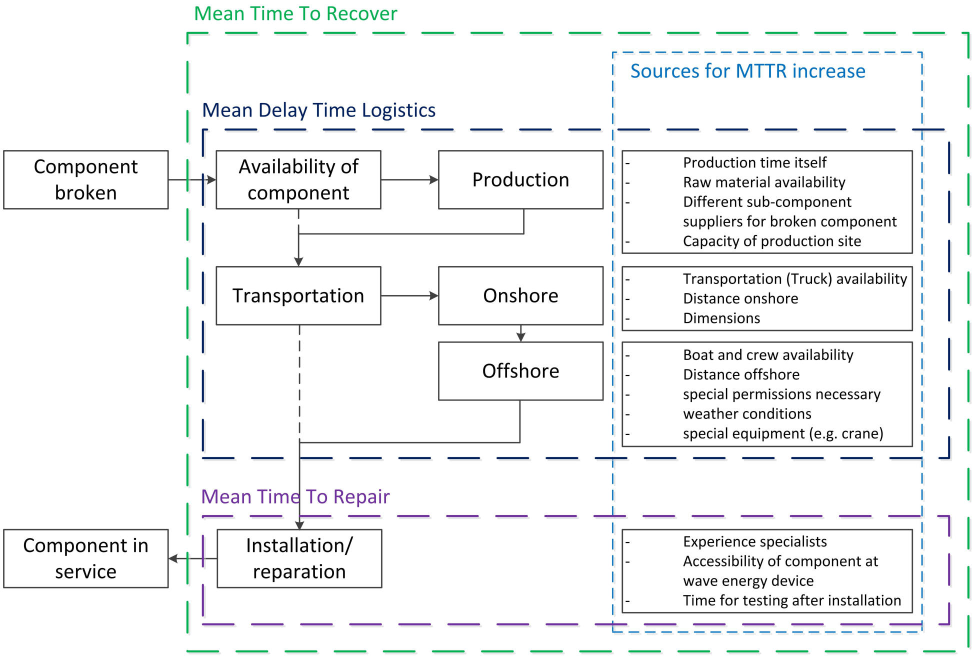


Figure 6.1: Sources for total repair time increase when component at a WEC is broken. MTTR: Mean time to recover.

6.1 Risk Assessment

But before considering structural failure modes due to failure of the electrical/mechanical system and the load cases ’Power production plus occurrence of fault’ and ’Parked and fault condition’, the working principle as well as the most probable failure modes of the system need to be discovered. Based on a risk analysis, the most important failure modes can be identified. Risk R is commonly defined as the probability P that a certain event (system failure mode) occurs multiplied with the consequence C given the occurrence of the event:

$$R = P \cdot C \tag{6.1}$$

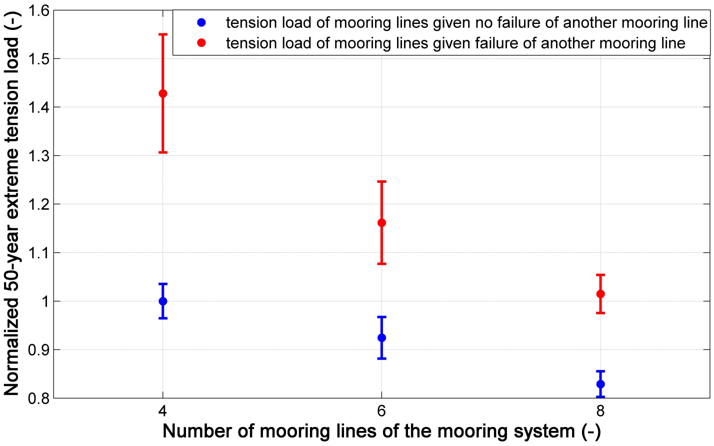


Figure 6.2: Normalized extrapolated 50-year extreme tension load of catenary mooring line systems dependent on the number of installed mooring lines with and without failure of one mooring line. The values are normalized by the recurrence period load of a mooring line system with 4 mooring lines given no failure of a mooring line. [Paper 4]

A risk assessment is location and system dependent and should, therefore, be performed for each specific location and system. There are different types of consequences, which may occur in case of failure. Table 6.1 presents different consequence categories and their importance for WEC investigations. Financial consequences are the main focus for WEC risk assessments. Also societal and property consequences can be considered when performing risk assessments of WECs. Societal consequences are of importance in the early development stage of WECs where failure of a certain device may lead to mistrust in the society. Property consequences become important when WECs are arranged in farms and e.g. failure of mooring lines may lead to collisions with ships. Of minor importance for WEC considerations are consequences based on injuries/fatalities (devices assumed to be unmanned) as well as environmental pollution (no danger of fire, no storage of dangerous materials).
There are different strategies of how to assess the most critical failure modes of the system, which identify possible hazards. Table 6.2 shows different methods to find important system failure modes.

Table 6.1: Consequence types including examples and importance measure for WEC designs.

Consequence types	**Possible related Consequence**	**Importance for WECs**
Person	Injury/fatality	low
Financial	Loss of Production, Cost of repair, compensation	very high
Property	Damage of device or third party property	high
Environmental	Possible injury, harassment, or death of local ecosystem	low
Societal	Negative public perception	high: prototype low: developed stage

For WEC system considerations e.g. the Fault Tree Analysis (FTA) or the Failure Mode and Effects Analysis (FMEA) can be used. The FTA is a top-down method where the starting point is a certain failure mode (e.g. device not able to move into storm protection mode) and the combinations of failed system components are found leading to the considered event. An FMEA is built from the bottom up, which means that the question is asked what happens when a certain component (or a certain combination of components) fails and leading at the end to a certain overall effect (e.g. device not moveable into storm protection mode). For each electrical/mechanical component, a failure rate, which is often assumed to be constant over time, can be estimated based on experiments, data books as well as guidelines. Due to lack of knowledge, almost no data is available for WEC components, but as a first approach failure rates from components used in oil and gas platforms as well as for (offshore) wind turbines can be taken. An overview about available failure rate databases from petrochemical industry, wind industry and also generic databases is given in Paper 2.
Documents of interest for estimating failure rates of electrical and mechanical components of WEC systems are as follows:

Petrochemical industry:	[86]
(Offshore) wind turbines:	[123], [98], [59]

- Generic reliability databases: [63], [78], [104]

Table 6.2: Different methods to define and find important system failure modes from [42].

Method	**Advantages**	**Challenges and Disadvantages**
Failure Mode and Effects Analysis (FMEA)	Systematic and simple to apply	Investigating ONE failure mode at a time may not identify critical combinations of failures
Hazard and Operability study (HAZOP)	Systematic method which enables identification of the hazard potential of operation outside the design intention or malfunction of individual items	Resource-consuming; Requires detailed information for producing useful results; Experienced facilitator required
Fault Tree Analysis (FTA)	Thorough investigation of (already) identified incidents	Not applicable for identifying (new) incidents; Time-consuming to set up; Not suitable for accurately modeling all types of systems
Structured what-if checklist (SWIFT)	Applicable even if detailed design information is not available	Experienced facilitator essential, as well as good checklists
Operational Problem Analysis (OPERA)	Emphasis on the product interfaces	Emphasis on technical problems and human errors without going into details about causes
Independent review	Can be more time-efficient or less resource demanding	Not as multidisciplinary and robust as other techniques

In the end, which system failure modes are of importance and should be considered as so-called 'Load cases' is not only driven by the probability of occurrence that a certain system failure will occur, but more on the resulting risk. In [53] a review and discussion about risk assessments for civil engineering structures are given. A methodology for risk assessments with focus on WECs is shown in [58] where the approach is based on a risk ranking matrix and a traffic light system (green: low risk, orange: medium risk, red: high risk) as shown in Fig. 6.3. The level of low, medium and high level thresholds should be fitted according to the followed safety philosophy. The different probability classes are presented as the logarithm of the probability of occurrence.

It might be that the risk for some cases is too high and needs to be decreased. Risk mitigation can be performed in two ways:

- reducing the consequences (costs) in case of failure
- reducing the probability of failure

For structural details and mechanical/electrical components, in order to reduce the consequences, a protection system could be included. The probability of failure can be reduced by increasing design safety factors, implementation of redundant systems or decreased inspection intervals and the use (where possible) of condition monitoring. The most effective method would be to eliminate the risk source, which is often not possible. In special cases the risk cannot be reduced and needs to be accepted.

When considering different limit state equations, the resulting overall (total) probability of failure can be estimated by a serial system of the different limit states where each element could be a parallel system. Fig. 6.4 shows a general approach presented in Paper 2 in order to find the annual probability of failure, $\Delta P_{F,tot}$, which includes the annual probability of structural failure of a certain failure mode given no failure of the system (leading to $\Delta P_{F,0}$) and given failure state i of the system (leading to $\Delta P_{F,i}$). The total structural annual failure probability $\Delta P_{F,tot}$ can be calculated as:

$$\Delta P_{F,tot} = \Delta P_{F,0} + \sum_{i} \Delta P_{F,i}(L_i|E_i) \cdot \upsilon_i \tag{6.2}$$

where υ_i is the annual failure rate for a certain failure case i, L_i the load on structural detail resulting from consequences E_i.

Risk assessment is also of importance when dealing with inspection actions and strategies in order to model the most critical failure mode and find the components which should be inspected. Inspection actions for WECs are described in Paper 5.

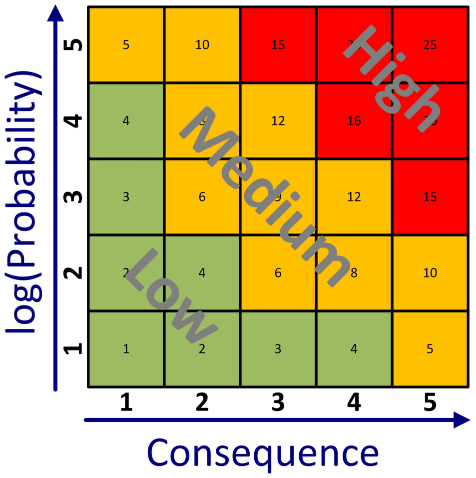


Figure 6.3: Risk ranking matrix [58].

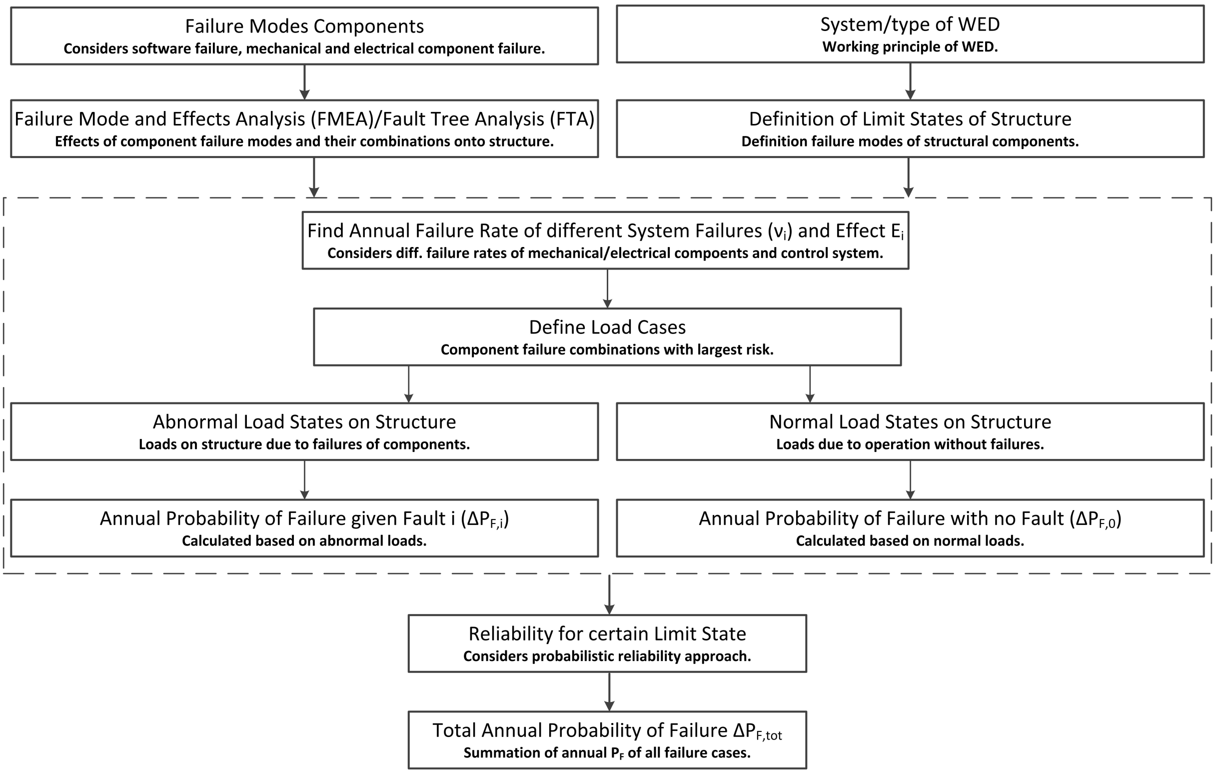


Figure 6.4: Sketch of different failure modes to be considered for structural design.

Chapter 7

Target Reliability Levels

Before performing probabilistic designs, a certain target reliability level should be defined in order to verify whether the chosen design is optimal for a certain application. The target reliability level might depend on the following factors [81]:

- Type of initiating events (hazards) such as environmental loads or various accidental loads, which may lead to different consequences/costs,
- Type of structural reliability analysis method or structural risk analysis, especially which uncertainties are included,
- Failure causes and modes (criticality of failure mode: in case of failure partial or total collapse),
- The possible consequences of failure in terms of risk of life, injury, economic losses and the level of social inconvenience and
- The expense and effort required to reduce risk (cost of safety measure).

Target reliability levels are often defined based on socio-economic considerations where the financial and social (pollution, loss of humans) consequences are judged. Table 7.1 shows the resulting target reliability level indexes for ultimate limit states dependent on the consequences and the costs of safety measures.

Reference [48] shows minimal annual reliability levels with focus on buildings and civil engineering works. The target annual reliability indices dependent on the consequences are shown in Table 7.2. Buildings are often located where people are in danger in case of structural failure. Therefore, the required reliability levels shown in Table 7.2 are higher compared with the general approach presented by [67] (see Table 7.1), even though the consequences are expected to be low.

Table 7.1: Target annual reliability index, $\Delta\beta$, and the corresponding annual probability of failure, ΔP_F, for an ultimate limit state (ULS), according to [67].

Relative cost of safety measure	Consequences of failure Minor	 Moderate	 Large
Large	$\Delta\beta$=3.1 ($P_F \approx 10^{-3}$)	$\Delta\beta$=3.3 ($P_F \approx 5\,10^{-3}$)	$\Delta\beta$=3.7 ($P_F \approx 10^{-4}$)
Normal	$\Delta\beta$=3.7 ($P_F \approx 10^{-4}$)	$\Delta\beta$=4.2 ($P_F \approx 10^{-5}$)	$\Delta\beta$=4.4 ($P_F \approx 5\,10^{-5}$)
Small	$\Delta\beta$=4.2 ($P_F \approx 10^{-5}$)	$\Delta\beta$=4.4 ($P_F \approx 5\,10^{-5}$)	$\Delta\beta$=4.7 ($P_F \approx 10^{-6}$)

When moving to offshore structures, there are minimum annual reliability indices for marine structures [26] and fixed offshore steel structures [65]. Marine structures in [26] refer to oil and gas production devices as well as transportation vehicles where the required minimal reliability level is defined based on availability of redundant systems and warning occurrences before failure as well as the consequences in case of failure. Table 7.3 shows the target annual reliability indices for marine structures, which are between 3.09 and 4.75 and, therefore, similar to the range proposed by [67] (see Table 7.1). The target reliability level range for fixed offshore steel structures in [65] is divided into exposure levels (L1, L2 and L3), which are dependent on the life safety and consequence category (see Table 7.4). The exposure levels correspond to the following annual probability of failure and reliability index ranges [65]:

• L1:	manned	Target probability of failure	$3\ 10^{-5}$
• L1:	unmanned	Target probability of failure	$5\ 10^{-4}$

Table 7.2: Recommended minimum annual reliability indices, $\Delta\beta$, for an ultimate limit state (ULS), according to [48] for buildings.

Reliability Class	Description	Target annual reliability index, $\Delta\beta$	Examples of building and civil engineering works
1	Low consequence for loss of human life, and economic, social or environmental consequences small or negligible	$\Delta\beta$=4.2	Agricultural buildings where people do not normally enter (e.g. storage buildings), greenhouses
2	Medium consequence for loss of human life, economic, social or environmental consequences considerable	$\Delta\beta$=4.7	Residential and office buildings, public buildings where consequences of failure are medium (e.g. an office building)
3	High consequence for loss of human life, or economic, social or environmental consequences very great	$\Delta\beta$=5.2	Grandstands, public buildings where consequences of failure are high (e.g. a concert hall)

Table 7.3: Values of acceptable annual probabilities of failure (ΔP_F) and target reliabilities ($\Delta\beta$), according to [26] for marine structures.

Class of failure	Consequences of failure	
	Less serious	Serious
I - Redundant structure	$P_F = 10^{-3}$ $\Delta\beta = 3.09$	$P_F = 10^{-4}$ $\Delta\beta = 3.71$
II - Significant warning before the occurrence of failure in a non-redundant structure	$P_F = 10^{-4}$ $\Delta\beta = 3.71$	$P_F = 10^{-5}$ $\Delta\beta = 4.26$
III - No warning before the occurrence of failure in a non-redundant structure	$P_F = 10^{-5}$ $\Delta\beta = 4.26$	$P_F = 10^{-6}$ $\Delta\beta = 4.75$

Table 7.4: Determination of exposure levels L1, L2 and L3 [65] for fixed offshore steel structures.

Life-safety category	Consequence category		
	C1 - High consequence	C2 - Medium consequence	C3 - Low consequence
S1 - Manned non-evacuated	L1	L1	L1
S2 - Manned evacuated	L1	L2	L2
S3 - Unmanned	L1	L2	L3

No standards and recommendations about target reliability levels and acceptable probability of failure ranges exist so far for WEC structures. The following section gives a deeper view into acceptable reliability levels for WEC structures and explains similarities to nearby industry sectors like offshore wind turbines or oil and gas structures. But the section also enlightens the uniqueness and challenges for the WEC community concerning standardization of structural safety factors.

7.1 Acceptable Reliability Levels for WECs and Comparison with Nearby Industries

Acceptable minimal reliability levels and maximum probabilities of failure for structural components of WECs are not defined yet. But experiences, similarities and guidelines from nearby industries can help to define appropriate acceptable reliability levels for WECs. Nearby industries are in this case offshore wind turbines and offshore/marine structures for oil and gas applications as well as ship structures.

Experiences and different approaches can be borrowed from structural design procedures for oil and gas, ships as well as offshore wind turbines. As a starting point the following standards for structural design of WECs may be of interest:

- (Offshore) structural design:
  - Basis for structural design: [66, 48, 64, 6, 1]
  - Structural design (steel structures): [30, 65, 50, 72]
  - Structural design (concrete structures): [35, 49, 73]
  - Structural design (composite structures): [34]
  - Offshore wind turbines (OWT) structures: [39, 60]
- For floating WECs:
  - Floating OWTs: [40, 3]
  - Ship structures: [31, 71, 74]
  - Floating oil and gas structures: [41, 32]
  - Mooring lines: [33, 36, 37, 38, 7, 8]

There are additional standards that go more into details about specific details (e.g. corrosion protection) important for structural designs of WECs but these are not mentioned above. Experiences (methodologies) from offshore wind turbines, ships and oil and gas industry can be overtaken, but some major differences need to be accounted for. Fig. 7.1 shows the similarities of WECs with and differences from nearby industries. Structures used in oil and gas industries as well as ships have higher reliability levels due to larger resulting costs/possible loss of human lives in case of failure. On the other hand it can be assumed that structural components of WECs can be designed using the same acceptable reliability levels as considered for OWTs. But OWTs are assumed to be exposed to wind-dominated loads whereas for WEC structures wave loads are dominating. Furthermore, WECs have a control system, which influences the load characteristics and may lead to extreme loads, which can occur during operation and not simultaneously with extreme environmental conditions due to the fact that in this case the devices are in idle/storm protection mode. Also ships have a control system consisting of a propulsion system, stabilizers and ballast tanks. The control system defines the loads onto the structure. Offshore wind turbine structures are modeled using minimal annual reliability levels between 3.1 and 3.7 (see e.g. [44]), which are in accordance with Table 7.1 for the case where the relative cost of safety measure is high. But even though considering the same reliability levels, structural designs of WEC devices might lead to different safety factors. Therefore, the safety factors used for OWTs cannot directly be transferred to WEC applications. There are some drafts for WEC standards and guidelines for design of WEC structures like [27, 61] available, but none of them are based on explicit definition of acceptable reliability levels, but rather on overtaking safety factors used in the oil and gas industry.

For standardization of WEC structural designs there are some additional challenges. So far there exists a huge variety of different devices which operate in different environments (air, on water surface, in water) and there is limited knowledge due to the fact that no device has reached commercial stage.

The diversity of working principles is not just a challenge for standardization of WEC structures but also a risk for the overall technology acceptance by the public. The working principle of WECs was not given at the beginning of the development as it was the case to a large extent for wind turbines and tidal stream turbines, where the principle of operation was overtaken from wind mills. A well-known working principle also makes it easier to be accepted by the public due to smaller mistrust.

7.2 Calibration of Safety Factors

Safety factors are applied in structural design codes in order to account for uncertainties when using deterministic approaches. Safety factors can be used for resistance R as well as load S of a certain limit state equation (see Equation 2.1). The resistance R is generally calculated as:

$$R = \frac{R_C}{\gamma_R} \tag{7.1}$$

where R_C is the characteristic resistance value (often 5% quantile) of the resistance and γ_R is the partial safety factor, which is typically between 1.1 and 1.5. The load S is generally equal to:

$$S = S_C \cdot \gamma_S \tag{7.2}$$

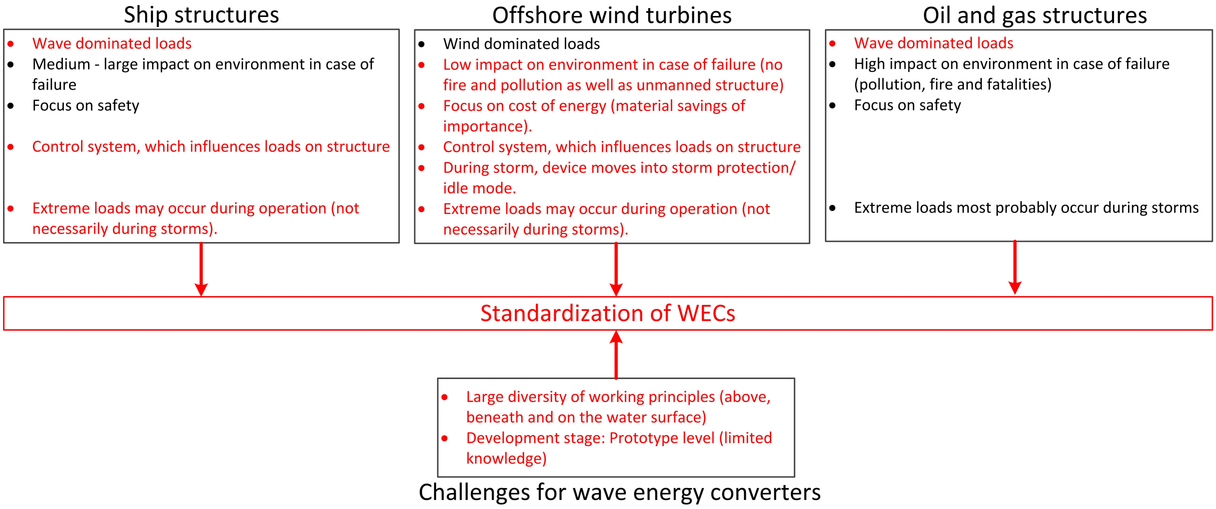


Figure 7.1: Sketch of different similarities from nearby industries as well as unique facts of WECs. Red color indicates topics which should be considered for WEC standardizations.

where S_C represents the characteristic load, which is typically the 98% quantile (extreme condition with 50-year return period) of the annual maximum load distribution function for variable actions and the 50% quantile (extreme condition with 2 years return period) for permanent loads. The partial safety factor γ_S is typically between 1.3 and 1.5.

Safety factors from nearby industries like offshore wind turbines as well as oil and gas structures cannot be directly overtaken for structural designs of wave energy converters due to the fact that:

- Load characteristics are different,
- A control system influences the loads,
- The ratio between wind and wave loads might not be the same,
- The target reliability levels are different and
- Different load calculation methods result in different load uncertainties.

The calibration procedure of safety factors for fatigue is explained using the so-called Fatigue Design Factor, FDF (Equation 4.5), which are calibrated in Paper 3 for WEC applications. Its relation to partial safety factors is shown in Equation 4.6. Calibration of safety factors is a combination of deterministic and probabilistic calculations. Figure 7.2 shows a flow chart of the calibration procedure. For a certain FDF value, a deterministic design of the considered detail (e.g. bolted or welded structure) is done. In a next step the same limit state (here fatigue limit) is considered in the probabilistic frame, where the probability of failure of the considered detail is estimated. The resulting probability of failure is compared with the required reliability level and if necessary another iteration is started using another FDF value.

Table 7.5 shows required FDF values for steel structures from nearby industries for fatigue assessments. The resulting FDF values for wave energy converters are assumed to be in the range shown in Table 7.5. Paper 3 shows an example of FDF calibration focusing on the Wavestar device. The results show that for this specific example the required FDF values are in the range between 6.5 and 1. According to Table 7.5, the resulting FDF values are in the range proposed by [40] for floating offshore wind turbines. But before giving recommendations to standards or guidelines for structural designs of wave energy converters, more details as well as other working principles with other load characteristics need to be considered.

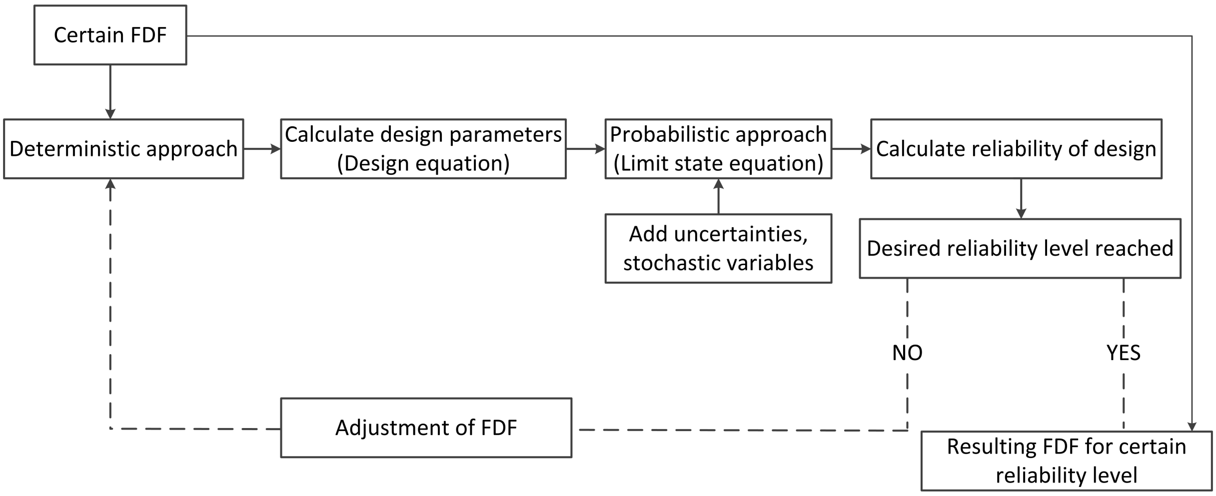


Figure 7.2: Sketch of iterative procedure used to calibrate partial safety factors.

Table 7.5: Fatigue Design Factors ($FDFs$) required for different offshore industries and conditions (criticality and inspections) of external structures. OWT: offshore wind turbine.

Failure critical detail	Inspections	Oil and Gas [65]	OWT bottom-fixed [39]	OWT floating [40]
Yes	No	10	3	6
Yes	Yes	5	2	3
No	No	5	2	3
No	Yes	2	1	2

Chapter 8

Optimization of WEC Structures

Optimizations of WECs can be performed with focus on the readiness of a technology to become a move from a lab-scaled device (research) to a prototype (demonstration) as well as with focus on the technology performance, which is reflected by the costs. Reference [127] presents a techno-economic assessment matrix (see Fig. 8.1) for WEC applications measuring the economic ability (costs) with the so-called Technology Performance Level (TPL) and the commercial ability (development stage) with an index called Technology Readiness Level (TRL). The development trajectory followed by the WEC community is indicated with a yellow curve. This curve shows that the WEC development has a high TRL, but a medium-low TPL. An 'optimal' development trajectory is shown as a green curve in Fig. 8.1 where first a lot of research is performed in order to guarantee that the technology is able to produce electricity at a competitive level. Then, in a second step, the readiness of the technology is increased and the technology is forced towards commercial stage, enabling a low cost of energy (COE). Increasing the TPL at low TRLs (research levels) is cheaper than improving the TPL at high TRLs (demonstration levels) and should be avoided because of the need of much funding.

When talking about structural optimization of WEC devices in the long run, the purpose is to minimize the overall COE. The COE is defined as:

$$COE = \frac{C_{I,tot} + C_{O\&M}}{T_L \cdot AEP} \tag{8.1}$$

where AEP (kWh) is the annual energy production and $C_{O\&M}$ the expected costs for operation and maintenance (O&M), which is also called OPEX (operational expenditures) during its lifetime T_L, and $C_{I,tot}$ indicates the total investment costs for producing the device, also called CAPEX (capital expenditures).

Often instead of COE, the so-called Levelized Cost of Energy (LCOE) is considered. The LCOE includes compared with COE the discount rate and transfers future expenses into present values. This makes it possible to compare different devices as well as technologies in a proper way due to the fact that the future expenses and incomes are discounted. The LCOE can be calculated as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{C_{I,tot}(t)+C_{O\&M}(t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP(t)}{(1+r)^t}} \tag{8.2}$$

where r is the interest rate and n the number of years considered (expected lifetime), $AEP(t)$ the annual produced electricity in the year t, $C_{I,tot}(t)$ the investment costs in the year t and $C_{O\&M}(t)$ operation an maintenance expenditures during the year t. The investment costs $C_{I,tot}$ often need to be paid in the first year when the device is put into operation. Equation 8.2 becomes more complicated when taxes and other financial aspects are included. LCOE indicates the minimal price energy should be sold at in order to reach a break even at the end of the considered lifetime and is of importance when the expenses and incomes are not the same every year during the considered lifetime.

WEC devices also contain a control algorithm, which can be used for optimization purposes. The control algorithm also impacts the extreme as well as fatigue loads onto the structure. The overall target for WEC optimization is not maximizing the power output of the device but minimizing its LCOE. Consideration of the control system in the structural design is important and shown in Paper 8. Paper 8 investigates the impact on the annual energy production (AEP) as well as the resulting cross section area of a welded structure at the Wavestar floater arm are investigated for five different control algorithms (P, PI, PIDc, MEC and MPC). Fig. 8.2 shows the resulting normalized AEP as well as normalized cross section area of the welded detail. Case (A) shows the unconstraint condition of the floater arm. The unconstraint case leads to large AEP values but also to large material use (large cross section area of welded structure). When constraining the velocity of the floater as well as its maximal deflections (Case B), the needed material (cross section area of the weld) can be much more reduced than the AEP is

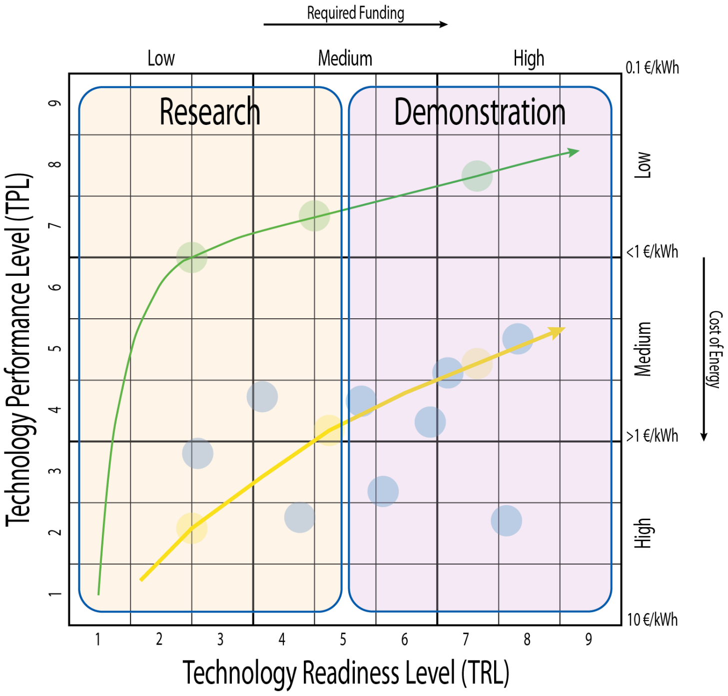


Figure 8.1: Performance and readiness index matrix including the trajectory representing the prospective of the WEC sector (in yellow) and a realistic development trajectory (in green). [127]

reduced.

The focus of optimization also depends on the development stage of a certain technology. WEC devices are intended to become a mass product and not to remain one of a kind. Therefore, a development process followed by many mechanical systems like e.g. wind turbines, cars or aeroplanes should be considered for WEC developments. For mass products one prototype or even different prototypes with different specifications/improvements are necessary due to the fact that the cost of design and analysis will normally be small compared with rectification of faults at a later stage [92].

Fig. 8.3 shows three different development levels together with its main focus. At prototype level, a certain technology needs to be proven and verified whether the expectations are reached. Due to the fact that financial subsidies can be expected to be obtained and structural failure of the system may mean the end for this technology, minimization of LCOE is of minor importance. In order to have easy access and no or low limitations by the waves and wind, the device is placed near-shore. In a next development level (early economical level), optimizations are applied in order to decrease LCOE. LCOE minimization becomes important because possible investors need to be convinced of the technology as well as the subsidies might be limited. The purpose of a fully commercial device is to produce LCOE at a competitive level. Therefore, for this development level, the LCOE should be minimized.

Fig. 8.4 shows the context of COE minimization. The environmental conditions define the loads onto the structure and therefore drive the structural design on the one hand. On the other hand also the control algorithm, which enables to harvest energy from the waves as well as might limit extreme/fatigue loads, is of importance for structural designs. The load characteristics (extreme and fatigue loads) drive the investment as well as O&M costs. The control algorithm as well as the environmental conditions influence the amount of harvested energy from the waves. Therefore, not only the control system itself, but also the loads on the structure need to be considered when optimizing the design. Overall optimization becomes important when moving from the prototype to commercial stage, where costs determine among others about success or fail of the device and its concept.

In general, there exist two different structural design concepts [92]:

- Safe life structures, and
- Fail safe structures.

The target for safe life structures is to prevent any kind of failure during the considered lifetime of the structure. Therefore, inspections can be necessary in order to prevent unexpected failures and control the condition of structural components. The safe life strategy can also be followed for components, where failure may lead to failure of the overall structure. On the other hand fail safe structures are structures based on damage tolerant concepts and

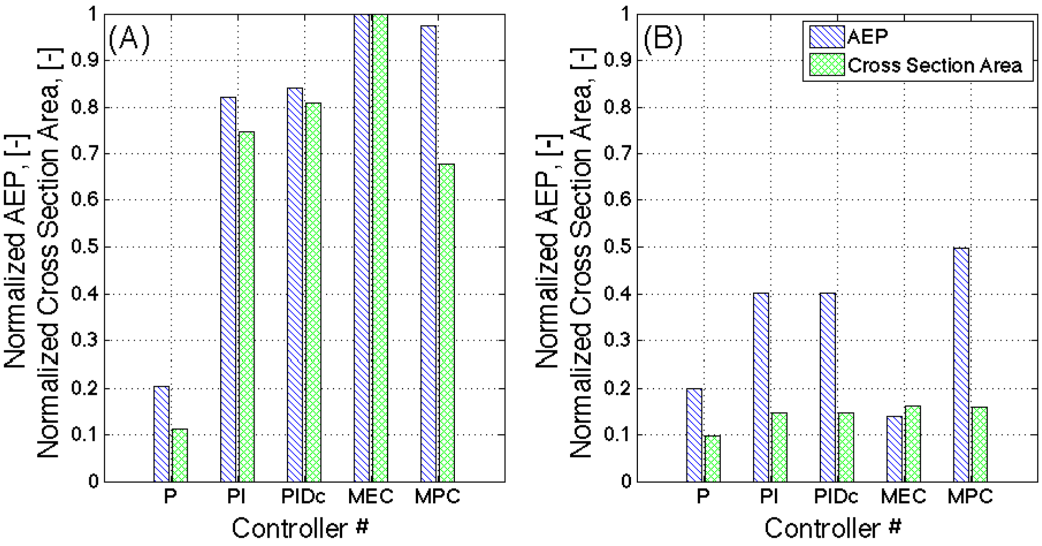
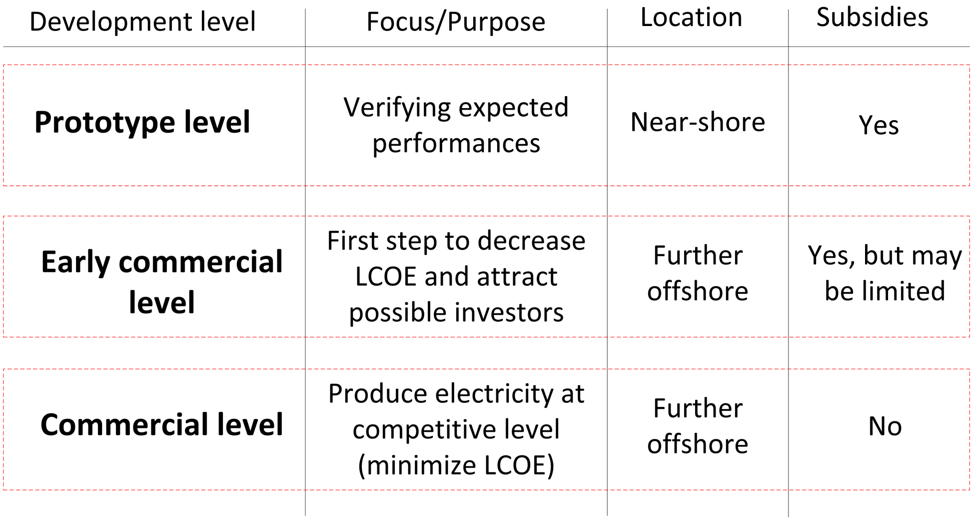


Figure 8.2: Comparison of AEP (blue) and cross section area (green) of a welded structure at the Wavetar floater arm for different control strategies. Case **(A)**: unconstraint (no velocity and location constraints of the floater arm); Case **(B)**: constraint case. The data is normalized by the AEP and cross section area of the unconstraint case using the MEC control algorithm. [Paper 8]



Development level	Focus/Purpose	Location	Subsidies
Prototype level	Verifying expected performances	Near-shore	Yes
Early commercial level	First step to decrease LCOE and attract possible investors	Further offshore	Yes, but may be limited
Commercial level	Produce electricity at competitive level (minimize LCOE)	Further offshore	No

Figure 8.3: Different development levels for a WEC technology from prototype level towards commercial stage. [Paper 6]

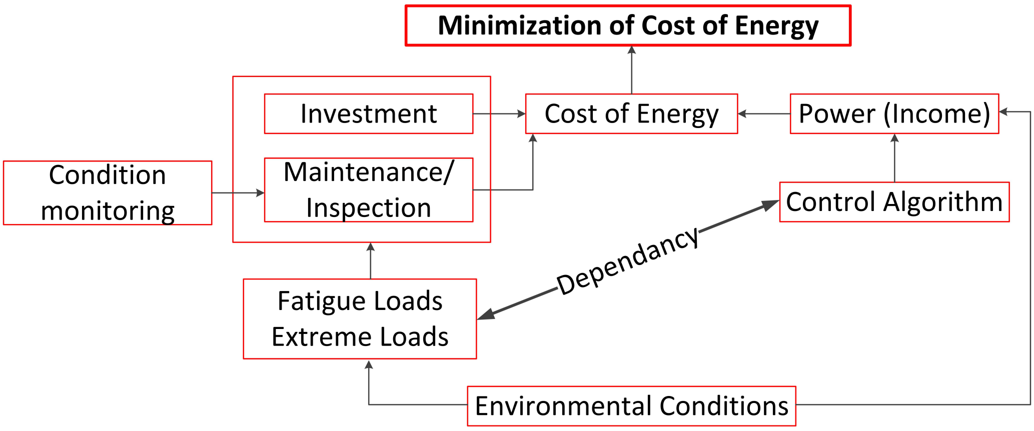


Figure 8.4: Sketch how cost of energy (COE) can be minimized.

redundant systems. For fail safe structures, failure should not lead to overall failure and can be considered when inspections are much more expensive than preventive replacements after a certain service life. In reality, most structural designs are a combination of safe life and fail safe design philosophies.

Another point-of-view when optimizing structural designs is not focusing directly on the COE, but maximizing the earnings from investments into WEC devices and focusing on a reliability-based approach. According to [93] designs, erections and preservations of structural facilities can be seen as a decision problem where maximum benefit and least costs are sought and the reliability requirements are fulfilled simultaneously. When a technology is developed and people/communities are interested in doing investments, they expect earnings from their investments. The optimum decision and structural design parameter z should be performed where the earnings W are maximized. The basic formula for optimum design is given by [93] when assuming that no inspections are performed:

$$\begin{aligned} \max_{z} W(z) &= B(z) - C_I(z) - C_F(z) \\ s.t. \quad \Delta P_F(z) &\leq \Delta P_F^{max} \end{aligned} \tag{8.3}$$

where $B(z)$ is the benefit derived from the existence of the structure, $C_I(z)$ is the structural investment costs (costs for design and construction) and $C_F(z)$ the expected costs in case of failure. The optimization problem in Equation 8.3 can be performed for different involved parties like e.g. constructor, owner, operator and the society. In general, for the different parties the costs B, $C_F(z)$ and $C_I(z)$ may be different. But an investment should only be performed, if $W(z)$ is positive for all involved parties.

Fig. 8.5 shows the optimization domain for a given control system. The benefit $B(z)$ is given by the feed-in tariff multiplied by the produced kWh of electricity and is, therefore, for a certain control system independent on the structural design. The structural (investment) costs increase when the design parameter increases due to larger use of material. The expected failure costs decrease when increasing the design parameter due to the fact that the probability of failure decreases. The optimum design point, z_{opt}, is reached where Equation 8.3 is fulfilled. There is a side condition for the structural design, where the resulting annual probability of failure $\Delta P_F(z)$ should be smaller or equal to a certain maximum annual probability of failure $\Delta P_F^{max} = \Delta P_F(z_{min})$. Reliability-based structural optimizations for offshore wind turbines are shown in [110, 115].

Some WEC devices are very complex devices from the structural as well as system (mechanical and electrical components) perspective. Furthermore, unproven technology or new materials are often used. All these facts increase the risk of failure as well as the needed investment costs. Therefore, general considerations on the working principle (e.g. installation of additional redundant systems at critical locations), used materials as well as mechanical and electrical components from stock may also decrease the probability of failure in connection with WEC devices. Additionally, a very simple and cheap device may not have a high harvesting efficiency of wave energy, but structural failure and replacement is not a big issue. Furthermore, inspection actions should be modeled and considered in structural design optimizations as well as total system optimizations (e.g. redundant systems). Section 4 shows how inspections are modeled and implemented in structural considerations. Different operation and maintenance strategies as well as the influence of different transportation strategies on O&M costs are discussed in the following section.

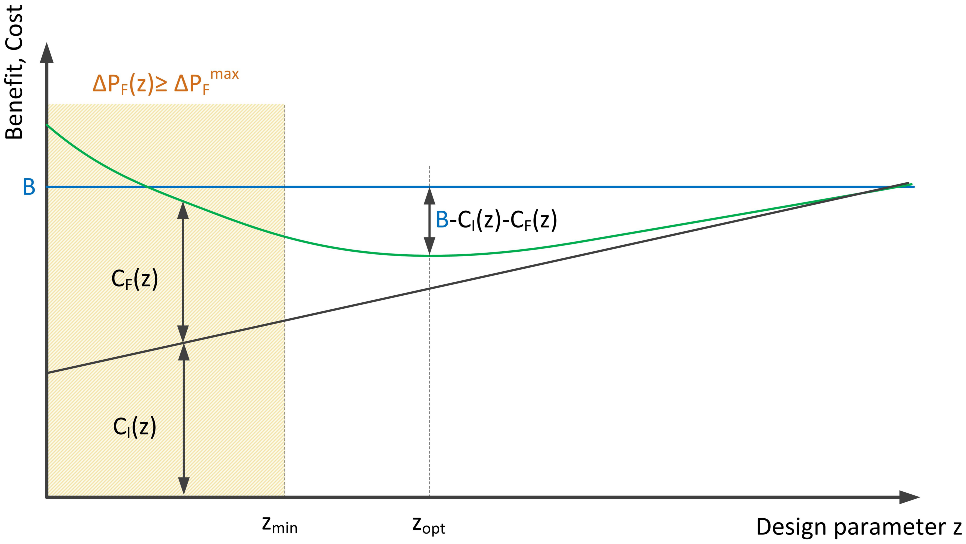


Figure 8.5: Sketch how to find optimum design z_{opt} dependent on the benefit B, the structural costs $C_I(z)$ and the expected failure costs $C_F(z)$.

8.1 Cost-Benefit Analysis

When optimizing a certain device, the structure is designed in such a way that the value of W, as presented in Equation 8.3, is maximized.

When different structural failure modes (e.g. overturning of the device and buckling of a Wavestar pile) are considered, they can be arranged in a serial system, based on the assumption that one failure leads to overall collapse of the structure. The upper bound of the overall annual failure probability, ΔP_F, can be calculated for a serial system as follows:

$$\Delta P_F = \sum_{i=1}^{n} \Delta P_{F,i} \tag{8.4}$$

where n is equal to the number of considered failure modes and $\Delta P_{F,i}$ the annual failure probability of failure mode i.

Equation 8.3 can be formulated in more detail depending on whether or not the device will be rebuilt in case of failure. More information about the different cost-benefit algorithms can be found in [94]. Furthermore, the design parameter z can be enlarged to a design vector $\mathbf{z} = [z_1, z_2, ...z_n]$ consisting of n design parameters like e.g. dimensions of a certain structure. When the device is systematically rebuilt after failure of the structure, the maximization problem can be formulated as [94]:

$$\begin{aligned} \max_{\mathbf{z}} W(\mathbf{z}) = \frac{b}{rC_0} - \frac{C_I(\mathbf{z})}{C_0} - \left(\frac{C_I(\mathbf{z})}{C_0} + \frac{C_F}{C_0}\right) \frac{\lambda P_F(\mathbf{z})}{r + \lambda P_F(\mathbf{z})} \\ s.t. \quad \lambda P_F(\mathbf{z}) \leq \Delta P_F^{max} \\ z_i^l \leq z_i \leq z_i^u \end{aligned} \tag{8.5}$$

where C_0 is the reference initial cost corresponding to a reference design $\mathbf{z}_0$, r the real rate of interest, $C_I(\mathbf{z})$ the initial (fabrication) costs, C_F the direct failure costs, b the annual benefits (income from selling electricity), λ the failure rate of failure events modelled by a Poisson process and $P_F(\mathbf{z})$ the failure probability given design $\mathbf{z}$. The annual failure rate of the system, which is equal to the overall annual probability of failure ΔP_F (see Equation 8.4), should not exceed a certain maximum annual failure probability ΔP_F^{max}. A further side condition considers upper (z_i^l) and lower (z_i^u) bounds for a certain design variable z_i e.g. due to transportation, production or installation limitations.

When the device is not rebuilt after failure, the expected lifetime T_L as well as the probability that the failure probability in the time interval $[0, T]$ (T in years), which is represented by $P_F(T, \mathbf{z})$ are of importance. The resulting annual probability of failure is $\Delta P_F(T, \mathbf{z}) = P_F(T, \mathbf{z}) - P_F(T - 1, \mathbf{z})$. The following equation should be considered when no rebuilding after failure takes place [94]:

$$\begin{aligned} \max_{\mathbf{z}} W(\mathbf{z}) = \sum_{i=1}^{T_L} \frac{b}{C_0}(1 - P_F(i,\mathbf{z}))\frac{1}{(1+r)^i} - \frac{C_I(\mathbf{z})}{C_0} - \sum_{i=1}^{T_L} \frac{C_F}{C_0} \Delta P_F(i,\mathbf{z}) \frac{1}{(1+r)^i} \\ s.t. \quad \Delta P_F(i,\mathbf{z}) \leq \Delta P_F^{max} \\ z_i^l \leq z_i \leq z_i^u \end{aligned} \tag{8.6}$$

The optimal design results from Equations 8.5 and 8.6. The initial structural investment costs, $C_I(\mathbf{z})$, for a WEC mainly depend on the installation process, the mooring/foundation, the housing, and the power-take off and costs in case of decommissioning. The failure costs C_F may vary for different failure modes.

In this PhD thesis the foundation of the Wavestar device is optimized (see Paper 6) based on the approach shown in Equation 8.5, where the parameters to be optimized are the foundation radius R, the diameter D of the pile and the pile thickness t. The following failure modes are considered based on extreme wave loads:

- Sliding of the gravity-based foundation,
- Overturning of the device,
- Bearing capacity limitation and
- Bending capacity failure of the piles.

The optimal dimensions where the benefit is maximized will be different for the different development stages explained in Fig. 8.3 due to different objectives. Ideally when moving from prototype to commercial development stages, the profitability W (see Equation 8.5 and 8.6) will increase due to the fact that earning money from investments becomes more important the further a technology is developed. Fig. 8.6 shows an example from Paper 6 of the profitability W for the different development stages dependent on the foundation radius R and the pile diameter D considering systematic rebuilding in case of failure (Equation 8.5).

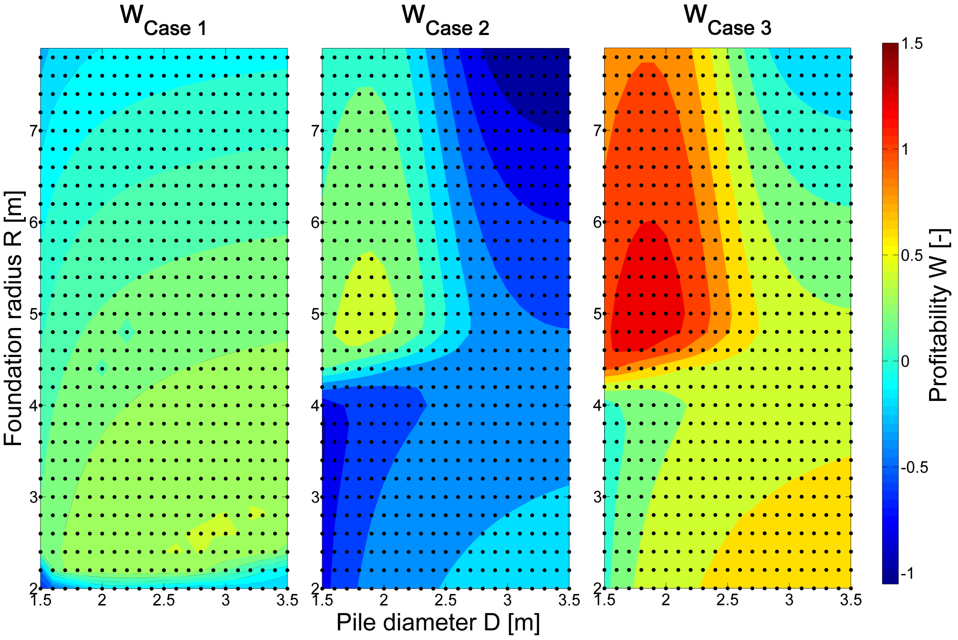


Figure 8.6: Profitability W dependent on the pile diameter D and foundation radius R. $W_{\text{Case 1}}$: Profitability prototype level, $W_{\text{Case 2}}$: Profitability early-commercial stage, $W_{\text{Case 3}}$: Profitability commercial level. [Paper 6]

8.2 Operation and Maintenance Considerations

The part of COE from offshore wind turbines related to O&M costs is generally high. According to [45] the contribution of O&M actions lies between 25% and 30% to the kWh price.

One reason for high O&M costs is the limited accessibility (mainly during winter months). This means that the broken component cannot be replaced/repaired immediately in case of failure and might lead to even more damage until it can be replaced. High relative O&M costs can also be expected for WECs. Therefore, it is important to maximize the resulting total income minus the total costs over the expected lifetime:

$$\max_{\mathbf{z},\mathbf{e},\mathbf{d}} W = B - C_I(\mathbf{z}) - C_{IN}(\mathbf{d},\mathbf{e}) - C_{REP}(\mathbf{d},\mathbf{e}) - C_F(\mathbf{d},\mathbf{e}) \tag{8.7}$$

where B is the total benefit from selling electricity, C_I the initial investment costs, C_{IN} the expected service and inspection costs (e.g. man-hours for inspections), C_{REP} the repair and maintenance costs of the broken component and C_F shows the expected costs in case of failure of the considered component. The following parameters are of importance for O&M considerations (there could also be other important parameters):

- $\mathbf{z}$ structural design parameters
- $\mathbf{e}$ inspection parameter/plan
- $\mathbf{d}$ decision rule for repairs

Fig. 8.7 shows how these three parameters are implemented in planning inspections and maintenances. Based on initial design parameters **z** (e.g. expected lifetime of the device or dimensions of structural components) and the inspection parameters **e** like considered inspection technique or inspection intervals, the result from the inspections can be calculated with the aid of a damage model. The damage model leads to a measurable parameter (e.g crack size), which can be measured and detected with a certain inspection technique. The damage model can e.g. be based on the Paris Law (see Equation 4.7). An inspection leading to the result indicated as **S**. The maintenance/repair plan **d(S)** defines when (e.g at which damage level or crack size) replacement/repair is performed. Together with the realization of uncertain parameters, **X**, a certain total gain minus costs, W, is calculated.

There are, in principal, two different maintenance strategies as shown in Fig. 8.8. When corrective maintenance strategy is performed, repair is performed after failure of the device and preventive maintenance tries to prevent failure of the device and, therefore, performs preventive replacement of the components. Preventive maintenance can be based on a fixed time interval between two replacements (scheduled preventive maintenance) or based on a certain condition (conditional preventive maintenance) like a certain damage or probability of failure, which should not be exceeded. When performing preventive maintenance, components may also fail and corrective maintenance needs to be performed. The advantage of preventive maintenance is decreasing the down-time of the device and increase its availability, but on the other hand the number of replacements is higher and, therefore, also the costs for repair/replacement is larger compared with corrective maintenance.

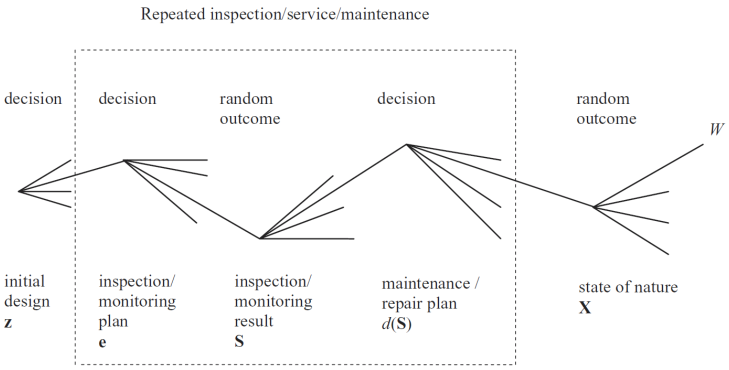


Figure 8.7: Decision tree for optimal planning and maintenance [106].

Operation and maintenance considerations for offshore wind turbines focusing on Equation 8.7 are performed in [106, 84]. The same approaches can also be transferred to O&M considerations of WECs.

There are two transportation technologies to be used in order to access the device for preventive as well as corrective maintenance:

- Access by helicopter (wind speed limited)
- Access by boat (wave height limited)

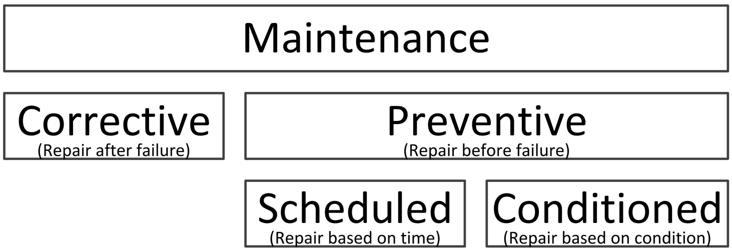


Figure 8.8: Different maintenance/replacement/repair strategies. [Paper 5]

These two transportation technologies can be combined in order to minimize the costs resulting from inspections and repairs. In Paper 5 three different transportation strategies are considered:

- Only use of boat (helicopter not available or boat owned by the operator).
- Repair as soon as possible (ASAP strategy), focus on minimizing down-time of the device.
- Risk-based approach, where the overall costs are minimized for a repair/replacement using perfect weather forecast.

An example of total O&M costs for an example with focus on the Wavestar device is explained in Paper 5. Fig. 8.9 shows the costs of different maintenance strategies as well as transportation strategies. In this case preventive maintenance leads to lower overall O&M costs. The optimal decision strategy should be based on a risk-based approach, where the focus is on minimizing the overall costs. Furthermore, preventive maintenance strategies lead for this specific example to smaller total maintenance costs compared with corrective maintenance strategies. Therefore, the use of condition monitoring and Structural Health Monitoring (SHM) can be very useful.
Equation 8.7 considers one WEC device, but when talking about WEC parks, the optimization should consider minimization of the total O&M cost of the whole WEC park. Furthermore, for large WEC farms, the use of an offshore-based accommodation could be of interest in order to decrease transfer time from shore to the devices. Paper 5 only considers O&M actions on mechanical and electrical components. But also maintenance of the foundation as well as cables are of importance when focusing on the whole system.

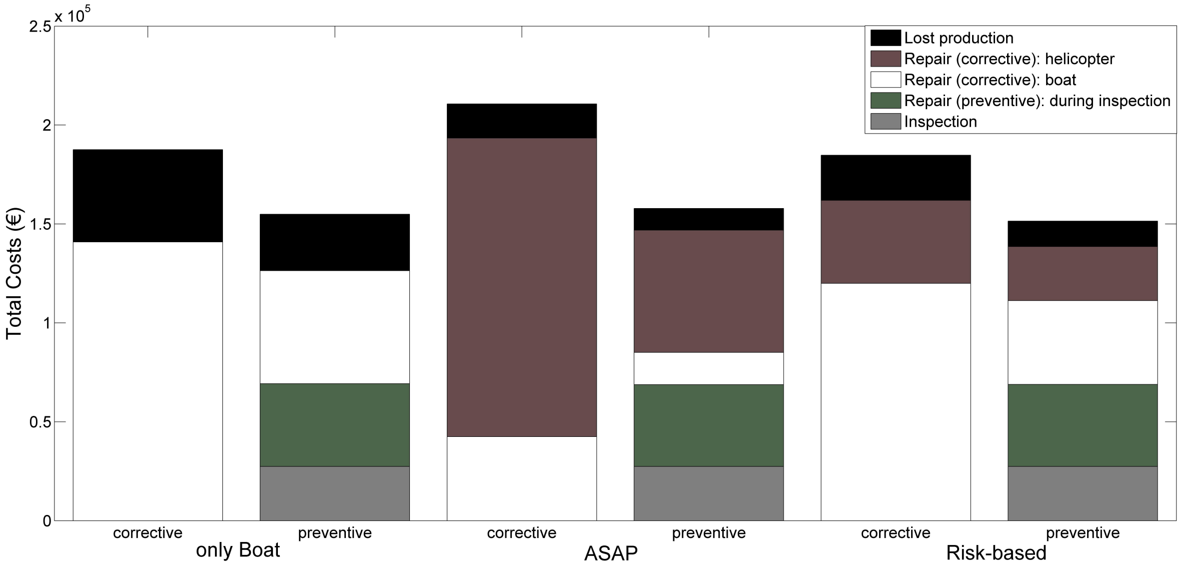


Figure 8.9: Influence of maintenance and transportation strategy on total maintenance costs during one lifetime of 20 years. only boat: only boat used to access device, ASAP: replacement/repair as soon as possible, Risk-based: minimization of overall costs. [Paper 5]

The related costs as well as the failure rates are related to uncertainties and should be modeled as stochastic variables and the expected costs should be estimated using Monte Carlo simulations. Furthermore, the total inspection costs are location dependent. Among the costs, there might be other limitations which will limit the suitability of the cheapest solution. A list of factors that might influence the suitability of offshore logistics solutions is mentioned in [56]:

- Safety and regulatory factors,
- Response time of needed transportation vehicle and crew/technicians,
- Flexibility,
- Equipment payload, and
- Number, size and failure rates of components.

An additional element when time passes is the learning process and exploitation of extra knowledge. Failure of structural components or mechanical/electrical components might occur due to reasons of which one was not aware and, therefore, did not consider in the design process. High failure rates might occur due to the fact that the loads are different as used for the design or different environmental conditions (e.g. high temperatures or high salinity) are present. In a next generation of the component, the learning process and gained knowledge will be included. This learning process will change the maintenance expenses as well as inspection/repair rates. The gained knowledge can be used to update the failure rates based on a Bayesian approach shown in section 5.2.

Therefore, in order to define maintenance and inspection actions, the most risky failure modes or critical components need to be found in order to get an idea of what and with which frequency inspections should be performed. Section 6 explains how to find the most risky failure modes.

Chapter 9

Conclusions and Outlook

9.1 Conclusions

Nowadays, there exist many different wave energy converter (WEC) concepts and devices designed to harvest energy from waves and transfer it to electricity. No concept has reached developed stage so far, but some technologies are on prototype level (e.g. Wavestar, Pelamis, WEPTOS or CETO). Others exist only on paper or are tested at lab-scale. In order to drive WEC technologies to economic success and increase the installed power capacity of WECs, among others the cost of electricity needs to be decreased, such that this technology can compete with other renewable sources used to produce electricity like solar power and wind. Another important aspect when focusing on optimizing WEC concepts is the structural reliability level, which should be maintained during the whole life cycle. Structural designs of WECs are subject to many, large uncertainties (e.g. stress concentrations or static load calculation of a dynamic process) which need to be accounted for in a rational way. This can be done by applying probabilistic methods. Design improvements made in order to reach a certain structural reliability level defined in accordance with the consequences in case of structural failure can be reached using so-called probabilistic reliability methods. Therefore, FORM (First Order Reliability Methods) techniques or Monte Carlo simulations can be applied to estimate the structural reliability index and the probability of failure of a certain design. Optimization strategies are defined in order to decrease the cost of energy directly and increase the lifetime of structural details as well as define and develop new designs.

In order to accelerate the learning process, knowledge from nearby industries like (offshore) wind turbines or oil and gas industry should be transferred due to large similarities. But due to some differences and singularities of WEC devices, not all methodologies can be directly transferred. Furthermore, challenges to success of WEC devices are the huge diversity of different working principles as well as the development stage of the devices (prototype level or lower).

Before performing probabilistic reliability assessments, WEC-specific uncertainties used as input for probabilistic reliability assessments need to be determined. In this thesis the following uncertainties are quantified:

- Uncertainties related to environmental parameter estimations as well as wave models of importance for WECs,
- Uncertainties of models used for fatigue assessments of WECs including inspection modeling,
- Model (load) uncertainties for different WEC control strategies and systems, and
- Uncertainties related to scatter diagram discretization as well as wave state uncertainties.

Different structural probabilistic reliability assessments of WECs performed in this PhD thesis showed the importance of the modeling uncertainties related with wave load assessments, stress calculations given a certain load, the impact of inspections, load characteristics of different control systems as well as loads occurring simultaneous with failure of the mechanical/electrical system. Furthermore, the studies showed that the statistical uncertainties impact the structural reliability when the considered load or wave elevation time-series are too short.

The second part of the thesis is dedicated to structural load and probabilistic reliability assessments. Fatigue failures become of importance for WEC optimizations due to the fact that a control system may limit the loads during extreme conditions and might be optimized to maximize the electricity production rate. When optimizing the control system, the loads on the structure dependent on the control system should also be considered and not only overall power maximization. The target of the control system should be to minimize the cost of electricity. Fatigue failure often happens for welded and bolted structures. Therefore, as an example welded and bolted details are considered in this thesis when focusing on structural fatigue failures. Extreme conditions should also be considered during structural WEC designs. Commonly, extreme loads do not occur simultaneously with extreme environmental conditions, where the device is in idle/storm protection mode, but during operation. One paper included in this thesis shows how to extrapolate extreme loads during operation based on short-term load time-series.

The most critical failure cases of electrical/mechanical systems as well as the control system should also be considered together with their failure rates as well as the influence on structural loads when optimizing structural designs of WECs. An example based on the Wavestar prototype is presented in this PhD thesis how to include and assess the influence of mechanical/electrical components on structural reliability.

Due to limited access of the devices, maintenance costs can have an important contribution on the overall electricity costs. Therefore, different maintenance strategies (preventive/corrective) as well as different transportation possibilities (boat/helicopter) should be considered when designing structural components.

Furthermore, structural safety factors are calibrated for welded structures of the Wavestar device. It is assumed that in case of structural collapse WECs have the same (financial) consequences as structural collapse of offshore wind turbines (no environmental pollution and unmanned structures). Therefore, the minimal annual reliability indices are in the range between 3.1 and 3.7, which correspond to a maximum annual probability of failure between 10^{-3} and 10^{-4}. The calibration showed that the resulting fatigue design factors are between 1 and 6.5, which is in the range proposed for floating offshore wind turbines in standards. These safety factors can be used as a starting point for defining safety factors in standards for WECs. WEC structural standards will accelerate the WEC development by lowering the financial risk and introducing equal guidelines for all WEC structures. In the longrun this will decrease the cost of energy (COE).

Further COE decrease can be reached by the use of reliability-based structural optimizations where the target reliability levels do not define the safety factors, but are used as side conditions in an optimization process, where the overall costs are minimized. A reliability-based structural optimization is presented for the gravity-based foundation of the Wavestar, but can be applied for different devices as well as components.

The main topic of this thesis - reliability of WECs with focus on probabilistic methods - may due to the fact that only a small amount of concepts have reached the prototype level and the whole community is far from reaching the developed stage, be seen as too early to be included in the WEC development process. But due to the fact that other renewable sources already reached commercial stage and are able to compete with non-renewable electricity sources, it is necessary to develop design guidelines already at an early stage in order to accelerate the development process of a whole technology. An important step for bringing the whole WEC community to success is decreasing the cost of energy from WECs down to the order of electricity prizes from other renewable electricity sources. This should be the focus once the concept has reached prototype level. All other strategies and ideas presented by the WEC community on how to convince the society why (e.g. due to limited visibility from shore, no noise, large resource) to go for wave energy as electricity source are of secondary importance and could be used in a second step as arguments to convince the society of this technology.

Money talks - also when talking about renewable technologies.

9.2 Outlook

Generally, in this work, the focus is on two WEC concepts (Wavestar and WEPTOS). But the considered methodologies should also be applied to other working principles in order to complete the picture and gain a complete overview for design standardization purposes of WEC structures.

This thesis presents an example of fatigue design factor (FDF) calibration. However, in order to get a broader and general overview about the required FDF range, more examples and also other details as well as other materials should be considered. This would make it possible to give recommendations to guidelines and standards for structural design of WECs. In [58] a generic approach of how to break down a WEC system is presented and could be used as a starting point for defining different working principles and as a proposal for WEC classification in order to define different required FDF values for the different WEC types.

The study performed on operation and maintenance considerations should also be considered in more details before applying to real devices. This part of the work is generic in the sense that it is only valid for a certain cost and location. Furthermore, in the future, WECs will be most probably installed in farms in order to benefit from cost-sharing effects. Therefore, also the operation and maintenance consideration should focus on minimizing the overall costs for the whole WEC farm in the future. Furthermore, information from condition monitoring and structural health monitoring could be used at a later date to optimize inspection intervals as well as replacements of components.

This thesis focuses on fatigue assessments of welded and bolted structures. Another important structural component where fatigue/damage accumulation is of importance are bearings, which should also be considered in structural reliability assessments of WECs. Furthermore, due to the complexity of some devices, custom-made structural components (like e.g. gyro-bearings for the Wavestar power take off) are necessary, where limited knowledge is available and could be a critical structural component.

The use of non-metallic materials like composites is popular in offshore applications due to the absence of corrosion. In this thesis only metal fatigue failures are considered. But fatigue failure of composite material should also be considered.

An important uncertainty source, which should be quantified, is uncertainties related to up-scaling of the device from lab-scale to full-scale devices. Uncertainties related to the electricity production as well as the structural loads might be different. New measurement devices will be installed on the Wavestar device to measure the loads on the structure and makes it possible to directly compare with up-scaled results from the lab. This setup enables quantifying of scaling uncertainties of WEC applications.

For standardization, definition of load cases need to be performed. Paper 2 showed an example where mechanical/electrical component failures are included in structural reliability assessments. Due to the large diversity of different working principles, different devices should also be analyzed in more detail in order to define the necessary load cases. A starting point could be the load cases used for offshore wind turbines [39].

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Appendix

This appendix contains the following papers:

Paper 1: Ambühl, S., Kofoed, J.P. and J.D. Sørensen. 2014. ”Stochastic Modeling of Long-term and Extreme Value Estimation of Wind and Sea Conditions for Probabilistic Reliability Assessments of Wave Energy Devices.” *Ocean Engineering*, 89(2014): 243-255.
DOI: 10.1016/j.oceaneng.2014.08.010.

Paper 2: Ambühl, S., Kramer, M., Kofoed, J.P., Bittencourt Ferreira, C. and J.D. Sørensen. 2013. ”Reliability Assessment of Wave Energy Devices.” 11th International Conference on Structural Safety and Reliability (ICOSSAR) 2013, New York, USA.

Paper 3: Ambühl, S., Ferri, F., Kofoed, J.P. and J.D. Sørensen. 2015. ”Fatigue Reliability and Calibration of Fatigue Design Factors of Wave Energy Converters.” *International Journal of Marine Energy*, 10 (2015): 17-38.
DOI: 10.1016/j.ijome.2015.01.004

Paper 4: Ambühl, S., Kofoed, J.P. and J.D. Sørensen. 2014. ”Extrapolation of Extreme Response for Different Mooring Line Systems of Floating Wave Energy Converters.” *International Journal of Marine Energy*, 7(2014): 1-19.
DOI: 10.1016/j.ijome.2014.09.003.

Paper 5: Ambühl, S., Marquis, L., Kofoed, J.P. and J.D. Sørensen. 2015. ”Operation and Maintenance Strategies for Wave Energy Converters.” *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, (Published online).
DOI: 10.1177/1748006X15577877.

Paper 6: Ambühl, S., Kramer M. and J.D. Sørensen. 2014. ”Reliability-based Structural Optimization of Wave Energy Converters.” *Energies*, 7(12): 8178-8200.
DOI: 10.3390/en7128178.

Appendix A

Paper 1

Title:

Stochastic Modeling of Long-term and Extreme Value Estimation of Wind and Sea Conditions for Probabilistic Reliability Assessments of Wave Energy Devices

Authors:

Simon Ambühl, Jens Peter Kofoed, John Dalsgaard Sørensen.

Published in:

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DOI: 10.1016/j.oceaneng.2014.08.010.

Appendix B

Paper 2

Title:

Reliability Assessment of Wave Energy Devices

Authors:

Simon Ambühl, Morten Kramer, Jens Peter Kofoed, Claudio Bittencourt Ferreira, John Dalsgaard Sørensen.

Conference:

11th International Conference on Structural Safety and Reliability (ICOSSAR) 2013, New York, USA.

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Reliability Assessment of Wave Energy Devices

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ABSTRACT: Energy from waves may play a key role in sustainable electricity production in the future. Optimal reliability levels for components used for Wave Energy Devices (WEDs) need to be defined to be able to decrease their cost of electricity. Optimal reliability levels can be found using probabilistic methods. Extreme loads during normal operation, but also extreme loads simultaneous with failure of mechanical and electrical components as well as the control system, are of importance for WEDs. Furthermore, fatigue loading needs to be assessed. This paper focus on the Wavestar prototype which is located near Hanstholm (DK). In the present paper, a generic example for an extreme limit state is considered. The extreme limit state case considers important failure modes of the system which are determined by a Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA). The resulting reliability indices are then compared with related industries like offshore wind turbines.

1 INTRODUCTION

Wave energy has big potential for contributing to sustainable electricity production. Compared to other renewable energy sources like wind and solar power, the electricity production costs from wave energy are, at present, larger and less competitive. Therefore, the cost of electricity from Wave Energy Devices (WEDs) needs to be decreased. One possibility to contribute to this objective is to derive an optimal reliability level for wave energy devices where the whole system (including electrical and mechanical components as well as the control system) is considered. Optimized reliability levels can be found using probabilistic design methods where explicit account for uncertainties connected to loads, strengths and calculation methods are considered. Sørensen et al. (2011) presented a framework for probabilistic design reliability analysis of wave energy devices which will be used as basis for this paper.

The methodology for structural reliability assessments of WEDs is divided into three major steps.

In the first step, the environmental conditions (wave and wind conditions) are assessed.

Based on the environmental conditions, the loads onto the structure are calculated in the second step. Loads are modeled corresponding to different limit states e.g. defined by a Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA) focusing on the following load cases for the structure:

- Extreme wave and wind loads during normal operation.
- Extreme wave and wind loads during operation simultaneous with failure of electrical components.
- Extreme wave and wind loads during operation simultaneous with failure of mechanical components.
- Extreme wave and wind loads during operation simultaneous with failure of control system.

Other load cases that should also be considered:

- Wave and wind loads when the WED is in a 'parked' position.
- Fatigue due to wave and wind loads.

In the third step, the reliability of the WED plant is assessed by using a probabilistic approach. The probabilistic reliability assessment accounts for uncertainties due to natural randomness of the considered parameters, imperfect measurements (e.g. wave measurement device far away from WED location), imperfect knowledge of the mathematical model, limited sample sizes and choice of probability distribution types.

The probability of failure, P_F, for a certain limit state is obtained based on a limit state function with correspondent stochastic model and is derived by FORM/simulation methods. Based on the probability of failure, the reliability index β is determined. The derived reliability index is then compared with reliability indices from related industries like offshore wind turbines. This allows for make suggestions and recommendations about the design of WEDs.

At the moment, there are many different WED concepts under development. For illustration in this paper, the Wavestar power plant will be used, and a generic example for an extreme limit state shows the application of this methodology for WEDs.

2 STRUCTURAL RELIABILITY ASSESSMENT

For structural components such as beams, moorings or foundations, a limit state equation can be formulated for a certain failure mode and probabilistic reliability assessments can be performed. For each failure mode of a structural component, a limit state equation $g(\mathbf{X})$, where different uncertainties using stochastic variables $\mathbf{X} = \{X_1, X_2, .., X_n\}$ are defined, can be established. The reliability assessment can be solved using FORM/SORM methods or simulations (see e.g. Lemaire et al. 2009, Madsen et al. 2006). The probability of failure, P_F, is equal the probability that the limit state equation is smaller or equal to zero and can be used to estimate the reliability index β:

$$P_F = P(g(\mathbf{X}) \leq 0) \approx \Phi(-\beta) \tag{1}$$

where $\Phi()$ is the standardized normal distribution. For time-dependent failure probability $P_F(t)$, the annual probability of failure $\Delta P_F(t)$, given the survival of the structure, is obtained from:

$$\Delta P_F(t) = \frac{(P_F(t) - P_F(t - \Delta t))}{(1 - P_F(t)) \cdot \Delta t} \tag{2}$$

where $\Delta t = 1$ year and $t > \Delta t$. $P_F(t)$ is the probability of failure in the time interval $[0, t]$.

2.1 *Consideration of Mechanical/Electrical Components and Control System*

Failures of mechanical and electrical components as well as the control system may change the load distribution on a structural component of a WED. A methodology for considering different failure modes of mechanical and electrical components of the system as well as its control system is shown in Figure 1.

The impact on a structural component due to failure of a mechanical or electrical component as well as the control system can be identified e.g. by performing a Failure Mode and Effects Analysis (FMEA) or Fault Tree Analysis (FTA) (see e.g. Limnios 2010). A point to be considered is that components may have different failure modes and can fail in different ways which then lead to different load distributions onto the structure. FMEAs make it possible to find the failure modes of mechanical/electrical components and the control system with high impact due to large resulting costs or high probabilities of occurrence. These large impact failure modes should be considered for structural reliability analyzes. It has to be noted that the FMEA is WED type dependent.

In the next step, the different load cases, due to failures of components and their probability of occurrence, need to be assessed. The structural reliability assessment includes different cases with normal (no failure of subcomponents) or abnormal load cases which are a consequence of failures of the system. The total annual probability of failure, ΔP_F, for a certain structural component can be written approximately as the sum of the probabilities of failure, $\Delta P_{F_i}(L_i|E_i)$, of a certain failure case, i, leading to the load distribution, L_i, given the consequences, E_i, onto the system and the annual probability of failure ΔP_{F_0} during normal operation (no failure of the system):

$$\Delta P_F = \Delta P_{F_0} + \sum_i \Delta P_{F_i}(L_i|E_i) \cdot \upsilon_i \tag{3}$$

where υ_i is the annual failure rate for a certain failure case i. The annual probability of failure, $\Delta P_{F_i}(L_i|E_i)$, is estimated using a limit state equation where the mechanical behavior for a certain given fault is modeled, and where the variable load (e.g. wave load) is modeled as the maximum load within the time interval where the fault is 'active' (e.g. until the failure is repaired).

The time interval where a certain failure case is 'active' can be indicated as the Mean Time to Recover ($MTTR_1$). The Mean Time to Recover itself consists of Mean Logistics Delay Time ($MLDT$) and Mean Time to Repair ($MTTR_2$):

$$MTTR_1 = MLDT + MTTR_2 \tag{4}$$

$MLDT$ considers the time necessary for transportation and manufacturing/obtaining the component which needs to be replaced/repaired. $MLDT$ is location and season-dependent due to different transportation distances and infrastructure as well as harsher environmental conditions during winter. $MTTR_2$ considers the time on board of the WED used for replacing the component. Data for $MTTR_2$ is available from related industries and can be transferred to WED applications. Figure 2 shows sources for $MTTR_2$ and $MLDT$ variations.

The annual failure rate υ_i of failure case i is calculated from component failure rates λ. Electrical and mechanical component failures are often modeled assuming time-independent failure rates. Failure rate data of electrical and mechanical components is often difficult to get access to, and for WEDs no data is available due to lack of experience. But surrogate failure rates from related technologies like offshore wind

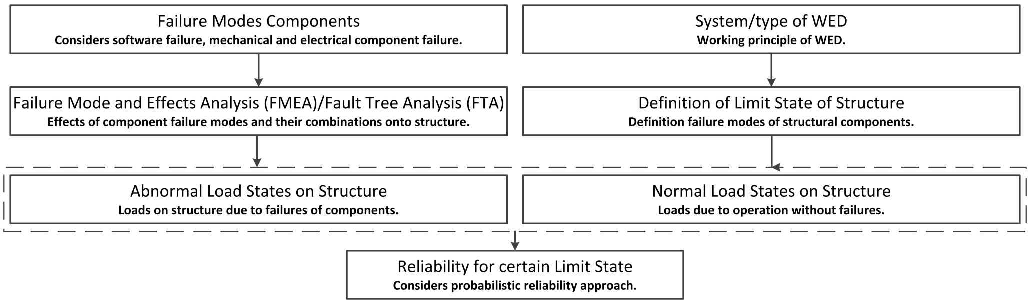

Figure 1: General procedure for structural reliability assessments including abnormal loads due to failures of electrical and mechanical components as well as the control system.

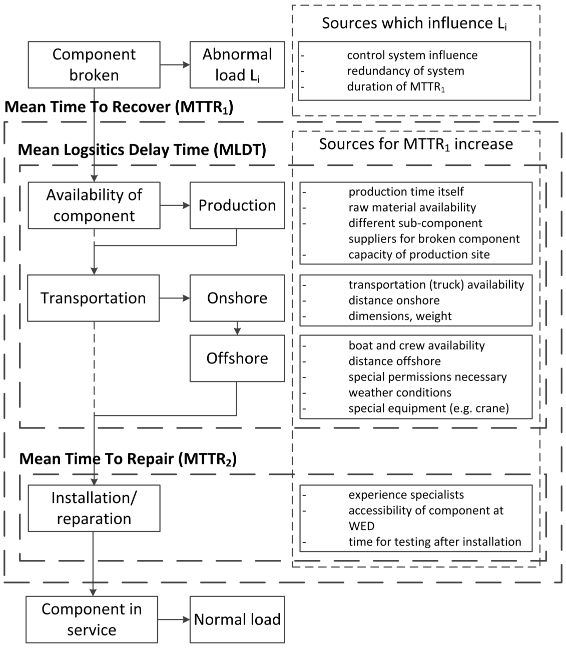

Figure 2: Sources for $MTTR_1$ and load L_i variations for different WEDs when a component needs to be replaced or repaired.

turbines or oil/gas industry can be taken and adjusted for the environmental conditions in wave energy devices. For WEDs, the following databases could be used:

- Petrochemical industry: OREDA (2009)
- (Offshore) wind turbines: van Brussel and Zaaijer (2003), Ribrant and Bertling (2007), IEA Wind Task 33 (2012)
- Generic reliability databases: IEEE Std 500-1984 (1984), MIL-HDBK-217F (1991)

Failure rates of electrical and mechanical components often need to be adjusted for the different environments in which they are operating. MIL-HDBK-217F (1991) presented a procedure for adjusting the failure rate of a component failure mode by using adjustment factors which account for different operating environments or different materials and different material qualities used for production. A general qualification methodology for finding the adjustment factors is described in DNV-RP-A203 (2012) where each component is divided into proven technology (experience available) or new/unproven technology. Another way to adjust failure rates is based on a Bayesian approach (see e.g. Thies et al. 2012, Val and Iliev 2011), which can also be used for updating the failure rate if new data becomes available.

3 EXAMPLE - WAVESTAR

The Wavestar prototype is placed at Hanstholm (DK). The device has an installed capacity of 110 KW and has been feeding electricity into the grid since February 2010. It consists of two floaters, four piles and a main platform where the electrical and mechanical components are placed. When the measured significant wave height H_S is too high (larger than 3 m) or the wave height is too small (H_S less than 0.5 m), the floater is taken out of the water and moved into so called storm protection mode. Figure 3 shows a picture of the device where one floater is in production mode and the other one is in storm protection mode.

The floater drives a hydraulic cycle which impels a turbine and a generator. The turbine and the generator can be used as pump - motor combination for lifting the float out of the water. Additionally, an auxiliary pump is mounted. The auxiliary pump lifts the floater if the turbine or generator is broken. A diesel generator is on board in order to produce electricity in case of lacking electricity supply from the shore. The floater is connected with 4 bearings to the main platform. The significant wave height, H_S, is measured with an ultrasonic sensor and a pressure sensor.

A larger Wavestar WED is planned for 20 floaters. It should be placed at the wind farm Horns Rev 2 (see Marquis et al. 2012). For the generic example the sea conditions at Hanstholm and the system used in the prototype are considered. However, $MTTR_1$ considerations are based on assumptions used in the offshore wind turbine industry.

One generic example of reliability assessments for an extreme situation is described in the following section. The purpose of this example is to illustrate how to implement the system reliability into structural analyses of WEDs.

Figure 3: Wavestar prototype at Hanstholm with one floater (left) in operational mode and the other (right) in storm protection mode.

3.1 *Limit State Equations - Sliding of Gravity-based Foundation*

The limit state 'sliding of gravity-based foundation due to extreme wave and wind loads' is considered here. Wave loads are assumed to be the dominating load for this limit state. Extreme wind gusts and wave heights do not occur at the same time. Therefore, the non-dominating wind load, Q_S, is assumed to be obtained corresponding to the mean 10-minute extreme wind speed while extreme wave loads W_S on the piles occur. The dominating wave load W_S onto the piles is obtained as the maximum wave heights during an extreme 3-hour wave state. The limit state equation which considers annual extreme 3-hour significant wave heights $H_{S_{ex}}$ and the annual extreme 10-minute mean wind speed $V(H_{S_{ex}})$ conditional on $H_{S_{ex}}$ can be written as:

$$g_s = fGgz - 4\underbrace{C_W C_d C X_C H_{S_{ex}}}_{W_s} X_{wave} - \underbrace{\underbrace{0.5\rho_{air} V(H_{S_{ex}})^2}_{pressure} A C_d X_{wind}}_{Q_s} \quad (5)$$

where G is the weight of the device (permanent load), g the acceleration of gravity, f the friction coefficient, C_W ($= 10$ kN/m) the mean force per meter of wave height, C_d the drag coefficient, C (=1.86) the factor leading from the significant wave height to the maximum instantaneous wave height during a certain wave state, X_C the uncertainty about the extreme wave height given by $H_{S_{ex}} \cdot C$ within one sea-state, X_{wave} the model uncertainty of the wave load given a certain significant wave height, ρ_{air} (=1.25 kg/m^3) the density of air, A (=210 m^2) the front area and X_{wind} the model uncertainty of wind load given significant wave height. The design factor, z, accounts for non-uniform pressure distribution of the foundation onto the soil due to moments at the seabed induced by the wind and the waves which lead to a smaller effective foundation area than the real foundation area. Therefore, z is always smaller or equal than 1 and proportional to the cross-section of the foundation.

The limit state equation (Equation 5) has to be enlarged in case abnormal loads due to a certain failure case i of the electrical and mechanical system have to be included. In this example, only abnormal wave loads onto the floater are considered and it is assumed that system faults occur at a random point of time. In other cases system failures (failure of electrical/mechanical components and control system) can be correlated with extreme wave and wind loads. The enlarged limit state equation includes extreme wave loads L_i onto the floater for a given failure case i of the system. The maximum wave load L_i is equal the extreme wave load on a floater over a time interval that corresponds to the time from failure to repair of the component given that the fault occurs at a random point of time. The extreme horizontal wave loads at the floater $L_i(H_{S_{ex,i}}|E_i)$ given the consequences E_i on the system due to failure case i depends on the extreme significant wave height distribution $H_{S_{ex,i}}$. The limit state equation $g_{s,i}$ for the failure case i can be written as:

$$g_{s,i} = fGgz - 4\underbrace{C_W C_d C X_C H_{S_{ex,i}}}_{W_s} X_{wave} - \underbrace{0.5\rho_{air} V(H_{S_{ex,i}})^2 A C_d}_{Q_s} X_{wind} - X_{wave} L_i(H_{S_{ex,i}}|E_i) N_i \quad (6)$$

where $H_{S_{ex,i}}$ is the extreme maximum significant wave height distribution during $MTTR_{1,i}$ and $V(H_{S_{ex,i}})$ is equal the extreme 10-minute mean wind speed given the extreme maximum significant wave height distribution $H_{S_{ex,i}}$. $MTTR_{1,i}$ corresponds to the time needed to repair the failure case i. N_i represents the number of affected floaters for the failure case i.

3.2 *System Failure Cases*

System failures are here mechanical and electrical component failures as well as failure of the control system and assumed to constitute the failure cases in section 3.1. In this example 5 different system failure cases and one normal operation case (no failure of the system) are considered. The 5 considered system failures result that the floater remains in the water during storms. These failure cases are described in Table 1 and their effects are shown in Table 2.

Case 5 is assumed to be a software problem and therefore solvable with online access within 48 hours. Access to the device is not necessary for this failure case. For offshore wind turbines, $MTTR_1$ is often assumed to be in the range of 490 hours (see e.g. Barberis Negra et al. 2007). To control the hydraulic cy-

Table 1: Considered failure cases of mechanical and electrical components as well as the control system of the Wavestar prototype.

Case	Title	Description
0	Normal operation	Floater out of water during storm.
1	Total loss of electricity	Electricity connection broken and failure of onboard diesel generator.
2	Lifting floater fails	Failure of auxiliary pump or valve in front as well as failure of motor (generator) or pump (turbine).
3	Failure of bearing	Failure of one bearing (in total 4 bearings).
4	Wrong measurements of wave state	Pressure sensor and ultrasonic sensor broken.
5	Failure control system	Software failure of control system.

Table 2: Effects of the different load cases. N_i shows the number of floaters on the water surface and exposured to extreme wave loads due to failure case i.

Case	Effect	N_i
0	No loads on floater considered (out of water).	-
1	Blocking of hydraulic cycle (valves in standby position). Movement of both floaters is hindered.	2
2	Floater remains on water surface, broken turbine/generator blocks hydraulic cycle. Movement of one floater is hindered.	1
3	Increased friction movement of floater. Movement of one floater is hindered.	1
4	Both floaters remain in normal operation mode, wave state measurements too low.	2
5	Both floaters remain in operational mode.	2

cle and in case of an emergency, valves are positioned within the hydraulic cycle. These valves are designed and mounted in such a way that if they are not activated, they close the hydraulic cycle.

The 5 different failure cases and the normal operation case lead to 4 different load cases:

- Case 0: Extreme wave conditions and no loads on floaters (L_0).
- Case 1, 2, 3: Extreme wave conditions and high resistance of hydraulic cycle/higher damped floater motion during 490 hours (L_1, L_2, L_3).
- Case 4: Extreme wave conditions and normal operation of the floater during 490 hours (L_4).
- Case 5: Extreme wave conditions and normal operation of the floater during 48 hours (L_5).

Larger loads at the floater occur due to blockage of the hydraulic cycle which dampens the movement of the floater and therefore increases the loads onto the floater. The increased loads are modeled using a 4 times larger damping coefficient than during normal operation. Nevertheless, the device contains passively pressure-driven safety valves which limit the maximum pressure in the cylinder to ± 180 bar which corresponds with a maximum force at the power take-off of ± 420 kN.

The extreme significant wave height distribution $H_{S_{ex}}$ for the extreme load at the floater is assumed to be Weibull distributed. The peak period T_P which is conditional on $H_{S_{ex}}$ is assumed to be LogNormal distributed. The distribution parameters for T_P conditional on $H_{S_{ex}}$ are detected based on the model proposed in Bitner-Gregersen (2005). Table 3 shows the distribution values for the different load cases. These distribution parameters are based on wave state measurements over several years at Hanstholm (DK) and lead to the following relation:

$$\begin{aligned} \mu_{T_P} &= \exp\left(1.436 + 0.041 {\mu_{H_{S_{ex}}}}^{1.93}\right) \\ \sigma_{T_P} &= \exp\left(0.131 + 0.938 \mathrm{e}^{\left(-3.269 \mu_{H_{S_{ex}}}\right)}\right) \end{aligned} \tag{7}$$

The joint probability for each load case is divided into 20 discretizations. Table 4 shows the joint probability for load case L_5 and Table 5 for L_1, L_2, L_3 and L_4.

Table 3: Extreme wave states with significant wave height $H_{S_{ex,i}}$ (m) and peak period $T_{P,i}$ (s) for load case i.

Case	$H_{S_{ex,i}}$		$T_{P,i}$	
	μ	σ	μ	σ
0	4.79	0.29	-	-
1, 2, 3, 4	3.56	0.44	6.76	1.14
5	1.71	0.68	4.72	1.14

Table 4: Discretized joint probability for extreme wave states with significant wave height $H_{S_{ex}}$ (m) and peak period T_P (s) during 48 hours (L_5).

$H_{S_{ex}}$/T_P	3.00	4.00	5.00	6.00	7.00
0.75	0.003	0.092	0.138	0.030	0.002
1.75	0.006	0.180	0.271	0.059	0.004
2.75	0.002	0.070	0.104	0.023	0.001
3.75	0.000	0.005	0.008	0.002	0.000

Table 5: Discretized joint probability for extreme wave states with significant wave height $H_{S_{ex}}$ (m) and peak period T_P (s) during 490 hours (L_1, L_2, L_3 and L_4).

$H_{S_{ex}}$/T_P	4.625	5.875	7.125	8.375	9.625
2.125	0.001	0.007	0.009	0.003	0.000
2.875	0.005	0.073	0.096	0.027	0.003
3.625	0.017	0.223	0.294	0.084	0.009
4.375	0.004	0.053	0.070	0.020	0.002

For each extreme wave state (joint probability) shown in Tables 4 and 5, 50 3-hour time-series of wave elevation are simulated using the JONSWAP spectrum with peak factor k_P equal to 3.3 and white noise filtering. For each time-series, the maximum horizontal load on one floater is recorded for each load case using the hydrodynamic code developed by Zurkinden et al. (2012). In this example, a linear damping control strategy of the floater movement is chosen with a damping coefficient of $4.2\ 10^6$ kgm^2/s during normal operation. The maximum loads of the different wave states and time-series are weighted with the probability of occurrence shown in Tables 4 and 5. Distributions are fitted to the resulting maximum values. Figure 4 shows the resulting axial load distributions for 490 hours extreme wave states and normal operation. The Weibull distribution fits the data better compared with a Gumbel distribution. For load case L_4, Weibull distribution has a mean value of 103661 N and a standard deviation of 18213 N. For the load cases L_1, L_2 and L_3, the Weibull distribution has a mean value of 184025 N and a standard deviation of 26569 N (see Figure 5). Load case L_5 leads to a Weibull distribution with mean value of 53116 N and a standard deviation of 22645 N (see Figure 6).

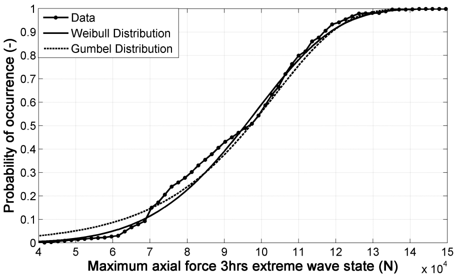

Figure 4: Fitted Gumbel and Weibull distribution to 490 hours extreme axial load onto floater during 3 hours extreme wave conditions and normal operation mode (L_4).

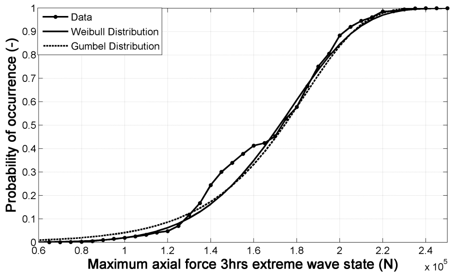

Figure 5: Fitted Gumbel and Weibull distribution to 490 hours extreme axial load onto floater during 3 hours extreme wave conditions and increased damping (L_1, L_2 and L_3).

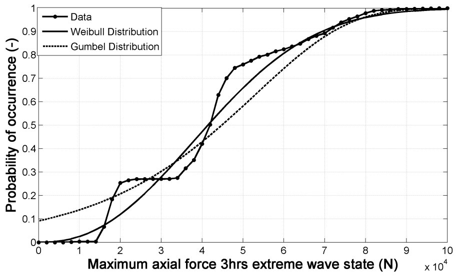

Figure 6: Fitted Gumbel and Weibull distribution to 48 hours extreme axial load onto floater during 3 hours extreme wave conditions and normal operation mode (L_5).

For the different failure cases, the 10-minute mean wind speed V given $H_{S_{ex}} = h$ is modeled using a LogNormal distribution (Christensen and Arnbjerg-Nielsen 2000) with mean value equal to $4.55 \cdot h$ m/s and standard deviation to 2.61 m/s.

The annual failure rates λ of the different electrical and mechanical components of the Wavestar system are shown in Table 6. The component failure rates are used to calculate the system failure rate υ_i of failure case i. In Table 6, different hours in storm protection mode and operational mode are already considered. Based on wave state measurements at Hanstholm, 89% of the year the floaters are in operational mode, and 5% of the year the floater components used to move floaters into storm protection mode are activated. Failure modes 1, 3, 4 and 5 can only occur if the floaters are in operational mode. During storm protection mode, the considered components are in fail-safe mode. Failure case 2 can only occur when the floater has to be moved from operational mode into storm protection mode. The electricity connection from shore to the WED is assumed to consist of 3 redundant cables each 30 km in length. Absence of electricity supply only occurs if all three cables break at the same time. Seasonal influences are not considered here.

Table 6: Component failure rates λ (1/year) used for calculating the system failure rate υ_i of failure case i.

Component	Failure Mode	λ	Source
Turbine	Failure when turbine is pump	0.026	OREDA
Generator	Failure when generator is motor	0.009	OREDA
Bearing	Mechanical failure	0.004	Arabian-Hoseynabadi et al.
Pressure sensor	Failure wave measurements	0.053	OREDA
Ultrasonic sensor	Failure wave measurements	0.053	OREDA
Diesel generator	no electricity production	0.22	OREDA
Electricity cable	Broken electricity cable to shore	0.401	Sannino et al.
Auxiliary pump system	Pump failure	0.026	OREDA
	Motor of pump failure	0.009	OREDA
	Malfunction opening/closing valve	0.005	OREDA
Control system	Failure of hardware control system	0.507	OREDA

3.3 *Design Equations*

The design equation is based on 50-year extreme values for the significant wave height and the conditional wind speed. The design parameter z accounts for design changes in the foundation cross section area. The design equations which are closely related to the limit state equations (see Equations 5 and 6) using partial safety factors and characteristic wave loads $W_{s,C}$ onto the piles and wind loads $Q_{s,C}$ on the platform as well as extreme loads onto the floaters in case of a system failure. When no system failure is considered (Case 0, see Table 1), the design parameter is calculated based on the following design equation:

$$G_0 = \gamma_{G_0} f_C G_C g z - \gamma_{L_0} 4 \underbrace{C_{W,C} C_{d,C} C H_{S,C}}_{W_{s,C}} - \gamma_{L_0} \underbrace{0.5 \rho_{air} V_C (H_{S_C})^2 A C_{d,C}}_{Q_{s,C}} = 0 \tag{8}$$

where G_C, $Q_{s,C}$ and $W_{s,C}$ are characteristic values. The characteristic wave load $W_{s,C}$ is calculated based on a significant wave height $H_{S,C}$ (=5.25 m) with 50-year return period (98% quantiles of annual maximum significant wave height distribution) and the characteristic wind load $Q_{s,C}$ based on a 10-minute average wind speed V_C (=23.89 m/s) which is the mean of V given $H_S = H_{S_C}$. The characteristic value of the weight G_C is estimated based on 5% quantiles. For the other characteristic values, the mean values in Table 7 are taken. The resistance safety factors γ_{G_0} is set equal to 0.9 and the load safety factor γ_{L_0} equal to 1.35 (see IEC 61400-1 (2005)). For the load cases, where only one floater is affected if failure of the system occurs, the design load case considers failure of one floater during extreme conditions. The design equation can be written as:

$$G_{2,3} = \gamma_{G_{2,3}} f_C G_C g z - \gamma_{L_{2,3}} \underbrace{(4 C_{W,C} C_{d,C} C H_{S,C} + C_F C_{d,F} C H_{S,C})}_{W_{s,C}} - \gamma_{L_{2,3}} \underbrace{0.5 \rho_{air} V_C (H_{S_C})^2 A C_{d,C}}_{Q_{s,C}} = 0 \tag{9}$$

where $C_{d,F}$ is the drag coefficient of the floater (=1) and C_F the horizontal wave load at the floater (=15 kN/m). The load safety factor $\gamma_{L_{2,3}}$ (=1.1) is chosen according to IEC 61400-1 (2005) (Design load case with fault). The resistance safety factor $\gamma_{G_{2,3}}$ is set equal to 1. For the failure cases 1, 4 and 5 where component failures impact both floaters, the design load case considers failure of both floaters at the same time:

$$G_{1,4,5} = \gamma_{G_{1,4,5}} f_C G_C g z - \gamma_{L_{1,4,5}} (4 C_{W,C} C_{d,C} C H_{S,C} + 2 C_F C_{d,F} C H_{S,C}) - \gamma_{L_{1,4,5}} 0.5 \rho_{air} V_C (H_{S_C})^2 A C_{d,C} = 0 \tag{10}$$

The load safety factor $\gamma_{L_{1,4,5}}$ (=1.1) is chosen according to IEC 61400-1 (2005) (Design load case with fault). The resistance safety factor $\gamma_{G_{1,4,5}}$ is set equal to 1.

3.4 *Stochastic Model and Results*

For the probabilistic reliability analysis, the COMREL software (RCP GmbH 2004) and the stochastic model shown in Table 7 are used. The results of the different failure cases considered here are shown in Table 8. This results in a total annual probability of failure $\Delta P_{F,tot}$ of 3.7 10^{-4} which is equal an annual reliability index $\Delta\beta$ of 3.4. If no failures of the system are considered (only Case 0 considered), the annual failure probability is equal to 2 10^{-4} which corresponds with an annual reliability index of 3.5.

Table 7: Stochastic variables for gravity-based sliding failure mode. N: Normal, LN: LogNormal, W: Weibull, Std. dev.: standard deviation.

Variable		Dist. type	Mean value	Std. dev.
$H_{S_{ex}}$	Annual max. significant wave height	W	4.79 m	0.29 m
G	Weight Wavestar	N	1000 tons	100 tons
f	Friction coefficient	LN	0.65	0.07
C_d	Drag coefficient	LN	1	0.1
X_{wave}	Model uncertainty wave loads	N	1	0.05
X_C	Uncertainty about C	N	1	0.1
X_{wind}	Model uncertainty wind loads	N	1	0.15
L_4	Normal operation floater under extreme wave conditions during 490 hours	W	103661 N	18213 N
$L_{1,2,3}$	High resistance floater under extreme wave conditions during 490 hours	W	184025 N	26569 N
L_5	Normal operation floater under extreme wave conditions during 48 hours	W	53116 N	22645 N

Table 8: Annual probability of failures $\Delta P_{F,i}$ for the different failure cases i, N_i the number of affected floaters at failure case i, υ_i the failure rate of failure case i and ΔP_F (=$\Delta P_{F,i} \cdot \upsilon_i$) shows the resulting annual probability of failure ('sliding of foundation') due to failure case i of the Wavestar prototype.

Failure case i	N_i	$\Delta P_{F,i}$	υ_i	ΔP_F
0	-	2.0 10^{-4}	1.000	2.0 10^{-4}
1	2	7.4 10^{-3}	0.014	1.0 10^{-4}
2	1	2.1 10^{-3}	0.002	4.2 10^{-6}
3	1	2.1 10^{-3}	0.032	6.7 10^{-5}
4	2	1.3 10^{-4}	0.003	3.9 10^{-7}
5	2	7.8 10^{-8}	0.507	4.0 10^{-8}

The results indicate that the safety factor for load cases with faults can be decreased. The major impact on the reliability is due to failure of electricity supply for lifting the floaters (Failure case 1). Failure cases 5 (control system failure) and 4 (wrong measurement of wave state) have, in this generic example, the smallest impact on the structural reliability. Due to the fact that the failure rates of the different components are taken from nearby industries, these values are approximations. The authors are aware that these failure rates may in reality be different for WEDs.

4 CONCLUSIONS

In this paper, one example of an ultimate limit state modeling a structural failure mode of WEDs is shown. The example focuses on sliding of the gravity-based foundation due to extreme wave and wind loads including extreme loads due to failure of mechanical and electrical components as well as the control system. The example considers the Wavestar prototype located at Hanstholm (DK).

When the mechanical and electrical system of a WED is included in structural reliability assessments, important component failure modes and their effects need to be identified by performing a Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA). Failure rates of mechanical and electrical components used by WEDs are not available due to lack of experience. But component reliability databases from related industries like offshore wind turbines can be taken.

Including extreme loads due to failures of mechanical and electrical components as well as the control system decrease the reliability of the system. Important parameters affecting the reliability of structural components are the time during which the structure is exposured to abnormal loads due to failure of electrical/mechanical components as well as the degree of redundancy of electrical/mechanical systems.

For the extreme case sliding of the gravity-based foundation, no system failure consideration results in an annual reliability index $\Delta\beta$ of 3.5 (annual probability of failure of $2.0\ 10^{-4}$). When considering 5 failure cases of the system and their resulting loads as well as the annual occurrence rate of each failure case, the annual probability of sliding increases to $3.7\ 10^{-4}$ ($\Delta\beta = 3.4$). The major impact is due to failure of electricity supply where the floater cannot be moved out of the water.

Annual minimal reliability indices of structural components for offshore wind turbines should be in the range between 3.1 (P_F equals to 10^{-3}) and 3.7 (P_F equals to 10^{-4}). The presented example results for all cases (with and without component failure case considerations) to annual reliability indices between 3.1 and 3.7.

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Appendix C

Paper 3

Title:
Fatigue Reliability and Calibration of Fatigue Design Factors of Wave Energy Converters

Authors:
Simon Ambühl, Francesco Ferri, Jens Peter Kofoed, John Dalsgaard Sørensen.

Published in:
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Appendix D

Paper 4

Title:

Extrapolation of Extreme Response for Different Mooring Line Systems of Floating Wave Energy Converters

Authors:

Simon Ambühl, Martin Sterndorff, John Dalsgaard Sørensen.

Published in:

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DOI: 10.1016/j.ijome.2014.09.003

Appendix E

Paper 5

Title:

Operation and Maintenance Strategies for Wave Energy Converters

Authors:

Simon Ambühl, Laurent Marquis, Jens Peter Kofoed, John Dalsgaard Sørensen.

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Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability,
Year 2015, published online.
DOI: 10.1177/1748006X15577877

Appendix F

Paper 6

Title:

Reliability-based Structural Optimization of Wave Energy Converters

Authors:

Simon Ambühl, Morten Kramer, John Dalsgaard Sørensen.

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Energies, Volume 7, Number 12, Year 2014, pp. 8178-8200.
DOI: 10.3390/en7128178.

This PhD thesis focuses on probabilistic structural reliability assessments of wave energy converters, considering uncertainties related to physical properties, limited data sets, considered simplified models and measurement errors. The resulting structural probability of failure can be used to calibrate safety factors used in structural standards as well as for reliability-based structural optimizations including operation and maintenance considerations.

The main objectives of this PhD thesis are as follows

a.) to determine wave energy converter specific uncertainties in connection with estimating structural loads onto wave energy converter structures,

b.) to perform probabilistic reliability assessments of wave energy converter details,

c.) to find appropriate structural reliability levels for wave energy converter structural details as well as

d.) to calibrate partial safety factors for design of wave energy converter structures,

e.) to introduce a method to extrapolate extreme loads of wave energy converters as well as

f.) to present different maintenance and operation strategies including different transportation strategies.

Furthermore, the thesis will use a reliability-based optimization method with focus on minimizing the resulting cost of energy.