

# Different Reliability Assessment Approaches for Wave Energy Converters

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**Abstract**—Reliability assessments are of importance for wave energy converters (WECs) due to the fact that accessibility might be limited in case of failure and maintenance. These failure rates can be adapted by reliability considerations. There are two different approaches to how reliability can be estimated: the so-called classical reliability theory and the probabilistic reliability theory. The classical reliability theory is often used for failure rate estimations of mechanical and electrical components, whereas the probabilistic reliability theory is commonly used for structural components. For WECs, mechanical/electrical components as well as structural components are of importance. Therefore, both reliability theories need to be incorporated in WEC designs, WEC developments and improvements of WECs. This paper gives an overview of the two reliability theories and how they can be combined for WEC applications.

**Keywords** - Classical reliability theory, probabilistic reliability theory, risk assessment, reliability, wave energy converter.

## I. INTRODUCTION

Some wave energy converter (WEC) technologies have reached prototype level. In the next step towards a commercial technology, among others the cost of energy of electricity produced for WECs needs to be decreased. Therefore, the WEC technology needs to be optimized in order to decrease the overall cost of energy (CoE). When talking about optimizations of WECs, there is no way around reliability because reliability defines the investment costs as well as drives the operation and maintenance expenses.

The technical reliability definition of a certain product describes the probability that this product does not fail under given functional and environmental conditions during a defined period of time. [1]

Reliability can be understood as structural reliability of the device as well as reliability of the mechanical and electrical components of the system. In the first impression, these two topics are the same. But based on essential differences there are two different reliability theories behind these two topics. The so-called classical reliability theory, which is commonly used for system reliability investigations consisting of parallel and serial systems of electrical and mechanical components, is based on estimated failure rates calculated from former documented failures of the same sort or from similar kind of

components. The failure rate in the classical reliability approach is often assumed to be constant over time and given in number of failures per year or per number of hours in service. Often a so-called ‘Bathtub-curve’ is used with hopefully a long period with a constant, low failure rate. Failure rate data is costly, but for a product from stock failure data could be gained in a decent amount of time. However, failure rates are not available or can be collected for all components to be designed by engineers. There are different possibilities as to why failure rates cannot be collected, like the considered object might be one of a kind or the failure rates are too small such that collecting failure rate data would take too much time. Therefore, for such kind of devices (low failure rates or customized components), other reliability assessment approaches need to be used. The so-called probabilistic approach which is based on explicitly formulated limit states can be applied in such cases. Furthermore, uncertainties related to the considered environmental parameters, the limited amount of data, measured data and the considered models are included in a probabilistic reliability assessment. Probabilistic reliability assessments are often used for structural details where no failure data is available, the number of failure modes is manageable and the failure probabilities are low compared with mechanical/electrical components.

WECs are complex systems where structural, mechanical and electrical components are mounted together with a control system. Furthermore, the main focus in optimizing WEC devices is on minimizing CoE. Therefore, reliability assessments are an important topic for WEC technology development and both reliability assessments need to be applied in order to optimize WEC technology and they even need to be combined e.g. by looking at structural reliability given a failure of the mechanical/electrical system. The mentioned combination of reliability methods will help in a later state when structural standards for WEC application are developed to elaborate the so-called ‘Design Load Cases’.

This paper describes the two different reliability approaches with regard on WEC applications from an engineering point of view.

## II. WHY DIFFERENT RELIABILITY ASSESSMENT APPROACHES?

The two different reliability assessment approaches were developed separately in two different engineering branches. Fig. 1 gives a broad overview in which engineering sectors which reliability methods are commonly used.

The classical reliability theory comes from the mechanical engineering branch (historically widely used in the automobile and aeroplane industry) which are used to produce products in large numbers and, therefore, obvious to start building databases with failure rates. Furthermore, these kinds of machines consist of thousands of components where physical formulations of failure modes will be too complicated.

On the other hand, the probabilistic reliability theory has its origin in the civil engineering community where the devices were often one of a kind, the consequences were large (many fatalities) in case of failure (e.g. collapse of a bridge) and the investment costs were high in general. But for one of a kind objects, no failure data is available and the objects are built for a certain location. Therefore, an estimation of the failure probability needs to be performed in another way than estimated failure rates from experiments or databases. This leads to the so-called probabilistic reliability theory.

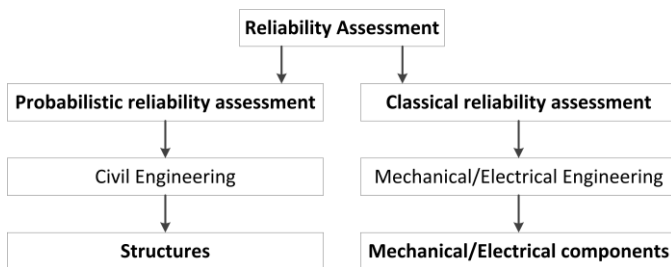


Fig. 1 The two commonly used reliability assessment methods.

But apart from which engineering branch developed which theory, there are also many other limitations which drive the decision for which approach one should use when estimating failure probabilities or failure rates of a certain object. Fig. 2 gives a selection of possible reasons which drive the decision of which reliability assessment approach to choose. When failure rate data is available or the considered system is too complex in order to find the most critical failure modes or when the failure rates are generally large for the considered detail but also cheap to replace, failure rate estimations would be enough and, therefore, the classical reliability method is appropriate. Furthermore, relatively high failure rates together with the aid of accelerated fatigue tests enable failure rates in a relatively short amount of time.

When a system allows more detailed analysis about possible failure modes and the most critical failure modes can be formulated in a limit-state equation or a reliability-based optimization of a certain design needs to be performed as well as safety factors need to be defined in an iterative process, the probabilistic reliability assessment would be the better approach due to the fact that it enables iteratively performing and doing the design based on a certain target reliability.

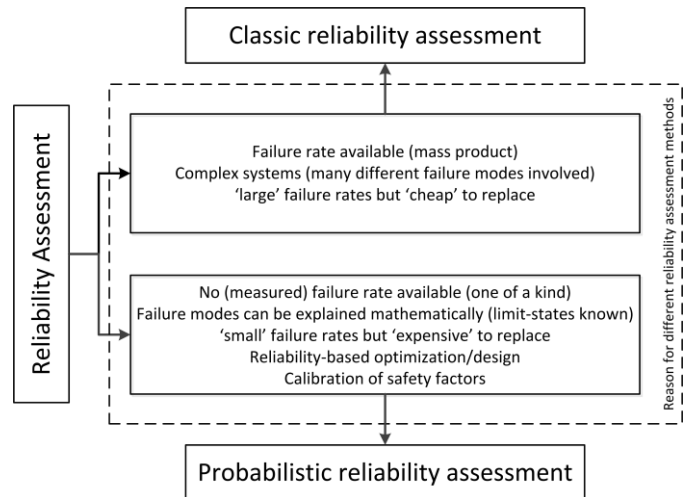


Fig. 2 Different reasons that decide which reliability assessment approach to choose.

Independent of the approach to estimate reliability of a component, the overall reliability of critical elements needs to be assessed and indicated as early as possible in the development process of WECs simply because the earlier problems are detected, the cheaper they are to repair. In the design phase, the drawings or a prototype need to be adapted based on adaptive reliability analyses whereas in later phases, call-backs are necessary.

In order to give the reader some background information and highlight the differences of the two approaches, theoretical background information about the two reliability approaches are given in the following two sections.

## III. CLASSICAL RELIABILITY THEORY

### A. Theoretical Background

The so-called classical reliability theory is based on counted failures of a certain component. Based on a database containing the points in time of failure as well as their causes, failure rates can be estimated and used for reliability assessments.

The classical reliability theory is based on the bathtub curve, shown in Fig. 3. The bathtub curve shows the failure rates at different points in time in the lifetime of a component. The failure rate behaviour can be distinguished in three phases and be modelled e.g. with a Weibull distribution using different distribution parameters for the three phases. In phase I, the failure rate decreases due to the presence of early life failures like quality problems (manufacture failure) or wrong dimensioning (dimension failure). Once the component is burnt-in, the phase II will only have operation failures like handling failures, maintenance failures, physical random failures and failure due to disturbances. In this phase (phase II), the failure rate is assumed to be constant over time and can be calculated as:

$$\lambda_{PhaseII} = \frac{1}{MTBF} = \frac{\left( \frac{\text{Total number of failures}}{\text{Component population}} \right)}{\text{Operating period (years)}} \quad (1)$$

where *MTBF* is the so-called Mean Time Between Failures that indicates the mean time between two subsequent failures. For phase II, the reliability  $R_r(t)$  which indicates the probability that the component survives until time  $t$  is exponential distributed:

$$R_r(t) = e^{-\lambda_{PhaseII} \cdot t} \quad (2)$$

After a certain time, the failure rate increases due to wearing problems and moves to phase III. In all phases random faults, which define the failure rate in phase II, occur.

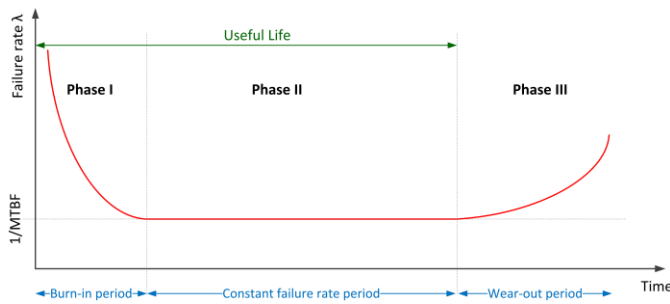


Fig. 3 Bathtub curve showing failure rate behaviour over time. MTBF: Mean time between failure.

Ideally, the lifetime of the considered component ends at the transition point between phases II and III. Where this point is located is dependent on the corrosion (fatigue), the temperature and other factors, which are different for the same component in different applications. The high failure rate phases I and III can be prevented by checking the component (quality control) and operating them under realistic conditions (pre-aging) before selling it to the customer (phase I) or by preventive replacement (preventive maintenance in phase III) as well as condition monitoring which leads to conditional maintenance actions in phase III.

According to [2], attention needs to be paid to failure rate estimations when at least one of the two points is fulfilled for the considered component/system:

- New environment
- New technology

The failure rates are different for the same component if it is used in a new environment (e.g. offshore instead of onshore) or the component is mounted in a new technology that impacts the load characteristics for which the component was designed. The worst case (uncertain failure rates) would be a new technology in a new environment, which means that an undeveloped technology is installed in an unfamiliar

environment. For WEC components, this is e.g. the case when custom-made components are installed with a specific control system. Therefore, component failure rates are connected to large uncertainties when not accounting for different environmental conditions. Possibilities to obtain failure rates are by doing field tests, taking failure rates from reliability databases as well as performing experimental reliability tests by the use of e.g. accelerated tests at high temperatures.

For WEC applications, either component failure tests or component failure rates from nearby databases like [3] could be considered. How component tests for WEC applications can be performed is given in [4]. But failure rates from databases need to be handled with care for WEC applications due to the fact that no failure data specifically for WEC applications is available. As a starting point, the following failure databases from nearby industries can be taken:

- Petrochemical industry: [3]
- (Offshore) wind turbines: [5], [6], [7]
- Generic reliability databases: [8], [9]

To account for different environmental conditions of a certain failure rate taken from databases, adjustment factors can be considered. A failure rate,  $\lambda_{database}$ , from a certain database is adjusted by using different adjustment factors as proposed by [9], [10]:

$$\lambda_{adapted} = \lambda_{database} \cdot \pi_E \cdot \pi_M \cdot \pi_{FM} \cdot \pi_{DQ} \quad (3)$$

where  $\pi_E$  is the environmental factor which contains influences due to e.g. different temperatures or humidity the component is operating in,  $\pi_M$  is the material factor if other materials are used as for the component on which the failure rate estimation is based,  $\pi_{FM}$  accounts for the failure mode specific correction factor as well as influences on maintenance strategies and  $\pi_{DQ}$  is the data quality factor which considers uncertainties related to different data sources. The data source uncertainties can be arranged in the following areas including upper and lower boundaries leading to the variability of the adapted failure data [11]:

- site and industry specific data: 10% uncertainty
- generic data source: 30% uncertainty
- expert judged failure rates: 50% uncertainty

Another way to adjust failure rates is the use of a Bayesian approach. This procedure is described in [12] and [13]. The Bayesian approach can also be used to update the failure rate if new data becomes available and can, therefore, reduce the

uncertainties of reliability assessments. Due to the fact that the data amount is sparse for mechanical components and electrical components installed at wave energy devices, the Bayesian approach can be used to reduce the main uncertainties related with failure rate estimations through incorporation of test data and ‘engineering knowledge’ [13].

When dealing with failure rates of components, it should be accounted for that a component can fail in different ways which can impact the overall effect onto the system. A valve can e.g. fail to open and stay closed or fail to close and remain in open position. These two different failure modes may have different impacts on the overall system.

The failure rate characteristics discussed here are valid for mechanical and electrical components (hardware failures). But when taking software reliability into account, constant failure rates cannot be assumed any longer due to the fact that once a software failure is repaired, it will not occur any longer. For software failures, this means the failure rate decreases over time.

### B. Risk Assessment

Risk assessments assess, as the name states, the risk for different faulty system states. Risk assessments are of importance when analysing systems and finding critical system states that are costly or often occur.

The risk of a certain event is defined as the probability (P) that this event occurs multiplied by the consequences (C) in case it occurs:

$$R = P \times C \quad (4)$$

Risk is associated with negative events and is desired to be as small as possible. But nevertheless, the overall risk cannot be decreased to zero. Therefore, an appropriate way of clustering risk is necessary.

One approach to clustering and assessing risk is by using a so-called risk ranking matrix, see Fig. 4, using a traffic light system to identify the risk levels. Risk can be reduced by diminishing the probability of occurrence or by diminishing the consequences in case of failure. When and how much a certain high risk should be reduced in practice follows the ALARP (as low as reasonably practicable) principle. Here, the risk is reduced so the costs involved in reducing the risk are disproportionately smaller than the gained benefit.

It should be noted that what is acceptable risk very much depends on context and device. Furthermore, when performing risk assessments using risk matrices, attention needs to be paid on the level of detail of the division of hazards and events. A sub-division of a failure event into multiple sub-events might move the sub-divided events due to lower probabilities of occurrences compared with the original event from the high risk regions to medium/low risk regions. No standards for adequate detail of event divisions exist.

Before starting the risk assessments, the failure rates of different system failure modes need to be found. There are

many different approaches of how to identify critical failure modes.

Table I shows different methods of how to find important system failure modes. In this context, important failure modes mean the failure mode with the highest risk either because of high occurrence rates or large costs in case of failure.

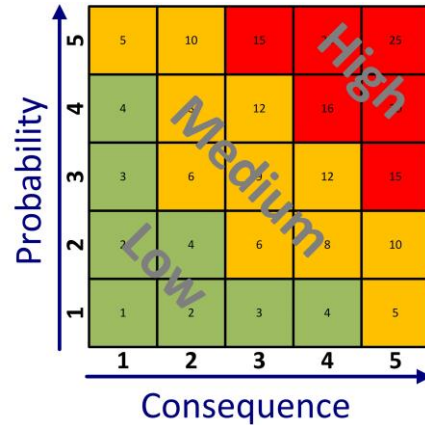


Fig. 4 Risk ranking matrix [14].

TABLE I  
DIFFERENT METHODS TO DEFINE AND FIND IMPORTANT SYSTEM FAILURE MODES. [2]

Method	Advantages	Challenges and/or 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 modelling all types of systems
Structured what-if checklist (SWIFT)	Applicable even if detailed design is not available	Experienced facilitator essential, as well as good checklist
Operational Problem Analysis (OPERA)	Emphasis on the product interfaces	Emphasis on technical problems and human errors without going into details about cases
Independent review	Can be more time-efficient or less resource demanding	Not as multidisciplinary and robust as other techniques

Risk assessments make it necessary to consider the whole system and not only a certain component due to the fact that the placement of component in the system is of importance.

The system reliability or the probability of occurrence of a certain failure mode can be estimated as a combination of serial (failure of one component leads to overall failure of the system) and parallel (only failure of all components lead to system failure) arranged components. Mathematically, the resulting probability of occurrence,  $P_{FM}$ , of a certain failure mode can be written as assuming independent failure occurrences of the considered components:

$$P_{FM} = \sum_{i=1}^N \prod_{j=1}^{M_i} P_{i,j} \quad (5)$$

where  $M_i$  shows the number of parallel components at section  $i$  of  $N$  serial system sections. The probability of failure of the component located at the  $j$ th parallel section in the  $i$ th serial position is equal to  $P_{i,j}$ .

### C. Operation and Maintenance

Important aspects when talking about reliability of electrical and mechanical components together with operation and maintenance are as follows:

- Maintenance strategy
- Transportation strategy

Maintenance strategies are important due to the fact that unplanned maintenance (e.g. because of broken component) is connected to a large amount of cost where transportation and weather constraints become of importance. Maintenance can (as presented in Fig. 5) be corrective where only components are replaced when they were broken or maintenance can be preventive where the components are replaced after a certain amount of time (scheduled) or after a certain threshold (e.g. crack size detected during inspection) is reached. Preventive maintenance strategies generally lead to larger number of replacements during the expected lifetime of the device compared with corrective replacements. But on the other hand a corrective replacement is more expensive than a preventive replacement of a component due to e.g. long waiting times because of bad weather conditions. It needs to be kept in mind that when following a preventive strategy, some corrective replacements might still be needed. But the number of corrective replacements decreases when replacing the critical components on a preventive strategy. This means the optimal maintenance strategy most probably is a mixture of different maintenance strategies.

The optimal maintenance strategy might be different for different WEC technologies. Optimized strategies in this context mean the strategy which leads to the lowest expenses during a lifetime.

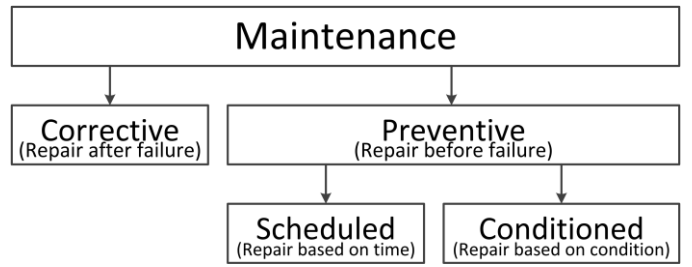


Fig. 5 Different maintenance strategies that can be followed for WECs. [15]

Transportation of equipment for maintenance can be performed by helicopter, which is faster and limited by the wind speed but expensive or by boat, which is limited by the wave characteristics and slower but cheaper than by helicopter. Most studies on operation and maintenance costs only consider transportation by boat. Boats as well as helicopters might not be able to operate under all environmental conditions. Reference [16] showed that the accessibility is season dependent for boat access in northern European sea. Summer time shows larger time windows for possible maintenance actions than during winter time. Also, the waiting time in case of bad weather conditions and needed repair at the device are larger during winter seasons compared with summer periods. Additionally, the time windows where access to the device is possible depend on the location of the considered device as well as the transportation strategy.

An important point which should also be considered when optimizing the transportation strategy is the losses due to loss in electricity production. Reference [17] showed in a case study on the Wavestar device that between 5% and 20% of the total operation and maintenance costs correspond to the lost electricity production.

## IV. PROBABILISTIC RELIABILITY THEORY

### D. Theoretical Background

Probabilistic reliability assessments are used when no explicit data of failure rates is available. Probabilistic reliability assessments consider uncertainties related to e.g. the environmental conditions or the load calculation method. This approach can be used to estimate the probability of failure of a certain structural component and a certain failure mode. The uncertain parameters are modelled by stochastic variables or processes/fields. The failure mode is assumed to be modelled by a limit state equation  $g(\mathbf{X})$  where the stochastic variables  $\mathbf{X}$  are included. The limit state equation represents the limit state of a certain structural failure mode like e.g. sliding, overturning, buckling or fatigue failure. The limit state equation is commonly formulated as:

$$g(\mathbf{X}) = R(\mathbf{X}) - S(\mathbf{X}) \quad (6)$$

where  $R(\mathbf{X})$  indicates the resistance of the limit state and  $S(\mathbf{X})$  the load. If the value of the limit state equation is smaller than or equal to zero, failure will occur. For the probability of failure, annual failure probabilities are often considered by e.g. taking annual extreme environmental conditions. But also cumulative failure probabilities over a whole lifetime can be used. Furthermore, the probabilistic reliability theory enables modelling the failure probability dependent on time.

The probability of failure,  $P_F$ , described by a failure mode, can be calculated using the FORM/SORM approach, where the most probable failure point, which defines the reliability index  $\beta$ , is calculated. The probability of failure can be calculated from the reliability index  $\beta$  as follows:

$$P_F = P_F(g(\mathbf{X}) \leq 0) \approx \Phi(-\beta) \quad (7)$$

where  $\Phi(\cdot)$  is the standard Normal distribution function. The FORM/SORM procedure is based on a transformation from real space to a space where all considered parameters become normalized and independent of each other. For more information about probabilistic reliability analyses, see e.g. [18] or [19].

The probability of failure can be directly estimated from Monte Carlo simulations. Monte Carlo simulations perform a large number of realizations of the limit state function where for each realization random values of the stochastic values are considered. The probability of failure can then be estimated by the following ratio:

$$P_F = \frac{\text{Number of realizations leading to failure } (g < 0)}{\text{Total number of realizations}} \quad (8)$$

Table II shows the relationship between the probability of failure  $P_F$  and the reliability index  $\beta$ .

TABLE II  
RELATION BETWEEN THE PROBABILITY OF FAILURE  $P_F$  AND THE  
CORRESPONDING RELIABILITY INDEX  $\beta$ .

$P_F$	$10^{-7}$	$10^{-6}$	$10^{-5}$	$10^{-4}$	$10^{-3}$	$10^{-2}$
$\beta$	5.2	4.7	4.3	3.7	3.1	2.3

### E. Uncertainties

There are the following different sources of uncertainties, which can be considered in a probabilistic reliability assessment:

- Physical uncertainties
- Modelling uncertainties
- Statistical uncertainties

- Measurement uncertainties

Physical uncertainties occur due to Mother Nature and are always present. Examples of this kind of uncertainty are e.g. inter-annual variations of extreme wave conditions or yield stress variations of different steel tensile tests. Modelling uncertainties are present when models are used to calculate stresses, loads or environmental conditions. Statistical uncertainties are of importance when small data sets are considered or rare events are considered (e.g. extreme wave heights). Statistical uncertainties account for the limited length in data points. The measurement uncertainties are of importance when measurements are used as input for probabilistic reliability assessments.

Another way of distinguishing the types of uncertainty is based on whether or not they can be reduced. Reducible uncertainties are called epistemic and cover statistical, measurement and modelling uncertainties. On the other hand, the so-called aleatory uncertainties (cover physical uncertainties) are irreducible even though an infinite number of measurements are available.

### F. Limit States

When the reason for failure is known and this failure mode can be physically formulated, a limit state condition is elaborated. From a structural point of view, there are four different limit states:

- Ultimate limit states (ULS)
- Fatigue limit states (ALS)
- Accidental limit states (ALS)
- Serviceability limit states (SLS)

Ultimate limit states cover limit states due to excess of maximum load carrying capacities. The fatigue loads are dedicated to failure modes due to cyclic loading and structural damage accumulation. Accidental limit states are limit states resulting from accidental load caused e.g. by collisions, floods or fire/explosions. Serviceability limit states occur when the following appear: excessive vibrations, leakages, deflections or drainage, which disable the function for which the device was built.

With regard to WECs, fatigue limit states are of importance due to the fact that many structural parts are exposed to cyclic loading from the waves. Fatigue is a time-dependent process and, therefore, the failure probability will increase with time for this failure mode, whereas for ultimate limit states a time-independent annual probability of failure can be expected.

But extreme loads do not occur simultaneously with extreme environmental conditions for all WECs due the fact that a control system limits the loads onto the structure during extreme environmental conditions.

### G. Target Reliability Levels for WECs

The basis of probabilistic reliability assessments is the definition of appropriate reliability levels for the considered device. This discussion should be held before probabilistic reliability assessments are performed. The target reliability level basically depends on the consequences in case of failure. The consequences are often measured in monetary values, but also other measures like danger of humanities, number of fatalities or pollution levels can be considered. Another parameter influencing the choice of target reliability levels is the cost needed to increase safety. If the costs for structural safety reduction are high, it might make sense due to lower overall costs to accept that the structure might collapse and needs to be rebuilt instead of investing a lot of money in increasing structural safety by decreasing the probability of failure. Reference [20] gives recommendations on the target annual reliability index,  $\Delta\beta$ , (see Table III) for different consequence levels in case of failure as well as relative costs of safety measures. For WECs, the relative costs of safety measures are large due to the fact that the overall target of WECs is minimizing the cost of energy. This means that minimal annual target reliability indices for WEC applications should be in the range between 3.1 and 3.7.

TABLE III

TARGET ANNUAL RELIABILITY INDEX,  $\Delta\beta$ , FOR STRUCTURAL COLLAPSE DEPENDENT ON THE CONSEQUENCES IN CASE OF FAILURE AND THE RELATIVE COSTS OF SAFETY MEASURES. DATA IS FROM [20].

Relative costs of safety measures	Consequences of failure		
	Minor	Medium	Large
Large	3.1	3.3	3.7
Normal	3.7	4.2	4.4
Small	4.2	4.4	4.7

Fig. 6 shows how the target reliability indices are commonly chosen for different technologies. Buildings are manned and, in case of collapse, fatalities are to be expected. Therefore, for buildings, large target reliability values are chosen. Manned offshore structures contain trained people and safety equipment to escape in case of failure. Therefore, in comparison with buildings, the target reliability levels are lower. Offshore wind turbines as well as wave energy converters can be assumed to be unmanned and, in case of collapse, there is no danger for humans. Furthermore, low pollution and no danger of fire/explosions occur in case of collapse. These devices are only manned during inspection actions, which are performed during summer season when extreme events are unlikely to occur.

$\Delta P_f$	$10^{-7}$	$10^{-6}$	$10^{-5}$	$10^{-4}$	$10^{-3}$	$10^{-2}$
$\Delta\beta$	5.2	4.7	4.3	3.7	3.1	2.3
Buildings						
Manned offshore structures						
Offshore wind turbines						
Wave energy converters						

Fig. 6 Acceptable annual reliability levels (Annual reliability index  $\Delta\beta$  and its corresponding annual probability of failure  $\Delta P_f$ ) for structural components of different technologies.

The uniqueness of probabilistic reliability assessments is the ability to use a target reliability index for structural design. This means that design optimizations where the cost of energy is minimized can be performed using the target reliability indice as side conditions. Furthermore, probabilistic reliability methods can be used for calibration of safety factors when a certain target reliability level is defined. More information about partial safety calibration processes for WEC applications can e.g. be found in [21] where Fatigue Design Factors (FDF) for welded and bolted steel structures at the Wavestar WEC are calibrated.

### H. Design Load Cases

Calibration of safety factors is performed in order to help defining safety factors implemented in structural standards. Based on the probabilistic reliability theory, safety factors can be found according to a certain target reliability level as well as including the application-specific characteristics (loads, control system influence) as well as technology-specific uncertainties. For WECs, there are some additional challenges concerning safety factor definition like the large diversity of working principles. There are devices which are operating under the water surface as well as on and above the water surface. This leads to different safety factors for different devices. Furthermore, the low development stage (prototype or lower) may complicate the development of standards for WEC structures due to limited knowledge.

In structural standards, different load cases including the control principle of the device are commonly considered. The following load cases are of interest for structural designs of WECs:

- Extreme environmental conditions during normal operation
- Extreme environmental conditions and fault state of the system
- Extreme environmental conditions in idle mode (storm protection mode)
- Fatigue conditions

Due to the control system, extreme loads do not always occur simultaneously with extreme environmental conditions. Therefore, extreme loads during operation (electricity production mode) should be accounted for. Furthermore, the system, which consists of electrical and mechanical components as well as a control system, might fail. The fact that the system might stay for some time in faulty state due to the fact that access to the device may not be able at every time (e.g. due to extreme wave conditions) underlines the importance of the load case considering the faulty system. An example of how to include mechanical and electrical components into probabilistic structural reliability assessments for WEC applications is given in [22].

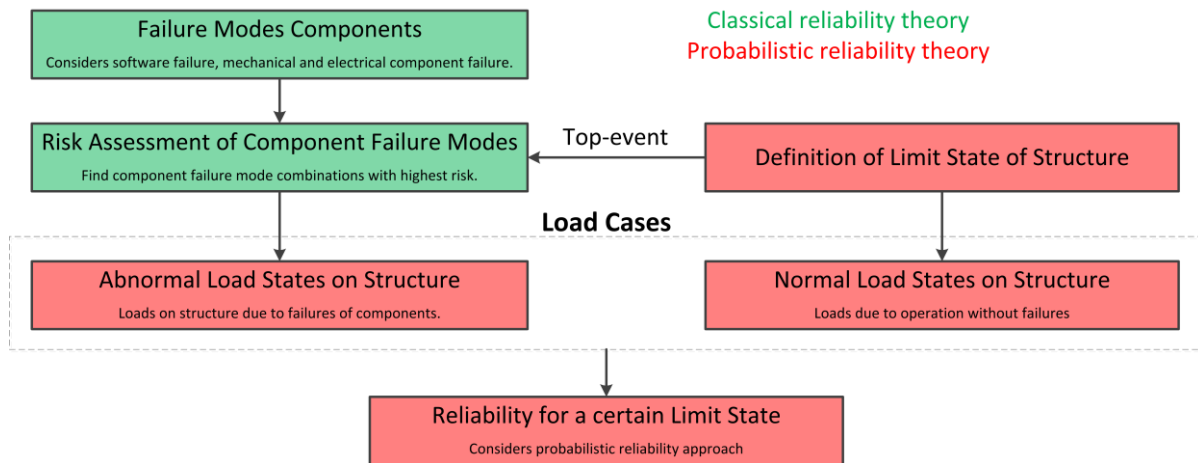


Fig. 7 Example of classical and probabilistic reliability theory for structural reliability assessment taking different load cases into account.

When talking about load cases, the combination of both reliability theories has to be applied. Classical reliability theories are used to consider the mechanical and electrical system in order to find the most costly failure combinations and modes of the different components. Based on the classical reliability theory, the conditions for abnormal loads, which are the structural loads in case of mechanical/electrical system failure, can be found. The probabilistic reliability theory can then be used to estimate the probability of structural collapse given the risky fault system states. Fig. 7 presents an example of how the combination between classical reliability theory and probabilistic reliability methods can look like. This approach enables to estimate the impact of failure rates of the mechanical and electrical components on the probability of structural collapse.

## V. CONCLUSIONS

This paper presents two different reliability assessment approaches which can be used for reliability assessments of wave energy converter (WEC) components and systems. The so-called classical reliability theory assumes constant failure rates and is commonly applied for mechanical and electrical components. This approach is based on failure rate measurements and can be used for mass product components. Furthermore, this approach enables a simplification of many different failure modes to one failure rate. For structural components like welded or bolted details, no measurements are available due to the fact that buildings and other civil engineering structures with welds and bolts are often one of a kind. For safety relevant structures, the failure rates are small compared with mechanical and electrical components. Small failure rates make the collection of failure rate data time-consuming. Therefore, the classical reliability theory cannot be used for these details. But often the failure mode leading to failure is known and the physical behaviour can be explained in a limit state equation. These kinds of problems are predestinated for the probabilistic reliability approach. This reliability approach is based on a limit state equation and enables including uncertainties related to the considered

parameters, the used models, the considered measurements and the limited data sets. For WEC applications, both reliability approaches are of importance due to the fact that structural components as well as mechanical and electrical components are used. Furthermore, both reliability theories need to be combined for WEC applications due to the fact that the working and failure principle of the mechanical/electrical system impacts the structural reliability.

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