RiaSoR2

RELIABILITY IN A SEA OF RISK

Outline Load Assessment Numerical Tool

May 2018

Vessel trials, Orkney © Aquatera

Project Information

Project title	Reliability in a Sea of Risk 2
Project Acronym	RiaSoR 2
Duration	24 months
Month 1	September 2017
Project manager	Johannes Hüffmeier | RISE
Work package leader	Mairead Atcheson | Cruz Atcheson Consulting Engineers
Work package number/name	3 | Numerical Tool for Load Assessment
Date of submission	30/05/18

Revision

Revision no.	Revision Text	Initials	Date
0.1	Initial Release – For Partner Feedback	MA, JC	23/03/18
1.0	Release Following Partner Feedback	MA, JC	30/05/18

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1 Introduction

1.1 RiaSoR Background

The goal of the RiaSoR project is to consistently learn from the physical interactions between the devices and their environments, while embedding this understanding and building robustness into marine energy technology designs to improve reliability.

Marine energy devices operate in harsh environments but still need to perform reliably and produce an expected amount of energy, which gives rise to huge engineering challenges.

The OceanERANET-funded RiaSoR 2 project will use the theoretical reliability assessment framework for wave and tidal energy converters (WEC/TEC) developed in RiaSoR1 and apply it to the field.

This will enable WEC/TEC developers to validate their findings, and establish a practical condition based monitoring platform to prepare for future arrays where big data handling and processing will be vital to drive down operational expenditures (OPEX).

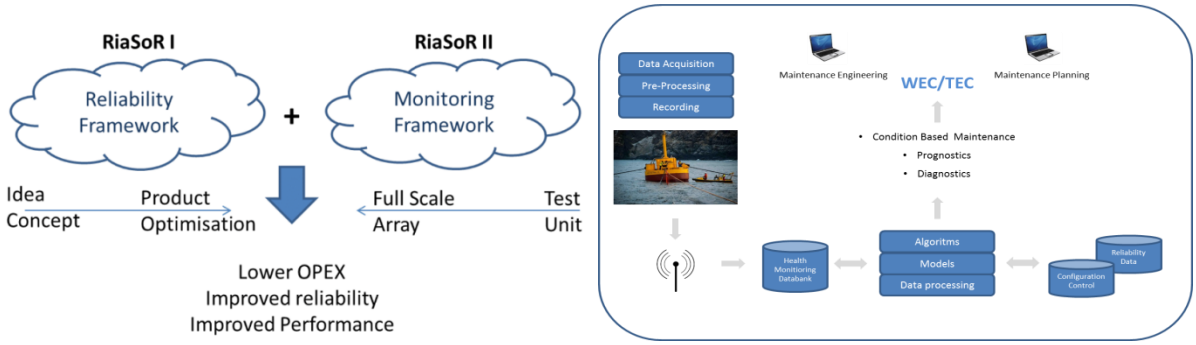

Figure 1 RiaSoR 1 & RiaSoR 2 overview

The RiaSoR 1 reliability framework built upon established practices from the automotive industry where a monitoring framework is applied to a fleet of test-vehicles. Through design iterations, the reliability is improved and a final reduced set of sensors are deployed in the commercial vehicle.

For RiaSoR 2, the chosen components for monitoring are equipped with several sensors to collect the required data, which will then be fed into the reliability process to reduce uncertainties. Sea tests act as case studies to feed the methodologies and training into the framework. The findings from this will then be trialled with the other developers.

The key objective of the RiaSoR 2 project is to offer a comprehensive suite of testing methodologies to wave and tidal developers that will enable a systematic approach to achieve optimal reliability and performance, while minimising cost and time-to-market.

1.2 Deliverable Description

The Research Institutes of Sweden AB (RISE) have contracted Cruz Atcheson Consulting Engineers (CA) to provide support to the RiaSoR 2 project (Reliability in a Sea of Risk 2).

In the RiaSoR I project, a reliability assessment framework for marine energy technologies was developed, based on established practices from the automotive industry. In particular, the reliability assessment framework was built around the Variation Modes and Effects Analysis (VMEA) methodology, which aims to assist in finding critical aspects of a technology that it is subject to the effects of unwanted variation. In the wake of RiaSoR I, RiaSoR 2 aims to use the reliability assessment framework and apply it to wave energy converter (WEC) design.

In WP3 of the RiaSoR 2 project, a toolbox to assess the reliability of the WEC loads output from a numerical model will be devised. Within the scope of RiaSoR 2, CA will develop a baseline generic WEC model in a modified version of WEC-Sim (Wave Energy Converter SIMulator), which will be used to estimate WEC loads. The estimated loads for the generic WEC will provide an input to the reliability assessment. The numerical toolbox will build on work completed in RiaSoR I and apply the VMEA methodology to the numerical load estimates, in an attempt to assess the effects of variations in key metrics and quantify the related uncertainty.

This report outlines the specification of the numerical load analysis and the reliability assessment, and is organised in six main sections. Following this introduction (Section 1), an overview of the WEC design process and an introduction to the concept of WEC reliability assessment is given in Section 2. In Section 3, a description of the design basis for the generic WEC is documented, including the metocean conditions, design situations, and ultimately the design load cases (DLCs) proposed by CA for the load analysis exercise. An overview of WEC-Sim and of the proposed generic WEC model is provided in Section 4, while Section 5 presents an outline of the proposed approach for the reliability assessment of the loads. Finally, the proposed next steps in WP3 of the RiaSoR 2 project are outlined in Section 6.

This report constitutes deliverable D3.1 of the RiaSoR 2 project and is the first of three deliverables in WP3.

2 Design of Wave Energy Converters

2.1 WEC Design Process

At a high-level, the WEC design process comprises of three key stages: design basis definition, concept design and detailed design [1]. A brief outline of the key objectives and tasks associated with the WEC design process is presented in [1] and illustrated in Figure 2.

The initial step in the design process is typically the definition of a design basis for the WEC technology. This step supports the selection of design load cases (DLCs) that should be investigated to inform the concept and detailed design efforts. Typically, load and structural integrity assessments are then conducted, initially for preliminary design conditions and subsequently for a complete set of DLCs [1].

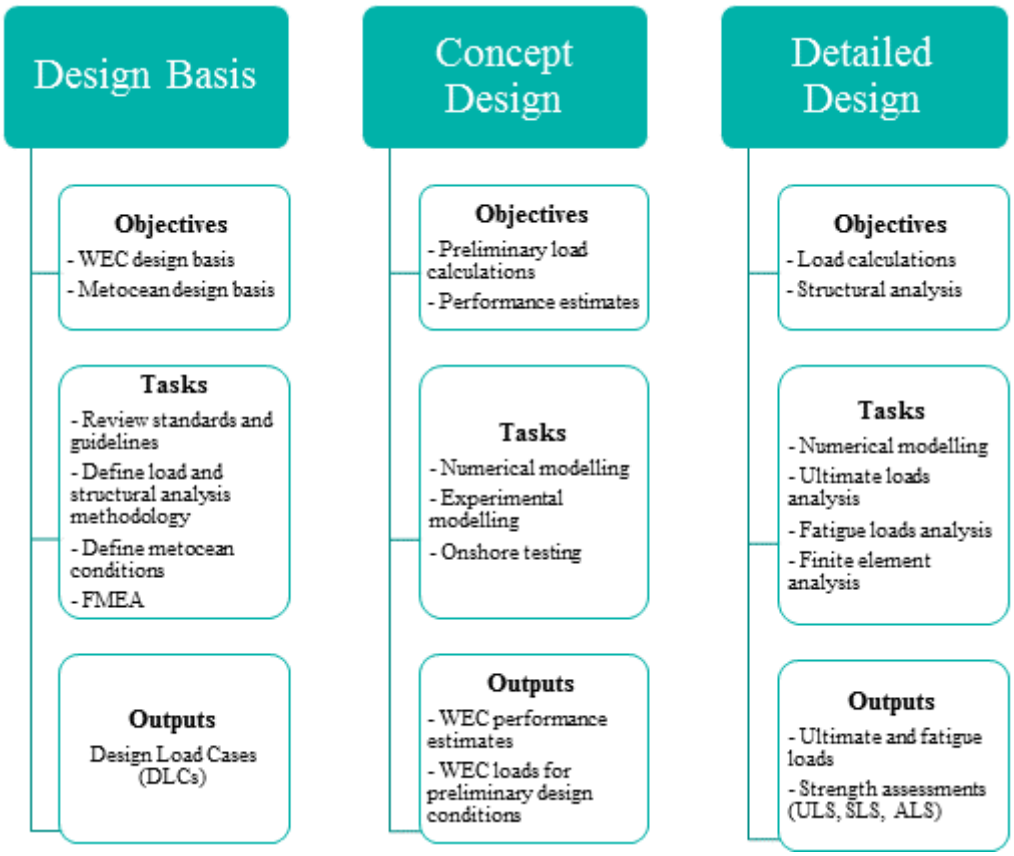

Figure 2 WEC Design Process: Key objectives and tasks [1]

The WEC design process presented in Figure 2 does not incorporate any specific activities to assess the reliability of a proposed WEC design. Under WP3 of RiaSoR 2, CA's tasks will focus on the development of a load analysis model, which can be used to provide inputs to a reliability assessment of the WEC loads. In addition, a toolbox will be devised to provide a framework for the reliability assessment approach, with a focus on WEC loading.

The development of the toolbox will expand the work conducted in RiaSoR I project, which applies a VMEA approach to reliability assessments (see also Section 2.2).

2.2 WEC Reliability Assessment

This section introduces possible methods to assess the reliability of WECs. In Section 2.2.1, the VMEA approach is introduced. Such methodology can be applied to assess the reliability of a WEC at different stages of a project, namely at design stage (using data from e.g. numerical assessments) and once the WEC is deployed (using data gathered via e.g. condition monitoring systems, CMS). Section 2.2.2 discusses how numerical modelling can be incorporated into a WEC reliability assessment at the design stage. A high-level review of state-of-the-art condition monitoring systems is also presented in Section 2.2.3, noting that the reliability assessment could be refined during the operating WEC phase by feeding measured data into an iterative reliability assessment.

2.2.1 Introduction to the VMEA Approach

This section provides a brief introduction to the VMEA approach and its application to the WEC design process. The progression of WEC technologies to an industrial level can be directly related to a reduction in the key risks associated with their development. In an attempt to help the marine energy sector to reduce such risks, the RiaSoR I project investigated potential risks associated with the development of marine energy converters, and reviewed methodologies applied in other industries to increase the reliability of their products [2].

The characteristics of long-term established industries (such as e.g. automotive and aerospace industries) may differ significantly from the present context of WEC technology developments. In particular, the level of risk that is judged acceptable to release a certain product may depend on e.g. financial and safety constraints, which may in turn depend on the level of understanding of the technology and the availability of efficient design tools. As an example, and according to [3], consideration of fatigue and introduction of *fail-safe* and *damage-tolerance*[1] design methodologies in the aerospace industry only started after the 1940s, although there had been commercial developments of aircrafts for public transport during the previous decade. Despite these potential differences, the development of the marine renewable energy sector is likely to benefit from lessons learned and good practices adopted in other industries. Namely, it is expected that the methodologies to identify and mitigate risks used in long-term established industries can be at least partially transferred to the marine renewable energy sector.

In the RiaSoR I project, an extensive review of reliability assessment methodologies was conducted, leading to a reliability guidance document for marine energy converters [2]. The RiaSoR I literature review covered publications from a number of distinct industries, and concluded that VMEA (see e.g. [4], [5] and [6]) is a reliability methodology that is well suited to the requirements of WEC technology developments.

As pointed out in [2], the VMEA methodology has already been successfully implemented to study fatigue design and maintenance in the automotive [7] and aeronautic industries [6]. VMEA builds upon the method of Failure Mode and Effect Analysis (FMEA), which is a qualitative method that can be used to identify potential weaknesses in a design, but that may not necessarily provide a quantitative assessment of reliability. Studies of FMEA have indicated that the failure modes are in most cases triggered by the type of variation which

[1] *Fail-safe* and *damage-tolerance* design methodologies assume that the device can be inspected in service and damage of the component does not necessarily have the device failing.

causes them [8]. As a consequence, VMEA was conceived to assess the robustness of a design against multiple sources of variation.

The possibility to quantify the level of variation in a design makes VMEA a quantitative method to assess reliability. VMEA is a so-called first-order, second moment method; as opposed to a first-moment method which is based on the calculation of a single value (e.g. expected value; given percentile in a distribution) to which a partial safety factor is applied, second-moment methods also include the variance of the variable in the reliability calculation in order to refine the calculation of associated safety factors [2].

The VMEA 7-step process presented in RiaSoR I is summarised in Table 1. It is noted that the first five steps form the core VMEA activities, while step number six and seven are additional (post-calculation) activities. Steps number six and seven use the results of the core activities to assess reliability and robustness of the device, define improvement measures and the potential for iterations / loop back to the first step of the VMEA.

Step No.	Name	Description
1	Target Function Definition	Define the target function (i.e. the property to be studied), which can be e.g. the life of a component, the maximum stress or the largest defect.
2	Uncertainty Sources Identification	Identify all sources of uncertainty that can have an impact on the target function. The sources may be classified as scatter, statistical, and model uncertainties.
3	Sensitivity Assessment	Evaluate the sensitivity coefficients of the sources of uncertainty with respect to the target function, e.g. by numerical calculations, experiments, or previous experience.
4	Uncertainty Size Assessment	Quantify the size of the different sources of uncertainty, e.g. by experiments, previous experience, or engineering judgement.
5	Total Uncertainty Calculation	Calculate the total resulting uncertainty in the output of the target function by combining the contributions from all uncertainty sources according to their sensitivities and sizes. This is the last step of the core VMEA activities.
6	Reliability and Robustness Evaluation	The result of the VMEA can be used to evaluate component reliability and robustness, e.g. to compare design concepts, to find the dominating uncertainties or to derive safety factors
7	Improvement Actions	Feedback the results to the improvement process, e.g. by identifying uncertainty sources that are candidates for improvement actions and evaluate their potential for reliability improvements

Table 1 VMEA 7-step process (adapted from [2])

At a high-level, VMEA is a reliability assessment methodology with a large scope of application, which can be used at all stages of the development of a technology – namely from design to operational stages. However, the level of accuracy of VMEA will depend on the level of knowledge of the technology that is assessed, which is expected to progress during the development of a technology. As a result, three types of VMEA are proposed in RiaSoR I; a *Basic*, *Enhanced* and a *Probabilistic* version. Table 2 provides a brief description of the three VMEA approaches that are presented in RiaSoR I.

In general, each VMEA approach applies the 7-step process described in Table 1, with varied levels of detail applied to quantify uncertainty sources and sensitivities. For example, in a basic VMEA engineering judgment may be used, whilst the P-VMEA relies on more advanced calculations (e.g. application of numerical models, such as the one described in Section 4).

VMEA Approach	Overview
Basic VMEA ([4], [5])	A key goal is to identify the most important sources of variation. • The sizes of the sources of uncertainties as well as their sensitivities are evaluated on a scale from 1 to 10. • In RiaSoR I [2], the application of the basic VMEA is presented in the context of a concept design phase. • The Basic VMEA only gives a qualitative judgement which can be used for comparisons but cannot be related to failure probabilities.
Enhanced VMEA [9]	A key goal is to identify weak spots of information and to prioritise work. • Assessment of sensitivities and uncertainties is made using physical units. The physical uncertainty coefficient and the standard deviation of the uncertainty is evaluated (the same metrics are used in the P-VMEA). • In RiaSoR I, the enhanced VMEA is seen as an initial version of the P-VMEA, and it is presented in the context of the design phase.
Probabilistic VMEA (P-VMEA) ([6], [9])	The P-VMEA is focused on specific weak spots in a design, identified by engineering experience and / or from a preceding FMEA, based on e.g. basic and enhanced VMEA studies. • Quantifications require detailed studies of influencing parts and external loads. • The first evaluation of the P-VMEA is seen as a framework to compare and combine detailed investigations on the influences on an identified weak spot. • In RiaSoR I, the application of the P-VMEA is presented in the context of a more advanced design phase.

Table 2 Overview of the basic, enhanced and probabilistic VMEA approaches (based on information from [2])

The use of a load analysis numerical tool can benefit the accuracy of a VMEA. For example, when going through the 7-step process of a P-VMEA (see Table 1), there may be merits in quantifying the unwanted variations with the help of a numerical model, rather than simply relying on engineering judgment and available data. Section 4 presents the numerical modelling tool, WEC-Sim, which will be used for the RiaSoR 2 load assessment exercise. The outputs from WEC-Sim can provide a basis for estimating the coefficients needed to perform a P-VMEA, and analyse the reliability of a WEC design (see Section 5).

2.2.2 Virtual Reliability Assessment

WEC design is often supported by numerical models to obtain an estimation of metrics related to e.g. WEC performance and survivability. As an example, numerical models can be used estimate the ultimate loads to be expected with a return period of e.g. 25, 50 or 100 years – see e.g. [10].

At the design stage, the main causes of uncertainties can be identified through VMEA. As discussed in [2], at such stage a significant number of uncertainties are linked to assumptions in the WEC modelling process (see also Section 5.3). For example:

- A number of model assumptions are generally needed to develop a numerical model of the system, to obtain estimates of metrics of interest with a reasonable computational effort. Such model assumptions are associated with an uncertainty in the results, which should in turn be quantified. Methods proposed to quantify identified uncertainties are given in Section 5.4.
- Uncertainties at a design stage may also come from the range of design parameters (e.g. the data source of the site scatter diagram), or the statistics associated with the methods involved to obtain e.g. long-term return values.

When using VMEA to assess WEC design reliability, engineering rules of thumb and high-level estimates are often used in a first approach to quantity uncertainties – see e.g. estimation of the nominal life of a WEC piston rod provided in [2]. However, it may be possible to quantify those uncertainties in a more accurate manner if a numerical tool such as the one described in Section 4 is available. Namely, the variance of simulation outputs and given target functions can be processed to quantify the uncertainties in the WEC loads modelling approach with the help of a P-VMEA, and subsequently contribute to an estimation of appropriate safety factors for the design process.

2.2.3 Condition Monitoring Systems

At later stages of development (e.g. when a WEC has been deployed), an updated assessment of the VMEA can be made with the support of additional data obtained via e.g. a condition monitoring system (CMS). As suggested in [11], data acquired by a CMS on operating devices can also benefit the design of a next generation of devices.

When CMS measurements are available, the reliability assessment can incorporate additional information from actual WEC data to potentially reduce the level of uncertainty in the assessment of given target functions. A discussion on how monitored data and numerical modelling can improve loads assessment can be found in e.g. [12], where a summary of how monitored data and results issued from numerical models have been compared is presented in the context of Joint Industry Projects (JIPs) related to the assessment of fatigue in floating production storage and offloading (FPSO) units.

Failures of any components of the WEC can damage the system and subsequently cause significant repair costs and long down-time events. In an attempt to limit the occurrence of failures and / or limit their impact, condition-based preventive maintenance strategies are usually implemented. Such strategies require that an extensive set of sensors are deployed on the device, as detailed for the case of typical wind turbine systems in [13]. The nature of a CMS may depend on the component it is targeting, and on the type of failure that is monitored.

As an example, Table 3 proposes a shortlist of techniques that can be used to monitor the most critical elements of an offshore wind turbine. A comprehensive description of the CMS can be found in [13].

Component	CMS	Comment
Drivetrain (bearings,	Vibration-based	Most-widely used CMS for drivetrains. Often standard equipment on offshore wind turbines.
	Oil-based	Shall be used in addition to vibration-based CMS

Component	CMS	Comment
shaft and gearwheels)	Others (e.g. Thermography)	At R&D level
Rotor blade	Vibration-based	Widely used for damage detection
	Acoustic emissions	Widely used for damage detection
	Ultra-sonic wave propagation	Sometimes used for damage detection
	Strain measurement	Mostly used for loads monitoring
	Deflection-based	Sometimes used for damage detection
Support-structure	Vibration-based	Commonly used to assess fatigue of the support structure
	Strain Measurements	Commonly used to assess fatigue of the support structure
	Echoes	Sometimes used to detect scours
	Displacement-based	Used to assess state of grouted joints
	Electrical	Used to track corrosion

Table 3 CMS used in the offshore wind industry (from [13])

When a significant number of devices are deployed, industries may collectively benefit from the analysis of data collected by CMS. The development of risk mitigation methodologies based on the analysis of operating devices can also help reducing failures in the devices being operated and monitored, as well as improving the design of the next generation of devices. As an example, in the offshore wind industry Siemens have developed a methodology to improve the Availability, Reliability and Maintainability (ARM) of offshore wind farms, which is based on the monitoring and statistical analysis of data collected onsite [11].

WECs and offshore wind turbines have similarities in several aspects that influence their reliability and robustness. Namely, both systems are offshore structures, subjected to harsh sea conditions and related phenomena such as corrosion and marine growth. Moreover, the architecture of both systems is composed of similar components - e.g. shafts, bearings, gearwheels, steel structures, etc. Therefore, it is possible that a relevant number of CMS approaches proposed in Table 3 can be applied to monitor WECs, supporting the development of a reliability strategy for WECs.

In some cases, the data measured by CMS does not correspond directly to the variable targeted by the reliability analysis. When assessing reliability of a WEC component, using e.g. VMEA, a distinction can be made between *direct* inputs, for which a direct measure of the sensor is available, and *indirect* inputs, which can be deduced from the direct inputs and the help of a model. Potential benefits that numerical models can bring to the reliability assessment of a component, and how they may support the monitoring of indirect inputs, were detailed in Section 2.2.2.

Although data from CMS may help refining the reliability assessment of the loads issued from the WEC simulation tool, the primary focus of WP3 of RiaSoR 2 concerns the potential use of a WEC simulation tool (describe in Section 4.1) to conduct a reliability assessment of the loads acting on a WEC for design purposes. A design basis for the RiaSoR 2 load assessment exercise is presented in Section 3.

3 Design Basis

In order to illustrate the initial stages of the application of a numerical design tool to quantify WEC reliability, a design basis is outlined in this section. A reference generic WEC design for WP3 is proposed, along with a high-level definition of the environmental conditions and design situations that may be experienced during the lifetime of the WEC. Following [1], possible scenarios issued from the combination of environmental conditions and design situations may be represented by a set of Design Load Cases (DLCs). A shortlist of DLCs is proposed to perform a reliability assessment on the generic WEC with the help of a numerical load modelling tool.

Section 3.1 features a description of a proposed generic two-body heaving point absorber type WEC to focus on within WP3 of RiaSoR 2. The WEC is equipped with a hydraulic power conversion chain (PCC) that is described in the same section. Both the baseline environmental conditions and the design situations to be considered are also detailed in Sections 3.2 and 3.3, respectively. DLCs are derived from combinations of environmental conditions and design situations, and a shortlist of the priority DLCs for the load assessment is presented in Section 3.4. This shortlist of DLCs may be considered when applying the load assessment numerical tool to estimate the target functions proposed in Section 5.2.3.

3.1 Generic WEC Description

A generic WEC was selected for the load assessment exercise that can provide inputs to the reliability assessment within WP3 of RiaSoR 2. This section describes the main features of the generic WEC, including a high-level description of the components which WP3 work may focus on. A complete description of the WEC model implemented in WEC-Sim is provided in Section 4.2.

The generic WEC is a two-body point absorber which can convert wave energy from the translational motion between the WEC prime mover and the spar buoy. The WEC is moored by a catenary mooring system composed of three mooring lines. The generic WEC is inspired by the RM3 WEC concept that was introduced in the Reference Model Project by Sandia National Laboratories [14]. A visualisation of the RM3 WEC at full-scale is provided in Figure 3.

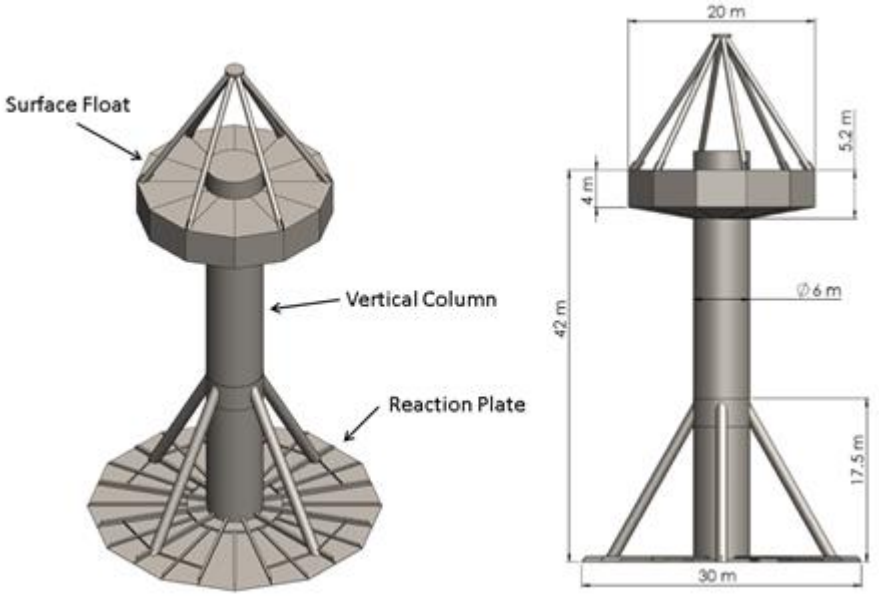

Figure 3 RM3 WEC model description [14]

The generic WEC proposed for RiaSoR 2 has a 10m diameter float and a spar buoy with a 15m draft[2]. It features a heave plate at the bottom of the spar column. Heave plates are typically used in offshore structures to damp vertical motions by increasing viscous effects at the location of the plate; in the generic WEC case, it intends to allow the spar column to become a reference to the float.

The geometry and mass properties of the generic WEC (see Table 4) were derived from [15] and scaled down to meet the target diameter and draft. Small adjustments to the spar buoy mass as well as to the location of the centre of mass of each WEC body were made to ensure the overall stability of the scaled WEC. CA notes that the mass and inertia properties of the WEC bodies provided in Table 4 correspond to global values, including all WEC components such as prime mover hull, structural reinforcements, ballast and PTO subsystems. All coordinates are provided in the coordinate system described in Section 4.1.

	Mass [t]	Centre of Buoyancy [m]	Centre of Gravity [m]	Moments of Inertia about Respective CoG [kg.m²]		
		x,y,z	x,y,z	Ixx, Iyx, Izx	Ixy, Iyy, Izy	Ixz, Iyz, Izz
Float	90.5	0	0	6.6e5	0	0
		0	0	0	6.6e5	0
		-0.65	-0.8	0	0	1.16e6
Spar buoy	191.0	0	0	2.94e6	0	0
		0	0	0	2.94e6	0
		-7.55	-12.0	0	0	9.1e5

Table 4 Geometry and mass properties of the generic WEC

[2] CA notes that several models of the RM3 - with distinct diameter / draft ratio - can be found in the literature. The RM3 version from [15] was chosen as additional details could be found in the literature for this version.

The generic WEC is equipped with a simplified hydraulic power conversion chain (PCC) designed from data available in the public-domain, for which an extensive description of the working principle can be found in [16]. The PCC is activated by a hydraulic piston driven by the relative motion between the WEC prime mover (i.e. the float) and the spar buoy. The piston motion drives a fluid through a set of four check valves, which ensure that the fluid always passes through a variable-displacement motor in the same direction. The motor, which is connected to an electrical generator, is driven by the pressure difference between two accumulators. One high-pressure accumulator is placed on the inlet of the hydraulic motor, and one low-pressure accumulator (or reservoir) is on the outlet of the hydraulic motor. A boost pump and a pressure relief check valve are also included to prevent cavitation and maintain a minimum pressure in the system.

A summary diagram of the hydraulic PCC used for the generic WEC in RiaSoR 2 is shown in Figure 4. Proposed values for the main properties of the hydraulic PCC components are listed in Table 5. It is assumed that the boost pump and relief valve assembly that can be seen in Figure 4 will not be solicited in normal operating conditions. As such, those two elements are not presently modelled in the Simulink PTO model.

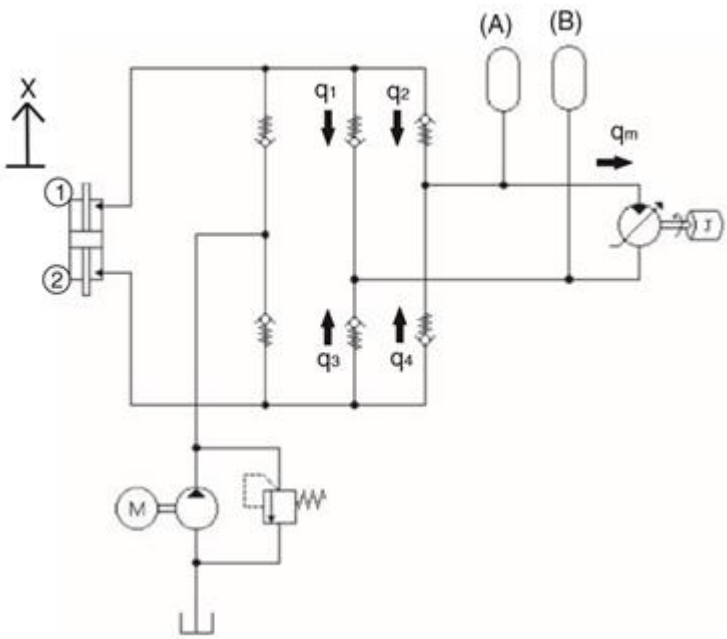

Figure 4 Generic WEC Hydraulic PCC diagram [16]

Component	Property	Unit	Preliminary Value
Piston	Area	m^2	0.05
	Volume	m^3	0.75
	Effective Bulk Modulus	MPa	1860
Hydraulic Fluid	Density	$kg.m^{-3}$	850
Valves	Minimum Area	mm^2	0.01
	Maximum Area	cm^2	20
	Discharge coefficient	-	0.61

Component	Property	Unit	Preliminary Value
	Minimum Delta Pressure	MPa	0
	Maximum Delta Pressure	MPa	1.5
HP Accumulator	Initial Volume	m^3	17
	Rated Working Pressure	MPa	31
	Pre-Charge Pressure	MPa	19.2
LP Reservoir	Initial Volume	m^3	12
	Rated Working Pressure	MPa	16
	Pre-Charge Pressure	MPa	9.6
Hydraulic motor	Total Inertia (incl. Generator Inertia)	$kg.m^2$	20
	Friction	$kg.m^2.s^{-1}$	0.05
	Volume	l	0.02 – 0.31
	Efficiency	-	0.76 – 0.94
Generator	Rated Speed	$rad.s^{-1}$	150
	Drive Efficiency	-	0.98

Table 5 Hydraulic PCC component properties

3.2 Environmental Conditions

3.2.1 Guidance and Standard Documents

The estimation of the target functions proposed in Section 5.2.3, as well as the size of their respective uncertainty sources, will depend on the definition of target site conditions for the WEC. A well-defined characterisation of the environmental conditions is required to estimate the environmental loads acting on a WEC (and the associated uncertainties).

To date, several documents outlining the information required to describe the environmental conditions have been produced, either specifically for marine renewable energy technologies or for broader applications in e.g. the oil and gas sector. In particular, the following key documents can be followed:

- Section 3 (B) of the DNV-OSS-312 (2008) *Certification of Tidal and Wave Energy Converters*, which provides an overview of the environmental data used as a basis for the design certification.
- Section 1 of the GL Rules and Guidelines IV-6-4 (2007) *Offshore Structures: Structural Design*, that documents technical definitions specifically related to the environmental conditions (wind, wave, currents, tides, etc.).
- Section 7 of the DNV-RP-C205 (2014) *Environmental Conditions and Environmental Loads*, where an overview of appropriate theory for wave and current induced loads on large volume structures is presented.
- Section 6 of the IEC TS 62600-2 (2016) *Marine energy: Wave, tidal and other water current converters – Part 2: Design requirements for marine energy systems*, where the external conditions to take into consideration during modelling, analysis and prediction of environmental loads are detailed.

Based on relevant standards and guidance documents, metrics were proposed in [1] to summarise the environmental conditions in a format suitable for immediate coupling with the design situations. These are also proposed in the relevant standards and include:

- Normal operational sea states (*NSS*).
- Extreme operational sea states (*ESS*).
- Focused wave groups (*FWG*).
- Regular waves (*RW*).

It is expected that the most significant environmental effects that may dominate extreme and fatigue loads can be captured by simulating a combination of these environmental metrics in distinct design situations. Section 3.2.2 introduces the *NSS* and *ESS* environmental metrics for a specific target site near the European Marine Energy Centre (EMEC) off the West coast of Orkney, Scotland, which is proposed as the reference site for the RiaSoR 2 project. Section 3.3 subsequently reviews the different design situations that may be considered, combining environmental and WEC metrics in the context of a loads reliability assessment.

3.2.2 Target Site Conditions

Site conditions representative of the Billia Croo wave energy test site at EMEC are proposed to contextualise the reliability assessment of the generic WEC to be conducted in RiaSoR 2 WP3. To define the long-term representative conditions at the EMEC site, data from the National Oceanic and Atmospheric Administration's (NOAA) NCEP CFSR hindcasts was processed. The data covers a 30-year period between January 1979 and December 2009. A measured scatter diagram for a 10-year period has also been provided by EMEC[3].

Figure 5 illustrates the data locations for the North Sea Grid (4min) in the vicinity of the Orkney islands. The coordinates of the data point closest to EMEC's Billia Croo test site is 59N, 3.467W, and the water depth at this location is estimated to be approximately 50m. Data points containing 3-hour averages of significant wave height, H_s, peak period, T_p, peak direction, D_p, as well as 10m (above Mean Sea Level) wind speed and direction, were extracted at this location.

[3] Email from Johannes Huffmeier (RISE) to Mairead Atcheson (CA) on the 27th February 2018, with the scatter diagram provided by EMEC in attachment ("*10 yr Hs-Tp.xlsx*").

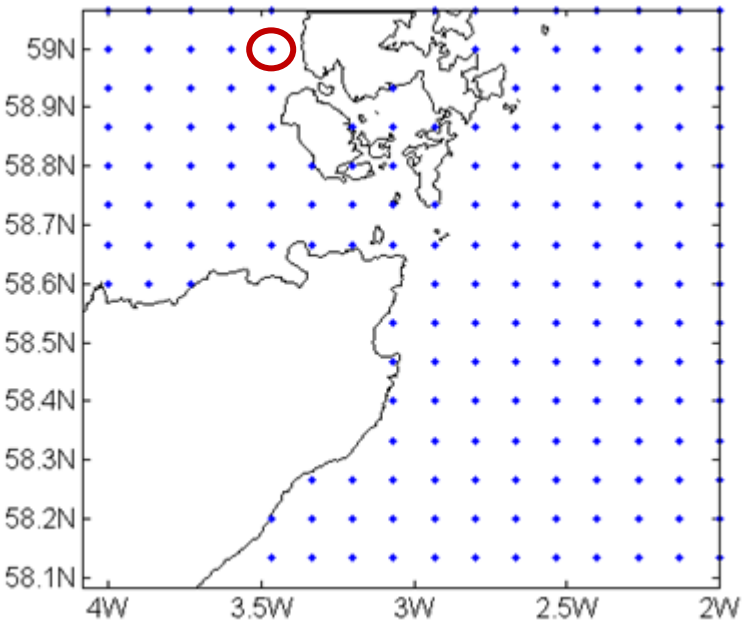

Figure 5 Metocean data point locations for the North Sea Grid (4min) around the Orkney islands. Selected point circled in red (59N, 3.467W) [17]

The probability of occurrence of each H_s, T_p pair (long-term average) is shown in Figure 6. The *NSS* conditions proposed in Table 6 were derived from the analysis of this probability of occurrence plot, and cover 94% of the annual occurrences at the target location. A plot of the directional wave spectrum at the target site is also provided in Figure 7.

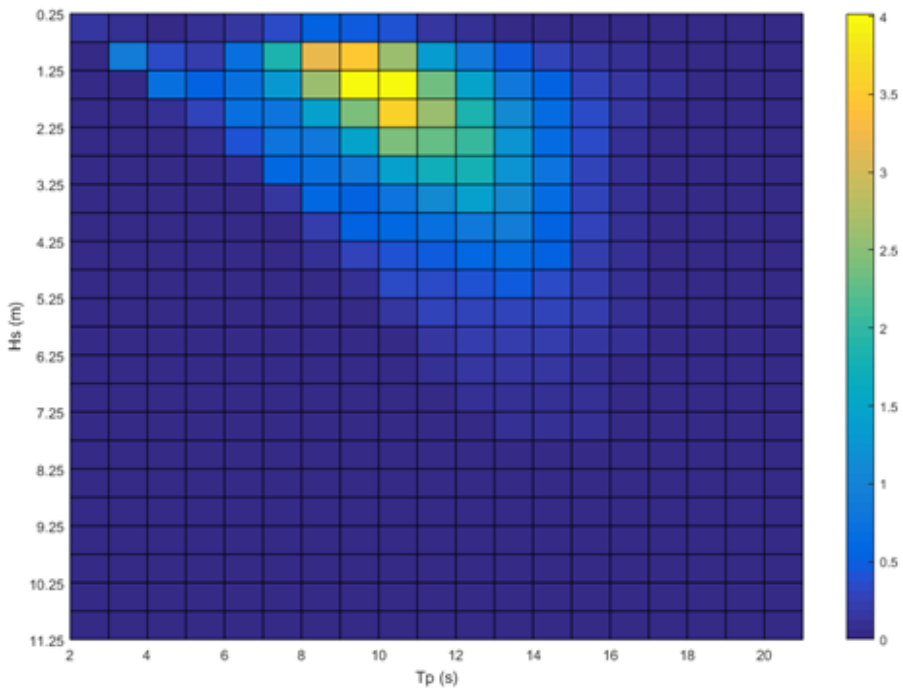

Figure 6 Probability of occurrences (%) for selected grid point (59N, 3.467W) [17]

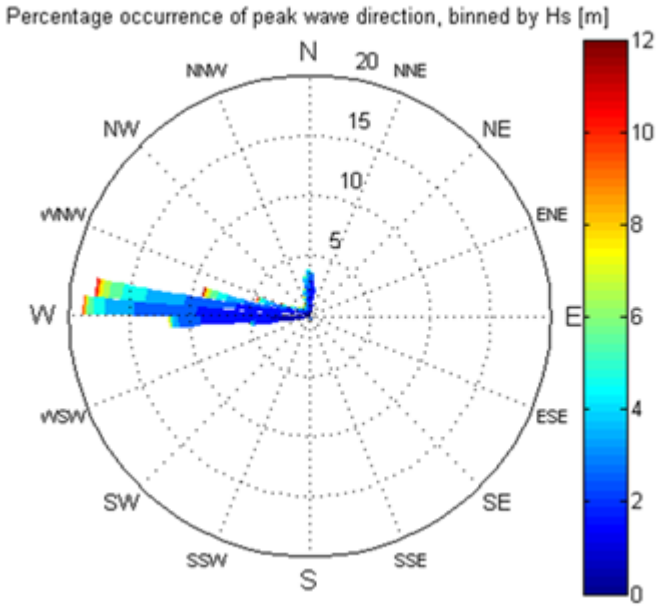

Figure 7 Directional wave spectra (59N, 3.467W, North Sea 4min grid, Jan 1979 – Dec 2009) [17]

The complete dataset of H_s, T_p pairs issued from the 30 years of hindcast data, as well as the environmental contour for return periods of 1, 50 and 100 years, is illustrated in Figure 8. Defined environmental contours were also derived.

In Figure 8, two types of environmental characterisation sampling methods are visible:

- A contour approach (yellow triangles), where a reduced number of samples are taken from each environmental contour.
- A full environmental characterisation (red dots), where a larger number of samples (circa. 200) are taken within the 100-year contour.

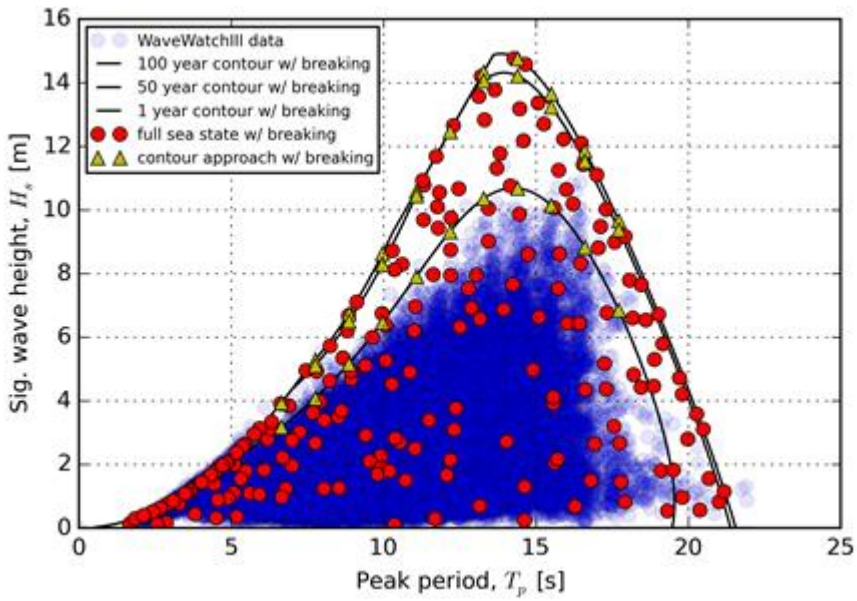

Figure 8 Detailed environmental characterisation (59N, 3.467W, North Sea 4min grid, January 1979 – December 2009) [17]

Finally, Table 6 presents the defined environmental condition metrics proposed for the target site.

Environmental Conditions Metric	Target Values		Notes
NSS	H_s (m) [0.75:0.5:5.75] T_p (s) [4:1:16]		Where applicable: [Start_Value:Step:End_Value] In total: 143 sea states evaluated (covering 94% of occurrences)
ESS – H_{s1}	H_s (m)	T_p (s)	*ESS* for additional return periods (50y and 100y) also identified. Full environmental characterisation (red dots in Figure 8) will also potentially be used.
	3.17	6.64	
	4.07	7.75	
	5.17	8.86	
	6.46	9.96	
	7.91	11.07	
	9.32	12.18	
	10.36	13.28	
	10.68	14.39	
	10.15	15.50	
	8.83	16.61	
	6.85	17.71	

Table 6 Definition of environmental condition metrics for the target site [17]

For the environmental conditions proposed in Table 6, the following notes apply [17]:

- The range of H_s, T_p combinations considered for both *NSS* and *ESS* is restricted by the wave breaking criteria (steepness and depth limitations).
- The data collected at the target location shows that there is a clear predominance of a westerly swell with a narrow spread, which suggests that the model waves can be considered unidirectional in a first approach.
- Due to the axisymmetric nature of the generic WEC body, a single mean wave direction is considered sufficient to address the dominant loading effects.
- A standard spectral shape (JONSWAP) will be assumed for all H_s, T_p combinations.

In addition to the wave climate, other environmental load sources (e.g. wind, currents, tide height, marine growth) could be considered within the scope of defining the environmental conditions. These additional environmental conditions will not be considered in the RiaSoR 2 exercise.

3.3 Design Situations

3.3.1 WEC Lifetime Design Situations

The selection of relevant design situations is a key aspect when using numerical modelling to assess the target functions that characterise WEC reliability. In an attempt to represent the dominant loading scenarios experienced by a WEC during its lifetime, the following design situations were proposed in [1]:

- Power Production;

- Power Production Plus Occurrence of a Fault;
- Start-up;
- Normal Shutdown;
- Emergency Shutdown;
- Parked / Survival (standstill or idling);
- Parked / Survival Plus Fault Conditions;
- Transport, Installation, Maintenance and Repair;
- Accidental / Abnormal Events (if not covered in any of the other load cases);
- Damaged Stability.

As pointed out in [1], the PTO and other machine settings that apply to each design situation should be defined in anticipation of the load calculation exercises. In particular, conditions of components which will be focused during the loads reliability assessment should be defined as accurately as possible (these also include the definition of target design situations and DLCs in Sections 3.3.2 and 3.4, respectively). Multiple component conditions and / or machine operational states may apply to a design situation. In such cases, component conditions and other machine settings that lead to the highest loads should be selected for the design situation.

For the load assessment to be conducted in RiaSoR 2, and using the numerical model presented in Section 4.2, a restricted set of design situations can be considered within the project constraints. The selection of target design situations is presented in the next section.

3.3.2 Target Design Situations

In the context of loads assessment that can be used as an input to the reliability assessment, the number of design situations to be considered should be limited in order to keep the computational effort within feasible boundaries. In WP3, design situations which are expected to be the most relevant to the RiaSoR 2 project were selected, namely:

- Power Production;
- Parked / Survival (standstill or idling);
- Parked / Survival Plus Fault Conditions.

In all design situations, only component conditions and machine operational states that are the most severe in terms of loading will be considered. The analysis of transient design situations (e.g. start-up, normal shutdown, emergency shutdown) requires that a complete description of the system procedures is provided. Considering the scarce information regarding transient design situations of the reference generic WEC, such situations will not be considered in the RiaSoR 2 exercise.

3.4 Design Load Cases

Methods to derive DLCs that can lead to fatigue and ultimate limit states can be found in the following key documents:

- The GL Rules and Guidelines IV-6-4 (2007) *Offshore Structures: Structural Design*, that defines design loads for marine structures and specifies which design loads are to be used in structural analysis of offshore structures.
- The GL Rules and Guidelines IV-2 (2012) *Guideline for the Certification of Offshore Wind Turbines (Chapter 4 – Load Assumptions)*, that details the methods to derive DLCs for fatigue and ultimate strength scenarios.
- IEC 62600-2 (2016) *Marine Energy – Wave, Tidal and Other Wave Current Converters. Part 2: Design Requirements for Marine Energy Systems*, that provides a list of DLCs for WECs.

A global description of DLCs as a function of environmental conditions and relevant design situations is proposed in [1] and replicated in Appendix A. In a first approach to the WEC reliability assessment, the fatigue limit state (FLS) and the ultimate limit state (ULS) will be targeted in RiaSoR 2 (see also Figure 2). The analysis of the target functions presented in Section 5.2.3, will focus on the shortlist of DLCs listed in Table 7.

Design Situation	DLC	Wave Condition	PTO Condition	Other Condition
1. Power Production	1.1	*NSS*	*Power Production*	
6. Parked (standstill or idling)	6.1	*ESS - H_{s1}*	*Parked*	
7. Parked plus fault conditions	7.1	*ESS - H_{s1}*	*Parked*	Fault condition

Table 7 RiaSoR 2 DLC shortlist

In a first approach, and in an attempt to focus the numerical load assessment exercises, only the DLCs listed in Table 7 will be considered in RiaSoR 2. Section 4 describes the loads modelling approach and model set-up that will be applied in the RiaSoR 2 exercise.

4 Loads Modelling

This section presents the numerical modelling tool, WEC-Sim (v3.0), an open-source WEC simulation tool developed in MATLAB/Simulink that can be used to simulate the WEC behaviour. The setup of the generic WEC model and the associated conventions are detailed.

The use of a numerical design tool can support the WEC reliability assessment by quantifying the level of variations of the distinct sources of uncertainty in the load calculations. An appropriate post-processing of the outputs from WEC-Sim can provide an estimate of the coefficients needed to perform a P-VMEA and estimate the reliability of the WEC component design (see also Section 5).

4.1 WEC-Sim Overview

WEC-Sim (Wave Energy Converter SIMulator) [18] is an open-source WEC simulation tool developed in MATLAB/Simulink using the multi-body dynamics solver SimMechanics[4]. The WEC-Sim project is funded by the U.S. Department of Energy's Wind and Water Power Technologies Office and the code development effort is a collaboration between the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL).

WEC-Sim has the ability to model WECs that involve rigid bodies, PTO and mooring subsystems. Simulations are performed in the time-domain by solving the governing WEC equations of motion in all relevant degrees of freedom (DoF), in a fully-coupled format (i.e. simultaneously accounting for all relevant load sources). The distinct modules that can be connected to form a complete WEC model in WEC-Sim are detailed in Section 4.2.

WEC-Sim can be used for regular and irregular wave simulations. A linear formulation based on a boundary element method (BEM) potential flow solver (e.g. NEMOH [19]; WAMIT [20]) can be used to estimate the hydrodynamic forces on the WEC. WEC-Sim also offers the possibility to calculate the hydrodynamic forces on the WEC using Morison's equation. With regard to power extraction, WEC-Sim allows PTO properties to be applied to any joint in the system, where energy converted from the motion of a body (relative to another body or to a fixed reference point such as the seabed) may be used to drive a PCC. WEC-Sim models can also include additional features such as e.g. a moorings model, viscous fluid effects and end-stops. WEC-Sim outputs contain a wide range of variables to be analysed, including motions of the WEC bodies, global loads and local pressures on the WEC bodies, loads and motions at connection points, and relevant variables within the PCC (e.g. generator speed, valve delta pressure, etc.).

WEC-Sim can be applied to a range of design situations for WEC performance and load calculation exercises. However, for highly non-linear scenarios, considering the combination of both hydrodynamic nonlinearities and machine nonlinearities, as well as viscous effects, the implementation of a fully nonlinear model (e.g. computational fluid dynamics, CFD, models) is likely to be required / recommended [1]. Cruz Atcheson has implemented several modifications to WEC-Sim that aim to (at least partially) mitigate for some of the above limitations.

[4] Further details regarding WEC-Sim can be found at http://wec-sim.github.io/WEC-Sim/.

The WEC-Sim coordinate system is defined in Figure 9. The generic WEC model follows this nomenclature, namely the three translations (surge along the x-axis, sway along the y-axis and heave along the z-axis) and three rotations (roll around the x-axis, pitch around the y-axis and yaw around the z-axis). The origin of the coordinate system lies at the mean water surface level.

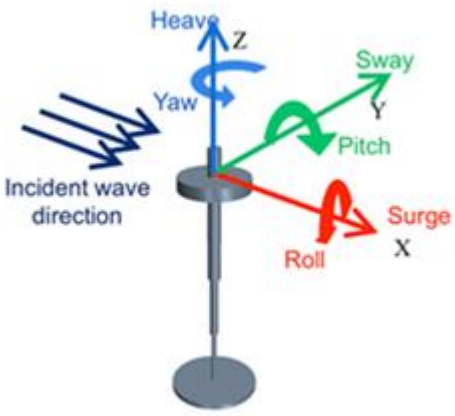

Figure 9 WEC-Sim Coordinates System (source: http://wec-sim.github.io/WEC-Sim**). The origin is located at the mean water surface level**

4.2 WEC Model Setup

WEC-Sim simulation models are constructed on a multi-body basis, as a collection of linked components with specific physical properties. These components include wave-activated rigid bodies, joints at which PTO forces may be applied and mooring lines that can be attached to the WEC structure and to which an anchor point may be assigned. The primary functions of WEC-Sim that interact to solve the multi-body dynamics of the WEC model include:

- **Wave class**, that defines the wave conditions for the simulation;
- **Body class**, that defines the body properties (e.g. mass, moments of inertia, centre of gravity, hydrodynamic properties);
- **Constraint class**, to connect the WEC bodies to one another or to the seabed;
- **PTO class**, that connects the WEC bodies to one another (or possibly to the seabed) by constraining DoFs and applying linear damping and stiffness. More complex representations of PTO systems can also be implemented by incorporating other Simulink libraries (e.g. PTO-Sim);
- **Mooring class**, that contains information on the definition of the mooring system. Mooring options available include the implementation of a mooring matrix or MoorDyn[5].

Each class contains several parameters with predefined properties the user must choose from to build up a mathematical representation of the WEC. Sections 4.2.1 to 4.2.4 provide a

[5] Further information on MoorDyn can be found at https://nwtc.nrel.gov/MoorDyn.

more detailed description of the distinct features of WEC-Sim and detail how elements of the distinct classes can be combined together to form the WEC model.

4.2.1 Model Structure

The WEC is represented in WEC-Sim as rigid bodies with mass, inertia, PTO and hydrodynamic properties. The relative position of each body is defined by the location of their centre of gravity in the global reference frame. The component connectivity is defined using elements from the *constraint* and *PTO* classes that connect the bodies to the global reference frame. For rotational PTO constraints, the user also needs to specify their location with respect to the global reference frame.

The Simulink structure of the WEC-Sim model for the generic WEC to be studied in RiaSoR 2 is illustrated in Figure 10. The model of the hydraulic PCC fits within the *PTO location* block that can be seen in Figure 12, and is described in more details in Section 4.2.3.

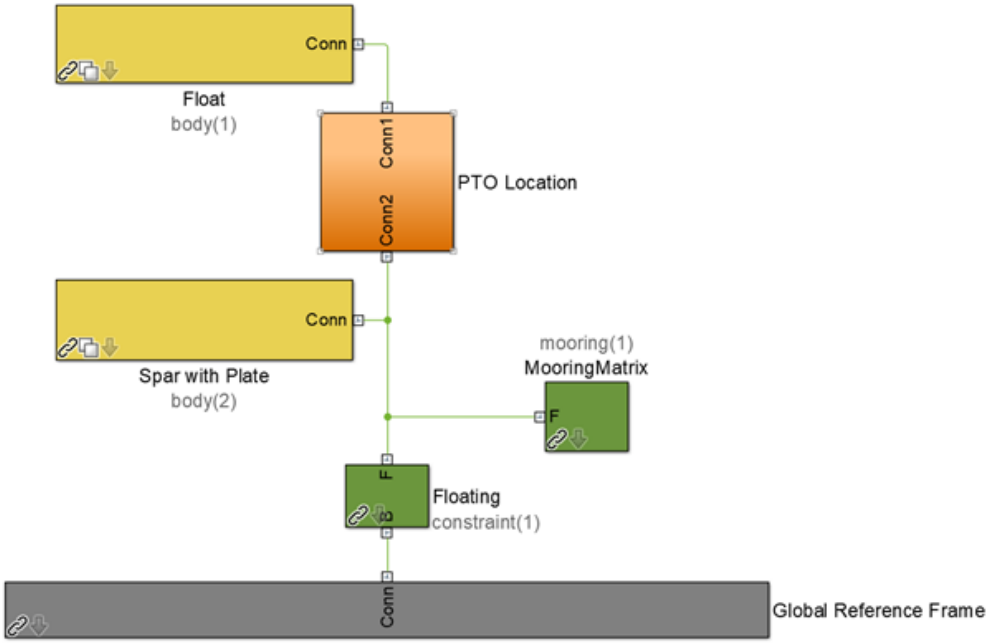

Figure 10 Structure of the proposed generic WEC-Sim model

4.2.2 Hydrodynamic Model

Hydrodynamic loads and pressures acting on the WEC are derived from first-order potential flow theory, using hydrodynamic coefficients derived in the NEMOH BEM solver. The hydrodynamic mesh used to derive the hydrodynamic coefficients of the WEC in NEMOH is shown in Figure 11. Best practices were applied to determine the mesh size and the resolution of the hydrodynamic data to provide an accurate representation of the hydrodynamic coefficients. This was conducted by checking the coherence and consistency of the output coefficients for multiple mesh refinements.

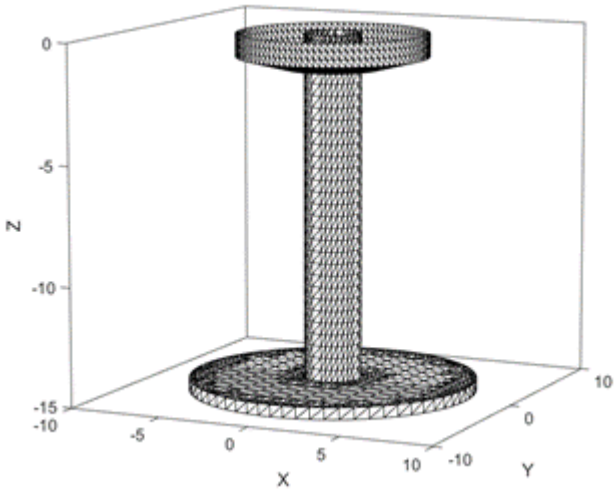

Figure 11 Mesh used to derive the hydrodynamic coefficients of the generic WEC in NEMOH

The generic WEC includes a heave plate at the bottom of the spar column. Heave plates are typically used in offshore structures to damp vertical motions by increasing viscous effects at the location of the plate. To model the impact of the heave plate on the WEC dynamics, the drag forces acting on the WEC can be estimated and included in the equation of motion using a Morison based quadratic term, following:

$$F_d = -\frac{1}{2}\, C_d\, \rho A_d\, \dot{X}|\dot{X}|$$

with ρ being the fluid density, $\dot{X}$ is the body velocity, C_d the drag coefficient and A_d the characteristic area for the degree of freedom under consideration. Following [15], Table 8 summarises the values of the drag coefficients C_d and characteristic areas A_d to be used for the calculation of drag forces acting on the spar buoy.

	Surge	Sway	Heave	Roll	Pitch	Yaw
C_d [-]	0.0	0.0	4.5	4.5	4.5	0.0
A_d [m^2] or [m^5]	0.0	0.0	177	1.0e5	1.0e5	0.0

Table 8 Characterisation of viscous drag forces acting on the spar buoy

4.2.3 Power Take-Off (PTO) Model

In WEC-Sim, PTO models typically consist of an assembly of linear and / or rotational joints to which stiffness and damping properties can be attributed to. In particular, PTO models may incorporate elements of the *body* class, *constraint* class and *PTO* class. WEC-Sim also offers the possibility to implement user-defined functions to model specific behaviour of the PTO subsystem. As an example, physical limits of the system such as e.g. maximum generator speed or efficiencies related to specific component variables can be modelled through user-defined functions. Additional elements from Simulink libraries (e.g. Simscape library) can be added to refine the PTO model.

The translational PTO constraints in the generic WEC allow a relative vertical motion between the WEC prime mover and the spar buoy (i.e. along the spar axis). The PTO system includes a hydraulic PCC (see description in Section 3.1), which converts relative translational motion between the WEC prime mover and the spar buoy into electrical power. The structural WEC-Sim model of the hydraulic PCC is illustrated in Figure 12.

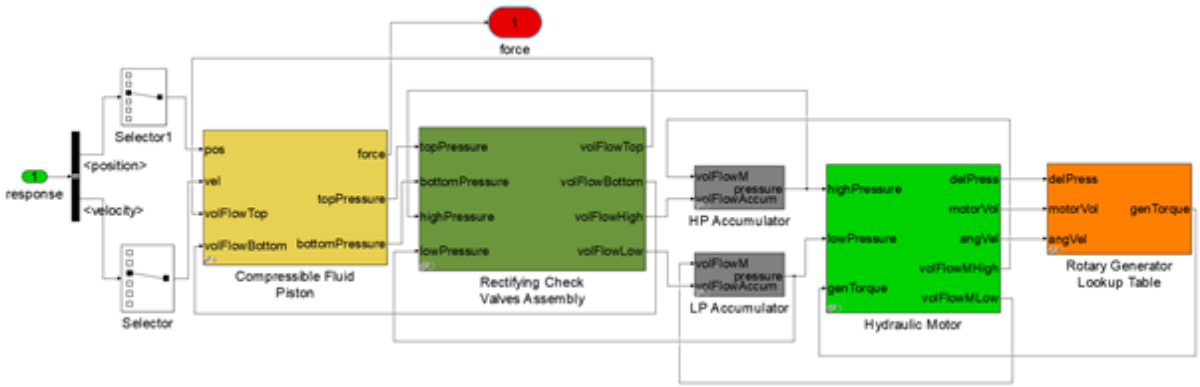

Figure 12 Simulink structure of the hydraulic PCC model

The equations used to model the behaviour of the hydraulic system components are detailed in [21], and reference values for a small-scale hydraulic PCC are given in [16]. The PCC properties for the generic WEC proposed in RiaSoR 2 are detailed in Table 5. The priority list of DLCs also includes fault conditions as a design situation for consideration. Multiple fault conditions (e.g. increasing the piston friction coefficient to simulate a piston fault) can be tested in the PTO model (see Section 5.4).

4.2.4 Mooring System

A simplified (linear) representation of the mooring system is implemented in the WEC-Sim model, consisting of a stiffness matrix to model forces applied at a user-defined location on the floating body. WEC-Sim can also accommodate a more detailed representation of moorings, incorporating terms dependent on the displacement, velocity and acceleration of the lines.

In the generic WEC model, the global effects of the mooring system are characterised by a linear mooring module attached at the centre of gravity of the generic WEC. The coefficients of the stiffness matrix used to estimate the mooring loads are detailed in Table 9. In the uncertainty assessment, changes from a linear mooring model to a more detailed mooring modelling approach can be considered (see Section 5.4).

K_{11} [kN/m]	K_{22} [kN/m]	K_{33} [kN/m]	K_{44} [kN.m/rad]	K_{55} [kN.m/rad]	K_{66} [kN.m/rad]
2.5	0	0	0	0	0

Table 9 Linear mooring model properties

5 Reliability Assessment

In RiaSoR 2, a P-VMEA approach will be applied to assess the uncertainty associated with the numerical estimates of the dominant WEC loads. It is expected that the analysis will provide a quantitative indication of the uncertainty associated with load calculations exercises, which may assist in the WEC design process from inception. The assessment will focus on the generic WEC proposed in Section 3.1, operating at the target installation site described in Section 3.2. Simulations will be completed for a selected number of DLCs (see Section 3.4).

This section provides an overview of the stages proposed for the numerical reliability assessment, with an outline of the P-VMEA approach to be applied (Section 5.1). Sections 5.2 to 5.5 describe the different steps involved in the P-VMEA process to quantify the numerical load uncertainty, namely:

- **Target function definition** (Section 5.2). This section identifies and selects the specific variables and target functions to be assessed via the P-VMEA in RiaSoR 2.
- **Uncertainty source identification** (Section 5.3). With the variable(s) and target function(s) selected, the second step of the P-VMEA process focuses on listing the potential sources of uncertainty that can affect the target function(s) and the related variables.
- **Sensitivity and uncertainty size assessment** (Section 5.4). Once the uncertainty sources have been identified, the third and fourth steps of the VMEA aim to quantify the effects of variations associated with each uncertainty source. This involves estimating, for each target function, a sensitivity coefficient (c_i) that assesses the effects in the target function of univariate changes of each uncertainty source, as well as quantifying the dispersion (s_i) in the load estimate(s) associated with each uncertainty source and a correction factor (t_i), if necessary.
- **Total numerical load uncertainty calculation** (Section 5.5). Estimated values from the previous steps (i.e. c_i, s_i and t_i) are input into the VMEA template from RiaSoR I to calculate the combined total load uncertainty.

5.1 P-VMEA Approach

An overview of the P-VMEA approach proposed in WP3 of RiaSoR 2 is illustrated in Figure 13. The process aims to adopt the VMEA template from RiaSoR I, with a focus on identifying and quantifying load uncertainties using data from WEC-Sim.

Following the definition of the generic WEC model and of the priority DLCs, an estimate of the target function(s) of interest can be derived. Additional calculations with varying input parameters can be done in order to estimate the amplitude of the variations for each uncertainty sources and / or the sensitivity of the target functions to those variations. Section 5.4 provides some examples of possible parameters to be varied in order to assess the amplitude of the variations caused by the uncertainties sources identified in Section 5.3. The analysis of the variations of the model results leads to the calculation of the relevant coefficients (c_i, s_i and t_i) to be input to the P-VMEA (see Section 5.5).

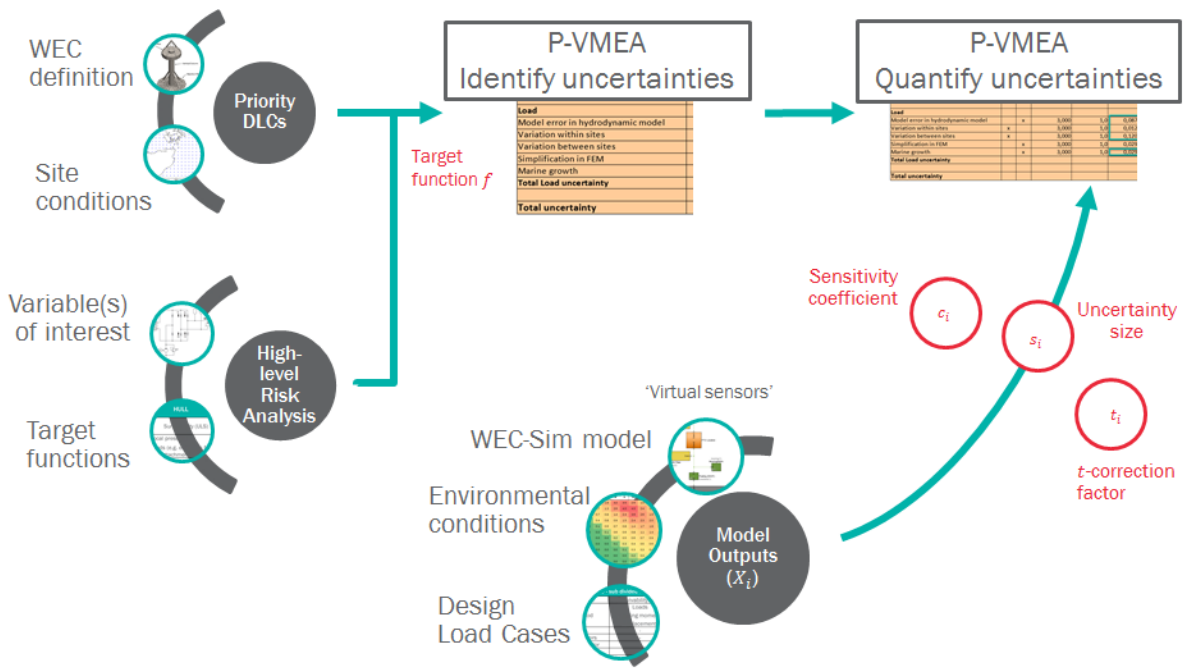

Figure 13 RiaSoR 2 – P-VMEA approach

5.2 Target Function Definition

In practice, specific target areas (or potential *hot spots*) may be identified by an initial FMEA exercise, and / or previous VMEA studies conducted by WEC developers. However, in WP3 of RiaSoR 2 a generic WEC is used in the loads analysis exercises, and there is no prior information relative to the WEC failure modes. As a result, a high-level assessment is required to select a range of proposed target functions. This process is described in the following subsections.

5.2.1 Limit States

In RiaSoR I, it was assumed that a suitable reliability target is to ensure that a design that can withstand the environmental conditions during the lifespan of the WEC [2]. Under this assumption, WEC design activities shall aim to meet the requirements of three main criteria: durability, maintainability and survivability. In [2], the RiaSoR I project members chose to apply the VMEA methodology to assess WEC durability and survivability, which requires the definition of suitable target functions (which may depend on the nature and role of the components).

At the design stage, standards and guidance documents can guide WEC developers through the design process and support the definition of specific target functions. For example, some certification bodies suggest that distinct design criteria can be assessed via the study of limit states[6], examples of which are listed in Table 10. Limit states are states of loading or deformation at which a structure / component loses its operability status. As an example, target functions characterising a Fatigue Limit State (FLS) can be defined to assess the durability of components such as e.g. mooring chains, valves in a WEC PCC, etc.

[6] See [22] for an example definition of limit states in the offshore wind industry.

Limit State	Acronym	Examples of failures
Ultimate	ULS	Failure caused by the maximum load on a structure or a component
Fatigue	FLS	Structural failure due to cyclic loading
Accidental	ALS	Structural collapse after accidental damage
Serviceability	SLS	Impairment of operation other than structural failure envisaged towards the normal use of the device; e.g. vibrations, deformation, or leakage

Table 10 Example of design criteria - limit states

5.2.2 WEC-Sim Output Variables

The variables output by the WEC-Sim model presented in Section 4.2 provide an extensive set of data. A large number of measurements related to e.g. motions, pressures, loads, at different locations on the WEC, can be derived and post-processed in order to assess metrics related to survivability and durability of the WEC components.

Table 11 proposes a shortlist of output variables that can be directly assessed in WEC-Sim for the purpose of WEC reliability assessment.

Component	Variable
Hull	Global restoring forces and moments
	Global hydrodynamic forces and moments (e.g. excitation, radiation)
	Attachment forces and moments (e.g. PTO connection)
	Local hydrostatic pressure
	Local hydrodynamic pressure (incident and diffracted)
Piston	Displacement, Velocity, Acceleration
	Force
	Pressures (top / bottom)
	Volumetric flow
Valves	Valve delta pressure
	Volumetric flow
Accumulators	Pressure
	Volume
	Volumetric flow
Motor	Pressure (inlet / outlet)
	Speed
	Volume
	Volumetric flow
Generator	Speed
	Torque

Table 11 Sample of relevant WEC-Sim output variables

Section 5.2.3 proposes a selection of target functions that can be looked at in the context of the RiaSoR 2 reliability assessment. The proposed target functions can be estimated by tracking and post-processing some of the target output variables from WEC-Sim listed in Table 11.

5.2.3 Proposed Target Functions

As detailed in Section 5.2.1, the evaluation of the reliability of a WEC design through the assessment of durability and survivability metrics requires the definition of suitable target functions. Some guidance regarding the reliability assessment of marine structures can be found in DNV Classification Notes Nº 30.6 (1992) *Structural Reliability Analysis of Marine Structures*, where guidance for the analysis of uncertainties in the structural design of marine structures is provided.

Following recommendations from relevant guidance documents, and in an attempt to address, even if partially, critical areas of a generic WEC design, a shortlist of target functions for different WEC components are proposed for the RiaSoR 2 load assessment reliability exercise. These are summarised in Table 12.

No.	Component	Type	DLC	Target Function	Code Checks
1	Hull	ULS	{6.1; 7.1}	Hull bending moment	$M_g - M^{ULS} > 0$
2	Hull	FLS	1.1	PTO connection shear force	$\ln(s_{FAT}) - \ln(L_{eq}) > 0$
3	Piston rod	ULS	{6.1; 7.1}	Piston force	$y_r A_c - F^{ULS} > 0$

Table 12 Shortlist of proposed target functions for the generic WEC

In Table 12, the following nomenclature is used:

M_g	[N.m]	Ultimate hull moment capacity, determined by critical buckling stress [23]
M^{ULS}	[N.m]	ULS characteristic value of the structural bending moment
s_{FAT}	[N]	Material fatigue strength[7] at N cycles
L_{eq}	[N]	DEL[8] at N cycles, counted over the connection component lifetime
y_r	[Pa]	Material yield strength of the piston rod
A_c	[m^2]	Cross-sectional area of the piston rod
F^{ULS}	[N]	ULS characteristic value of the axial force on the piston rod

The first proposed failure mode has its origin in the buckling of e.g. a hull girder. This failure mode may occur when the structural bending moment is higher than the ultimate hull girder moment capacity. As described in DNV Classification Notes Nº 30.6 and in [23], the hull girder moment capacity depends on a set of possible failure mechanisms, including e.g. buckling of the stiffeners, plate failure and overall buckling of the hull girder. In an attempt to

[7] The material fatigue strength can be interpreted as the maximum load range the material can survive for N cycles.

[8] The Damage Equivalent Load (DEL) is the load range at which N cycles produce a damage equivalent to all load cycles (with possibly different load ranges) counted over the lifetime of the component (via e.g. Rainflow cycle counting).

assess the reliability of the WEC hull with regard to buckling of the hull girder, a target function addressing ULS of the hull bending moment is proposed in Table 12.

The second proposed failure mode results from potential fatigue at the connection point between the hull and the PTO system. For this case, it is assumed that interfaces between components may be a source of weakness in the structural design. Moreover, it is expected that such interface would be subjected to significant fatigue loading from the cyclic translational motions of the PTO piston. As a result, a target function addressing FLS at the PTO connection joint is proposed in Table 12, via the quantification of the shear force at the PTO connection.

Finally, failure of an axially loaded steel truss is another possible failure mode identified in DNV Classification Notes Nº 30.6. A target function addressing ULS of the axial piston rod is proposed in Table 12. The variable identified to quantify the ULS of the axial piston rod is the piston force. The ULS load assessment is expected to increase the confidence in the design of the PTO piston.

5.3 Uncertainty Source Identification

As a first step in the P-VMEA and in an attempt to identify the uncertainty sources in the load assessment, a schematic summarising the numerical load assessment methodology is presented in Figure 14.

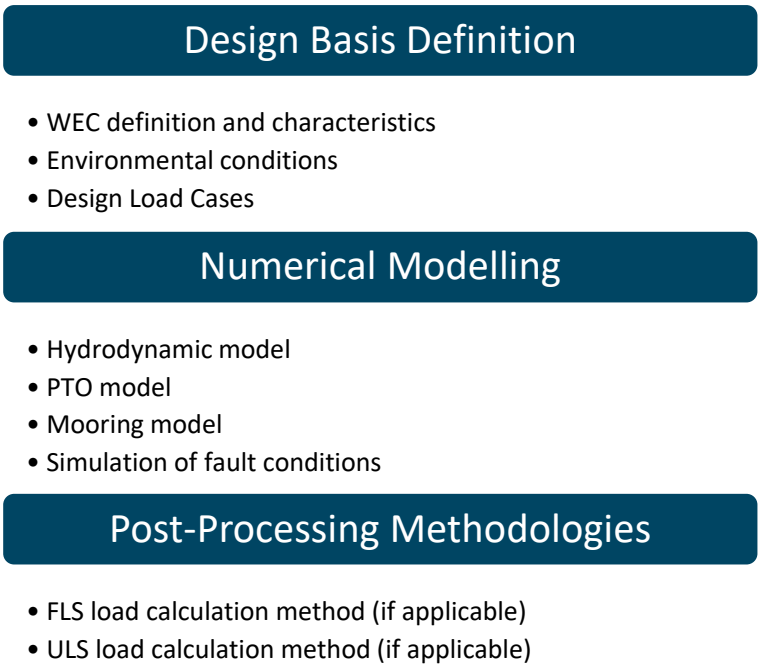

Figure 14 Outline of the proposed numerical load assessment methodology

The load estimation method was initiated with the definition of the design basis in Section 3. The design basis includes the characteristics of the generic WEC (e.g. working principle, PCC type), the identification of a target installation site and the selection of a shortlist of priority DLCs.

A numerical model of the proposed generic WEC will be built in WEC-Sim to estimate the WEC loads (see Section 4.2). The WEC-Sim model includes a range of numerical modelling assumptions that may introduce uncertainty into the load estimates. The derived loads will be post-processed to estimate the FLS / ULS for the respective target functions. Various post-processing approaches may be applied, which introduces another source of uncertainty into the load estimates for specific target functions.

It should be noted that a range of assumptions have been made for the purpose of the RiaSoR 2 numerical load assessment. A summary of some of the key assumptions is provided in Table 13. For clarity, the assumptions listed in Table 13 result in model simplifications that have been considered in RiaSoR 2.

Key Assumptions	
WEC definition	A generic WEC was defined using publicly available information. The WEC was scaled down to have characteristic dimensions (e.g. buoy diameter) similar to designs proposed by the WEC developers participating in the RiaSoR 2 project. The size of the WEC was not optimised for the proposed EMEC site. A passive control strategy will be applied in the WEC model for RiaSoR 2.
Environmental conditions	Additional environmental loads beyond the wave loads (from e.g. currents, wind, tidal heights) are not included in the definition of environmental conditions for the RiaSoR 2 exercise.
Design Load Cases	In practice, a full range of DLCs should be assessed in the WEC design process. For example, Appendix A provides a list of the target DLCs listed in [1]. For the purpose of the RiaSoR 2 exercise, a shortlist of DLCs have been prioritised for the reliability assessment exercise (see Table 7). The shortlisted DLCs aim to capture the dominant behaviour of the WEC in representative normal operating and extreme conditions.

Table 13 Key assumptions for the RiaSoR 2 numerical load assessment

A high-level assessment has been completed to identify possible sources of uncertainty in the RiaSoR 2 numerical load assessment. A summary of the uncertainty sources that have been identified is listed in Table 14. Details on how to quantify the sensitivity and uncertainty coefficients associated with each uncertainty source are provided in Section 5.4.

Source of Uncertainty	Description
Design Basis	
WEC mooring model	A detailed mooring arrangement is not defined in the generic WEC model. A linearised mooring model will be initially implemented (see Table 9). Nonlinear behaviour that may occur in some situations is not captured by a simplified mooring representation. A more complex model may therefore be considered for assessing the relative impact of changes to the moorings model.
Environmental conditions: data source	The environmental conditions at the target site will be derived using NOAA NCEP CFSR hindcasts, which contain 30 years of data (see Section 3.2.2). Other sources of environmental data include e.g. buoy measurements taken at a target site. Comparisons between the statistics associated with each data source can yield differences, potentially affecting the WEC design process.

Source of Uncertainty	Description
Environmental characterisation	An environmental characterisation is typically conducted to obtain specific environmental metrics to define the environmental conditions at the target site(s) (see Table 6). In relation to the methods illustrated in Figure 8, both sampling methods contain sufficient information to derive the long-term extreme loads acting on the generic WEC with specific return periods. However, the accuracy of one method compared to the other is unknown.
Influence of DLCs on the same target function	As presented in Table 12, multiple DLCs may be used to calculate the same target function. This introduces a potential uncertainty regarding the influence of specific DLCs on the target function(s).
Numerical Modelling	
Hydrodynamic formulation	In the FLS and ULS calculations, linear and weakly nonlinear formulations are available in WEC-Sim. These can be used to assess the relative impact of the using nonlinear formulations e.g. nonlinear hydrostatic restoring and Froude-Krylov forces when solving the WEC dynamics. CA notes that in the current WEC-Sim implementation diffraction and radiation forces are issued from a linear model.
Viscous forces	The estimation of viscous drag forces is based on the definition of a drag coefficient which needs to be estimated (see Section 4.2.2). The influence of the magnitude of the coefficient itself can be assessed.
Slap and slam forces	Slap and slam forces on the WEC are not considered as a default option in the WEC-Sim numerical model. CA custom modifications to WEC-Sim can be made to assess the influence of these additional load sources in specific events.
Calibration of PTO coefficients	Initial values have been assigned to the hydraulic PCC in the numerical model (see Table 5). The equivalent PTO damping coefficient, which depends on a number of parameters including piston area, motor displacement and generator damping has not been optimised for every sea state. Further calibration of these values may be conducted, and lead to variations in the resulting load profiles.
Fault conditions	The shortlist of priority DLCs include modelling a design situation with a fault. A variety of fault types, with different levels of severities could be considered.
Post-Processing Methodologies	
FLS post-processing methodology	WECs are subjected to variable amplitude loads that need to be processed into a form that can be used to estimate the FLS. The FLS post-processing methodology applies a Rainflow cycle counting algorithm. However, different algorithms and processing techniques can be applied, and their relative influences are unknown at the onset of the design process.
ULS post-processing methodology	The ULS post-processing methodology depends on the environmental characterisation approach adopted (i.e. contour approach or a full environmental characterisation, see *Environmental characterisation* above). Different extreme value distributions can also be applied. Their relative influences are unknown at the onset of the design process.

Table 14 Summary of uncertainty sources in the numerical load assessment

5.4 Sensitivity and Uncertainty Size Assessment

The RiaSoR 2 load assessment reliability exercise will investigate methods of quantifying the size of identified uncertainties using the WEC-Sim model described in Section 4.2. A high-level description of possible methods to quantify the amplitude of variations related to the uncertainty sources (namely the c_i, s_i and t_i coefficients) identified in Section 5.3 is presented in Table 15.

The approach proposed in WP3 is to complete a baseline simulation for each target function listed in Table 12. An uncertainty / sensitivity assessment will be subsequently conducted for each source of uncertainty identified, as proposed in Table 15.

Source of Uncertainty	Proposed Quantification Method
Design Basis	
WEC mooring model	As an initial assumption, a simplified mooring arrangement is implemented in the generic WEC model. A sensitivity study on the values of the linear mooring stiffness coefficients (see Table 9) can be carried out to assess the impact of the mooring arrangement on the output load estimates. A more detailed mooring modelling approach may also be applied in the WEC-Sim model.
Environmental conditions: data source	The uncertainties associated with the source of the site scatter diagram (e.g. measured or hindcast) can be assessed by analysing the impact of deviations in the reference scatter diagram. The reference data source for the model environmental conditions at the target site is the NOAA NCEP CFSR hindcasts. EMEC have also provided a scatter diagram for the Billia Croo site from 10 years of measurements. • A comparative study using the measured and hindcast scatter diagrams will be conducted to investigate potential uncertainty associated with data sources used to describe target WEC deployment site.
Environmental characterisation	At a high-level, two environmental characterisation methods (see Figure 8) are available: • A contour approach that is based on the simulation of a limited number of sea states along the 1-year environmental contour, then fitted with an appropriate short-term extreme value distribution. The ULS characteristic value is identified as a certain percentile of this distribution. • A full environmental characterisation that is based on the simulation of a large number of samples within the 100-year contour area, followed by the calculation of a survival function. In order to quantify the amplitude of variations related to the application of different methodologies, simulations will be conducted for both of the methods described above. To further investigate the uncertainty / sensitivity of target functions to the environmental conditions, the following approaches may be considered: • Simulations could be conducted for sea states with varying significant wave height; period; spectral shape and / or wave heading to identify the impact of changes in the input environmental conditions on the shortlisted target functions.

	• Changes in the overall distribution of occurrences could be mimicked to investigate the potential impact of changes in the site scatter diagram on the FLS target function.
Influence of DLCs on the same target function	Two DLCs (6.1 and 7.1) will be simulated for target function #1 and # 3 (see Table 12). The results from these DLCs will be compared to assess the influence of different DLCs on the same target function.
Numerical Modelling	
Hydrodynamic formulation	Simulations with a linear hydrodynamic formulation will be repeated with an enhanced formulation (including e.g. weakly nonlinear corrections from WEC-Sim) to assess and quantify the amplitude of variations related to varying hydrodynamic formulations.
Viscous forces	Simulations with alternative drag coefficients will be conducted to quantify the amplitude of variations related to changes in the viscous forces applied in the numerical model.
Slap and slam forces	For ULS estimates, a slap and slam empirical correction will be included to quantify the amplitude of variations related to the inclusion of these additional load sources. A confidence interval for the correction factor, which can be translated to a standard deviation, may also be appropriate and will be considered.
Calibration of PTO coefficients	Simulations with alternative PTO coefficients (e.g. motor friction, valve discharge) will be conducted to quantify the amplitude of variations related to changes in the calibration of the PTO in the numerical model. The equivalent PTO damping coefficient, which depends on a number of parameters including piston area, motor displacement and generator damping (i.e. slope of the generator torque vs. speed characteristic) can be used to quantify the amplitude of variations related this variable.
Fault conditions	Various PTO faults, with different levels of severity, can be considered for DLC 7.1 to quantify the amplitude of variations related to the simulations of fault conditions.
Post-Processing Methodologies	
FLS post-processing methodology	Alternative algorithms to assess the fatigue loads may be used to post-process the load results from the WEC-Sim numerical model. For example, varying cycle counting algorithms may be tested to quantify the amplitude of variations related the application of different methodologies.
ULS post-processing methodology	In order to quantify the amplitude of variations related to the application of different ULS post-processing methodologies, various extreme value analysis methods will be applied to derive comparable numerical load estimates.

Table 15 Summary of uncertainty sources and proposed quantification methods

5.5 Total Numerical Load Uncertainty Calculation

With the uncertainty sources identified and the c_i, s_i and t_i coefficients quantified following the studies proposed in Section 5.4, the total load uncertainty associated with the three target functions listed in Table 12 can be estimated.

As described in Section 2.2.1, P-VMEA is a first-order second moment method that uses the expected value of the target function as well as the dispersion of its variables in order to assess the reliability of the target WEC component. The approach is based on the statistical

property (see e.g. [2]) that the variance of the sum of two random variables can be approximated by the sum of the variance of those two variables (under the assumption that covariance of the variables can be neglected), i.e. $Var[X_1 + X_2] \approx Var[X_1] + Var[X_2]$.

This property can be generalised to several variables, which means that the final variance of the target function can be obtained by a quadratic summation of the variance resulting from each uncertainty source.

In RiaSoR I [2], a template VMEA spreadsheet was provided to combine the coefficients (c_i, s_i and t_i) of the distinct uncertainty sources into a total uncertainty for a specified target function. The total uncertainty, denoted τ, was obtained by calculating the root sum of square (RMS) of each uncertainty source:

$$\tau = \sqrt{\sum_i (c_i s_i t_i)^2}$$

Examples of the VMEA spreadsheet, which were updated for the proposed numerical reliability assessment of the load calculations, are presented in Figure 15 (for a ULS related target function) and Figure 16 (for the FLS related target function).

Input: E.g. Target Function 1 (ULS) - Hull bending moment						Result		
Uncertainty components	scatter	uncert.	Sensitivity coefficient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Load								
WEC characteristic: Mooring arrangement								
Environmental conditions: Data source								
Influence of DLCs on the same target function								
Hydrodynamic formulation								
Viscous forces								
Slap and slam forces								
Calibration of PTO coefficients								
Fault conditions								
ULS post-processing methodology								
Total numerical load uncertainty						0.000	0.000	0.000

Figure 15 Example of a VMEA spreadsheet for the reliability assessment of a ULS related target function

Input: E.g. Target Function 2 (FLS) - PTO connection shear force						Result		
Uncertainty components	scatter	uncert.	Sensitivity coefficient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Load								
WEC characteristic: Mooring arrangement								
Environmental conditions: Data source								
Hydrodynamic formulation								
Viscous forces								
Calibration of PTO coefficients								
FLS post-processing methodology								
Total numerical load uncertainty						0.000	0.000	0.000

Figure 16 Example of a VMEA spreadsheet for the reliability assessment of a FLS related target function

6 Next Steps

This report outlines the specifications of the load assessment numerical exercise proposed in RiaSoR 2, to support the development of the load assessment reliability toolbox.

A design basis was created for the load assessment exercise in WP3, including the definition of a generic WEC design, environmental conditions and a shortlist of DLCs. An outline of the numerical loads modelling exercise, including the WEC model description and setup of the generic WEC, is also provided. Finally, the approach proposed to integrate the numerical load model outputs and the P-VMEA methodology is detailed, forming the basis for the development of the load assessment reliability toolbox.

Following the completion of the outline load assessment numerical tool specification, the next steps in WP3 of the RiaSoR 2 project include:

i. Simulation of the shortlisted target functions for the generic WEC using the baseline modelling approach and initial assumptions. The investigations shall allow the estimation of baseline results for the shortlisted target functions.
ii. Simulation of load analysis model combinations to quantify the size of the identified uncertainty sources and the sensitivity of target functions to sources of uncertainty.
iii. Combination of all load uncertainty sources in the RiaSoR I VMEA spreadsheet to obtain the value of the total load uncertainty for each target function.
iv. Within the development of WP3, a user-manual for the proposed load assessment reliability toolbox, which will present the shortlisted target functions as case studies, will be compiled in D3.2 (Month 18).
v. Procedures to verify the methodology will be suggested and potentially investigated in D3.3 (Month 24). CA notes that the validation of the toolbox may only be carried out if sufficient data from is available, in the timeframe of the RiaSoR 2 project.

Abbreviations and definitions

Abbreviation	Definition
BEM	Boundary Element Method
CMS	Condition Monitoring System
DEL	Damage Equivalent Load
DLC	Design Load Case
DoF	Degrees of Freedom
ESS	Extreme Sea State
FLS	Fatigue Limit State
FMEA	Failure Mode and Effect Analysis
NSS	Normal Sea State
PCC	Power conversion Chain
PTO	Power Take-Off
RiaSoR I	Reliability in a Sea of Risk, finalized project
RiaSoR II	Reliability in a Sea of Risk, this project
TRL	Technological Readiness Level
ULS	Ultimate Limit State
VMEA	Variation Mode and Effect Analysis
WEC	Wave Energy Converter

Table 16 Abbreviations and definitions

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Appendix A: List of Design Load Cases

An extensive list of Design Load Cases is proposed in [1] and replicated in Table 17, for convenience. The following abbreviations are used in Table 17:

NSS	Normal Operational Sea States
RNSS	Reduced Range Normal Operational Sea States
RW	Regular Waves
FWG	Focused Wave Group
ESS	Extreme Operational Sea States
H_{s1}	Significant wave height with a recurrence period of 1 y
H_{s50}	Significant wave height with a recurrence period of 50 y
H_{s_T}	Significant wave height for transport
NCM	Normal Current Model
MCD	Multiple Current Directions

Design situation	DLC	Wave conditions	PTO conditions	Other conditions
1. Power Production	1.1	*NSS*	*Power Production*	NCM
	1.2	*RNSS*		NCM MCD
	1.3	*RNSS*		Range of spectral shapes, including bimodal seas
	1.4	*FWG*		
	1.5	*FWG*		Grid Loss
	1.6	*RNSS*		Marine growth or freeboard ice accumulation
2. Power production plus occurrence of fault	2.1	*RW* *FWG*	*Power Production*	Fault in control system(s)
	2.2	*RW* *FWG*		Fault in safety system or preceding internal electrical fault
	2.3	*RW* *FWG*		Fault in the control or safety system(s)
3. Start-up	3.1	*RNSS*	*Start-up Procedure*	
4. Normal shut-down	4.1	*FWG*	*Normal Shutdown Procedure*	Vary shut-down time to different points during the wave group
	4.2	H_{s1}		
5. Emergency shut-down	5.1	*FWG*	*Power Production*	
6. Parked (standstill or idling)	6.1	*ESS* - H_{s1}	*Parked*	NCM
	6.2	*ESS* - H_{s50}		Tide height/current due to storm surge
	6.3	*ESS* - H_{s50}		Grid loss
	6.4	*NSS*		
7. Parked plus fault conditions	7.1	*ESS* - H_{s1}	*Parked*	Fault condition
	7.2	*ESS* - H_{s50}		
	7.3	*NSS*		
8. Transport, installation, maintenance and repair	8.1	*NSS* - H_{s_T}	*Transportation configuration*	To be specified by manufacturer (transport / tow)
	8.2	*RNSS*	*Installation configuration*	To be specified by manufacturer (installation / removal)
	8.3	*RNSS*	*Maintenance configuration*	To be specified by manufacturer (including tidal currents where applicable)
	8.4	*RNSS*	*Maintenance configuration*	Absence of grid for long period
	8.5	*NSS* - H_{s_T}	*Maintenance configuration*	Collision with transport or installation vessels
	8.6	*ESS* - H_{s1}	*Locked in maintenance configuration*	

Design situation	DLC	Wave conditions	PTO conditions	Other conditions
9. Accidental / Abnormal Events	9.1	*RW*	*Power Production*	Ship impact
	9.2	*RW*		Ice impact
	9.3	*Tsunami due to earthquake/ cyclone*	*Controller in survival mode (if this can be done remotely) Otherwise: Power Production*	
	9.4	*NSS*	*Power Production*	Varying ground conditions
10. Damaged stability	10.1	*NSS*	*Power Production*	Transient condition between intact and redundancy check condition
	10.2	*NSS*		Single mooring line failure, redundancy check.
	10.3	*NSS*		Leakage (damaged stability)
	10.4	*ESS - H_{s50}*	*Parked*	Transient condition between intact and redundancy check condition
	10.5	*ESS - H_{s50}*		Single mooring line break, redundancy check
	10.6	*ESS - H_{s50}*		Leakage (damage stability)

Table 17 Reference design load cases (DLCs) [1]

RiaSoR 2

RELIABILITY IN A SEA OF RISK

RiaSoR 2 project partners

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RiaSoR 2 is funded under OCEANERA-NET in association with the Swedish Energy Agency and Highlands and Islands Enterprise

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