Quantification of load uncertainties in the design process of a WEC

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Abstract—**This paper provides an overview of a study completed which aims to increase WEC system reliability by using numerical tools to quantify load uncertainties at an early stage of the wave energy converter (WEC) design process. A case study that applies the variation mode and effects analysis (VMEA) methodology to a load assessment exercise for a reference WEC is presented. A first step in the methodology is the identification of uncertainty sources in the load assessment, considering the design basis definition, the numerical modelling approach and the post-processing methodologies applied. Simulations were conducted in WEC-Sim for a wide range of scenarios with the aim of quantifying the identified sources of uncertainty. Results from the case study presented indicate that the post-processing methodology applied when deriving ultimate limit state (ULS) metric can be responsible for a high degree of uncertainty in the ULS results. In future work, it is recommended that additional investigations are conducted to assess methods of identifying the most appropriate extreme value distribution to apply (e.g. through a goodness-of-fit parameter). This study was conducted as part of the RiaSoR 2 project.**

Keywords—**Concept design, load analysis, numerical modelling, reliability, uncertainty, wave energy converter (WEC).**

I. Introduction

RELIABILITY has been identified as a key issue for the successful development of the marine energy sector. The RiaSoR (Reliability in a Sea of Risk) project addresses the strategic industrial need for guidance in reliability design. 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. The RiaSoR 1 project developed a reliability framework, building on established practices from the automotive industry, by implementing and adapting the variation mode and effects analysis (VMEA) methodology to ocean energy applications [1]. In RiaSoR I, an extensive review of reliability assessment methodologies was conducted (e.g. Table II), leading to a reliability guidance document for marine energy converters [1]. The VMEA methodology has already been successfully implemented to study fatigue design and maintenance in the automotive [2] and aeronautical industries [3]. It builds on a failure mode and effect analysis (FMEA) approach, which is a qualitative process 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 causes them [4]. Consequently, VMEA was conceived to assess the robustness of a design against multiple sources of variation.

The RiaSoR 2 project builds on the theoretical framework developed in RiaSoR 1, aiming to develop methodologies that enable optimal reliability and performance of wave energy converters (WECs), while minimising cost and time-to-market. Under RiaSoR 2, the project team aims to apply the VMEA methodology to the WEC design process [5]. The application of the VMEA methodology in combination with a numerical load analysis tool provides a methodology to quantify load uncertainties at a preliminary design stage. Developers could use this information to assess the reliability of critical WEC components from an early-stage, incorporating such information in an iterative design approach.

This paper describes the integration of the VMEA methodology in the WEC design process under the RiaSoR 2 project. Firstly, a design basis was developed to establish baseline conditions for a preliminary numerical load assessment. A reference generic WEC design was used, along with a high-level definition of environmental conditions and design situations that may be experienced during the lifetime of a WEC. A model of the WEC was developed in WEC-Sim, which was used to generate load estimates for a shortlist of design load cases (DLCs). Secondly, a probabilistic VMEA process was applied. The

Paper number ID 1332 track SMM. This work was completed under the RiaSoR 2 project. The RiaSoR 2 project has received funding under OCEANERA-NET in association with the Swedish Energy Agency and Highlands and Islands Enterprise.

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initial steps in the process included the definition of a target function to be assessed, and the identification of uncertainty sources related to the target function (e.g. design basis inputs, numerical modelling assumptions, post-processing methodologies applied). Following the identification of relevant uncertainty sources, a sensitivity and uncertainty size assessment was conducted using load estimates obtained via WEC-Sim. The impact of univariate changes of each uncertainty source on the target function was assessed, and the dispersion in the load estimates associated with each uncertainty source was quantified. Thirdly, the results from the numerical sensitivity and uncertainty size assessment were input into the VMEA template developed in RiaSoR 1 to calculate the total load uncertainty.

In summary, this paper aims to provide both an overview of activities conducted under the RiaSoR 2 project, more specifically the application of the VMEA methodology to assess the uncertainty associated with numerical estimates of dominant WEC loads at a preliminary design stage, and general guidance to stakeholders that wish to follow a similar load uncertainty assessment approach when tackling WEC design.

II. DESIGN BASIS

A. *The case study WEC model*

The WEC analysed in this study 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 generic WEC is based on the RM3 WEC concept that was introduced in the Reference Model Project by Sandia National Laboratories [6]. A schematic of the full-scale RM3 WEC is provided in Fig. 1.

The WEC model analysed in this study is a scaled version of the RM3. The geometry and mass properties of the generic WEC model were derived from [7] and scaled down to meet a target float diameter of 10m and draft of 15m. The mass of the float is 90.5t and the mass of the spar buoy is 191.0t. 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.

The WEC model 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 [8]. 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 hydraulic 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 (see [5] for further details).

B. *Environmental conditions*

Site conditions representative of the Billia Croo wave energy test site at the European Marine Energy Centre (EMEC) off the west coast of Orkney were selected as the reference conditions for this study.

To define the long-term representative conditions at the site, data from the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) hindcasts was processed. Fig. 2 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 the Billia Croo test site is 59N, 3.467W, and the water depth at this location is estimated to be

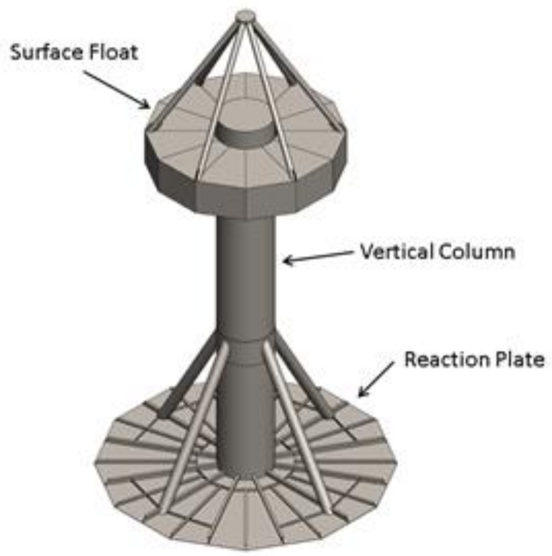

Fig. 1. Schematic of RM3 WEC model (full-scale) [6].

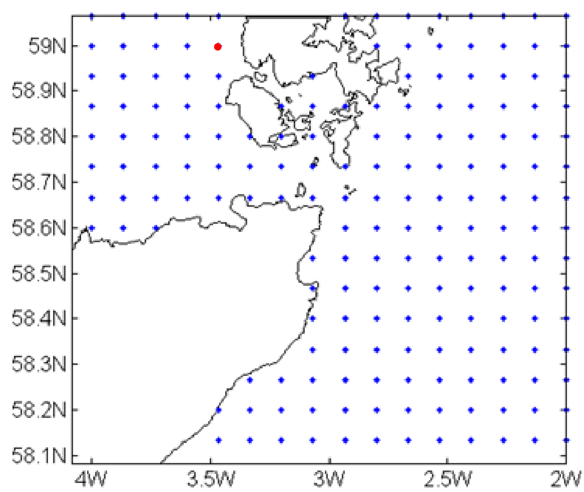

Fig. 2. Metocean data point locations for the North Sea Grid (4min) around the Orkney Islands. The selected data point (59N, 3.467W) is indicated in red [9].

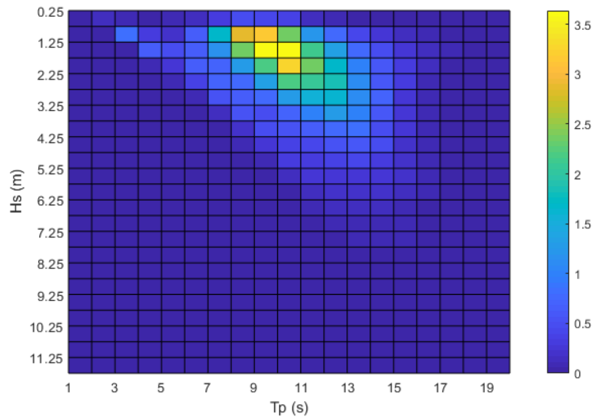

Fig. 3. Probability of occurrence (%) for reference site (59N, 3.467W, North Sea 4 min grid, Jan 1979 – Dec 2009) [9].

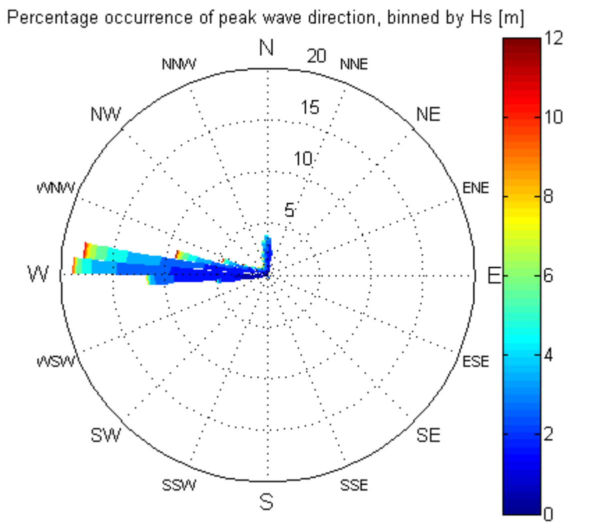

Fig. 4. Directional wave spectra for reference site (59N, 3.467W, North Sea 4 min grid, Jan 1979 – Dec 2009) [9].

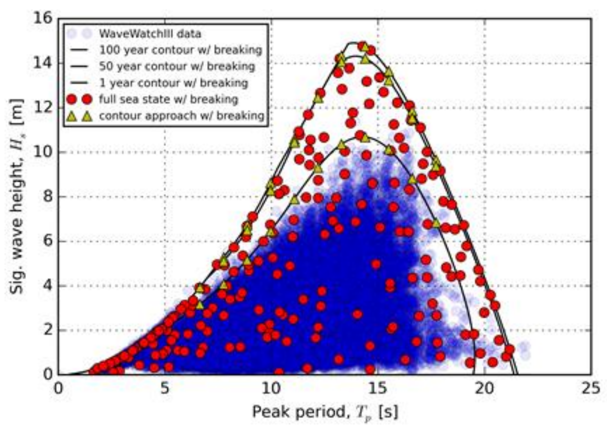

Fig. 5. Environmental characterisation for reference site (59N, 3.467W, North Sea 4min grid, Jan 1979 – Dec 2009) [9].

approximately 50m. A scatter diagram based on measured data for a 10-year period was also provided by EMEC.

The data covers a 30-year period between January 1979 and December 2009. Each data point contains 3-hour averages of significant wave height, H_s, peak period, T_p, peak direction, D_p, and 10m (above mean sea level) wind speed and direction. This data was reorganised to define the wave conditions at the reference site, including:

- Probability of occurrence of H_s, T_p pairs (Fig. 3)
- Directional wave spectra (Fig. 4)
- Environmental contours (yellow triangles) and sample points for a full environmental characterisation (red dots) (Fig. 5)

Table I presents the environmental conditions defined at the reference site. The following notes apply to environmental conditions:

- The range of H_s, T_p combinations considered for both normal sea states (*NSS*) and extreme sea states (*ESS*) is restricted by the wave breaking criteria.
- The directional wave data at the reference site shows the predominance of a westerly swell with a narrow spread. Due to the axisymmetric nature of the generic WEC body, a single mean wave direction is considered as an initial assumption.
- A standard spectral shape (JONSWAP) is assumed for all H_s, T_p combinations.

C. *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, a range of design situations were proposed in [10] (e.g. power production, parked, start-up, shut-down).

The design situations considered in the RiaSoR 2 project include power production and parked/survival

TABLE I
ENVIRONMENTAL CONDITIONS DEFINED AT THE REFERENCE SITE [9]

Environmental condition	Target values		Notes
Normal Sea State (NSS)	H_s (m) [0.75: 0.5: 5.75] T_p (s) [4: 1: 16]		[Start value: Step: End value] 143 sea states evaluated (94% of occurrence).
	H_s (m)	T_p (s)	
Extreme Sea State (ESS) H_{s1}	3.17	6.64	Sea states selected from the 1-year environmental contour.
	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	

conditions. In principle, the component conditions and other machine settings that lead to the highest loads should be selected for each design situation. In the RiaSoR 2 load assessment, power take-off (PTO) and other machine settings were defined to create a baseline numerical model setup.

A global description of DLCs as a function of environmental conditions and relevant design situations is proposed in [10]. In the case study presented, the ultimate limit state (ULS) is investigated for the selected target function, corresponding to design load case (DLC) 6.1 in [10]. However, it is noted that due to the absence of a parked specification for the reference WEC the baseline PTO model settings are applied (see [5] for details on the PTO settings).

D. WEC-Sim model

A model of the reference WEC was developed in WEC-Sim. WEC-Sim (Wave Energy Converter SIMulator) [11] is an open-source WEC simulation tool developed in MATLAB/Simulink using the multi-body dynamics solver SimMechanics. 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 can model WECs that involve rigid bodies, PTO and mooring subsystems. The relative position of each body is defined by the location of their centre of gravity in 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 Fig. 6.

A brief description of the WEC model subsystems is provided below (see [5] for further details). Hydrodynamic loads and pressures acting on the WEC were derived from first-order potential flow theory, using hydrodynamic coefficients derived in the NEMOH boundary element method (BEM) solver. Best practices were applied to determine the mesh size and the resolution of the hydrodynamic data by checking the coherence and consistency of the output coefficients for multiple mesh refinements. To model the impact of the model heave plate on the WEC dynamics, drag forces acting on the WEC were estimated and included in the equation of motion using a Morison based quadratic term. The translational PTO constraints in the reference WEC allow a relative vertical motion between the WEC prime mover and the spar buoy (i.e. along the spar axis). The PTO system is based on a hydraulic PCC, which converts the relative translational motion between the prime mover and the spar buoy into power (see II A.). A simplified mooring system was also implemented in the baseline model, consisting of a stiffness matrix to model forces applied at a user-defined location on the floating body.

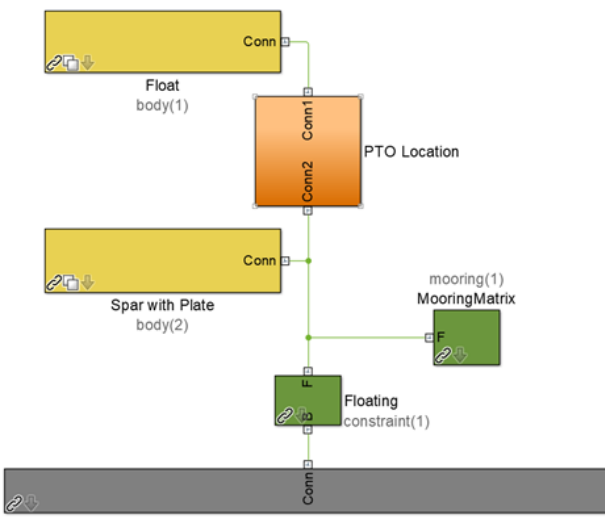

Fig. 6. Simulink structure of the WEC model [5].

Simulations were 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. The WEC-Sim model was used to estimate loads, and combinations of simulations were run to identify key load uncertainty sources (see IV).

E. Extreme value analysis

The output results from WEC-Sim were subsequently post-processed to derive ULS estimates for the respective target functions. An extreme response analysis was conducted to estimate the ULS for specific long-term, return periods. The ULS post-processing methodology depends on the environmental characterisation approach adopted. At a high-level, two environmental characterisation methods are available for the analysis:

- A contour approach based on the simulation of a limited number of sea states along the 1-year environmental contour. The results are then fitted with an appropriate short-term extreme value distribution. The ULS characteristic value is identified as a certain percentile of this short-term extreme value distribution.
- A full environmental characterisation based on the simulation of a large number of samples within e.g. the 100-year contour area, followed by the calculation of a survival function.

In addition to the environmental characterisation approach, different types extreme value distributions were also applied (e.g. Gumbel, Weibull). The WEC design response toolbox (WDRT) developed by SNL and NREL [12] was modified to apply the ULS post-processing methodologies.

III. Uncertainty Assessment Methodology

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 – covering design and operational stages. However, the level of accuracy of VMEA will depend on the level of

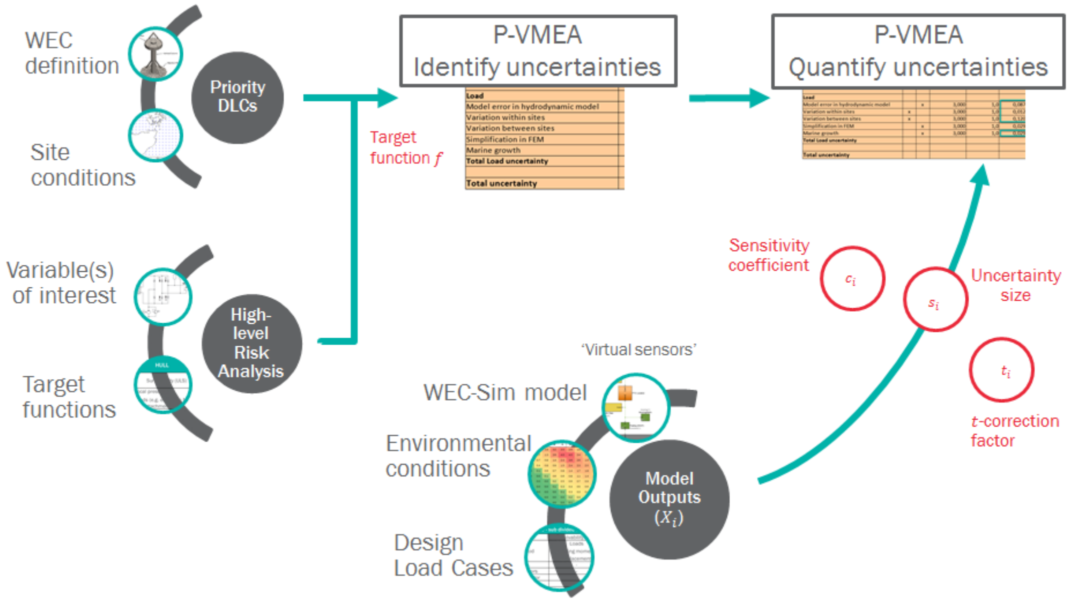

Fig. 7. Flow chart illustrating the integration of the numerical model load uncertainties in the P-VMEA [5].

TABLE II
OVERVIEW OF THE BASIC, ENHANCED AND PROBABILISTIC VMEA APPROACHES (BASED ON INFORMATION FROM [1])

Basic VMEA ([13], [14])	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. • The Basic VMEA gives a qualitative judgement which can be used for comparisons but cannot be related to failure probabilities. • In RiaSoR I, the application of the basic VMEA is presented in the context of a concept design phase.
Enhanced VMEA ([15])	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) ([3], [15])	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.

knowledge of the technology that is assessed, which is expected to progress as a technology matures. As a result, three types of VMEA were proposed in RiaSoR I; a basic, an enhanced and a probabilistic version. Table II provides a brief description of the three VMEA approaches from RiaSoR I.

The P-VMEA approach was applied in the current study to assess the uncertainty associated with numerical estimates of dominant WEC loads (see Fig. 7). The analysis provides a quantitative indication of the uncertainty associated with characteristic load calculation exercises, which may assist in the WEC design process. The use of a numerical modelling tool supports the WEC uncertainty assessment by quantifying the level of variations for distinct sources of uncertainty in the load calculations.

There are a number of different steps involved in the P-VMEA process to quantify the numerical load uncertainty. These are described in the following subsections (for further information see also [5]).

A. *Target function definition*

The process is initiated with the identification and selection of the specific variable and target function to be assessed. 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 should be assessed via the study of limit states. 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.

The variables output by the WEC-Sim model 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.

B. Uncertainty source identification and size assessment

The second step in the process focuses on listing potential sources of uncertainty that can affect the estimation of the target function(s) and the related variables. For example, a summary of the uncertainty sources identified in the case study is provided in Table V.

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 applying a correction factor (t_i), if necessary.

Finally, the estimated values from the previous steps (i.e. c_i , s_i and t_i) are input into the VMEA template developed in the RiaSoR I project to calculate the total load uncertainty [1] (see Table VII).

IV. Case Study Results

Results from the case study are presented in this section. The axial force acting on the piston rod of the WEC was selected for analysis, and the variable to be investigated is the ULS characteristic value of the axial force for a 50-year return period. A summary of the conditions for the worked example is provided in Table III.

The first step in the assessment was to define a baseline numerical model set-up for the reference WEC, from which a benchmark could be made. Details of the conditions assumed for the baseline design basis, numerical model setup and post processing methodology are presented in Table IV. A simulation of this baseline model setup was conducted to derive a base case value for the target variable (i.e. the ULS of the axial force on the piston rod for a 50-year return period). The base case value for the target variable was estimated at 2.287MN.

In the following steps, a pre-screening exercise was conducted to identify possible sources of uncertainty relevant to the estimation of the ULS characteristic value of the axial force on the piston rod.

TABLE III
CASE STUDY – OVERVIEW OF SELECTED TARGET COMPONENT, VARIABLE AND OTHER INPUT CONDITIONS [5]

Component	Piston rod
Variable	ULS characteristic value of the axial force (50-year return period)
Design load case	6.1
Code Check	$\gamma_r A_c - F^{ULS} > 0$

where, γ_r (Pa) is the material yield strength of the piston rod, A_c (m^2) is the cross-sectional area of the piston rod and F^{ULS} (N) is the ULS characteristics value of the axial force on the piston rod (50-year return period).

TABLE IV
BASELINE NUMERICAL MODEL SETUP AND POST-PROCESSING METHODOLOGY [5]

Category	Description
Environmental conditions: data sources	Calculated using 30-year hindcast data at the reference site
Environmental characterisation	ESS conditions: sea states selected from the 1-year contour
WEC mooring model	Mooring matrix applied K_m= K = 2.5 kN/m; C_m= 0 Ns/m
Hydrodynamic formulation	Linear formulation
Viscous forces	Body velocity approach. Drag coefficient: Float = [0 0 0 0 0 0] Heave plate = [0 0 4.5 4.5 4.5 0]
Inclusion of slap and slam forces	Not implemented
PTO coefficients	Baseline PTO setup (see [5])
ULS post-processing methodology	Short term extremes (Gumbel, positive peaks), 98%

TABLE V
IDENTIFIED UNCERTAINTY SOURCES AND PROPOSED VARIATION SCENARIOS [5]

Source of uncertainty	Proposed methods to quantify the amplitude of variation
Environmental conditions: data source	Environmental conditions at a target site could be derived using hindcasts or measured data sets of different durations. Scenarios will consider measured and hindcast data (of different durations) to investigate potential variations associated with data sources used to describe target deployment site. The following inputs will be simulated: • Divide the 30-year hindcast into three 10-year datasets (first, middle and last 10-years) • Use measured wave data provided by EMEC (10-years of data)
Environmental characterisation	An environmental characterisation aims to specify environmental metrics at a target site. Different methods are available to derive the long-term extreme loads with specific return periods. Scenarios will apply two environmental characterisation methods to quantify potential uncertainties related to the method of describing target site conditions: • A contour approach which is based on the simulation of a limited number of sea states along a 1-year environmental contour (using different wave phases). • A full environmental characterisation that is based on the simulation of many samples within a defined contour area.

TABLE V (CONTINUED)
IDENTIFIED UNCERTAINTY SOURCES AND PROPOSED VARIATION SCENARIOS [5]

Source of uncertainty	Proposed method(s) to quantify the amplitude of variation
WEC mooring model	A simplified linear mooring model is implemented in the baseline model. Scenarios will investigate: • Variations in values of the linear mooring stiffness coefficients. • Implementation of a more detailed mooring modelling approach using MoorDyn (3-lines).
Hydrodynamic formulation	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. instantaneous hydrostatic and Froude-Krylov forces when solving the WEC dynamics. Scenarios with enhanced formulations (e.g. weakly nonlinear corrections from WEC-Sim and higher order wave formulations) will be conducted to assess and quantify the amplitude of variations related to varying hydrodynamic formulations.
Viscous forces	The estimation of viscous drag forces is based on the definition of a drag coefficient which needs to be estimated. Scenarios will investigate: • Varying the drag coefficients of the float in WEC-Sim. • Varying the body velocity input in the drag force calculation.
Inclusion of slap and slam forces	Slap and slam forces on the WEC are not considered as a default option in the WEC-Sim model. Custom modifications to WEC-Sim can be made to assess the influence of these additional load sources in specific events. Scenarios investigated will consider the inclusion of slap and slam forces in the model.
PTO coefficients	Initial values have been assigned to the hydraulic PCC in the numerical model (see [5]). Further calibration of these values may lead to variations in the resulting load profiles. 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.
ULS post-processing methodology	In order to quantify the amplitude of variations related to the application of different ULS post-processing methods, various extreme value distributions will be applied to assess their impact on the ULS estimates.

TABLE VI
RESULTS FROM THE UNIVARIATE ANALYSIS EXERCISE

Category	Description	ULS axial force (MN)
Environmental conditions: data source	Hindcast model for EMEC (30yr data) - initial 10 years	2.227
	Hindcast model for EMEC (30yr data) - middle 10 years	2.333
	Hindcast model for EMEC (30yr data) - last 10 years	2.242
	EMEC measured data (10 years)	2.209
Environmental characterisation	Contour approach (1-year) (different wave phase to baseline)	2.359
	Full environmental characterisation	2.493
WEC mooring model	Mooring matrix variation: K_m= 0.5*K, C_m= 0	2.288
	Mooring matrix variation: K_m= 1.5*K, C_m= 0	2.286
	Mooring matrix variation: K_m= 0.5*K, C_m= 1.0	2.267
	Mooring matrix variation: K_m= 1.5*K, C_m= 1.0	2.288
	MoorDyn setup: 3 lines	2.249
Hydrodynamic formulation	Using nonlinear correction	2.101
	Using higher order wave formulations	2.199
Viscous forces	Drag coefficients: Float = [0.5 0 0.5 0 0.5 0] Heave plate = [0 0 4.5 4.5 4.5 0]	2.176
	Relative velocity approach. Drag coefficients: Float = [0 0 0 0 0 0] Heave plate = [0 0 4.5 4.5 4.5 0]	2.126
	Relative velocity approach. Drag coefficients: Float = [0.5 0 0.5 0 0.5 0] Heave plate = [0 0 4.5 4.5 4.5 0]	2.142
Inclusion of slap and slam forces	Correction implemented	2.256
	Correction implemented with different coefficient values	2.460
PTO coefficients	Check valve discharge coefficient: +5%	2.274
	Check valve discharge coefficient: -5%	2.280
	Piston area: +2%	2.313
	Piston area: -2%	2.237
	Piston bulk modulus: 0.01% air	2.509
	Piston bulk modulus: 0.1% air	2.611
	Hydraulic motor friction: +10%	2.290
	Hydraulic motor friction: -10%	2.285
ULS post-processing methodology	Extreme distribution: Gumbel (right sided) negative peaks	2.293
	Extreme distribution: Gumbel (left sided)	1.078
	Extreme distribution: Weibull	1.856
	Extreme distribution: Weibull tail fit	1.386

TABLE VII
VMEA SPREADSHEET FOR THE RELIABILITY ASSESSMENT OF THE ULS CHARACTERISTIC VALUE OF THE AXIAL FORCE ON THE PISTON ROD

Input: Target Function - (ULS) - Axial force on the piston rod						Result		
Load uncertainty sources	scatter	uncertainty	Sensitivity coefficient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Environmental conditions: Data source	x		1.000	1.000	0.022	0.022		
Environmental characterisation	x		1.000	1.000	0.046	0.046		
WEC mooring model		x	1.000	1.000	0.007		0.007	
Hydrodynamic formulation		x	1.000	1.000	0.041		0.041	
Viscous forces		x	1.000	1.000	0.032		0.032	
Inclusion of slap and slam forces		x	1.000	1.000	0.048		0.048	
PTO coefficients		x	1.000	1.000	0.056		0.056	
ULS post-processing methodology		x	1.000	1.000	0.237		0.237	
Total numerical load uncertainty						0.051	0.253	0.259

A range of scenarios were defined with the aim to quantify uncertainty considering different approaches and inputs to the baseline model inputs, numerical formulations and post-processing methodologies (see Table V).

A univariate analysis was subsequently completed, changing one variable (compared to the base case) at a time and running simulations for each scenario to re-calculate the ULS characteristic value of the axial force on the piston rod. The results from the univariate analysis are presented in Table VI.

In order to integrate the results from the univariate analysis with the VMEA, the standard deviation and sensitivity coefficient for each uncertainty sub-category were calculated following:

- The standard deviation s_i (in %) was estimated as the sample standard deviation of the sub-category (e.g. environmental characterisation), including the base case value, divided by the base case value.

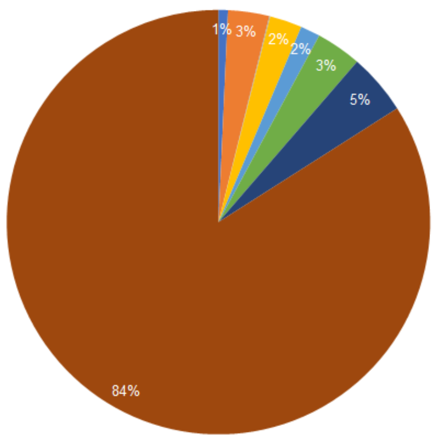

Fig. 8. Uncertainty results, percentage distribution of variance for each uncertainty sources, for the ULS characteristic value of the axial force on the piston rod.

- The sensitivity coefficient c_i assumes that simulated scenarios are judged to be representative of the possible variation around the "true" model. In this case, c_i equals unity, since the standard deviation refers directly to the variation in the target function.

The results from the uncertainty assessment are presented in the P-VMEA spreadsheet format in Table VII. The total load uncertainty calculated for the ULS characteristic value of the axial force on the piston rod for the reference WEC is estimated at 25.9%.

Fig. 8 illustrates the contribution from the different identified sources of uncertainty, presented in the sub-categories outlined in Table VI. The results show that the percentage distribution of variance associated with the ULS post-processing methodology (84%) is the largest contribution to the load uncertainty. This is followed in magnitude by variation due to the calibration of PTO coefficients (5%), the inclusion of slap and slam in the numerical model (3%) and the environmental characterisation method (3%). Most significantly, the results from this example highlight that the ULS post-processing methodology has the greatest influence on the target variable. It is noted that no explicit guidance is given in marine energy standards on extreme value analysis methodologies for WEC design (see Section V).

V. CONCLUSIONS AND POTENTIAL NEXT STEPS

This paper summarises work completed in the RiaSoR 2 project to integrate the VMEA methodology in the WEC design process. A case study that outlines the steps taken to quantify load uncertainties is presented, using the numerical modelling design tool WEC-Sim.

A design basis was created for the load assessment exercise, which included the definition of a reference WEC design and environmental conditions, the setup of a numerical model, and a description of the methodology applied to integrate load assessment outputs with the VMEA methodology.

In the case study presented, the results indicate that the ULS post-processing methodology has the greatest influence on the target variable. Current marine energy standards do not provide explicit guidance regarding extreme value analysis, namely on topics such as e.g. how to evaluate and judge the quality of a distribution fit, or the criteria to exclude data for poor quality distribution fits. In future work it is recommended that additional investigations are conducted to assess methods of identifying the most appropriate extreme value distribution to apply (e.g. through a goodness-of-fit parameter).

Potential next steps in the process of increasing the system reliability of a WEC may include the investigation of additional target variables and for a wider range of DLCs, covering both ultimate and fatigue limit states. Results from these additional assessments may be fed back into the design process, with the objective of further reducing uncertainty in the design process.

ACKNOWLEDGEMENT

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

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