THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Analysis of Fatigue Characteristics in Mooring Lines and Low Voltage Cables for Wave Energy Converters

SHUN-HAN YANG

Department of Shipping and Marine Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

Analysis of Fatigue Characteristics in Mooring Lines and Low Voltage Cables for Wave Energy Converters

SHUN-HAN YANG

ISSN 1652-9189
Report No 16:163

Department of Shipping and Marine Technology
Division of Marine Technology
Chalmers University of Technology
SE-412 96, Gothenburg
Sweden
Telephone: + 46 (0)31-772 1000

Printed by Chalmers Reproservice
Gothenburg, Sweden 2016

Analysis of Fatigue Characteristics in Mooring Lines and Low Voltage Cables for Wave Energy Converters

SHUN-HAN YANG
Department of Shipping and Marine Technology
Division of Marine Technology

Abstract

To reduce both carbon emission and fossil fuel consumption, there is a pressing need for the exploitation of renewable sources of energy such as biomass, hydropower, solar power, waves, and wind. This thesis addresses the application of wave energy, which has a large potential to contribute to the world's renewable emission-free energy supply. However, the challenge for current wave energy technology to make a commercial impact is to reduce its levelised cost of energy and, as part of this task, to ensure the long-term reliability and durability of the mooring lines and power cables used in wave energy converter (WEC) systems. This thesis contributes to the development of a numerical analysis procedure for assessing the fatigue characteristics of these mooring lines and power cables.

The main objective of this thesis is to develop a complete numerical analysis procedure for the assessment of mooring lines and power cables used in WEC systems. A WEC system consisting of a heaving-point-absorber WEC, a catenary mooring chain system, and a low voltage power cable was chosen as the subject of this case study. The numerical study was conducted based on a first-principles approach. The simulation methodology and analysis procedure consisted of a hydrodynamic and structural analysis, a stress and fatigue damage analysis, a parametric study, an energy performance analysis, and an assessment of the influence of biofouling on the WEC energy performance and the fatigue of the moorings and power cable.

Coupled and de-coupled simulation procedures were compared using DNV DeepC. It was found that the coupled procedure should be used to simulate the hydrodynamic and structural response of the WEC system to capture the coupling effect in the system. A stress-based rainflow counting fatigue analysis was developed, which enabled the identification of fatigue-critical locations along the mooring lines and power cable under varying environmental conditions. A fatigue-wave height-wave period matrix and a simulation matrix were designed as tools to visualise the fatigue damage to the mooring lines and power cable under various environmental conditions. In comparison with the biofouling-free condition, it was shown that biofouling on the WEC system can reduce the time-averaged power absorption of the WEC by up to 20% and reduce the fatigue life of the mooring lines by approximately 80%. Hence, it is recommended that biofouling is considered during the early stage of WEC system design. The influence of biofouling on the fatigue life of the power cable was found to be negligible. However, considering the long fatigue life calculated for the power cable, it was concluded that it is necessary to develop a more detailed model of the power cable.

Keywords: catenary mooring chain, coupled analysis, de-coupled analysis, dynamic cable, fatigue, heaving point absorber, low voltage cable, marine biofouling effect on absorbed power, marine biofouling effect on fatigue, mooring line, power absorption, power cable, wave energy converter.

Preface

This thesis comprises work conducted during the years of 2013 to 2016 in the Department of Shipping and Marine Technology at Chalmers University of Technology in Gothenburg, Sweden. The research work was performed as part of two projects funded by the Swedish Energy Agency, “Ocean Energy Centre – Durability analysis of cables and moorings used in systems for harvesting renewable ocean energy”, under contract No. 36357-1 during 2013-2015, and “R&D of dynamic low voltage cables between the buoy and floating hub in a marine energy system”, under contract No. 41240-1 during 2015-2017. Additionally, the thesis work was initiated with support from the former Ocean Energy Centre at Chalmers University of Technology.

I would like to express my gratitude to the companies nkt cables, Waves4Power, and SP Technical Research Institute of Sweden for providing me with a fantastic environment in which to explore my research topic. In no particular order, grateful acknowledgements are due to Mr. Ulf Lindelöf and Dr. Filip Alm at Waves4Power for valuable insight based on their industrial experience, Mr. Pierre Ingmarsson at SP Technical Research Institute of Sweden for sharing ideas and research opportunities, Mr. Göran Johansson at GVA-Consultants in Gothenburg for advice on developing the numerical model, Dr. Helge Skåtun at DNV GL for assistance with using DNV DeepC, and Mr. Claudio Bittencourt Ferreira at DNV GL for encouragement and friendly care.

I am forever grateful to my supervisor Professor Jonas Ringsberg and my co-supervisor Adjunct Professor Erland Johnson. Thank you for fruitful discussions, dedicated support, and most importantly, directing me on the right track. I also must express my gratitude to Professor Lars Bergdahl, Associate Professor Claes Eskilsson, Lic. Eng. Johannes Palm, Dr. Luis Felipe Sánchez-Heres, Associate Professor Lena Granghag, and Dinis Soares Reis de Oliveira at Chalmers University of Technology as well as Associate Professor Zhiqiang Hu at Shanghai Jiao Tong University for sharing your knowledge. Your assistance and support have helped me to perform this research with great enthusiasm.

I would also like to thank to my colleagues at the Department of Shipping and Marine Technology.

Thank you Nicole, Francesco, Vanesa, and Huong. You make me feel that Sweden is my second home.

Thank you Diana for being my friend in all stages of my life. I would also like to thank you for designing the cover figure for this thesis.

I especially would like to thank my boyfriend, Jeff, who is always there to listen, to help, and to make life joyful.

I would like to dedicate this thesis to my parents and my brother. Without your constant support, I would not be here to live for my dream.

Gothenburg, May 2016
Shun-Han Yang

Contents

List of appended papers

For each of the three appended papers, the author of this thesis contributed to the ideas presented, planned the paper with the co-authors, performed the numerical simulations, and wrote the majority of the manuscript.

Paper I Yang, S.-H., Ringsberg, J.W., Johnson, E., Hu, Z.Q., Palm, J. (2016). A comparison of coupled and de-coupled simulation procedures for the fatigue analysis of wave energy converter mooring lines. Ocean Engineering 117: 332-345. doi:10.1016/j.oceaneng.2016.03.018

Paper II Yang, S.-H., Ringsberg, J.W., Johnson, E. (2016). Parametric study of the dynamic motions and mechanical characteristics of power cables in wave energy converter array systems. *Submitted to the Journal of Marine Science and Technology. (Under review.)*

Paper III Yang, S.-H., Ringsberg, J.W., Johnson, E. (2016). The influence of biofouling on power capture and the fatigue life of mooring lines and power cables used in wave energy converters. *Submitted to the Second International Conference on Renewable Energies Offshore (RENEW2016) in Lisbon, Portugal, October 24-28, 2016.* 10 pp. *(Under review.)*

List of other published papers by the author

For each of the two papers listed below, the author of this thesis contributed to the ideas presented, planned the paper with the co-authors, performed the numerical simulations, and wrote the majority of the manuscript.

Paper A Yang, S.-H., Ringsberg, J.W., Johnson, E. (2014). Analysis of mooring lines for wave energy converters – A comparison of de-coupled and coupled simulation procedures. In: *Proceeding of the ASME 2014 Thirty-third International Conference on Ocean, Offshore and Arctic Engineering (OMAE2014) in San Francesco, California, USA, June 8-13, 2014.* OMAE2014-23377, 11 pp. (Presenting author.)

Paper B Yang, S.-H., Ringsberg, J.W., Johnson, E. (2015). Parametric study of the mechanical characteristics of power cables under dynamic motions. In: *Proceeding of the Eleventh European Wave and Tidal Energy Conference (EWTEC2015) in Nantes, France, September 6-11, 2015.* EWTEC2015-09D-5, 11 pp. (Presenting author.)

1 Introduction

In this chapter, the research background and motivation are presented, followed by the objective of the work.

1.1 Background and motivation

To reduce both carbon emission and fossil fuel consumption, there is a pressing need for renewable energy sources as all countries around the world seek to realise a sustainable energy policy. In Europe, the European Commission has set a goal of 20% total energy consumption from renewable sources by 2020 (European Commission, 2010), where such renewable sources include biomass, hydropower, solar power, tidal, waves, and wind, among others (European Commission, 2015).

Among the renewable energy alternatives, biomass and hydropower account for a significant share of Sweden's total energy production. In 2014, the total supplied energy was 555 TWh, of which biomass and hydropower contributed 23% and 12%, respectively (Swedish Energy Agency, 2016). However, additional renewable energy sources are needed to satisfy the Swedish energy policy, which targets a total changeover to renewable energy sources by 2050 (Gustavsson et al., 2011). According to the Swedish Society for Nature Conservation, the potential for wave energy production between 2020 and 2030 is approximately 10-34 TWh/year, growing from nearly zero in 2005 (Naturskyddsföreningen, 2012).

Renewable ocean energy sources can be utilised in various forms, such as offshore wind, wave, tidal, and ocean current energy. This thesis addresses the application of wave-based renewable energy, which has a large potential to contribute to the world's renewable emission-free energy supply. As presented by Barstow et al. (2008), the regions between the latitudes of 40° and 60° in both hemispheres, where Europe is located, are identified with the highest wave energy potential. The anticipated wave resources in Europe amount to 29500 TWh/year (Magagna et al., 2014), which is able to cover the net electricity generated in 28 countries in the European Union in 2013 (European Union, 2015). A similar prediction has also been calculated for the United States. The recoverable wave energy along the coastlines of the United States is on the order of 1000 TWh/year, which corresponds to approximately 1/3 of the total electricity consumption of the country (Jacobson, 2011).

In 2011, the Ocean Energy Centre (OEC) was founded at Chalmers University of Technology with the aim of supporting the development of methods and technologies for the harvesting of renewable ocean energy. According to a survey conducted by the OEC, the participating companies, including CorPower Ocean AB (2016), Minesto (2016), Ocean Harvesting Technologies AB (2016), Waves4Power (2016), and Vigor Wave Energy AB (2016), identified two major obstacles limiting the commercial impact of their technologies for extracting energy from the ocean and distributing it to shore: the insufficient mechanical service life of the mooring lines and power cables compared with the expected service life of the wave energy converter (WEC) device itself, and the lack of an established methodology to generate reliable predictions of the mechanical service life of the device components. The results of this survey and a recently initiated research programme by the Swedish Energy Agency on marine renewable energy served as the motivation for the current thesis project.

A comparison among the energy production costs of different energy sources can be performed based on their levelised costs of energy (LCOEs). The LCOEs of established energy technologies, such as biomass, coal, hydropower, nuclear power, and onshore wind power, range from 40 to 230 USD/MWh, whereas the LCOEs for current wave energy technologies range from 280 to 1100 USD/MWh (Salvatore, 2013). For wave energy to be profitable and competitive compared to other types of energy production, its LCOE must be reduced (Magagna et al., 2014). Gao et al. (2015) have further noted that to achieve this goal of reducing the LCOE, survivability under extreme wave conditions and long-term performance with respect to fatigue are particular challenges for the structural design of WECs and require further investigation. One reason for the high LCOE of wave energy is that the long-term operation and usage of WECs requires maintenance such as the removal of biofouling, the repair of ageing mechanical parts, and even the replacement of device components if they fail as a result of fatigue damage. Among all these concerns, failure due to fatigue damage is crucial and should be mitigated to reduce the LCOE to a competitive level. This issue also serves as a strong motivation for the research presented in this thesis.

1.2 Objective

The work presented in this thesis has been funded by the Swedish Energy Agency through two projects: “Ocean Energy Centre – Durability analysis of cables and moorings used in systems for harvesting renewable ocean energy”, Contract No. 36357-1, and “R&D of dynamic low voltage cables between the buoy and floating hub in a marine energy system”, Contract No. 41240-1. The first project, conducted between 2013 and 2015, focused on the development of a numerical tool for assessing the mechanical service life of mooring lines and power cables. In the second project (2015-2017), the focus is on a newly developed low voltage cable and its application in a WEC array farm. Consequently, the objectives and goals of the research presented in this thesis are closely related to those of these projects.

The main objective of the work presented in this thesis was to develop a complete numerical analysis procedure for the mooring lines and power cables used in WEC systems. Such an analysis should address the fatigue life assessments of the moorings and cables while providing high-level assessments of the performance of the WEC system, such as its energy performance; see Figure 1. From the motions and hydrodynamics of a simulated WEC to the estimation of energy performance, our research fills the investigative gaps throughout the entire assessment spectrum. A schematic overview of the three main research topics addressed in this thesis and the interactions among them is presented in Figure 1.

This main objective can be further divided into the following three sub-objectives:

G1. Compare different simulation procedures, leading to a recommendation for the study of the behaviour of WEC systems with regard to the initial fatigue design assessment of WEC mooring lines and power cables.

G2. By means of a parametric study, investigate the sensitivity of the predicted service lives of the mooring lines and power cables with regard to the environmental and design parameters. Moreover, identify the values or ranges of the environmental and design parameters that will result in long (fatigue) service lives of the mooring lines and power cables.

G3. Investigate the potential impact of biofouling on a WEC system, primarily with regard to the energy performance of the WEC and the fatigue life of the moorings and cable.

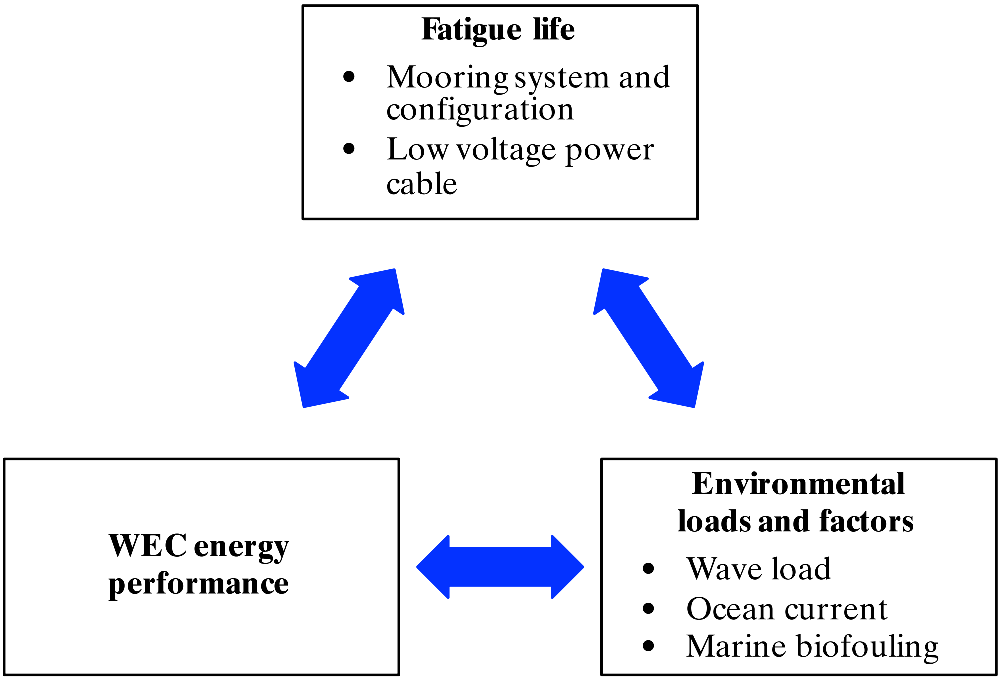

Figure 1. Interactions among the three main topics of this thesis: fatigue life analysis, energy performance analysis, and the influence of environmental loads and other factors.

1.3 Outline of the thesis

The outline of this thesis is as follows: Chapter 2 describes the methods used for the analyses presented in the thesis and the limitations of the research. This thesis is based on a brief summary of results drawn from the appended Papers I, II, and III, which is presented in Chapter 3. The conclusions of the thesis work are summarised in Chapter 4, followed by a proposal for future work in Chapter 5.

2 Numerical Model and Methodology

Because of the wide variety of different WEC concepts that have been proposed (150 types recorded in 2012 (Brennan et al., 2012)), numerical simulation methods are pivotal for the development of wave energy conversion technology for two reasons (Cruz, 2008). In the early stage, numerical simulations provide flexibility in assessing a large number of versions of a proposed technology with a relatively low marginal cost. In later development stages, numerical methods play a critical role in optimising the entire system and/or envisaging new generations of WEC systems. This chapter presents the numerical analyses and simulation models that were applied in this thesis project. An overview of the connections among the different analysis and assessment methods and the appended papers is presented in Figure 2.

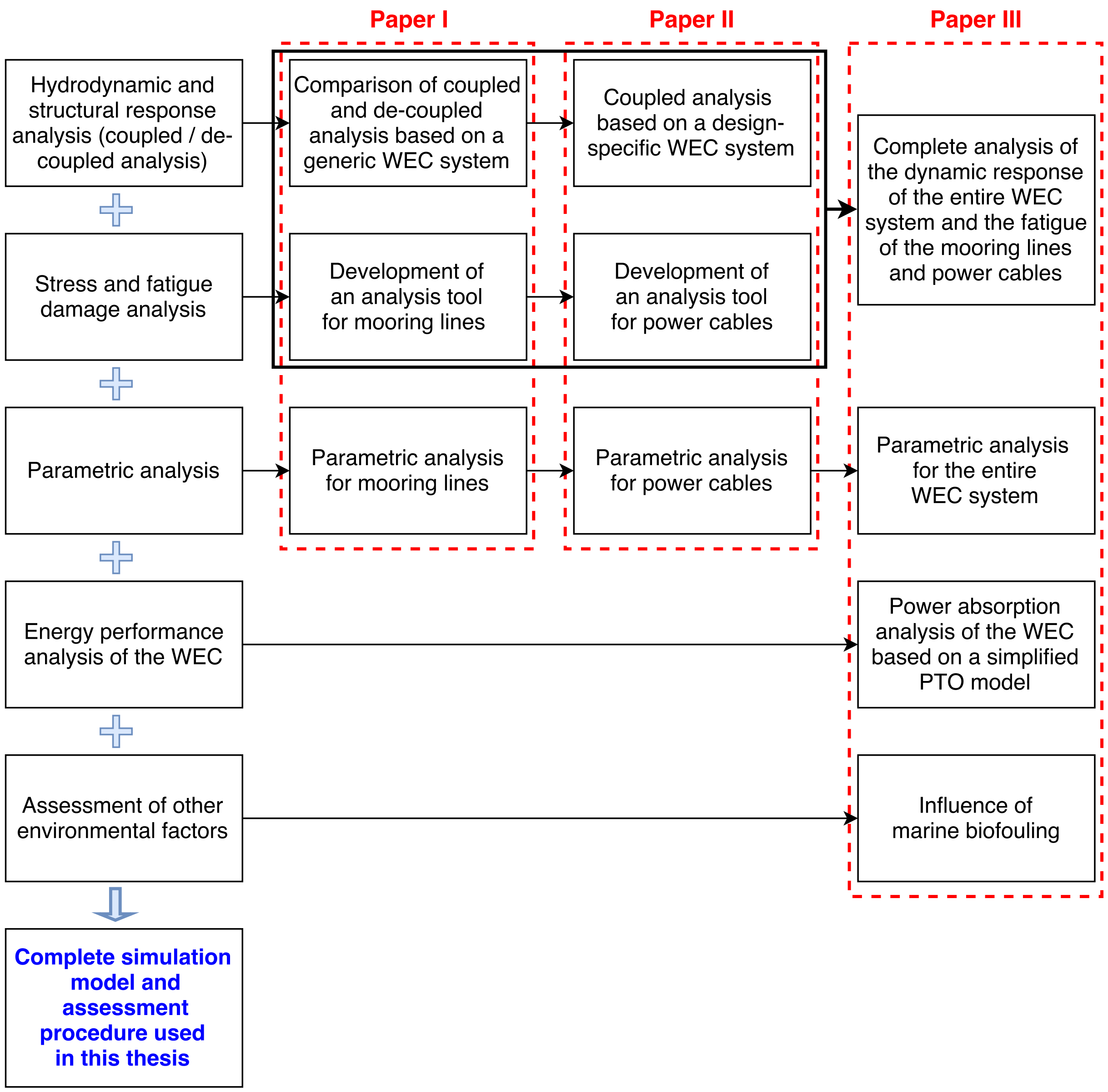

Figure 2. The connections between the numerical model and methodology described in Section 2 and the appended papers.

2.1 Numerical model of the WEC system

Figure 3 shows the schematic layout of the WEC system model studied in this thesis. The presented figure is taken from the appended Paper III, as this figure depicts the latest model considered in our research project. A WEC system is defined as the basic unit of a WEC array farm. The WEC system consists of a point-absorber-type WEC, a catenary mooring chain system, and a low voltage power cable that is connected to a stationary fixed power-collecting hub.

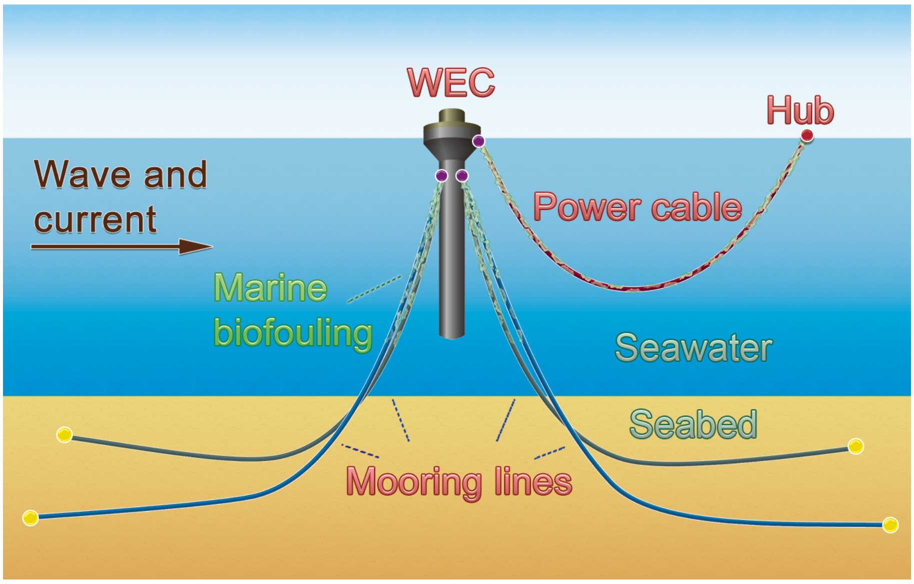

Figure 3. Schematic layout of the numerical model considered in this thesis (from Paper III).

The studies presented in the appended Papers I to III focused on an investigation of a point-absorber-type WEC. This type of WEC is able to exploit the more powerful wave regimes available in water depths of typically more than 40 metres (Fãlco, 2010). The WEC was modelled as a closed buoy with a given geometry and mass and a constant linear damping in the heave degree of freedom. This constant damping was used to incorporate a linear power take-off (PTO) into the model to capture the power absorption of the WEC.

The WEC floats freely in the seawater but is held in position by a mooring system that is anchored to the seabed. This thesis primarily considers a catenary mooring chain system, which consists of a number of mooring lines that are symmetrically attached around the outer rim of the WEC buoy (to fairleads on the WEC buoy).

The studied power cable is a low voltage power cable that has been recently developed by the company nkt cables (2016) and is currently being tested at the Runde test site in Norway (Runde Environmental Centre, 2016). The actual WEC buoy manufactured by Waves4Power (2016) and deployed at Runde is shown in Figure 4. In contrast to conventional submarine power cables (such as those described by Worzyk (2009)), the newly developed cable is specially designed with respect to two unique criteria. First, the electricity transmitted by this cable has a relatively low voltage of 1 kV because the electrical power generated by waves is typically low, on the order of 100 kW. Second, the cable is designed to hang freely in the seawater rather than to be in contact with the seabed. Hence, it is subject to motions and loads from the WEC, hub, waves, and currents and is therefore also called a "dynamic cable". In the following, this low voltage cable is simply referred to as the power cable.

Figure 4. Studied WEC buoy, designed by the Swedish company Waves4Power (2016).

The power cable carries the electricity from the WEC to a power-collecting hub. In a full WEC array farm, this hub collects the electricity from a number of WECs and then transmits it ashore. According to the original design for the studied WEC system, the hub is planned to be fixed at a stationary position in the seawater. Therefore, the hub was modelled as a fixed point in space.

The WEC system is exposed to external environmental loads induced by currents, waves, and winds. In addition, the seabed and seawater define the spatial boundaries of the system's movement. Hence, the currents, waves, seabed, and seawater were included in the numerical model; however, wind was excluded in the present investigation because it was assumed that the wind has a limited impact on the WEC system (see Section 2.3 for further discussion).

2.2 Method and software

Many studies have been reported in the literature in which the hydrodynamics, motion, and structural response of a WEC system and its fatigue life have been investigated. For example, Martinelli et al. (2012) proposed an iterative procedure that can be used in the verification phase of the design of a mooring system for a WEC. By means of a 1:20 scale model test of an oscillating water column WEC and a catenary spread mooring system, the proposed procedure was proved useful for capturing the motion and force response of the mooring system. Thies et al. (2012) assessed the fatigue life of a power cable used for a WEC. Using the prescribed motion of the WEC as measured in a 1:20 scale test, the motion and structural response of the cable were numerically simulated, and the fatigue life of the cable was then estimated based on the rainflow counting (RFC) method. Cerveira et al. (2013) modelled a point-absorber-type WEC with a catenary mooring chain system. The motion of the WEC system was simulated to estimate the power absorption of the WEC. In that paper, it was concluded that the catenary mooring chains have a negligible influence on the dynamics of the floating WEC and the captured wave energy. Langhamer et al. (2009) measured fouling assemblages on WEC buoys in the field. By calculating the response amplitude operators of a WEC buoy with and without biofouling mass, they concluded that the influence of marine biofouling is negligible with regard to the dynamic characteristics of a WEC buoy.

Table 1 summarises the various analyses that have been addressed through simulations in the literature. The various references are compared against the analyses identified in this study as required to achieve the objective presented in Section 1.2. According to the author's literature survey, all analyses required in this study have been studied separately by a number of researchers, but there is an investigative gap regarding how all of them should be performed in a single workflow so that both fatigue damage of the moorings and cables as well as the energy performance of the WEC can be evaluated in parallel. Therefore, we synthesised the cited literature to determine how to bridge the gaps between the required analyses and thus developed the simulation procedure summarised in Figure 5.

Table 1. Summary of the various analyses that have been addressed through simulation procedures proposed in the literature.

	Motion and structural response analysis			Stress and fatigue damage analysis		WEC energy performance	Parametric study		
	WEC	Mooring lines	Power cables	Mooring lines	Power cables		Design parameters	Environmental loads	Environmental factors
Cerveira et al. 2013	X	X				X	X	X	
Fitzgerald & Bergdahl 2008	X	X				X	X	X	
Johanning et al. 2006		X		X			X	X	
Langhamer et al. 2009						X			X
Martinelli et al. 2012	X	X						X	
Muliawan et al. 2013	X	X				X	X	X	
Sinha et al. 2016	X					X	X	X	
Thies et al. 2012			X		X		X	X	
Weller et al. 2013	X	X						X	
Zaroudi et al. 2015	X	X				X	X		
Thesis / Paper I-III	X	X	X	X	X	X	X	X	X

The workflow presented in Figure 5 consists of several types of components. The rectangular boxes represent actual analytical steps performed in our research, whereas the rounded boxes encapsulate the input/output information required to be carried through the different steps. The solid lines (solid arrows and solid boxes) indicate work performed as part of this research project, and the dashed lines (dashed arrows and boxes with dashed lines) indicate information obtained from third parties, including our industrial partners, design regulations, and guidelines.

Differently coloured boxes represent the different types of methods applied in this thesis. They can be summarised as follows:

- Hydrodynamic and structural response analysis of the WEC system (blue boxes).
- Stress and fatigue damage analysis of the mooring lines and power cable (red boxes).
- Energy performance analysis of the WEC (green boxes).
- Assessment of the influence of marine biofouling (orange boxes).
- Parametric analysis for quantifying the sensitivities and uncertainties of the information used throughout the entire workflow (boxes without colouring).

In the following sections, the basic information regarding each method will be further elaborated.

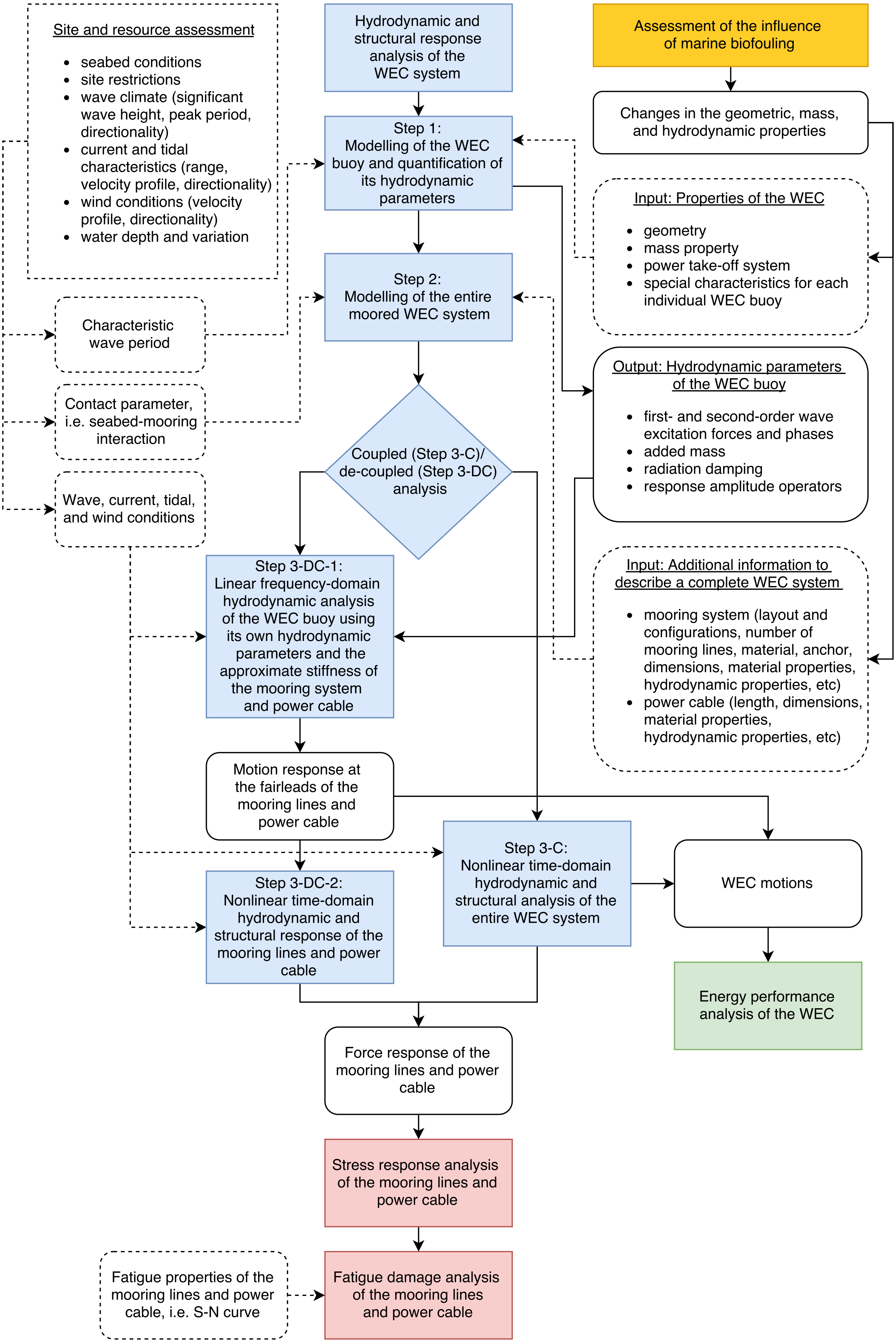

Figure 5. Methodology developed for the current thesis project.

2.2.1 Hydrodynamic and structural response analysis of the WEC system

In this context, the purpose of the hydrodynamic and structural response analysis was to assess the motion of the entire WEC system, the axial force response in the mooring lines, and the axial force and bending moments in the power cable. To numerically simulate the WEC system for motion and structural analysis, we chose to employ the simulation tool DNV DeepC (DNV, 2013). DeepC provides integrated functions for simulating an entire deep-water floating system. This integration facilitated the modelling of the WEC, moorings, and other environmental conditions in a manner suitable to our research interest. Furthermore, DeepC also provides the possibility of simulation using either a coupled or a de-coupled analysis approach, enabling a comparison of these approaches in our research within a single numerical toolbox. However, as in a recent study conducted by Bhinder et al. (2015), in which the different software packages AQWA, SIMA, and OrcaFlex were compared with respect to the simulated tension force of the mooring lines, the author may also consider testing another numerical package in the future to evaluate the feasibility of using different software to achieve our research objective; see the discussion in Chapter 5.

These two simulation alternatives, namely, coupled and de-coupled simulation procedures, are the two main approaches used to study the dynamics of WEC systems, including the motion and force response. In a coupled analysis, the motions of every modelled component (in our case, the WEC with the attached moorings and power cable) are solved simultaneously, whereas in a de-coupled analysis, the computations are separated into two sequential steps. In our de-coupled simulation, the motion of the WEC was solved first, followed by the motions of the moorings and power cable. Using a de-coupled simulation procedure reduces the complexity of the numerical simulation and often results in better numerical stability compared with the coupled approach, whereas the merit of the coupled procedure lies in the inclusion of the mutual interaction (coupling) effects between the WEC, mooring lines, and power cable in the simulation (such as the inertial load and damping effects from the moorings as well as the seabed friction).

However, the majority of studies referenced above in Table 1 were conducted from the hydrodynamics perspective. Only a select few considered both the structural response and the fatigue life in their assessment criteria. Hence, the objectives of our research were to compare the different simulation procedures from the perspective of stress and fatigue analysis and to propose a suitable methodology for future research. Our numerical simulation results were further verified against the case study conducted by Palm et al. (2013) to confirm their validity.

2.2.2 Stress and fatigue damage analysis of the mooring lines and power cable

In this thesis work, the numerical modelling and analysis were performed in accordance with first-principles design. In first-principles design, the model is simplified to a reasonable level to capture the characteristics of the system while requiring an acceptable computational effort. To this end, the catenary mooring chains were modelled as beam elements and the power cable was modelled as a thick-walled circular tube; see Papers I and II for details. Hence, the goal of the stress and fatigue analysis performed in our research was to identify the fatigue-critical locations along the mooring lines and power cable as well as their overall relative fatigue lives, and their intrinsic failure mechanisms were not considered in the model. The stress and fatigue damage analysis was performed using an in-house code developed using MATLAB (The MathWorks Inc., 2013), for which the force histories of the mooring lines and power cable were extracted from the simulation described in Section 2.2.1.

In Papers II and III, the mooring lines were constrained to exhibit stiffness in the axial direction only, namely, zero bending and torsional stiffness was assumed (DNV, 2010); the influence of bending and torsional stiffness was investigated in Paper I. The structural response of each mooring line was characterised in terms of the axial force, and then, the corresponding axial stress was calculated using the nominal cross-sectional area of the catenary chain.

For a power cable, the structural response must be considered in terms of the axial force and the bending moments (Barbeiro & Yamada da Silveira, 2013; Katsui et al. 2013). Accordingly, the stress components of the power cable included both axial and bending stresses. For each cross section of the power cable, we considered the outermost edge to be the most critical area for the stress response, and we calculated several points on the periphery to determine the most fatigue-susceptible location on the cross section.

The accumulated fatigue damage and fatigue lives of mooring lines and power cables can be calculated after their stresses have been calculated. At present, the calculated fatigue lives have not yet been verified against laboratory data. Hence, it is unknown which failure modes dominate the fatigue lives of the mooring lines and power cable. In addition, the calculated fatigue life could refer either to the occurrence of a crack in the structure or to complete fracture. Due to the uncertainties from the unknown failure mode and the lack of the laboratorial validation, the absolute value of the calculated fatigue life may be unrealistic and be less important in this study. Nevertheless, the chosen fatigue evaluation is judged to be relevant because it enables us to predict the relative lives of the mooring lines and power cables and to observe their fatigue characteristics.

Because the initial study showed that the stress levels of the mooring lines and power cable are considerably lower than their design yield stress, a stress-based approach was adopted in the fatigue analysis. Given the stress history obtained from the time-domain simulation, the RFC method was employed to extract the stress cycle for the fatigue analysis (Endo & Morrow, 1969; Rychlik, 1987). Finally, the accumulated fatigue damage (FD) was calculated using the Palmgren-Miner cumulative rule and the S-N (stress-number of cycles to failure) curve for the material of the mooring or cable under consideration.

For the fatigue damage calculation, two additional assumptions were made. First, only tensile stress was assumed to contribute to the fatigue damage in the fatigue analysis, and hence, any recorded negative (compressive) stress readings were rounded up to zero prior to the cycle-counting procedure. Second, no fatigue limit was considered; thus, all stress ranges contributed to the total fatigue damage.

2.2.3 Energy performance analysis of the WEC

The primary focus of this research was the fatigue analysis of WEC moorings and power cables. However, any change in the mooring and cable design parameters that lead to longer fatigue lives could have a negative effect on the WEC's energy production capability. Hence, according to Figure 1, a parallel energy performance analysis was warranted.

The energy performance of the WEC was evaluated in terms of the time-averaged absorbed power. The WEC absorbs energy through the activation of the PTO damping (Falnes, 2007). This study, however, used a simplified model of the PTO system. A constant damping in the heave degree of freedom was introduced to incorporate a linear PTO into the model for power absorption.

2.2.4 Assessment of other environmental factors – marine biofouling

The influence of marine biofouling was studied based on the energy performance of the WEC and the fatigue lives of the moorings and cable, as presented in Figure 1. Both aspects are considered to be important factors in determining the necessary maintenance procedures for deployed WEC systems.

A precise quantitative estimate of the marine biofouling on a WEC requires detailed *in situ* measurements of the flow properties and biological activity at the deployment site. However, such information is typically lacking during the initial design phase and only becomes available once the device has actually been deployed for a certain period of time, similar to the challenges currently faced by the offshore wind energy industry (Carswell et al., 2015; Krone et al., 2013; Wilhelmsson & Malm, 2008). Hence, to investigate the effect of biofouling, the author referred to the public literature, which provided us with a reliable reference point for fouling conditions; for this purpose, Tiron et al. (2012) and NORSOK (2007) were used as the two core references.

The biofouling effect was included by modelling an increase in the masses and drag coefficients of the moorings and cable, following the recommendation defined in the Position Mooring standard (DNV, 2010). Although the standard cited above is intended for mooring systems, we adopted the same principle for the cable because of its similar slender geometric characteristics relative to the floating WEC buoy. With regard to the fatigue damage analysis of the WEC moorings and cable, their S-N curves were assumed to remain unchanged with respect to the original S-N curves for the materials of the moorings and cable under consideration, i.e. no influence of bio-corrosion on the S-N curves was considered.

In this research, it was assumed that an anti-fouling coating had been applied to the WEC buoy. Therefore, only the biofouling effects on the moorings and cable were considered. However, to consider fouling on the WEC buoy, additional mass could be added to the buoy while retaining the buoy's geometry, following the procedure described in Langhamer et al. (2009) and Tiron et al. (2012).

2.2.5 Parametric analysis

Various numerical and physical parameters are involved in describing the entire WEC system and in controlling the numerical simulations. By numerical parameters, we refer to those parameters adopted to assist in numerical simulation. The parameters that are needed typically depend on the chosen numerical simulation technique and/or software. For example, a mesh size must be specified in finite element analyses for structural element discretisation, and the artificial stiffness used in DNV DeepC is a numerical parameter that is used to improve the numerical stability of the static solution (SIMO Project Team, 2012). By contrast, physical parameters are those that have a direct physical meaning, e.g. the wave height and wave period describe the real environmental loadings acting on the structures, the axial and bending stiffnesses describe the material properties of the structures, and the lengths and diameters describe the geometrical characteristics of the system.

The parametric analysis was performed by imposing systematic variations in a number of parameters. The sensitivity of the fatigue damage evaluation of the mooring lines and power cables as well as the energy performance analysis of the WEC to various parameters was quantified. All parameters investigated throughout the entire study are summarised in Table 2.

Table 2. Summary of the numerical and physical parameters investigated in this thesis project.

	Yang et al. (2014)	Paper I	Paper II	Paper III
Numerical parameters				
Mesh size	X	X		
Artificial stiffness	X			
Structural Rayleigh damping	X			
Physical parameters				
Wave drift force of the WEC	X			
Pretension force of the mooring system	X			
Length of a mooring line		X		
Bending and torsional stiffness of a mooring line		X		
Mooring configuration				X
Bending stiffness of the power cable			X	
Length of the power cable			X	
Mass of the power cable			X	
Wave height, period and direction	X	X	X	X
Current speed and direction			X	X
Time duration for marine biofouling development				X
Thickness of marine biofouling				X
Density of marine biofouling				X

In addition to the parametric analysis, a simulation matrix was also used to improve the presentation of our results, allowing them to be presented in the most compact form while clearly representing the potential correlations among different parameters. Figure 6 shows a schematic example of the simulation matrix from Paper III that was used to present the results of our parametric study.

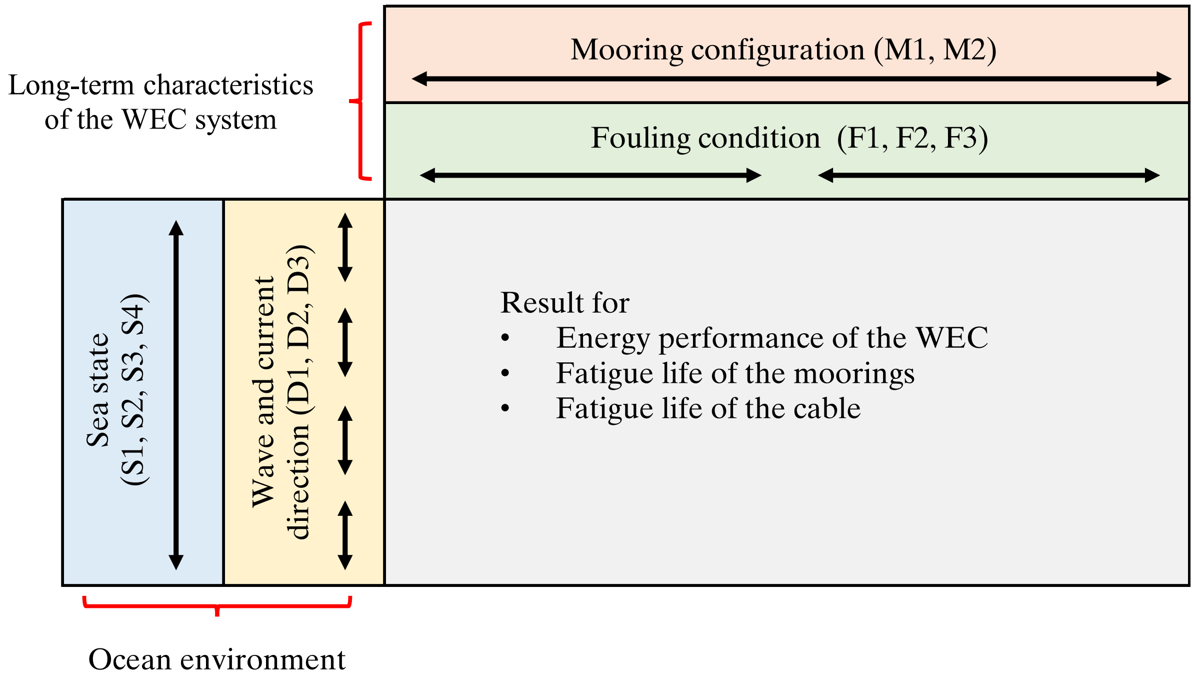

Figure 6. Schematic view of the simulation matrix.

2.3 Assumptions and limitations

The research presented in this thesis is multi-disciplinary, encompassing research disciplines such as numerical modelling, hydrodynamic analysis, marine structural analysis, and assessment of the influence of the ocean environment. The purpose of using this multi-disciplinary approach was to build a system model that can be used primarily to simulate the fatigue lives of mooring lines and power cables while also simulating the energy harvesting performance of WECs. To date, the adoption of several simplifications has been required to present the first suitable simulation procedure for this purpose, and this has resulted in certain limitations. Below, a summary of these assumptions and limitations is presented.

Type of WEC and its geometry

The developed simulation procedure is not limited to the study of point-absorber-type WECs. However, this type of WEC was chosen as the subject of our case study because of its research potential, as follows. Because a point-absorber-type WEC harvests energy from its own motion, more frequent periodic motion of the WEC can be expected.

Hence, mooring and cable fatigue accumulates more rapidly compared with other types of WEC systems, and therefore, the investigation of fatigue failure is particularly important (Gao et al., 2015). Yet, this limitation also poses an interesting research question: because the energy production of a point-absorber-type WEC affects its own motion, the question of how to strike a balance between effective mooring positioning and sufficient freedom of movement for the WEC itself is worthy of research attention (Johanning et al., 2007; Weller et al., 2013).

Two examples of WEC buoy geometry were studied during this thesis project: a generic cylindrical buoy (Paper I) and a specific buoy geometry designed by the Swedish company Waves4Power (Papers II and III). The generic WEC buoy was initially chosen to enable us to focus on the development of the simulation procedure. Furthermore, this generic WEC has been thoroughly investigated in the literature (Fitzgerald & Bergdahl, 2008; Palm et al., 2013), thereby providing the possibility to validate the results of Paper I through comparison with the cited literature. Using the methodology established in Paper I, the specific buoy design was then adopted to enable a more realistic case study in the latter two papers.

Stationary hub

According to the initial design of the hub, determined prior to this research project, it is planned to remain in a static position in the seawater. Therefore, the hub was treated as a spatially fixed point, meaning that there is no motional interaction between the hub and the power cable. This stationary constraint on the hub may later be further investigated in a possible future case study with our industrial partner, Waves4Power (see Chapter 5, which discusses possibilities for future work, for details).

PTO system

The PTO system of the WEC was modelled as a linear damper in this study. This simplification was made to restrict our focus to fatigue analysis while maintaining the possibility of calculating the energy performance of the WEC. If the developed analysis procedure is to be applied by other researchers or industrial partners, a more detailed PTO can be modelled for the WEC to provide better accuracy in the estimation of the energy harvesting performance of the WEC.

Mooring systems and materials

For the mooring systems to be used in WEC systems, which are required to exhibit highly compliant behaviour, research is actively ongoing for the investigation of various possible configurations and materials. The available configurations include single-point systems, taut systems, and dynamic positioning (Bosma et al., 2015; Harris et al., 2004), whereas the considered materials include nylon fibre rope, elastomeric rubber, and synthetics, among others (Fitzgerald & Bergdahl, 2007; Ridge et al., 2010; Thies et al. 2014; Weller et al., 2015). The focus of the current research was a spread mooring system, specifically, a system of steel catenary mooring chains. Steel mooring chains have a relatively moderate installation cost because of their ease of handling and installation, and hence, they are a more favourable choice in the development and manufacture of WEC systems. Additionally, more complete analytical tools and related theories are available for this type of mooring system because of its earlier adoption in marine engineering. Our research strove to build upon existing analysis methods and tools and to further extend it for the investigation of WEC systems.

Power cable – low voltage cable

Traditional submarine power cables are mostly static cables placed on the seabed surface, with typical lengths of up to hundreds of kilometres (Worzyk, 2009). Our research focused on dynamic cables; see Section 2.1 for details. Dynamic cables are designed not to be in contact with the seabed during operation, and the cable lengths are much shorter than those of static cables. Furthermore, dynamic cables operate in the free-hanging state, hence their dynamic motion. This motion can increase the risk of different failure modes in comparison with static cables, such as fatigue, fretting, and wear. Therefore, dynamic cables require a more sophisticated structural design and were an important focus of this study.

When the investigation of the power cable was conducted, the low voltage cable was still under development. Therefore, the model of the power cable was simplified from an umbilical cross section to a circular tube with a smaller inner diameter; for the details of this simplification, refer to the appended Paper II.

Software used and modelling of environmental loads

The hydrodynamic and structural response analysis of the WEC system was performed based on DNV DeepC in this study. Therefore, we naturally inherited all of the limitations of the software we used. Moreover, because of limitations related to computational complexity and research feasibility, the modelling of the WEC system was simplified to a reasonable extent. As our study progressed, more detailed modelling of the WEC system was included. Nevertheless, this study included a systematic investigation of the simulated results obtained using DeepC, and the simulation results were also partially compared with those obtained using a different software package, MooDy (Palm, 2014); see Paper I for details.

The DeepC software provides the possibility of considering the wind load on the WEC system. However, it was assumed that the wind load has a negligible effect on the dynamic response of the WEC system, and this load was therefore neglected in the present investigation. With respect to the wave load, restrictions were introduced under the assumption of small wave amplitudes and Airy wave theory (DNV, 2012a; SIMO Project Team, 2012). Hence, to ensure the validity of our simulated results, all studied wave conditions were examined in comparison with the wave steepness parameter and the shallow water parameter to avoid obtaining invalid results from the numerical simulations; see Paper II for details.

Fatigue damage analysis: elasticity theory

In this study, the material response of the mooring lines and power cable was assumed to always be elastic. Hence, the stress-based approach and the Palmgren-Miner cumulative rule could be used in the fatigue analysis. For the environmental loads considered in Papers I to III, the structural response was shown to remain below the yield stress. However, for harsh sea state conditions, or when snap loads occur, the elastic assumption may be violated. For these conditions, a different fatigue damage model must be developed; however, this is out of the scope of the current thesis.

Failure modes and failure points in the mooring lines and power cable

Two potential failure modes were not considered in this study because of the assumptions made when modelling the mooring lines and power cable. First, the potential failure modes for the mooring lines due to its torsional response was not considered (Hobbs & Ridge, 2005) because of the assumption of zero torsional stiffness of the mooring lines. Second, because the power cable was simplified as a thick-walled tube, no intrinsic failure mechanisms such as fretting or wear were considered as potential failure modes of the power cable (Nasution et al., 2013; Zhou et al., 1996).

The purpose of this study was to assess the structure failure of the moorings and cable; hence, the possible failure points were assumed to lie on the main structures of the moorings and cable themselves. Thus, our modelling focused on the main structures of the moorings and cable while neglecting possible failures of the connectors between components, such as the linkages between the WEC and the moorings, the linkages between the moorings and the seabed, and the linkage between the WEC and the cable.

3 Results

The entire contribution of this thesis is based on the three appended papers, each of which addresses a different stage of the study performed to achieve the overall goal, as described in Section 1.2. The purpose of this chapter is to provide the reader with an overview and brief summary of the most important results. For more detailed descriptions and results, the reader is referred to the appended papers.

3.1 Summary of Paper I

The objective of Paper I covers three aspects: first, the establishment of an analysis procedure to execute the basic workflow, as described in Figure 5, for studying the fatigue characteristics of mooring lines; second, the comparison of different simulation procedures, namely, coupled and de-coupled analysis, to obtain a recommendation for the initial fatigue design assessment of WEC mooring lines; and finally, a discussion of how the motion, forces, and stress response of the mooring lines vary for different simulation procedures and modelling parameters, both numerical and physical.

The main focus of Paper I is placed on the establishment and comparison of the analysis procedures and on the fatigue characteristics of the mooring lines. We begin with a simplified WEC system model that includes the essential components, namely, a WEC buoy, a four-mooring system, the waves, the seawater, and the seabed; the ocean current load is not considered. The results are evaluated with a primary focus on the differences in the motion, force, and fatigue damage results for the moorings obtained using different simulation procedures and different physical and numerical parameters.

Given regular wave conditions such as those considered in Paper I, the response, as predicted by the numerical simulations, will eventually reach a steady-state response—the amplitude and period of the motion response of the WEC are constant. Hence, one minute of such harmonic results is representative for comparing the differences between cases, and this approach serves as the basis for comparison in Figure 7 and Figure 8.

Figure 7 presents the results of the fatigue damage analysis for the two compared simulation procedures, namely, the coupled and de-coupled analysis procedures. The fatigue analysis encompasses all four mooring lines. Line 1 and Line 3 are positioned to trail and face into the encountered wave, respectively, whereas Line 2 and Line 4 are both located in a beam sea position. The two simulation procedures exhibit reasonable agreement in terms of the trend of the fatigue damage accumulation along the mooring lines. The fatigue damage is highest at the fairlead of a mooring line (at a line coordinate of 0 metres) and decreases as the distance from the fairlead increases. However, a greater difference between the two simulation procedures is evident in the prediction of the magnitude of the maximum fatigue damage. This difference is attributed to the limitations of the de-coupled simulation procedure, such as the lack of consideration of the dynamic influences of the moorings, the linearity assumption, and the absence of the wave drift force. These differences are expected to be larger under more severe wave conditions. From a fatigue design perspective, because the computational times are approximately equal for the two simulation procedures, the coupled simulation procedure is considered to be the better option for comprehensive studies of WEC systems.

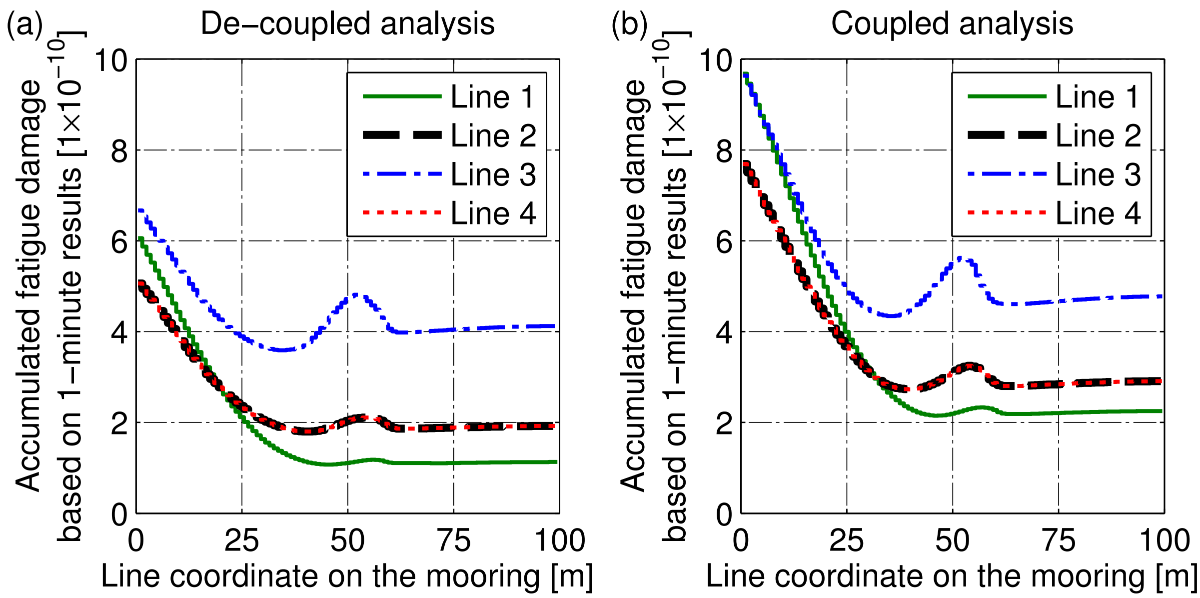

Figure 7. Presentation of the results of the fatigue damage calculations for the coupled and de-coupled simulation procedures along each entire mooring line, from the fairlead at the WEC to the anchor point at the seabed (at line coordinates from 0 to 100 m).

Figure 8 summarises the results for all cases investigated in the fatigue response analysis of the mooring lines in Paper I. The presented accumulated fatigue is that located at the fairlead of mooring line 3, because this was identified as the critical position for fatigue damage. All cases were simulated using the coupled simulation procedure because it was identified as the best means of capturing the necessary coupling effect with reasonable effort. The symbols E, RD, W, L, and B denote the element size for the mooring lines, the Rayleigh damping used to represent the structural damping in the mooring lines, the encountered wave height and period, the length of the mooring lines, and the bending and torsional stiffness of the mooring lines, respectively. Note, however, that for the catenary mooring chain system investigated in this study, the bending and torsional stiffness can be neglected. The investigation of the bending and torsional stiffness herein is regarded as a numerical investigation to examine the potential changes in the fatigue damage evaluation that could occur if a different mooring system were to be adopted. A standard value is defined for each investigated parameter. The combined set of standard values for all parameters is defined as the standard case. The results for the standard case are shown in Figure 7(b) and as the red bars in Figure 8 to allow observation of the trends in all varied parameters. The implications of each varied parameter are reported in the appended Paper I; overall, the main conclusion of the parametric study is that most physical parameters have a profound influence on the structural behaviour of a mooring system and its fatigue life. This finding indicates that it is important to consider the fatigue life assessment at an early stage during the design of a new WEC mooring system.

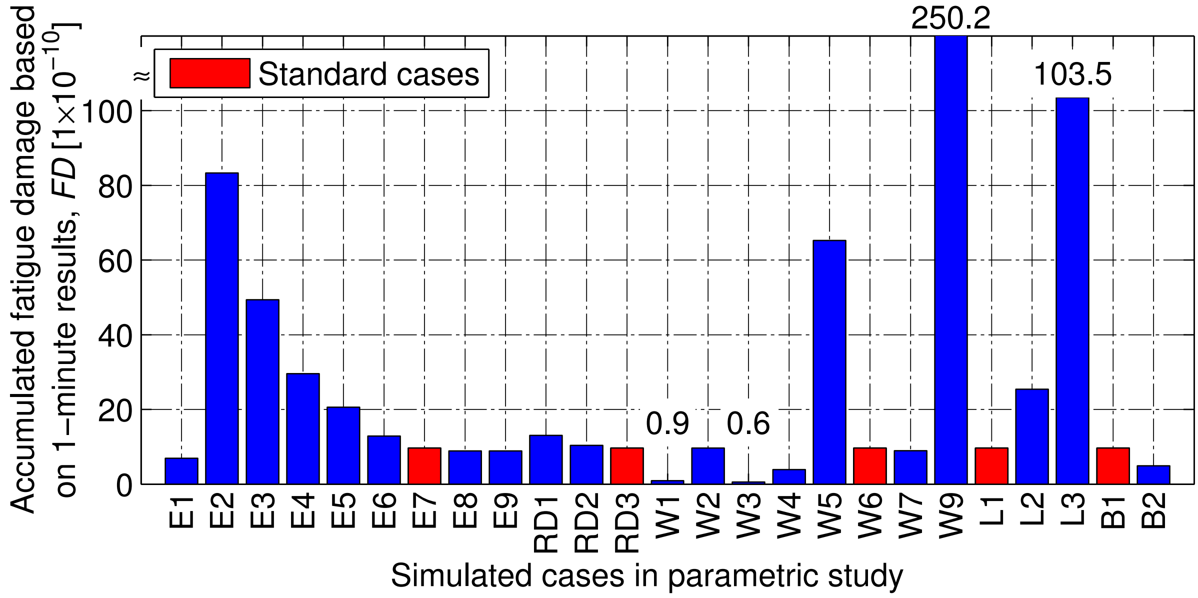

Figure 8. Summary of the results for the accumulated fatigue damage at the fairlead of mooring line 3 for all simulated cases in the parametric study. The symbols E, RD, W, L, and B denote the element size for the mooring lines, the Rayleigh damping used to represent the structural damping in the mooring lines, the encountered wave height and period, the length of the mooring lines, and the bending and torsional stiffness of the mooring lines, respectively.

3.2 Summary of Paper II

The objective of Paper II is to extend the analysis procedure to the fatigue analysis of the power cable and thus to provide recommendations regarding the design parameters of the power cable.

To investigate the power cables used in a WEC array farm, it is necessary to increase the model complexity such that the model is representative of a basic unit of the WEC array farm. Consequentially, the WEC system studied in Paper II consists of a WEC buoy, a mooring system, and a free-hanging power cable that is connected to a stationary fixed power-collecting hub. Paper II has two main research focuses: first, investigation of the motion and structural responses of the power cable to the actual environmental conditions at its expected site of operation, and second, identification of the design parameters that are important for reducing the fatigue damage to the power cable.

A fatigue-wave height-wave period matrix was computed that shows the cable fatigue damage under different wave load conditions; see Figure 9. A great deal of information can be read from this figure. Numerically, to avoid violating the conditions for the linear wave theory applied by DeepC, only sea states that satisfy this linear wave theory were simulated; see Paper II for details. According to the wave scatter diagram acquired from the Runde test site in Norway, the simulated cases cover 72% of all possible sea states, meaning that the predicted fatigue characteristics of the power cable are, to a large extent, representative of reality. However, because the contributions from the most severe wave conditions are disregarded, over-prediction of the actual fatigue life is expected. Physically, this figure already reveals an important concern for a WEC system.

In the region of high wave heights, greater fatigue damage is observed in the power cable. However, this is also the region in which the WEC is expected to exhibit the best power performance. Therefore, WEC designers must address the economic analysis which balances revenues, namely energy extraction performance of the WEC, and costs, such as the fatigue damage of the moorings and cables, of the WEC system.

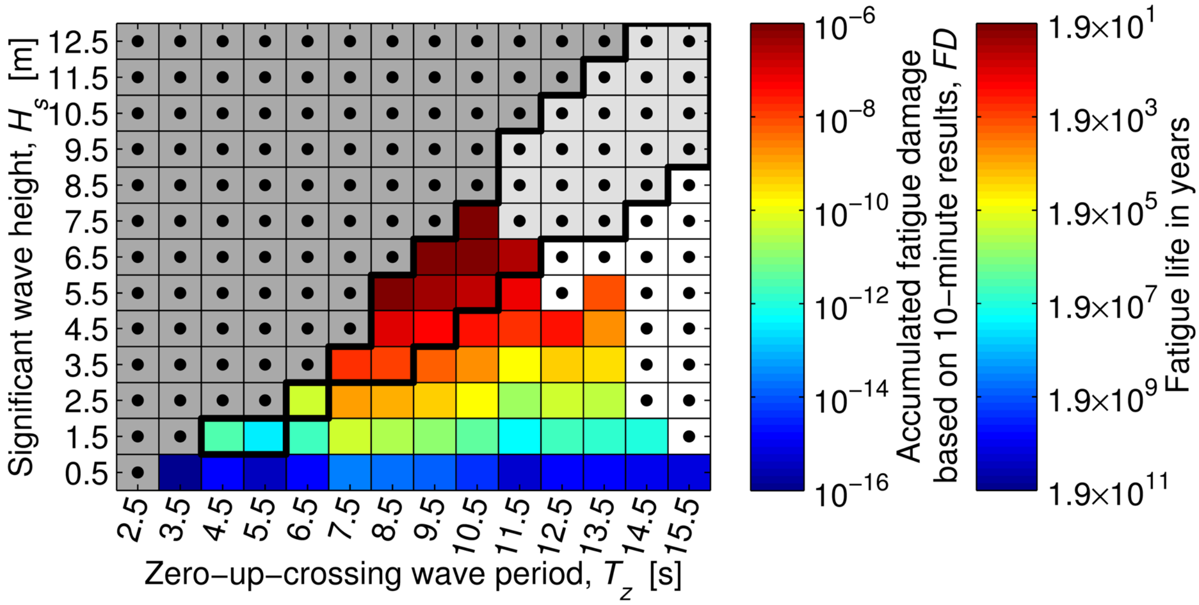

Figure 9. The fatigue-wave height-wave period matrix: maximum accumulated fatigue damage along the cable over 10 minutes for different wave heights and wave periods. The invalid and transitional ranges for the application of linear wave theory are indicated by the dark grey cells and thick black lines. The light grey and white cells were excluded from the simulations because their probabilities of occurrence are zero. The cells corresponding to all wave conditions that were not simulated are marked with black dots. Each wave condition was simulated as a regular wave represented by a mean wave height of $H = H_s/\sqrt{2}$, and an average wave period of $T = T_z$.

Figure 10 shows the absolute maximum curvature and fatigue damage of the power cable with various bending stiffnesses, and the results confirm the dilemma encountered when selecting the appropriate design parameters for the cable as well as the limitations of the current methodology. When the bending stiffness of the cable is increased, the curvature response of the cable decreases (Figure 10(a)) but the fatigue damage to the cable increases (Figure 10(b)). The results suggest that if a cable is designed for lower motion and curvature response (namely, with a high bending stiffness), then the cable will be prone to fatigue damage induced by cyclic tensile stress. However, if the cable is designed to allow for greater motion and curvature response (with a low bending stiffness), then an advanced model must also be used to predict the intrinsic failure mechanisms of the cable, such as bird caging, wear, and fretting damage between the internal cable umbilicals (DNV, 2012b), implying the need to further develop a numerical model to study the local behaviour of the power cable. Because such local failure mechanisms of the power cable were not modelled in this study, the presented fatigue lives should be interpreted as upper bounds on the service life.

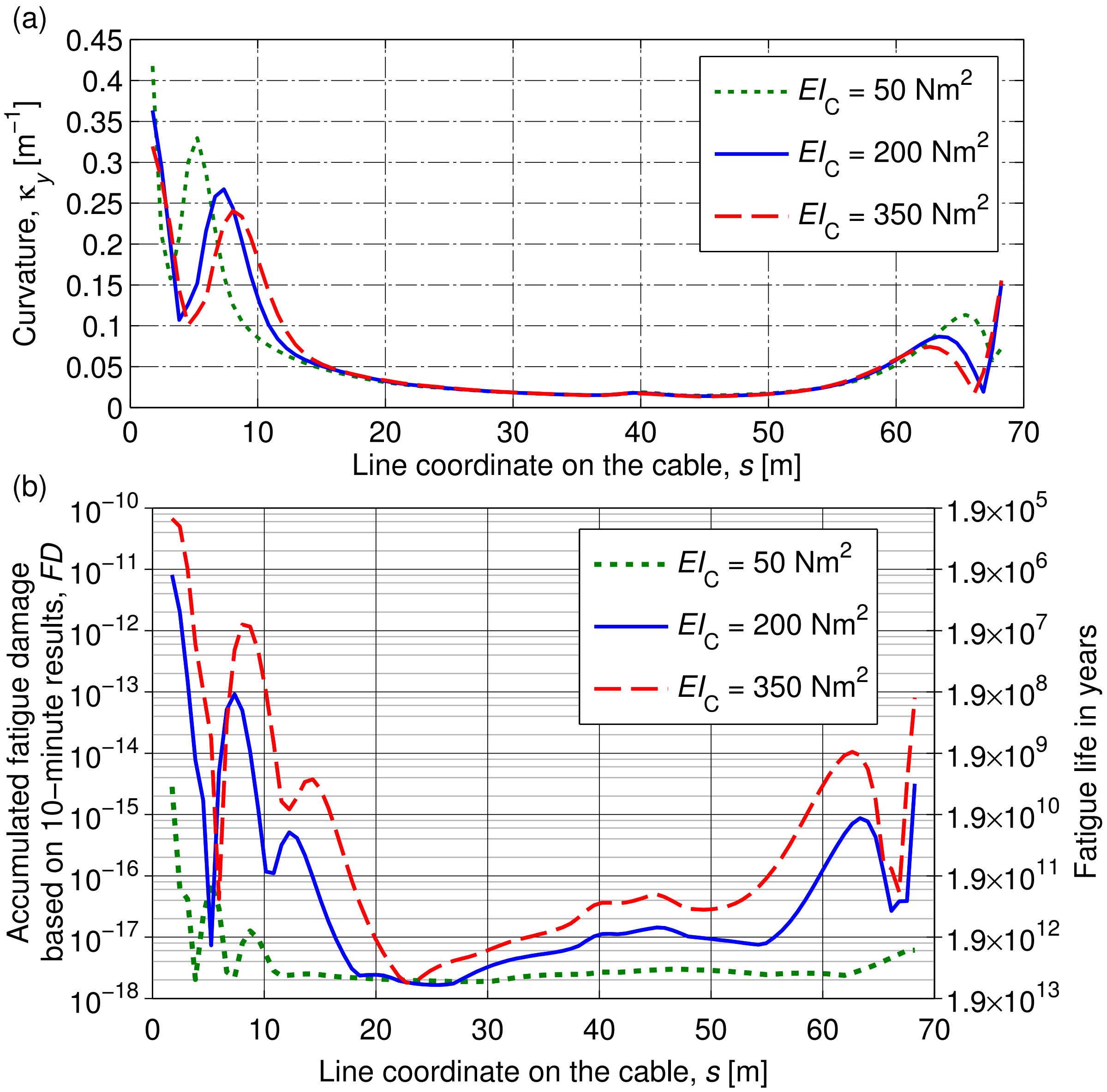

Figure 10. (a) Absolute value of the maximum curvature response and (b) fatigue damage accumulated during 10 minutes of stable response for different cable bending stiffnesses.

3.3 Summary of Paper III

Paper III presents the full simulation procedure and its opportunities, in accordance with Figure 1. The primary objective of Paper III is to investigate the characteristics of the entire WEC system with regard to its energy performance and the fatigue life of the mooring lines and power cable, considering the influence of the design parameters, loading conditions, and marine biofouling. This implies that one important task of Paper III is to present the complete analysis procedure as summarised in Figure 5.

In Paper II, the case study WEC system was used as a test case to simulate the cable's motion and fatigue characteristics. In Paper III, we adapted the modelled system to more closely replicate the Runde test conditions, which specifically required us to update the current load profile and seabed characteristics. However, our focus remained on the catenary mooring system, although a polyester mooring system is used at the Runde test site.

A parametric analysis was conducted in Paper III to study the system characteristics. Table 3 summarises all parameters investigated in Paper III; the detailed information for each parameter is provided in the appended paper. Illustrations of the orientation of the WEC system in relation to the incoming wave and current directions are presented in Figure 11.

Table 3. Summary of the parameters investigated in Paper III.

Investigated parameter	Case	Description
Mooring configuration	M1	Three moorings
	M2	Four moorings
Marine biofouling: density (ρ_b) and thickness (t_b)	F1	Biofouling-free condition
	F2	$\rho_b = 1325\, kg/m^3$; $t_b = 25.3\, mm$
	F3	$\rho_b = 1300\, kg/m^3$; $t_b = 60.0\, mm/40.0\, mm$ (water surface to a depth of 40 metres / water depth below 40 metres)
Sea state: significant wave height (H_s) and peak wave period (T_p)	S1	$H_s = 1.5\, m; T_p = 13.5\, s$
	S2	$H_s = 2.0\, m; T_p = 5.0\, s$
	S3	$H_s = 3.5\, m; T_p = 7.5\, s$
	S4	$H_s = 7.5\, m; T_p = 8.5\, s$
Incoming wave and current direction	D1	0 deg
	D2	130 deg
	D3	180 deg

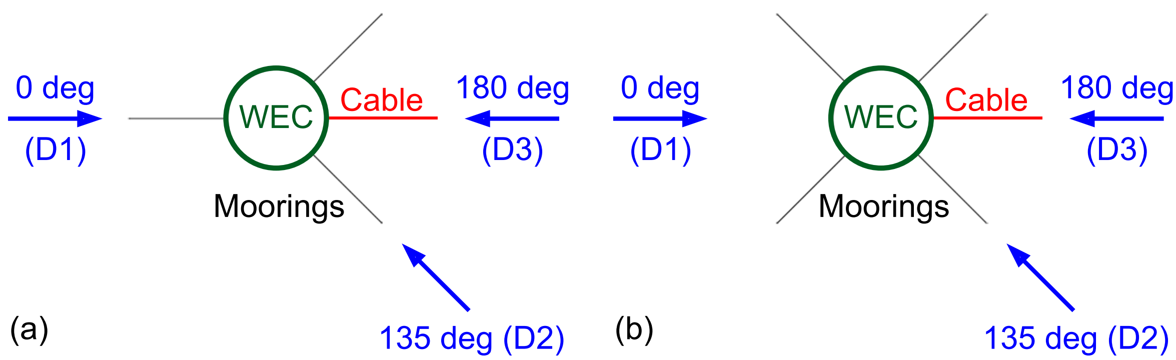

Figure 11. Illustration of the (a) three-mooring and (b) four-mooring WEC systems in relation to the incoming wave and current direction.

Table 4 to Table 6 summarise the results for the time-averaged absorbed power of the WEC device, the shortest fatigue life among all mooring lines, and the fatigue life of the power cable, respectively, for all cases investigated in Paper III. For comparison, all values are normalised with respect to the reference case, which is defined as M1-F1-S2-D3 and is indicated by a red border around the corresponding cell in Tables 4-6. Note that the results shown in these tables consider only the effects of biofouling on the moorings and cable, under the assumption that an anti-fouling coating is applied to the WEC buoy. The most important conclusions drawn from these tables are as follows:

- The modelled biofouling on the cable and moorings is found to result in a maximum 17% reduction in the WEC's energy performance.
- The occurrence of biofouling significantly reduces the fatigue life of the moorings, by up to 76% among the simulated cases.
- The influence of biofouling on the fatigue life of the power cable is found to be negligible.
- The long fatigue life calculated for the power cable confirms the need to develop a more detailed model of the power cable.
- The direction of the incoming waves and current has only a minor effect on the energy performance of the WEC. However, an incoming load with a direct heading on a mooring or cable will cause a significant decrease in its fatigue life. Hence, from the structural safety perspective, the orientation of each WEC system should be carefully considered with respect to the prevailing load direction at its site of operation.

Table 4. Normalised average absorbed power results for the WEC, where the reference case corresponds to 18.44 kW.

Mooring configuration				Three moorings (M1)			Four moorings (M2)		
Fouling condition				F1	F2	F3	F1	F2	F3
Sea state	S1	Wave and current direction	D1	0.56	0.54	0.54	0.56	0.53	0.53
			D2	0.56	0.54	0.54	0.56	0.53	0.53
			D3	0.56	0.54	0.53	0.56	0.53	0.53
	S2		D1	1.00	0.91	0.86	0.97	0.87	0.81
			D2	1.00	0.91	0.87	0.97	0.87	0.82
			D3	1.00	0.91	0.87	0.97	0.87	0.82
	S3		D1	4.62	4.19	4.02	4.46	3.94	3.76
			D2	4.60	4.16	4.00	4.51	4.01	3.82
			D3	4.53	4.05	3.92	4.46	3.93	3.76
	S4		D1	18.34	16.80	15.90	16.84	14.89	13.96
			D2	18.07	16.40	15.48	17.58	15.62	14.60
			D3	17.08	15.29	14.54	16.81	14.85	13.92

Table 5. Normalised results for the shortest fatigue life among all moorings, where the reference case corresponds to 8 years.

Mooring configuration				Three moorings (M1)			Four moorings (M2)		
Fouling condition				F1	F2	F3	F1	F2	F3
Sea state	S1	Wave and current direction	D1	1.26E+1	4.52E+0	3.80E+0	9.22E+1	2.80E+1	2.19E+1
			D2	1.95E+1	7.38E+0	6.93E+0	2.30E+1	8.57E+0	7.98E+0
			D3	1.18E+2	3.99E+1	3.53E+1	9.35E+1	3.02E+1	2.59E+1
	S2		D1	7.88E-2	4.63E-2	4.78E-2	8.51E-1	4.33E-1	4.21E-1
			D2	1.08E-1	6.75E-2	7.79E-2	1.28E-1	8.10E-2	9.55E-2
			D3	1.00E+0	5.64E-1	6.24E-1	8.62E-1	4.64E-1	4.96E-1
	S3		D1	6.55E-3	4.22E-3	3.96E-3	4.47E-2	2.36E-2	2.23E-2
			D2	8.06E-3	5.31E-3	5.34E-3	8.97E-3	5.95E-3	6.13E-3
			D3	5.04E-2	2.86E-2	3.01E-2	4.52E-2	2.48E-2	2.51E-2
	S4		D1	3.22E-4	3.13E-4	3.00E-4	1.62E-3	1.38E-3	1.29E-3
			D2	3.70E-4	3.55E-4	3.52E-4	3.84E-4	3.73E-4	3.78E-4
			D3	1.76E-3	1.36E-3	1.56E-3	1.63E-3	1.42E-3	1.38E-3

Table 6. Normalised fatigue life results for the cable, where the reference case corresponds to 2.0×10^{10} years.

Mooring configuration				Three moorings (M1)			Four moorings (M2)		
Fouling condition				F1	F2	F3	F1	F2	F3
Sea state	S1	Wave and current direction	D1	4.25E+4	2.94E+6	9.65E+4	4.13E+4	2.74E+6	9.08E+4
			D2	6.34E+4	6.08E+4	3.37E+3	3.54E+4	3.52E+4	2.43E+3
			D3	4.13E+3	4.97E+3	5.26E+2	3.13E+3	3.89E+3	4.78E+2
	S2		D1	2.35E+2	1.05E+5	9.02E+2	2.22E+2	1.09E+5	8.72E+2
			D2	1.35E+2	2.48E+2	4.24E+0	9.08E+1	1.64E+2	5.37E+0
			D3	1.00E+0	1.58E+1	1.26E+0	9.43E-1	1.43E+1	1.20E+0
	S3		D1	8.31E+0	3.95E+2	6.68E+0	9.56E+0	5.44E+2	1.11E+1
			D2	1.08E-1	6.77E-1	1.36E-1	1.13E-1	4.45E-1	1.16E-1
			D3	5.28E-3	6.48E-2	2.46E-2	5.12E-3	6.36E-2	2.38E-2
	S4		D1	3.37E-4	1.98E-2	4.26E-3	3.44E-4	5.17E-2	8.43E-3
			D2	1.48E-2	1.01E-2	9.55E-4	1.63E-2	7.04E-3	1.07E-3
			D3	4.44E-4	1.92E-3	4.03E-4	4.19E-4	1.92E-3	4.14E-4

4 Conclusions

This thesis contributes to the understanding of how numerical analysis can be applied to simulate and assess the fatigue characteristics of the mooring lines and power cables in a WEC system as well as the energy performance of the WEC. Additionally, the effect of biofouling on WEC systems was also studied in conjunction with this analysis, providing a complete systematic view of the WEC.

The methodology developed in this thesis has not yet been validated against experimental data. Nonetheless, the adopted numerical tool DNV DeepC has been extensively verified and validated by numerous researchers (Astrup, 2004), and some of the results reported in the appended Paper I have been compared against the validated data in Palm et al. (2013). Based on the systematic parametric analysis performed to study the sensitivity of the simulated results with regard to the numerical and physical parameters, it is believed that the developed methodology is suitable for its intended objective as expressed in Figure 1. However, to achieve a realistic fatigue life prediction for the cable, we conclude that a more detailed model of the cable's umbilical cross section is required.

Our first conclusion drawn from this research corresponds to the first research objective, namely, the comparison of different simulation procedures. Our research reported in the appended Paper I compared the coupled and de-coupled procedures, and the conclusion was to recommend the coupled simulation approach because it captures the interactions between the WEC and the other system components. These interaction effects are important for analyses of the types presented in Papers II and III, in which the interacting motions of the WEC, moorings, and cable in relation to the environmental loads should all be considered.

Once having established the proposed coupled simulation procedure, we performed a parametric study to identify critical design parameters contributing to the fatigue damage of the cable. Our results demonstrated that the motion and fatigue characteristics of the cable are profoundly affected by its design parameters. Therefore, we highlighted the importance of considering fatigue life assessment at an early stage in the design of a new WEC system. In addition, because the power cable was under development at the time of the study, we applied the methodology to a simplified model and provided design recommendations as reported in Paper II.

A fatigue-wave height-wave period matrix and simulation matrix was designed as a visualisation tool to represent the effects of various environmental loads (Papers II and III). Our simulation results suggested that the fatigue lives of mooring lines and power cable are critically affected by certain environmental loads, including sea state conditions and current loads and directions. Hence, it was concluded that the prevailing environmental conditions must be clearly understood and represented to determine the characteristics of the entire WEC system and to obtain a reliable fatigue design for the structures.

It was shown that marine biofouling significantly reduces the energy production performance of the WEC and the fatigue life of the mooring lines. From a comparison based on three fouling cases, it was concluded that marine biofouling should be considered during the early design phase of a WEC system from the perspectives of energy performance and fatigue life, both playing an important role to determine the maintenance schedule of the WEC system. The fatigue life of the power cable is found to be less influenced by the marine biofouling. Moreover, the calculated long fatigue life of the power cable confirms the necessity of a more detailed local model of the power cable to truly capture its failure mechanism.

5 Future Work

The purpose of this PhD research as a whole is to develop a complete numerical analysis procedure for the mooring lines and power cables used in WEC systems, which in the long-term perspective hopefully will contribute to lowering the LCOE for wave energy technology. The presented thesis work was conducted in accordance with the research principle summarised in Figure 1. A number of assumptions were made, as described in Section 2.3. With an emphasis on improving the fatigue lives of the moorings and cables while also considering WEC energy harvesting performance, a number of issues have been identified as potential topics of future work to enable us to reach the long-term goal. We aim to reach the goal by providing a solution to ensure long service lives of the mooring lines and power cables used in WEC systems.

Model test in a laboratory wave tank

A model test in a laboratory-based ocean wave test tank is planned to validate the simulation procedure developed in this study. This laboratory test is planned to be conducted using one point-absorber-type WEC system under various environmental loads to capture the motion and force responses of the WEC buoy and mooring lines. By performing this laboratory test, it will be possible to quantify the sensitivities and uncertainties associated with the different parameters investigated in this study and to further validate the results of the hydrodynamic and structural response analysis.

Full-scale test at Runde

A full-scale test of a WEC system that is similar to the WEC buoy modelled throughout our papers is currently deployed near Runde in Norway. This full-scale test will measure the forces in the power cable and the motion of the WEC. Therefore, we plan to extend our case study model such that the numerical simulation results will be comparable to the experimental measurements. For comparison to the system being tested at Runde, the update of the numerical model should include, but not be restricted to, the mooring configuration, the material properties of the mooring lines, and environmental conditions such as the wave climate and current characteristics.

Use of the OrcaFlex software

In this study, DNV DeepC was adopted as the numerical tool used to perform the hydrodynamic and structural analysis of the WEC system. However, other software packages are also available for such analyses, such as OrcaFlex (STA, 2014), WEC-Sim (NREL & SNL, 2014), and WaveDyn (DNV GL, 2015). The features for modelling the umbilical cross sections of power cables provided by OrcaFlex are well compatible with our case study WEC system. Therefore, the author plans to explore the possibility of using OrcaFlex to compare the usability of different software tools.

Life-cycle cost analysis and evaluation of the maintenance interval

Paper III presents the complete simulated results obtained through the procedure presented in Figure 5, which provide a holistic view of the WEC system and can be further extended to obtain insight for engineering applications. Hence, a life-cycle cost analysis of the system is planned to be incorporated into the overall analysis procedure in the hope of bridging the gap between our research and practical applications. Moreover, the author would like to provide an evaluation method for determining the recommended maintenance interval. The suggested maintenance interval should consider at least the expected service lives of the structures and the acceptable life-cycle cost of the entire WEC system.

Development of a local model for the power cable

The results of Papers II and III highlight the importance of developing a local model to capture the intrinsic failure mechanisms of the power cable. One obvious extension of our research is to develop a local model for the power cable. Additionally, fatigue tests of the power cable will be carried out within the project "R&D of dynamic low voltage cables between the buoy and floating hub in a marine energy system" to identify the real implications of the fatigue life calculated in this study. Based on the experimental results thus collected, it will be possible to validate the local power cable model and to more precisely predict the mechanical service life of the power cable.

Investigation of different mooring materials

As described in Section 2.3, numinous novel materials for WEC moorings have been proposed in the literature to cope with the dynamic characteristics of WEC systems. Therefore, to ensure the usability of our developed simulation procedure and to determine the best mooring solution with a long service life, we would like to study different mooring materials, such as the polyester moorings currently being tested as a prototype by Waves4Power or the elastic moorings provided by Seaflex (2016), which are currently attracting increasing attention.

Influence of extreme/survival loads on fatigue damage accumulation

Because we emphasised the normal operation of the WEC system, this study was focused on an analysis of the fatigue limit state (FLS). However, from the structural design perspective, analyses of both the FLS and the ultimate limit state (ULS) are important (Gao et al., 2015). Therefore, in future work, we would also like to investigate how much damage may be induced in the WEC system by the extreme loads imposed under severe environmental conditions.

Model of the power-collecting hub

In this study, the hub was modelled as a fixed point, consistent with the initial design assumption. However, this assumption should be further examined by explicitly modelling the hub as part of the WEC system. If a motion of the hub is observed in the numerical simulations, it will also be of interest to investigate to which extent its motion affects the dynamic and fatigue characteristics of the power cable.

6 References

Astrup, O. C. (2004) DeepC – Coupled analysis tool. A white paper. Rev 3. Høvik, Det Norske Veritas (DNV).

Barbeiro, I. D. C., & Yamada da Silveira, L. M. (2013) Investigation about the effect of axial stiffness on the global response of umbilicals. In: *Proceedings of the ASME 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2013), 9-14 June 2013, Nantes, France*. New York, NY, American Society of Mechanical Engineers. OMAE2013-10941.

Barstow, S., Mørk, G., Mollison, D., & Cruz, J. (2008) The wave energy resource. In: Cruz, J. (ed.) *Ocean Wave Energy*. Heidelberg, Springer-Verlag. pp. 93-132.

Bhinder, M. A., Karimirad, M., Weller, S., Debruyne, Y., Guérinel, M., & Sheng, W. (2015) Modelling mooring line non-linearities (material and geometric effects) for a wave energy converter using AQWA, SIMA and Orcaflex. In: *Proceeding of the 11th European Wave and Tidal Energy Conference (EWTEC2015), 6-11 September 2015, Nantes, France.* pp. 09D5-2-1–09D5-2-10.

Bosma, B., Thiebaut, F., & Sheng, W. (2015) Comparison of a catenary and compliant taut mooring system for marine energy systems. In: *Proceedings of the 11th European Wave and Tidal Energy Conference (EWTEC2015), 6-11 September 2015, Nantes, Frances.* pp. 08B5-4-1–08B5-4-6.

Brennan, F. P., Falzarano, J., Gao, Z., Landet, E., Boulluec, M. L., Rim, C. W., Sirkar, J., Sun, L., Suzuki, H., Thiry, A., Traieux, F., & Wang, C. M. (2012) Offshore renewable energy, Volume 2. Report of committee V.4. In: Fricke, W. & Brobsart, R. (eds.) *Proceedings of the 18th* International Ship and Offshore Structures Congress *(ISSC2012), 9-13 September 2012, Rostock, Germany.* Hamburg: Schiffahrtsverlag "Hansa" GmbH & Co. KG. pp. 153-200.

Carswell, W., Arwade, S. R., & DeGroot, D. J. (2015) Marine growth effects on offshore wind turbine support structures. In: Doctoral Dissertations May 2014 – current. Department of Civil and Environmental Engineering, University of Massachusetts, Amherst, MA. Paper 531. [Online] Available from: http://scholarworks.umass.edu/dissertations_2/531/ [Accessed 27th April 2016].

Cerveira, F., Fonseca, N., & Pascoal, R. (2013) Mooring system influence on the efficiency of wave energy converters. *International Journal of Marine Energy*. [Online] 3–4, 65-81. Available from: doi:10.1016/j.ijome.2013.11.006 [Accessed 27th April 2016].

CorPower Ocean AB. (2016) Homepage of CorPower Ocean AB. [Online] Available from: http://www.corpowerocean.com/ [Accessed 27th April 2016].

Cruz, J. (2008) Numerical and experimental modelling of WECs. In: Cruz, J. (ed.) *Ocean Wave Energy*. Heidelberg, Springer-Verlag. pp. 133-188.

Det Norske Veritas (DNV). (2010) *Offshore Standard DNV-OS-E301 Position Mooring*. Høvik, Det Norske Veritas. [Online] Available from: https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2010-10/OS-E301.pdf [Accessed 27th April 2016].

Det Norske Veritas (DNV). (2012a) RIFLEX theory manual version 4.0. Høvik, Det Norske Veritas.

Det Norske Veritas (DNV). (2012b) *Recommended Practice DNV-RP-F401 Electrical Power Cables in Subsea Applications*. Høvik, Det Norske Veritas. [Online] Available from: https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2012-02/RP-F401.pdf [Accessed 27th April 2016].

Det Norske Veritas (DNV). (2013) Sesam DeepC. V4.7-07 ed. Høvik, Det Norske Veritas.

DNV GL AS. (2015) Homepage of WaveDyn. Høvik, DNV GL AS. [Online] Available from: https://www.dnvgl.com/services/wavedyn-3800 [Accessed 27th April 2016]

Endo, T., & Morrow, J. D. (1969) Cyclic stress-strain and fatigue behavior of representative aircraft metals. *Journal of Materials,* 4 (1), 159-175.

European Commission. (2010) Energy 2020 – A strategy for competitive, sustainable and secure energy. Brussels. [Online] Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1409650806265&uri=CELEX:52010DC0639 [Accessed 27th April 2016].

European Commission. (2015) Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Renewable energy progress report. Brussels, European Commission. [Online] Available from: http://eur-lex.europa.eu/resource.html?uri=cellar:4f8722ce-1347-11e5-8817-01aa75ed71a1.0001.02/DOC_1&format=PDF [Accessed 27th April 2016].

European Union. (2015) Electricity production, consumption and market overview. [Online] Available from: http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview [Accessed 27th April 2016].

Falcão, A. F. d. O. (2010) Wave energy utilization: a review of the technologies. *Renewable and Sustainable Energy Reviews.* [Online] 14 (3), 899-918. Available from: doi:10.1016/j.rser.2009.11.003 [Accessed 27th April 2016].

Falnes, J. (2007) A review of wave-energy extraction. *Marine Structures*. [Online] 20 (4), 185-201. Available from: doi:10.1016/j.marstruc.2007.09.001 [Accessed 27th April 2016].

Fitzgerald, J., & Bergdahl, L. (2007) Considering mooring cables for offshore wave energy converters. In: *Proceedings of the 7th European Wave Tidal Energy Conference (EWTEC2007), 11-13 September 2007, Porto, Portugal.*

Fitzgerald, J., & Bergdahl, L. (2008) Including moorings in the assessment of a generic offshore wave energy converter: a frequency domain approach. *Marine Structures*. [Online] 21 (1), 23-46. Available from: doi:10.1016/j.marstruc.2007.09.004 [Accessed 27th April 2016].

Gao, Z., Bingham, H. B., Nicholls-Lee, R., Adam, F., Karmakar, D., Karr, D. G., Catipovic, I., Colicchio, G., Sheng, W., Liu, P., Takaoka, Y., Slätte, J., Shin, H. K., Mavrakos, S. A., Jhan, Y. T., & Ren, H. (2015) Report of committee V.4 offshore renewable energy. In: *Proceeding of the 19th International Ship and Offshore Structures Congress (ISSC2015), 7-10 September 2015, Cascais, Portugal.*

Gustavsson, M., Särnholm, E., Stigson, P., & Zetterberg, L. (2011) *Energy Scenario for Sweden 2050 Based on Renewable Energy Technologies and Sources*. Gothenburg and Stockholm, IVL Swedish Environment Institute and WWF Sweden. [Online] Available from: http://www.wwf.se/source.php/1409709/Energy%20Scenario%20for%20Sweden%202050_bakgrundsrapport%20IVL_sep%202011.pdf [Accessed 27th April 2016].

Harris, R. E., Johanning, L., & Wolfram, J. (2004) Mooring systems for wave energy converters: a review of design issues and choices. In: *Proceedings of the 3rd International Conference on Marine Renewable Energy (MAREC2004), 6-9 July 2004, Blyth, UK*: *New and Renewable Energy Centre (NaREC)*. [Online] Available from: http://abs-5.me.washington.edu/pub/tidal_wave/mooringsystems.pdf [Accessed 27th April 2016].

Hobbs, R. E., & Ridge, I. M. (2005) Torque in mooring chain. Part 1: Background and theory. *Journal of Strain Analysis for Engineering Design.* [Online] 40 (7), 703-713. Available from: doi:10.1243/030932405x30867 [Accessed 27th April 2016].

Jacobson, P. (2011) *Mapping and Assessment of the United States Ocean Wave Energy Resource*. [Online] CA, USA, Electric Power Research Institute. [Accessed 27th April 2016] Retrieved from http://www1.eere.energy.gov/water/pdfs/mappingandassessment.pdf [Accessed 27th April 2016].

Johanning, L., Smith, G. H., & Wolfram, J. (2006) Mooring design approach for wave energy converters. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment.* [Online] 220 (4), 159-174. Available from: doi:10.1243/14750902JEME54 [Accessed 27th April 2016].

Johanning, L., Smith, G. H., & Wolfram, J. (2007) Measurements of static and dynamic mooring line damping and their importance for floating WEC devices. *Ocean engineering.* [Online] 34 (14–15), 1918-1934. Available from: doi:10.1016/j.oceaneng.2007.04.002 [Accessed 27th April 2016].

Katsui, T., Inoue, T., & Akashi, M. (2013) Evaluation of moving capability of crawler driven ROV considering cable tension. In: *Proceeding of the ASME*, 2013 *32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2013), 9-14 June 2013, Nantes, France.* New York, NY, American Society of Mechanical Engineers. OMAE2013-10320.

Krone, R., Gutow, L., Joschko, T. J., & Schröder, A. (2013) Epifauna dynamics at an offshore foundation – implications of future wind power farming in the North Sea. *Marine environmental Research.* [Online] 85, 1-12. Available from: doi:10.1016/j.marenvres.2012.12.004 [Accessed 27th April 2016].

Langhamer, O., Wilhelmsson, D., & Engström, J. (2009) Artificial reef effect and fouling impacts on offshore wave power foundations and buoys – A pilot study. *Estuarine, coastal and shelf science.* [Online] 82 (3), 426-432. Available from: doi:10.1016/j.ecss.2009.02.009 [Accessed 27th April 2016].

Magagna, D., MacGillivray, A., Jeffrey, H., Hanmer, C., Raventos, A., Badcock-Broe, A., & Tzimas, E. (2014) Wave and tidal energy strategic technology agenda. [Online] SI Ocean. [Accessed 27th April 2016] Retrieved from http://www.si-ocean.eu/en/upload/SI%20Ocean%20-%20WaveTidal%20Strategic%20Technology%20Agenda.pdf [Accessed 27th April 2016].

Martinelli, L., Ruol, P., & Cortellazzo, G. (2012) On mooring design of wave energy converters: the Seabreath application. In: Lynett, P., & Smith, J. M. (eds.) *Proceeding of the International Conference on Coastal Engineering (ICCE 2012), 1-6 July 2012*, *Santander, Spain*. pp. 1-12. [Online] Available from: http://dx.doi.org/10.9753/icce.v33.structures.3 [Accessed 27th April 2016].

Minesto AB. (2016) Homepage of Minesto. [Online] Available from: http://minesto.com/ [Accessed 27th April 2016].

Muliawan, M. J., Gao, Z., Moan, T., & Babarit, A. (2013) Analysis of a two-body floating wave energy converter with particular focus on the effects of power take-off and mooring systems on energy capture. *Journal of Offshore Mechanics and Arctic Engineering*. [Online] 135 (3), 031902-1–031902-12. Available from: doi:10.1115/1.4023796 [Accessed 27th April 2016].

Nasution, F. P., Sævik, S., & Berge, S. (2013) Experimental investigation of fatigue performance of a 300 mm^2 copper power conductor. In: *Proceeding of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2013), 9-14 June 2013, Nantes, France.* New York, NY, American Society of Mechanical Engineers. OMAE2013-11193.

National Renewable Energy Laboratory, Office of Energy Efficiency and Renewable Energy (NREL), & Sandia National Laboratories (SNL). (2014) Homepage of WEC-Sim. [Online] Available from: http://wec-sim.github.io/WEC-Sim/ [Accessed 27th April 2016].

Naturskyddsföreningen (Swedish Society for Nature Conservation). (2012) Dags att välja framtidens energisystem. Stockholm. [Online] Available from: http://www.naturskyddsforeningen.se/sites/default/files/dokument-media/2012maj_energi_framtidens_energisystem.pdf [Accessed 27th April 2016].

nkt cables. (2016) Homepage of nkt cables. [Online] Available from: http://www.nktcables.com/ [Accessed 27th April 2016].

NORSOK. (2007) *NORSOK Standard N-003 Actions and Action Effects*. Lysaker, Norway, NORSOK. [Online] Available from: http://www.ivt.ntnu.no/imt/courses/tmr4195/literature/Standards%20and%20Recommendations/N-003e2.pdf [Accessed 27th April 2016].

Ocean Harvesting Technologies AB. (2016) Homepage of Ocean Harvesting Technologies AB. [Online] Available from: http://www.oceanharvesting.com [Accessed 27th April 2016].

Palm, J. (2014) *Developing computational methods for moored floating wave energy devices.* Thesis for Licentiate Degree, Department of Shipping and Marine Technology, Chalmers University of Technology, Gothenburg. [Online] Available from: http://publications.lib.chalmers.se/publication/204189-developing-computational-methods-for-moored-floating-wave-energy-devices [Accessed 27th April 2016].

Palm, J., Eskilsson, C., Paredes, G. M., & Bergdahl, L. (2013) CFD simulation of a moored floating wave energy converter. In: Frigaard, P., Kofoed, J. P., Bahaj, A. S., Bergdahl, L., Clément, A., Conley, D., Falcão, A. F. O., Johnstone, C. M., Margheritini, L., Masters, I., Sarmento, A. J., & Vicinanza, D. (eds.) *Proceeding of the 10th European Wave and Tidal Energy Conference (EWTEC2013), 2-5 September 2013, Aalborg, Denmark*.

Ridge, I. M. L. (2010) Nylon fibre rope moorings for wave energy converters. In: *Proceedings of OCEANS 2010 Conference, 20-23 September 2010, Seattle, Washington, USA*. pp. 1-10. [Online] Available from: doi:10.1109/OCEANS.2010.5663836 [Accessed 27th April 2016].

Runde Environmental Centre. (2016) Homepage of Runde Environmental Centre. [Online] Available from: http://rundecentre.no/en/ [Accessed 27th April 2016].

Rychlik, I. (1987) A new definition of the rainflow cycle counting method. *International Journal of Fatigue*. [Online] 9, 119–121. Available from: doi:10.1016/0142-1123(87)90054-5 [Accessed 27th April 2016].

Salvatore, J. (2013) *World Energy Perspective—Cost of Energy Technologies*. London, World Energy Council. [Online] Available from: https://www.worldenergy.org/wp-content/uploads/2013/09/WEC_J1143_CostofTECHNOLOGIES_021013_WEB_Final.pdf [Accessed 27th April 2016].

Seaflex AB (2016) Homepage of Seaflex. [Online] Available from: http://www.seaflex.net/ [Accessed 27th April 2016].

SIMO Project Team. (2012) SIMO – Theory manual version 4.0. Rev 1. Trondheim, Norway, Norwegian Marine Technology Research Institute (MARINTEK). Report number: 516412.00.03.

Sinha, A., Karmakar, D., & Guedes Soares, C. (2016) Performance of optimally tuned arrays of heaving point absorbers. *Renewable Energy.* [Online] 92, 517-531. Available from: doi:10.1016/j.renene.2016.02.043 [Accessed 27th April 2016].

Stewart Technology Associates (STA). (2014) Homepage of OrcaFlex. Houston, TX, Stewart Technology Associates (STA). [Online] Available from: https://www.orcina.com/SoftwareProducts/OrcaFlex/ [Accessed 27th April 2016].

Swedish Energy Agency (2016). *Energy in Sweden—Facts and Figures*. Eskilstuna. [Online] Available from: http://www.energimyndigheten.se/globalassets/statistik/overgripande-rapporter/energy-in-sweden-2016_160218.xlsx [Accessed 27th April 2016].

The MathWorks Inc. (2013) MATLAB. R2013b ed. Natick, MA, The MathWorks Inc.

Thies, P. R., Johanning, L., & McEvoy, P. (2014) A novel mooring tether for peak load mitigation: Initial performance and service simulation testing. *International Journal of Marine Energy.* [Online] 7, 43-56. Available from: doi:10.1016/j.ijome.2014.06.001 [Accessed 27th April 2016].

Thies, P. R., Johanning, L., & Smith, G. H. (2012) Assessing mechanical loading regimes and fatigue life of marine power cables in marine energy applications. *Proceedings of the Institution of Mechanical Engineers, Part O*: *Journal of Risk and Reliability.* [Online] 226, 18-32. Available from: doi:10.1177/1748006X11413533 [Accessed 27th April 2016].

Tiron, R., Pinck, C., Reynaud, E. G., & Dias, F. (2012) Is biofouling a critical issue for wave energy converters? In: *Proceeding of the 22nd International Offshore and Polar Engineering Conference (ISOPE2012), 17-22 June 2012, Rhodes, Greece*. International Society of Offshore and Polar Engineers (ISOPE). pp. 669-679.

Vigor Wave Energy AB. (2016) Homepage of Vigor Wave Energy AB. [Online] Available from: http://www.nordicgreen.net/startups/wavetidalhydro/vigor-wave-energy-ab [Accessed 27th April 2016].

Waves4Power AB (2016) Homepage of Waves4power. [Online] Available from: http://www.waves4power.com [Accessed 27th April 2016].

Weller, S. D., Johanning, L., & Davies, P. (2013) Best practice report-mooring of floating marine renewable energy devices. MERiFIC Marine Energy in Far Peripheral and Island Communities. [Online] Available from: http://www.merific.eu/files/2012/06/D3.5.3_Best-practice-report-mooring-of-floating-marine-renewable-energy-devicesv21.pdf [Accessed 27th April 2016].

Weller, S. D., Johanning, L., Davies, P., & Banfield, S. J. (2015) Synthetic mooring ropes for marine renewable energy applications. *Renewable Energy.* [Online] 83, 1268-1278. Available from: doi:10.1016/j.renene.2015.03.058 [Accessed 27th April 2016].

Wilhelmsson, D., & Malm, T. (2008) Fouling assemblages on offshore wind power plants and adjacent substrata. *Estuarine, Coastal and Shelf Science.* [Online] 79 (3), 459-466. Available from: doi:10.1016/j.ecss.2008.04.020 [Accessed 27th April 2016].

Worzyk, T. (2009) *Submarine Power Cables: Design, Installation, Repair, Environmental Aspects.* Dordrecht, Springer-Verlag.

Yang, S.-H., Ringsberg, J. W., & Johnson, E. (2014) Analysis of mooring lines for wave energy converters – A comparison of de-coupled and coupled simulation procedures. In: *Proceedings of ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2014), 8-13 June 2014, San Francisco, California, USA.* New York, NY, American Society of Mechanical Engineers. OMAE2014-23377.

Zaroudi, H. G., Rezanejad, K., & Guedes Soares, C. (2015) Assessment of mooring configurations on the performance of a floating oscillating water column energy convertor. In: Guedes Soares, C. (ed.) *Renewable Energies Offshore: Proceeding of the 1st International Conference on Renewable Energies Offshore (RENEW2014), 24-26 November 2014, Lisbon, Portugal.* London, Taylor & Francis Group. pp. 921-928.

Zhou, Z. R., Cardou, A., Goudreau, S., & Fiset, M. (1996) Fundamental investigations of electrical conductor fretting fatigue. *Tribology International.* [Online] 29 (3), 221-232. Available from: doi:10.1016/0301-679X(95)00074-E [Accessed 27th April 2016].