Final report

1.1 Project details

Project title	Forankringsløsninger for store bølgekraftanlæg
Project identification (program abbrev. and file)	EUDP 64014-0139
Name of the programme which has funded the project	EUDP 14-I
Project managing company/institution (name and address)	Aalborg Universitet, Inst. for Byggeri og Anlæg Thomas Manns Vej 23 9220 Aalborg Ø
Project partners	Tention Tecnology International Floating Power Plant A/S LEANCON Wave Energy WaveDragon ApS Development v/Kim Nielsen Chalmers University
CVR (central business register)	29102384
Date for submission	01-09-2018

1.2 Short description of project objective and results

English and Danish (600-800 characters)

The objectives of the project are to design, test and develop cost efficient mooring solutions for large, slack moored, floating wave energy converters (WECs), and to build national competences in design and modelling of mooring systems for WECs.

Projektets formål er at designe, teste og udvikle kosteffektive forankringsløsninger for store, flydende, løst forankrede bølgekraftanlæg, samt at opbygge nationale kompetencer inden for design og modellering af forankringssystemer for bølgekraftanlæg.

1.3 Executive summary

The worldwide wave energy resource has been estimated to be around 3.5TW, which is a third of the actual world consumption. Although in the last century hundreds of wave energy converters (WEC) have been conceived, this large energy resource is still untapped. The WECs differ in size, shapes, and working principles, but they all comprise of three macro systems:

- Absorber/Structure
- Power Take Off (PTO)
- Mooring

Among the three systems, the focus of this project is given to the Mooring, for the following reasons:

1. Depending on the WEC type, the cost of the Mooring system can sum up to the 30% of the total project cost.
2. Many of the WEC failures can be attributed to a direct failure of the mooring system, which increase the investment risk and reduce the number of possible investors.
3. The mooring system have an influence on the Absorber/Structure loads that is related to a large share of the total CAPEX.

The Danish wave energy sector consists among others of several large floating WECs. All these WECs need to have specifically designed mooring systems, as "standard" solutions (coming generally from the offshore oil and gas industry) are not well suited for the conditions and specifications of WECs. For these it is of importance to reduce the resulting mooring and structural loads rather than avoiding motions, which can be done by increasing the mooring compliance. This will reduce the cost of the mooring and structure of the WECs, and thereby the overall cost of the WECs and their produced energy, while making the systems more reliable.
The four WECs that have been part of this project are

- Floating Power Plant,
- Development,
- LEANCON Wave Energy,
- Wave Dragon.

Although these WECs have different shapes and working principles, they all require similar mooring solutions, as they are large floating structures operating at intermediate water depths (25 – 100m) at commercial scale deployments.

The project worked towards the optimisation of the mooring system for the selected WECs, where the optimal solutions comprise both economical and reliability indexes.

Within the initial phase of the project, the "best" design tool and design practice was identified. The choice of the commercial software package Orcaflex as design tool was made using a total of 13 selection criterions.
With respect to the design standard, for the wave energy sector a document is actually under development, "IEC TS 62600-10:2015: Marine energy - Wave, tidal and other water current converters - Part 10: Assessment of mooring system for marine energy converters (MECs)". The document is derived from DNV, API and ISO standards for traditional mooring systems, such as Oil&Gas.
The critical point in this context is the utilization of standards for systems that has a completely different request in terms of reliability and costs, as well a completely different dynamic characteristic. The project results are and will be used to update the above-mentioned IEC standard, to reflect the need for the wave energy sectors.

In the second phase of the project, different mooring solution concepts for the selected WECs were analysed, using a simplified methodology. The results were used to selected a specific solution for each device and their cost were evaluated; this formed the base for the comparison of the project outcome. In this phase, it was realised how the absence of a design practice resulted in non-standardized and potentially unsafe mooring systems.

The next step was the validation of the selected design tool, in order to quantify the results accuracy, followed by the actual design and optimisation of the mooring system for each of the selected WEC technologies. In order to validate the design tool selected, a test campaign was carried out in the wave basin at Aalborg University. The numerical model validation showed some criticalities in the numerical model, which were addressed during the project.
During the optimisation, it became clearer how the system reliability plays a key role in the cost of the system and highlighted how the design solution proposed by the developers were actually not reliable. It was chosen to prioritize the system reliability instead of cost, resulting in an optimised solution with minor or no cost saving, but reliable.

1.4 Project objectives

The objectives of the project were to design, test and develop cost efficient mooring solutions for large, moored, floating WECs, and to build national competences in design and modelling of mooring systems for WECs.
In order to achieve the above-mentioned objectives a number of smaller objectives and tasks has been accomplished and are listed in details in the following paragraphs.

<u>Identification of the design practises in use within WEC developers and available design practices from neighboring sectors (WP1).</u>
Due to the absence of a specific design procedure for the wave energy sector, design practice from offshore engineering have been identified and used. The closest design practises to the wave energy sector are the one used in oil and gas, naval architecture and offshore wind.
Of particular interest for the design of large wave energy converter are the new design practices for the offshore floating wind. In facts, large wave energy converters have similar structure dynamic and safety requirements; these last are less demanding if compared with oil and gas or naval architecture, due to the reduced impact of possible failures.
The collection of design practices from the four selected developers has the aims to identify what is the actual status of the sector in Denmark, to identify possible gaps and to possibly help the developers to find a sensible common ground for their development.

<u>Identification of the “best” design tool (WP1).</u>
In order to design a mooring system, a number of complex and interconnected problems need to be solved. The two key problems to be solved are the assessment of the hydrodynamic loads on the structure and the interaction between mooring, structure and waves. For many years, the lack of a proper understanding of the problem led to the utilisation of improper tools for the solution of the problem with an increased risk of failure or increase cost.
Nowadays, several off-shelf commercial software can be used to numerically solve the problem, but it is important to identify the “best” tool for the proposed objective.
During the selection of the tool 10 software packages have been compared using 13 metrics to identify the best candidate. The metrics includes accuracy, computational time, usability, etc.

<u>Preliminary design of the mooring systems (WP2-WP3).</u>
The preliminary design of the mooring system for the four selected WECs, has been carried out using a simplified tool (quasi-static analysis) from the Oil and Gas or Naval architecture sectors. It has been found out that this was the main design tool for the four WECs and, therefore, it has been used as baseline in the benchmark.
The methodology relies on sever assumptions, which are often violated if applied on the analysis of WECs.

Due to the installation requirements, it became clear during this phase that traditional chains could not be used to design a proper mooring system; therefore, the objective of the work has been expanded to find alternative solution to the actual problem.

Experimental validation of mooring analysis tool (WP4).
This objective formed a milestone for the overall project results, because it defined the quality of the numerical tool used to estimate the load on the structure and, therefore, to design the mooring system. The selected numerical model, as any numerical model, offer an approximation of the real complex system. It is of paramount importance to understand the accuracy of the results that is directly connect in the reliability of the design procedure.
Physical model scale tests have been used to quantify the range of error expected in the numerical model, as well as to identify possible error mitigation.

Optimal design of the mooring system (WP4-WP5-WP6).
This is the core objective of the project: identify an "economically" optimal, and yet reliable, mooring solution for each one of the selected WECs.
A side objective of the optimization was the identification of a cost database to be automatically used in the cost evaluation of the different mooring solutions. This cost database is intended to be relatively simple but still detailed enough to grasp all the critical cost members.
Another side objective was the selection of efficient numerical methods (optimizers) to automatically identify the optimal solution. Due to the complexity of the problem, standard methods either are inaccurate or requires extensive computations.
It is important to mention that during the course of the project, the department moved twice causing a consistent delay in the project; an extension of the project ending date was granted by EUDP.

1.5 Project results and dissemination of results

A summary of the project outcome is given in the following paragraphs, while the complete description of the project outcomes can be found in the reports and commercial milestones listed in the table below.

Identification of the design practises in use within WEC developers and available design practices from neighboring sectors (WP1).

To carry out this objective it became clear the need of a specific design practice for the wave energy sector. Without a clear and specific standardized procedure, several aspects are often neglected during the system analysis, some of which of paramount importance. At the beginning of the project, none of the initial design of the four selected WECs comprises all the critical elements, inducing a substantial error in the estimation of loads and dimensions. The most surprising outcome was that all the four mooring systems presented as initial design were indeed unfeasible and would have probably resulted in a mooring failure in extreme conditions.

Identification of the "best" design tool (WP1).
The outcome of this objective is the weakest between the project outcomes because the selection that has been made today may be completely different with the passing time: software updates, new software, development in computer power, etc… makes this result transient/volatile.
For example, the utilization of CFD methods for load calculation is still unusable at the time of writing but it will become most probably the best choice in a matter of few years.
The software selected and used in the project is de facto the standard in Naval architecture and Oil&Gas industries. It combines accurate results, with usability and great technical support. The initial cost could be a limiting factor for a small SME, but it can payback in term of ease of use. Further, time limited licenses are available at low price tag.

Preliminary design of the mooring systems (WP2-WP3).
Since wave energy is still at the pre-commercial phase, it is foreseen that the first machine will be installed in coastal areas, with intermediate to shallow water. During the preliminary analysis, it became clear that traditional mooring system composed of chains, cannot be economically adopted for large WEC. The need to reduce structural load to reduce the CAPEX, requires the system to be compliant, which will result in long mooring lines, in the range of kilometers, at an unfeasible cost level. The main alternative for this type of installation is the utilisation of fully synthetic mooring solution. Synthetic lines have been available on the market for long time, but due to the construction procedures, their fatigue life was poor. Due to the development of innovative lines and materials, synthetic mooring solutions are becoming a viable and economical alternative: the Oil&Gas sector is nowadays replacing old chain systems with synthetic ones.
During the preliminary design for each WECs, a mooring system archetype was defined: the identification of these archetypes followed the definition of the system requirements. Three different archetypes were selected: Spread turret system, Single leg mooring, and Multi leg mooring.
The preliminary design of the four WECs showed that the cost of the mooring system has a significant share of the total project cost, giving room for possible improvement.

Experimental validation of mooring analysis tool (WP4).

The experimental campaign was carried out at the Wave Basin of the Civil Engineering Dept. of Aalborg University. The Floating Power Plant was selected for the tests, because at an initial stage it seemed to be possible to use a pre-existing scaled model. The validation of the numerical results from Orcaflex showed some significant and critical points. The utilisation of simple linear potential theory is not suited for a reliable estimation of the mooring loads: hybrid models, with the inclusion of non-linear viscous terms, are need. These non-linear terms are often fitted to the datasets, but this is not a real option if experimental data is not available. It has been shown that decomposing the structure in simple and standard geometry and apply well-known non-linear terms to those elements, it is a good compromise

In addition, it was shown that the oversimplified quasi-static mooring analysis tool from Oil&Gas is not suited for a correct load estimation. In particular, it was shown that the loads are underestimated by 50%, which can result in a faulty design even with the inclusion of safety factors.

Optimal design of the mooring system (WP4-WP5-WP6).
For each of the four WEC, an optimal mooring solution was obtained using the model validated with the experimental campaign. Although, little or no cost reduction has been achieved if compared with the initial design, it is important to notice what follows:
The initial mooring design, obtained either from the developers or using the quasi-static analysis were not reliable solutions, as they would have most probably failed in extreme condition.

The identification of the optimal design was done using an optimization tool inherited from manufacturing engineering. It was selected as compromise between accuracy and reduced computational cost. The methodology allows the user to obtain a representation of the mutual importance of the different design parameters. This last feature showed great potential because it allows the developers to take control on the optimal solution based on additional parameters which were not included in the original problem. It was interesting for example to see how all the developers chose a more reliable option if the price to pay was only marginally higher.

Finally, in order to produce an automatic optimal solution, a cost database was developed together with TTI. Even if it was intended for a rough cost estimation, it turned out to be a complete costing tool for the mooring system, including mooring and anchor line databases as well as vessels and installation cost databases. The tool has been freely released to the consortium partners, while the distribution to a larger group of users is still under discussion.

The results produced within the project are of great interest for the development of the wave energy sector in Denmark and potentially worldwide. Mooring systems are not only a costly element, but are also directly related to several failures during the deployment of WEC. The project clearly showed how the commonly used design practise are either insufficient or wrongly adopted, and identified a better solution for the design problem.

As this project was partially research-oriented, some of the results have been disseminated through journal articles, conference participation, and meetings where relevant stakeholders for wave energy were present.

The table below contains a list of the dissemination material generated through this research project:

Type of dissemination	***Title***
Journal article	Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. Screening of Available Tools for Dynamic Mooring Analysis of Wave Energy Converters. Energies , 10(7), 2017. Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. Validation of a Tool for the Initial Dynamic Design of Mooring Systems for Large Floating Wave Energy Converters. Journal of Marine Science and Engineering , 5(4), 2017. Jonas Bjerg Thomsen, Francesco Ferri, Jens Peter Kofoed, and Kevin Black. Cost optimization of mooring solutions for large floating wave energy converters. Energies, 11(1), 2018. The article is published in a Special Issue of Energies, "Wave Energy Potential, Behavior and Extraction".
Conference participation	Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. Assessment of Current State of Mooring Design in the Danish Wave Energy Sector. In Proceedings of the 11th European Wave and Tidal Energy Conference EWTEC2015, 2015 Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. Experimental Testing of Moorings for Large Floating Wave Energy Converters. Progress in Renewable Energies Offshore RENEW2016, 2016. Jonas Bjerg Thomsen, Jens Peter Kofoed, Martin Delaney, and Stephen Banfield. Initial Assessment of Mooring Solutions for Floating Wave Energy Converters. In The 26th International Ocean and Polar Engineering Conference ISOPE2016 .

	Jonas Bjerg Thomsen and Morten Thøtt Andersen. Sensitivity and Cost Analysis of Mooring Solutions for Large Renewable Energy Structures. The 37th International Conference on Ocean, Offshore & Arctic Engineering OMAE2018 , 2018. Jonas Bjerg Thomsen, Jens Peter Kofoed, Francesco Ferri, Claes Eskilsson, Lars Bergdahl, Martin Delaney, Sarah Thomas, Kim Nielsen, Kurt Due Rasmussen, and Erik Friis-Madsen. On Mooring Solutions for Large Wave Energy Converters. In Proceedings of the 12th European Wave and Tidal Energy Conference EWTEC2017. Kim Nielsen, Harry Bingham, and Jonas Bjerg Thomsen. On the Absorption of Wave Power Using Ship-Like Structures. In The 28th International Ocean and Polar Engineering Conference ISOPE2018.
Stakeholders meetings	Partnerskab for bølgekraft møde, Fredericia, February 2015. Wave Energy International Business2business Event (WEIB), Aalborg, April 2015. International Network on Offshore Renewable Energy (INORE), Naples, May 2015. Wave Energy International Business2business Event (WEIB), Aalborg, April 2016. MSLWEC Project Workshop, Copenhagen, June 2016. Partnerskab for bølgekraft møde, Aalborg, November 2016. MLSWEC Project Workshop, Aalborg, November 2016. MSLWEC Project Workshop, Aalborg, September 2017.
Reports	Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. Current Mooring Design in Partner WECs and Candidates for Preliminary Analysis: CM1 & M3. Aalborg University, Department of Civil Engineering, 2016. Jonas Bjerg Thomsen, Claes Eskilsson, and Francesco Ferri. Assessment of Available Numerical Tools for Dynamic Mooring Analysis: WP1.2 & M1 . Department of Civil Engineering, Aalborg University, 2017. Jonas Bjerg Thomsen. Validation of Mean Drift Forces Computed with the BEM Code NEMOH . Depart-

	ment of Civil Engineering, Aalborg University, 2017. Jonas Bjerg Thomsen and Martin Delaney. Preliminary Analysis and Selection of Mooring Solution Candidates: M4 & WP3. Department of Civil Engineering, Aalborg University, 2018. Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. Experimental Testing and Validation of Selected Tools for Mooring Analysis: M5, T4.1 & T4.2. Department of Civil Engineering, Aalborg University, 2018. Jonas Bjerg Thomsen and Francesco Ferri. Full Dynamic Analysis of Mooring Solution Candidates - First Iteration: T4.3 & M6 . Department of Civil Engineering, Aalborg University, 2017. Jonas Bjerg Thomsen. Hydrodynamic Models of Partner WECs: T4.3 . Department of Civil Engineering, Aalborg University, 2018. Kim Nielsen, Jonas Bjerg Thomsen, Francesco Ferri, Erik Friis-Madsen, Kurt Due Rasmussen, Sarah Thomas, and Jens Peter Kofoed. Impact of Cost of Selected Mooring Solutions on CoE of Partner WECs: CM2 & WP5 . Department of Civil Engineering, Aalborg University, 2018. Kevin Black, Stephen Banfield, James MacKay, Martin Delaney, Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. Potential Cost Reduction Through Large Scale Production: CM3 & T5.3 . Department of Civil Engineering, Aalborg University, 2018. Guilherme Moura Paredes and Jonas Bjerg Thomsen and Francesco Ferri and Claes Eskilsson. Mooring Design for Large WECs - A Reliability Analysis: T6.1. Department of Civil Engineering, Aalborg University, 2018. Jonas Bjerg Thomsen and Francesco Ferri and Jens Peter Kofoed and Claes Eskilsson and Lars Bergdahl and Martin Delaney and Kevin Black and Stephen Banfield and James MacKay and Sarah Thomas and Kim Nielsen and Kurt Due Rasmussen and Erik Friis-Madsen. Summary of the MSLWEC Project: M7 & WP6. Department of Civil Engineering, Aalborg Uni-

	versity, 2018. Jonas Bjerg Thomsen. Scale 1:10 Test of the OWC WEC LEANCON at Nissum Bredning. Department of Civil Engineering, Aalborg University, Denmark, 2015.
PhD Thesis	Jonas Bjerg Thomsen. Mooring Solutions for Large Wave Energy Converters . PhD thesis, 2017.

1.6 Utilization of project results

The results from the project have proven to be very important in first instance for the four selected WECs. A sound cost estimation for the mooring system at the given location and with the given geometry has been developed.

The project results can be exploited at a larger scale due to quality of the results. Of particular interest to the larger audience are the following points:

- Identification of alternative mooring solution for shallow-intermediate water.
- Validation of numerical model with standardized methodology and quantified error range.
- Identification of automatized optimization tools which allow a user selection at posteriori.
- Additionally, the cost database could be a major outcome of the project, if it will be possible to release as open source. This was not identified as an outcome at the beginning of the project.

The results of the project have been disseminated through a series of dissemination activities as listed in 1.5. It is important to note that the results were presented several times to relevant Danish and international stakeholders in order to increase awareness to the mooring issues and possible solutions. At these stakeholders' meetings, other relevant institutions like DTU, DHI, and Offshoreenergy.dk were present.

It is important to note that the project resulted in strengthening of the high international level of expertise for Denmark both in the field of wave energy and more generally in mooring solutions for off-shore renewable structures.

The knowledge collected during the project is already now in use in other project, such as the EUDP-TetraSpar project, that as a direct industrial involvement.

1.7 Project conclusion and perspective

The motivation for this project has been the vision that the partners together could help the wave energy sector, leading to more renewable energy contributing to the global and Danish energy mix.

The interest shown by the international scientific community around the project development and outcome is a clear indicator of the user need. Mooring systems are key elements in the WEC development, but often are treated as a marginal item.

The methodology developed during the course of the project has already met the interest of industrial partners, both in the wave and floating wind sector.

Annex

The relevant documents have been listed in section 1.5 and are or will soon be made available through http://vbn.aau.dk/MSLWEC website from Aalborg University.