Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m

Project acronym	LIFES50+
Grant agreement	640741
	Collaborative project
Start date	2015-06-01
Duration	40 months

Deliverable D7.11: Design Practice for 10MW+ FOWT Support Structures

Lead Beneficiary	University of Stuttgart
Due date	2019-04-30
Delivery date	2019-04-30
Dissemination level	Public
Status	Completed
Classification	Unrestricted

Keywords	Wind, floating, offshore, design, recommended practices, LIFES50+
Company document number	Click here to enter text.

The research leading to these results has received funding from the European Union Horizon2020 programme under the agreement H2020-LCE-2014-1-640741.

Disclaimer

The content of the publication herein is the sole responsibility of the publishers and it does not necessarily represent the views expressed by the European Commission or its services.

While the information contained in the documents is believed to be accurate, the authors(s) or any other participant in the LIFES50+ consortium make no warranty of any kind with regard to this material including, but not limited to the implied warranties of merchantability and fitness for a particular purpose.

Neither the LIFES50+ Consortium nor any of its members, their officers, employees or agents shall be responsible or liable in negligence or otherwise howsoever in respect of any inaccuracy or omission herein.

Without derogating from the generality of the foregoing neither the LIFES50+ Consortium nor any of its members, their officers, employees or agents shall be liable for any direct or indirect or consequential loss or damage caused by or arising from any information advice or inaccuracy or omission herein.

Document information

Version	Date	Description	
01	2019-03-04	First draft for subtask internal review	
		Prepared by	Kolja Müller, Ricardo Faerron, Shengtao Zhou
		Reviewed by	
		Approved by	Kolja Müller
02	2019-03-18	Second draft for project internal review	
		Prepared by	Kolja Müller, Ricardo Faerron Guzmán, Shengtao Zhou, Markus Lerch, Roberts Proskovics, Germán Pérez, Iñigo Mendikoa, Denis Matha, Friedemann Borisade, Jayesh Bhat Ron Scheffler, Maxime Thys, Henrik Bredmose, Freddy Madsen, Antonio Pegalajar Jurado
		Reviewed by	Frank Lemmer, Wei Yu
		Approved by	Kolja Müller
03	2018-04-30	Third draft for project internal review	
		Prepared by	Kolja Müller, Ricardo Faerron Guzmán, Shengtao Zhou, Markus Lerch, Roberts Proskovics, Germán Pérez, Iñigo Mendikoa, Denis Matha, Friedemann Borisade, Jayesh Bhat Ron Scheffler, Maxime Thys, Henrik Bredmose, Freddy Madsen, Antonio Pegalajar Jurado
		Reviewed by	Andreas Manjock, Maxime Thys, Miren J. Sánchez, Håkon Andersen
		Approved by	Ricardo Faerron
Final	2018-04-30	Final version for GA before submission to EC	
		Prepared by	Frank Lemmer
		Reviewed by	Jan Arthur Norbeck
		Approved by	Petter Andreas Berthelsen

Authors	Organization
Kolja Müller	University of Stuttgart
Ricardo Faerron Guzmán	University of Stuttgart
Shengtao Zhou	University of Stuttgart
Markus Lerch	IREC
Roberts Proskovics	ORE Catapult
Germán Pérez	Tecnalia
Iñigo Mendikoa	Tecnalia
Denis Matha	Ramboll
Friedemann Borisade	Ramboll
Jayesh Bhat	Ramboll
Ron Scheffler	Ramboll
Maxime Thys	Sintef Ocean
Henrik Bredmose	DTU
Freddy Madsen	DTU
Antonio Pegalajar Jurado	DTU

Contributors	Organization
Frank Lemmer	University of Stuttgart
Wei Yu	University of Stuttgart
Andreas Manjock	DNV GL
Håkon Andersen	Olav Olsen
Miren J. Sánchez	Nautilus
Raúl Rodríguez Arias	Nautilus

Definitions & Abbreviations

AST	Administrative Support Team
CAPEX	Capital expenditure
CoG	Centre of gravity
CRI	Commercial Readiness Index
D	Deliverable
DFMA	Design for manufacturing and assembly
DLC	Design load case
DOF	Degree of freedom
DTU	Technical University of Denmark
FLS	Fatigue load state
FOWT	Floating offshore wind turbine
GSA	Global sensitivity analysis
H2020	Horizon 2020
HAZID	Hazard identification
HIL	Hardware in the loop
HSE	Health, safety and environment
KPI	Key performance indicator
LCA	Life cycle assessment
LCOE	Levelized cost of energy
MBS	Multibody
MRL	Manufacturing Readiness Level
NREL	National Renewable Energy Laboratory
O&M	Operation and maintenance
OMA	Operational Modal Analysis
PC	Project Coordinator
PM	Project Manager
QTF	Quadratic transfer function
RNA	Rotor-nacelle assembly
RWT	Reference wind turbine
SPR	Source-Pathway-Receptor
SPRC	Source-Pathway-Receptor-Consequence
TRL	Technical readiness level
ULS	Ultimate load state
USTUTT	University of Stuttgart
WPL	Work Package Leader
ULS	Ultimate Limit State

Executive Summary

This deliverable provides the summarized, condensed and scrutinized findings obtained throughout the LIFES50+ project with respect to design practices of FOWT substructures.

The project covered topics of site-selection and design basis definition, upscaled design of existing floating substructures, LCOE, LCA and risk assessment, concept evaluation and concept comparison and design considerations regarding all life cycle stages, identification of critical design load cases and environmental conditions, numerical model development and numerical model verification.

The lessons learned, findings, methodologies and knowledge generated within the project related to the design of FOWT substructures for large wind turbines are documented here. Information is given in particular on necessary pre-design requirements and specifications, experimental and numerical design practices, as well as LCOE, risk and industrialization considerations. The advances with respect to the state-of-the-art design practices for floating wind systems are high-lighted so that they may be implemented in both research and industry. The results provide practical guidance regarding the design process of technically and particularly economically viable 10MW+ floating platforms.

An important project result is the publication of two 10MW public substructures which are based on the real designs of the two selected designers Olav Olsen and Nautilus. These designs are optimized using numerical optimization procedures and design related constraints that were collected throughout LIFES50+.

Contents

1 Introduction

The EU Horizon 2020 (H2020) project LIFES50+ started in June 2015 with a budget of 7.3M € and a planned duration of 40 months. The main goal of the project was to raise the Technology Readiness Level (TRL) of four substructures to allow the introduction of commercially viable concepts for large wind turbines in deep water. Based on the obtained experiences within the project, the overall industry and research community will be supported by provision of public domain information/workflows and recommended practices.

The workflow of the project starts with three different environmental sites of varying severity as reference sites to present realistic scenarios for commercial FOWT projects. Four different substructure concepts were upscaled by the participating designers from the existing designs for 5MW turbines to hold 10MW turbines for the three reference sites. The applicability of available numerical models and design work flows was investigated with respect to their viability considering larger wind turbines and floating wind systems in general. At each of the considered sites, wind farms of varying size were considered for economic evaluation. The resulting concept-specific scenarios were evaluated with respect to LCOE, LCA and risk characteristics. Based on the evaluation, two concepts were further studied by wave tank testing and enhanced optimization with a focus on manufacturing and installation considerations.

The present document summarizes the condensed findings of the project and points out resulting innovation and research needs. This is done based on a state-of-the-art assessment, which was performed in the beginning of the project and is summarized in the next chapter. The document subsequently describes the main findings of the project linked to the core work packages as part of the project. Table 1 provides an overview on the tasks contributing to the design process of FOWT, linked to the work package they were addressed throughout the project.

Table 1: LIFES50+ Work Package and keywords describing the related activities

LIFES50+ Work Package	Keywords describing related activities
WP1: Concepts Development and Optimization	Site selection, environmental assessment, design basis definition, upscaling, marine operations, industrial design optimization
WP2: Concept Evaluation	LCOE & LCA assessment, global concept evaluation
WP3: Experimental Studies	HIL experiments in the wind tunnel and water basin
WP4: Qualification of Numerical Tools	Numerical procedures, optimization & automation, public concepts, model validation, simplified & advanced models, model cascading
WP5: Concept Industrialization	Design briefs, industrialization considerations, material considerations, fabrication and installation considerations
WP6: Uncertainty and Risk Management	Risk assessment, HAZID, HSE

This document itself is part of WP7, whose objective is to scrutinize, examine and summarize any relevant experiences gained within the project related to FOWT design practices. Some of the tasks performed in WP7 included more in-depth analysis and evaluation related to the disciplines addressed in other work packages. For better readability of this document, all findings resulting from work performed in WP7 are included into the related chapters.

2 How to Use this Document

Overall the document builds its main findings with respect to the state-of-the-art of FOWT substructure design which was assessed in the beginning of the project. This document is organized closely related to the structures of the LIFES50+ project. It starts with a brief summary of the state-of-the-art design. Following this, the main results of the different areas of research addressed in the project are presented. For each topic, a brief overview of the work performed in the project is given, together with the key findings and research & innovation needs, which are of interest for the future development of the industry.

Readers with specific research background may only read the chapters related to the field of their interests to obtain condensed information on the relevant project findings and expected future requirements. References are given to all publically available information disseminated throughout the project.

Readers looking for a general overview may read the chapters in the given order. All findings, recommendations and requirements listed in this document are built on the state-of-the-arts of the respective disciplines, as described in chapter3.

3 State-of-the-Art Design Practice for FOWT Substructure

Until 2015, the only commissioned demonstration projects with a large wind turbine were Hywind, WindFloat and Fukushima FORWARD. The potential of floating wind turbines was highlighted in a CarbonTrust report[1], which projected cost parity with offshore wind for the 2020s. The latter report documents over 30 concepts on the market, underlining the high activity in both research and industry with respect to this technology. The available standards for FOWT systems were largely built on the existing standards from both, oil and gas and offshore wind and often included large room for interpretation, which signalled a gap of standardized procedures and recommended practices.

In this light, one of the initial tasks of the project was to assess the general state-of-the-art design procedure of an arbitrary FOWT substructure up to a TRL 4 (technology validated in lab), based on documented design procedures and input from participating designers and project partners. This was used as a reference for new insights throughout the project and also as guideline towards the standardized procedures and methodologies.

According to a state-of-the-art assessment in the beginning of the project, the major steps of numerical design included calculations using spreadsheets and frequency-domain models followed by coupled aero-hydro-servo-elastic time domain simulations, and finally component-specific and detailed design. In most cases the substructure was considered as a rigid body. Advanced and computationally demanding effects like second order hydrodynamics for hydrodynamics and dynamic inflow effects of aerodynamics were not considered in coupled simulations. The controller was seen as a design-dependent component, requiring manual tuning and adaptations by a control engineer. Large conservative assumptions building on experiences from the offshore wind and oil and gas industries were made regarding environmental conditions in order to reduce computational costs. Manufacturing, transport and installation considerations were included as a final step in the design. According to the state-of-

[1] James, R., & Costa Ros, M. (2015). Floating offshore wind: Market and technology review.

the-art analysis, the resulting model is subsequently evaluated both, numerically and finally experimentally in the lab were performed for ultimate load assessment and validation and calibration of numerical models. The experimental testing often included open wind generators employing drag disks or even static wind forces. If design constraints were violated, a new iteration of the design process would be initiated. Design optimization was generally, if at all, considered only in the very early design stages. Predictions of LCOE, LCA and risk performances were isolated. No detailed, standardized procedures were available and, even less so, public and transparent data which was used in the presented procedures.

The assessed state-of-the-art design procedure is shown in Figure 1 and is described in more detail in D7.4 State-of-the-Art FOWT design practice and guidelines.

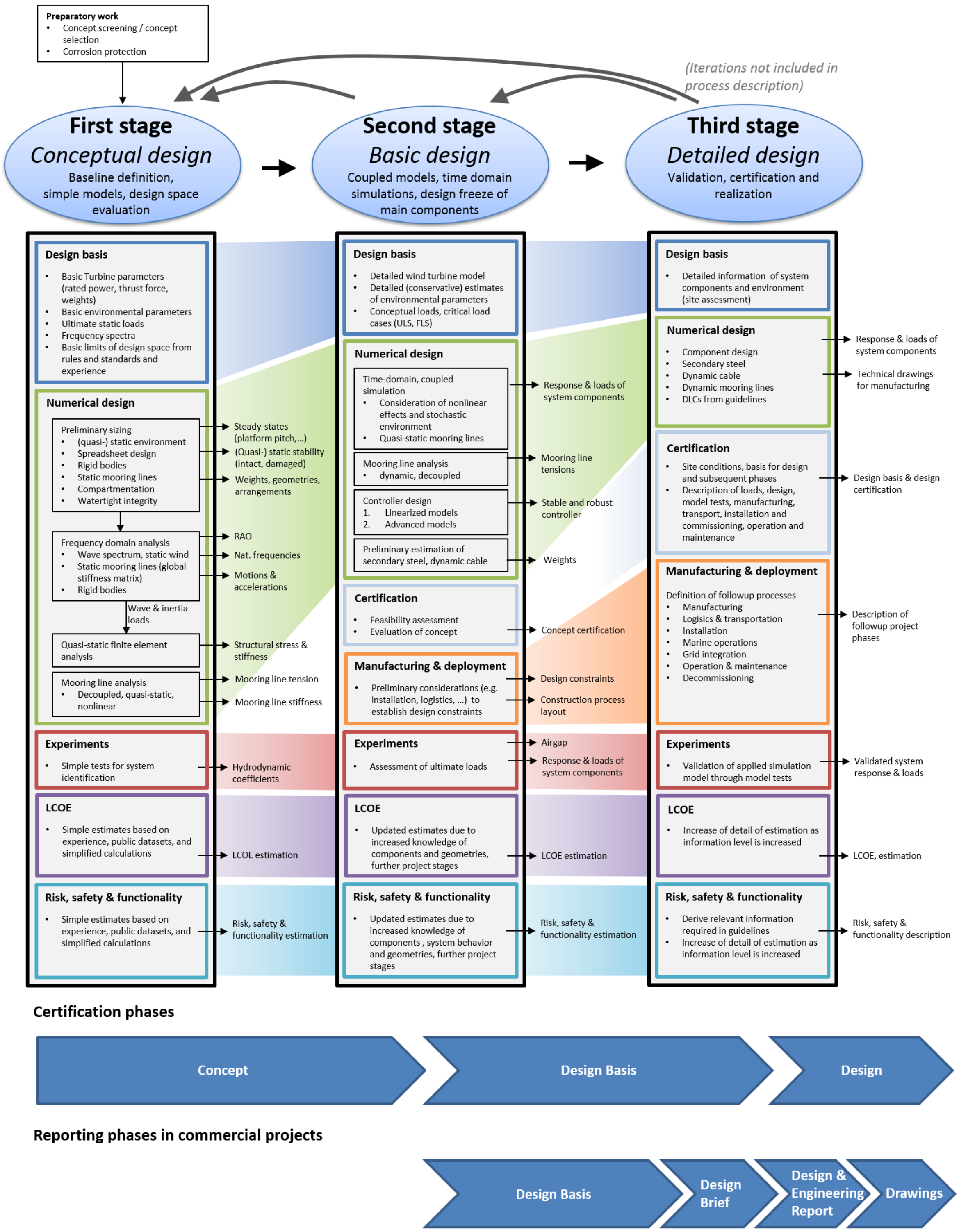

Figure 1: State-of-the-art reference design process of LIFES50+, adapted from D7.4

4 Concept Development and Optimization

LIFES50+ started out with four concepts designed to TRL4 to hold 5MW wind turbines. In order to facilitate the investigation of 10MW concepts at different sites while elevating the TRL of the concepts for large wind turbines, **defining the environment** in which the systems were to be placed in was necessary next to **upscaling and designing** feasible variations of the concepts for the considered sites. Figure 2 gives an overview of the concept design tasks performed in LIFES50+. It also highlights the interaction with the concept evaluation work package.

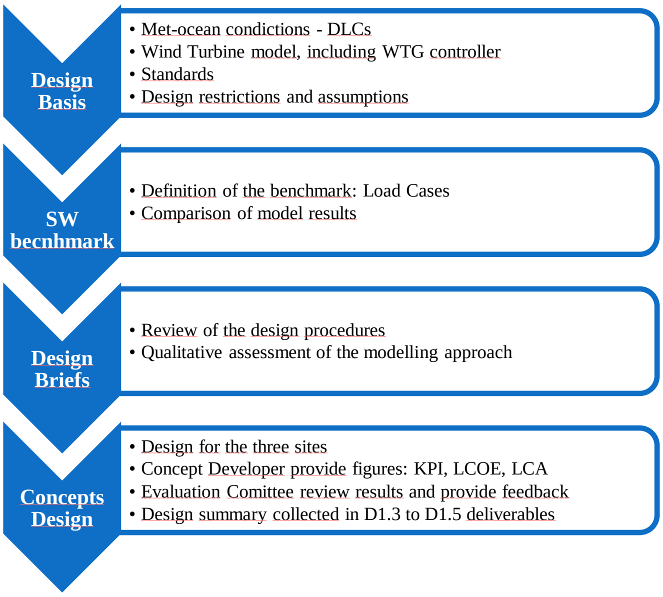

Figure 2: Summary of the design -upscaling- procedure and validation in LIFES50+.

4.1 Findings, Results & Recommendations

4.1.1 Definition of three benchmark sites

In order to define three representative sites and identify their environmental conditions, public domain information was assessed and evaluated. The outcome of the task provided useful insight in future definition of reference sites as well as establishing public datasets for environmental conditions.

The reference locations upon which the three generic representative sites were defined were chosen to be Golfe de Fos, south coast of France (A); Gulf of Maine, east coast of USA (B); and West of Barra, west coast of Scotland (C). The main criteria for choosing the sites were their representativeness of potential markets as well as varying environmental conditions (representing moderate, medium and severe met-ocean conditions), water depths and seabed soil type. Additionally, the availability of public domain data for the considered sites was taken into account.

Figure 3: Indicative locations of the three reference sites[2].

LIFES50+ Deliverable 1.1 provides valuable overview of the decision process on site selection as well as a summary of public data that was used for the detailed assessment of relevant environmental conditions at the different sites. Relevant data for the design included wind climate, wave climate, wind-wave combined conditions, current, water depth and water levels, soil conditions and marine growth (see Figure 4 for an overview). Additionally, location and weather windows were considered important due to their impact on installation and O&M procedures.

	50-year wind at hub height [m/s]	50-year significant wave height [m]	50-year sea-state peak period [s]	50-year current [m/s]	Extreme water level range [m]	Design Depth [m]	Soil Type
Site A	37	7.5	8-11	0.9	1.13	70	Sand/Clay
Site B	44	10.9	9-16	1.13	4.3	130	Sand/Clay
Site C	50	15.6	12-18	1.82	4.2	100	Basalt

Figure 4: Key environmental conditions for the selected sites.

Not all data could be derived from available information and also some information was altered to achieve the desired diversity of environmental conditions within the project. These changes are described in D1.1. Significant assumptions applied in the project included flat bathymetries for all sites, predefined types of seabed and a limitation of the 50 year mean wind speed to a maximum of 50 m/s.

4.1.2 FAST model for the DTU10MW RWT for use on FOWTs

The DTU 10MW RWT was used for all of the four substructure concepts. A FAST model was established based on a HAWC2 model to enable load calculations and comparisons within the consortium[3]. The applied methodology may be of use for future code transfers and/or model verifications and includes comparisons of component and whole system natural frequencies, steady state characteristics at varying wind speeds and stepped wind ramp as well as a reduced set of stochastic simulations for verifying performance of both the control and turbine response. The evaluations were performed based on graphical comparisons of rotor speed, blade pitch angle, tower top fore-aft shear force and electrical

[2] Map from OpenStreetMap, published under ODbL.
[3] Online availability: http://dtu-10mw-rwt.vindenergi.dtu.dk/

power. A reference tower design and turbine controller were also developed as a starting point for the concept's development.

4.1.3 Design basis for benchmark sites

A public, generalized design basis was provided in the early stage of the project. In order to initialize the design in this project, four data packages were defined and distributed to the participating designers as part of the design basis: site environmental conditions, wind turbine data, relevant standards/codes and technical requirements.

The design basis document categorized the three selected sites, a reduced load case table and defined methodologies to be applied in order to allow for a comparative evaluation of the concepts. Particular items addressed were the definition of serviceability limit states (SLS), which limit the operational capability of the used turbine as well as a simplified fatigue evaluation focussing only on power production and significantly reduced sets of wind/wave combinations. Further simplification is possible for design load cases (DLCs) representing ULS during power production, where a limited number of load cases is considered sufficient for preliminary design, such as the rated and cut-out wind speeds as well as wind speeds considering the rotational speed and natural periods of the system and its components. Sensitivity analyses are considered a useful tool in order to reduce simulation times and detail of specific DLCs. As part of WP7 analyses, they also helped to verify the consistency of the designs and identify individual sensitivities of combined environmental conditions.

The evaluation of the defined (DLCs) was required in order to prove the technical feasibility of the concepts for all sites. Due to the limited available public data, it was not possible to get realistic design conditions for all environmental parameters for all three sites. Thus, it was decided to take assumptions representative of harsh, medium and low conditions, which sometimes led to unrealistically conservative sea states. This was accepted as the conditions were still considered as representative for the concepts design and their evaluation.

4.1.4 Requirements for upscaling FOWT substructures

At the very start of LIFES50+, the participating designers were faced with an upscaling task of their existing 5MW-TRL4 concepts. This task sheds light on important implications of the changed boundary conditions when moving towards larger wind turbines or generally when considering design variations.

Overall, the general design procedures for wind turbines of varying sizes or for varying sites can be considered identical. In LIFES50+, all concept developers were able to employ the same design procedure for 10MW systems as they did for a 5MW system. Also, the driving load cases largely remained the same as for substructures designed for smaller turbines. The major items of interest in the upscaling procedure were related to the redesign of the tower and the controller.

Firstly, the upscaling required a **redesign of the tower**. Based on experience from “commercial” floating wind projects (previously installed as well as ongoing), it can be argued that the steel tower design is a key issue with focus on dynamics, natural frequency and fatigue life for the structure. Upscaling can possibly yield an overlap of the 3 times per revolution (3P) frequency with the tower eigenfrequency. This requires concept-specific solutions by ensuring soft-stiff or stiff-stiff configurations.

Regarding, the **adaptation of the wind turbine controller** for floating wind turbines, tuning of the blade pitch controller is crucial in order to avoid excessive platform motion due to controller-induced negative damping. In order to tune the PI controller of the wind turbine properly, the pole-placement method showed feasible results in this project. For FOWTs, additional control loops can be interesting, indicating the employment of more sophisticated controller architectures compared to fixed-bottom turbines. A questionnaire on employed controller design methods was sent to the responsible of different FOWT concepts, inside and outside the LIFES50+ consortium. The questionnaire and a summary on the responses by the designers is part of LIFES50+ Deliverable 7.4.

As part of a questionnaire to the four designers, evaluated in WP7, some general constraints for larger systems were identified. These include minimum water depths related to the **dynamic cable** and the risk of excessively **large footprints** of larger FOWTs (need to be increased due to turbine spacing requirements), which could lead to an overlap of mooring lines at deep sites. Also, it was identified that **logistics** for serial production may present a bottleneck for increasing component sizes, which at some point will reach limits of fabrication. The importance of modularization may be increased in this case. Furthermore, the feasible **hub height** may be reduced due to limited availability of lifting devices meeting the requirements. On the numerical evaluation side, in WP4 it was found that the consideration of **elastic substructure models** (as opposed to assumption of a rigid substructure, which is employed in state-of-the-art numerical evaluation) led to differences in the overall system dynamics. This effect may be negligible for smaller wind turbines but is expected to gain relevance with increased system dimensions.

Increasing the platform size has the advantages that larger systems result in lower relative costs of the substructure, tower and mooring costs, compared to multiple FOWTs of smaller rating.

4.1.5 Specification of manufacturing strategies and marine operations

A specific task during the site-specific design of the different concepts was the specification of the manufacturing strategy and marine operations to be carried out as part of the installation procedures. The framework was the development of a 500 MW wind farm at each of the three sites, with a time constraint of 2 years for the manufacturing and installation. Concluding on the general insights, it was found that several key differences compared to bottom-fixed offshore wind industry have to be taken into account. This includes shorter installation times of tasks performed at sea in general, as important tasks can already be performed onshore or at quayside (e.g. installation of tower and turbine), the expected modification of manufacturing facilities due to large dimensions of floating substructure units, the independent installation of inter-array cables, mooring systems and the platforms. This resulting capacity for parallelization of procedures also leads to increased demand for vessels in the installation procedure, whose availability may limit the overall installation speed.

A close relation to the evaluation procedure carried out in WP2, led to consider procedures and costs for O&M and decommissioning for the reference wind farms. The work to provide figures for the life cycle of the wind farms helped to identify critical means and procedures in terms of timing and costs, like the onshore crane to install the wind turbine in the port dock, or the different strategies for the major repair for different types of floating structures.

4.1.6 Considerations in the design of FOWT substructures

After the concepts design, a workshop was held to collect the experience of the concept developers, the project partners who gave support to the design and the external advisory board. The conclusions are summarized below:

- Working in direct collaboration with a turbine manufacturer is crucial for the optimum design of a floating structure for offshore wind: definition of turbine functional requirements, controller optimization and tower design. Turbine control has been highlighted by all partners as a very important part of the design that might need additional attention.

- Logistics can be a bottleneck for the deployment of large wind farms, using next generation of large wind turbines. Working with the industry is very important for reaching a concept design that keeps on 'standard' industry elements (installation means, auxiliary systems' components, manufacturing facilities capabilities…)
- A global vision of the whole wind farm may be critical for reaching the optimum design. Aspects like wind farm layout, wake effects, power production or O&M strategy may influence the sub-structure and moorings design. Although most of these aspects were out of LIFES50+ scope, they must be considered for a realistic project.
- Second order wave loads may be important for mooring line design.

4.1.7 Critical environmental conditions

A lean set of relevant DLCs enables fast design iterations in the early design phases. A particular focus was thus put on identifying critical DLCs for all substructures. Severe sea states are to be expected among the driving load cases for substructures, and the ALS in particular for those concepts considering redundant mooring systems. Generally, fatigue limit states (FLSs) were not found to be of significant impact, if assumptions were not set overly conservative. However, it was generally agreed as good practice to perform a simplified fatigue check as part of the predesign. The response to operational load conditions can be a good indicator of the performance within predesign sensitivity studies.

While concept-type specific critical conditions should always be considered, the DLCs 1.2, 1.6 and 6.1 (FLS and ULS during power production, and ULS during parked conditions) were found to be of support in early evaluation of various concepts.

4.1.8 Technical Comparison Methodology

In order to enable a fair comparison between the different concepts in the evaluation process, the technical feasibility of all participating designs had to be ensured which was done based on the following methodology. The quality check was performed based on a careful review of the designs, the design procedure employed by different designers and their designs' performance at the different sites. The applied tools, codes and numerical models were summarized in related design briefs. The interpretation of all DLCs, site specific for each concept was also made available for internal review. Comparability of the codes was ensured by a numerical software verification employing a predefined set of benchmark simulations was applied.

A similar procedure was carried out for the figures provided by concept developers for the whole life cycle of the wind farms designed. Different information submissions were followed by a review and feedback to ensure the consistency of the data provided, see also chapter 5.

4.2 Innovation Needs

4.2.1 Improvements in wind turbine modelling and turbine rating

The numerical models with higher fidelity may be required for larger wind turbines. As an example, according to the work within WP1 it was highlighted, that when using FAST, the BeamDyn module should be employed rather than ElastoDyn for blade sub-model to better capture bend-twist deformation and loads, and other structural blade coupling effects. While these may have impact on loads, the implemented BeamDyn version available at this point is not efficient enough from a computational speed perspective to allow implementation in FOWT design procedures. Additionally, the use of the module AeroDyn15, rather than AeroDyn14, allows the consideration of unsteady aerodynamics. Effects and impacts of increasing the structural and aerodynamic modelling fidelity also have to be determined based on sensitivity analyses.

Next to the numerical model, the rating of the turbine considered could be increased in future projects. The bottom fixed offshore industry already looks into projects considering 13-15MW in operation within the next 5 years[4], and 20MW public onshore models are also available in the research community.

4.2.2 Framework for Controller Design

The individual adaptation of the controller for each specific substructure design revealed a need for generalized frameworks and procedures which allow substructure designers to quickly tailor the controller according to design updates.

Additionally, it is foreseeable that advanced controllers such as multivariable control, LiDAR-assisted feedforward control and controllers with additional actuators may provide important benefits in the floating wind industry by offering new possibilities to control the dynamics of the floating structure.

4.2.3 Detailed reference sites with design basis for substructure classification

The definition of representative sites of LIFES50+ aimed at defining three sites with varying intensity of the expected environmental loads. The result was slight variations of the concepts for the different sites, which, according to WP2 evaluation, leads to +/-20% variation of the LCOE of a given substructure. Considering varied bathymetry at a given site, a redesign of the substructure is required for all different positions within a wind farm. However, the installation of the WindFloat platform at Kincardine shows that the same substructure may be suitable for different sites[5]. It is an open question if substructure classification will be implemented for floating wind substructures as it has been for onshore wind turbines or if floating substructures will be optimized for each location individually as is the case for bottom-fixed offshore wind. More research into the feasibility of the two alternatives is necessary next to the definition of benchmark problems to evaluate advantages and disadvantages.

In order to allow for a global evaluation of four concepts at the three sites, some assumptions were taken in LIFES50+ to simplify the overall procedure. Future projects should take into account also variations of the wind farm layout and step forward the wake effects, which are considered of high importance in general, but were considered outside the scope of LIFES50+. Furthermore, varying bathymetry and soil conditions across a site also lead to a higher complexity in the design of a wind farm, which could be a challenge for some concepts. Finally, the turbine availability, which was assumed to be 95%, is considered as conservative value in this project. Because the turbine availability has a high impact on overall project costs (O&M procedures), more certainty on this value is expected to reduce financial uncertainty significantly.

4.2.4 Availability of public datasets to support research and development of standardized procedures

Detailed, complete and accurate public datasets regarding the design basis could improve design assumptions and provide benchmark design problems for the industry and research community. These would help significantly in standardizing design assumptions as well as the development of new design methodologies (e.g. probabilistic design). Regarding environmental conditions, this includes in particular joint probability distributions for mean wind speeds, wave heights and –periods, as well as the geotechnical information. Wind turbine functional requirements like limits on nacelle tilt, acceleration, maximum inclination -operation and extreme conditions- as well as information on components and associated logistic and assembly requirements help to foresee the limitations of operations for different concepts. Finally, wind farm functional requirements (maximum FOWT excursion, minimum

[4] https://www.offshorewind.biz/2019/03/01/thor-throws-hammer-danish-north-sea/
[5] https://www.theengineer.co.uk/kincardine-project-floating-turbine

airgaps, etc.) and wind farm layout detailed definition should help to step forward and consider not only single FOWT in the design, but the whole wind farm and their interaction.

4.3 Related Publications, Available Online

The following documents related to the abovementioned findings may be found online for additional reading:

LIFES50+ Deliverable 1.1 Oceanographic and meteorological conditions for the design,

LIFES50+ Deliverable 1.2 Wind turbine models for the design,

LIFES50+ Deliverable 1.6 Upscaling procedures,

LIFES50+ Deliverable 4.7 Models for advanced load effects and loads at component level,

LIFES50+ Deliverable 7.5 Guidance on platform and mooring line selection, installation and marine operations

LIFES50+ Deliverable 7.1 Review of FOWT guidelines and design practice

LIFES50+ Deliverable 7.2 Design basis

Design Basis for the Feasibility Evaluation of Four Different Floater Designs
Ramachandran, Vita, Krieger, Müller, DeepWind, 2017

Floating offshore wind turbine design stage summary in LIFES50+ project
Pérez, DeepWind 2018

5 Concept Evaluation

The characteristic setup of LIFES50+ required a comparative evaluation of the performance of fundamentally different substructure concepts for a large variety of site conditions and wind farm sizes. In order to facilitate this comparison, a standardized evaluation procedure for technical, economic and environmental performance, based on early design information and predictions, was developed and applied at relevant stages of the project.

5.1 Findings, Results & Recommendations

5.1.1 Probabilistic LCOE Calculation as Part of the Design Process

The consortium constellation of LIFES50+ offered a unique chance to establish an advanced assessment of LCOE for floating wind projects. Having stakeholders with significant experience from oil & gas, bottom-fixed offshore wind and floating wind industries enabled to collect all relevant cost contributors and estimates which are to be expected in future commercial projects with large floating offshore wind farms in the 500 MW range. This is a new achievement compared to previous assessments, whose assumptions built on experiences from conventional offshore wind and/or small scale and pilot projects. These did not sufficiently take into account effects of mass production and operation and maintenance which are to be expected for floating wind.

The developed LCOE tool allows the assessment of substructures LCOE based on CAPEX, OPEX and DECEX, accumulated along the different life cycle phases. Additionally, the tool is able to assess the site-specific expected energy production, which is determined by the location and the wind farm layout. This enables the tool to consider available wind speeds, aerodynamic and mechanical losses, wake losses, grid connection losses, and system availability as key impacts on the production.

A specific feature of the tool is that input parameters can be associated with uncertainties (based on triangle distribution fits). This facilitates the computation of probability boundaries for expected LCOE values. Thus, sensitivity analyses become possible, helping to identify key influences on the LCOE of a project and robustness of LCOE towards specific input uncertainty.

The use of probabilistic LCOE calculation tools, which include detailed information of costs from all life cycle phases, is recommended from LIFES50+ experience for future floating projects. This helps to predict costs in the beginning of a project and identify influential items that should be monitored throughout the project. Updating the LCOE estimate throughout the projects helps keeping track of initial expectations and identifying prediction uncertainties for future projects.

5.1.2 Global Evaluation Measures for FOWT Concepts

Part of LIFES50+ was the comparative global evaluation of fundamentally different floating substructures. Here, an evaluation procedure was established to evaluate substructure concepts for FOWT regarding their economic, environmental and risk related performance based on early design information. In the procedure, the different criteria are evaluated separately. For the overall rating, a dimensionless score for each of the three main criteria is assessed and the weighted sums result in the total score of a considered concept.

The assessment of the LCOE is based on probabilistic calculation, considering the uncertainty of key input parameters that influence the LCOE, which have been identified previously by a comprehensive analysis. This leads to a distribution of expected LCOE values for all platforms and different sites and wind farm sizes. Statistical tests (such as ANOVA and Tukey's test) help to ensure that predicted LCOE distributions between concepts are significantly different. Key performance indicators are a low LCOE value and a small LCOE uncertainty. The LCA is assessed by the three distinctive measures of

Global Warming Potential indicator, Non-fossil Abiotic Depletion Potential indicator and Primary Energy consumption. Finally, a risk score was determined in line with risk assessment in WP6. This meant calculating risk scores for all identified hazards based on relative probability and consequence. Subsequently all risks scores within a risk category are averaged to achieve a representative value for the category. A weighted sum value of all category values is the overall risk score of a concept. Additional to the quantitative evaluations, technical information on the concepts is considered as relevant support. This may be provided in the form of technical key performance indicators (KPIs). In this project these were complementary to the LCOE analysis and provide quantitative information on aspects of platform performance that are not considered or not fully accounted for in the cost calculations. Three types of KPIs were considered in LIFES50+: key design parameters, fundamental properties of the platform (including hydrostatic evaluation) and DLC results. The technical KPIs proposed are particularly useful to help identify potential trouble spots from design changes.

Figure 5 visualizes the condensation of the separate assessment results to perform the global evaluation.

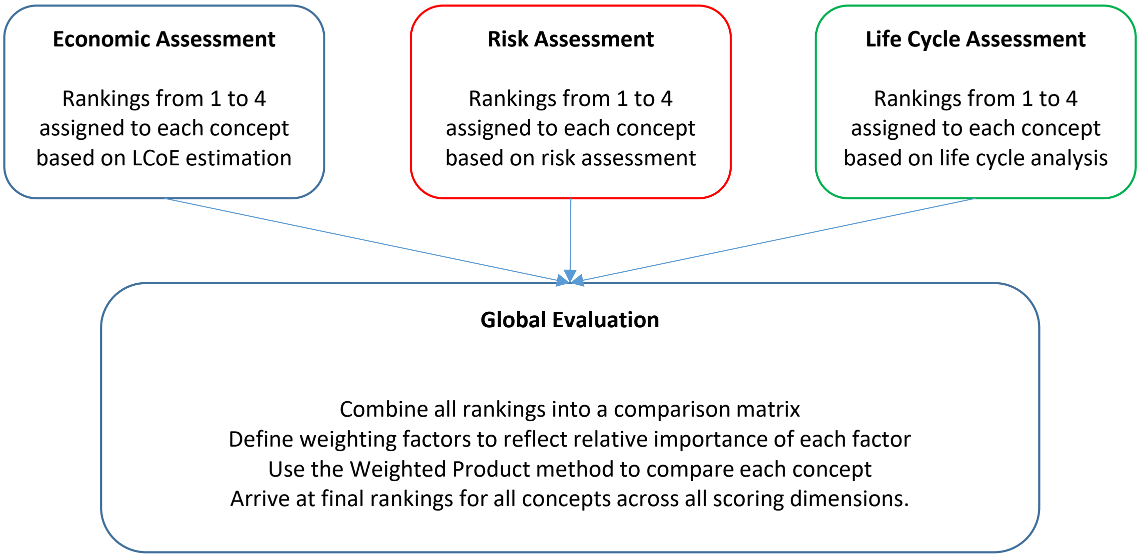

Figure 5: Illustration of Global Evaluation Procedure[6]

5.1.3 Evaluation of cost competitiveness of FOWT

The evaluation of the LCOE tool allowed to update previous predictions of floating wind LCOE, by adding insight into expected costs within commercialized systems rather than focussing on small scale projects or including significant assumptions from bottom-fixed offshore industry. An LCOE evaluation of three generic support structures was performed and evaluated for the three sites defined in LIFES50+[7]. The results show that based on data related to LIFES50+, LCOE can be expected to be competitive with offshore wind. Figure 6 shows the results of this study.

[6] LIFES50+ Deliverable 2.9: Presentation of the methodology
[7] The spar concept is analysed only for two offshore sites due to its larger water depth requirement

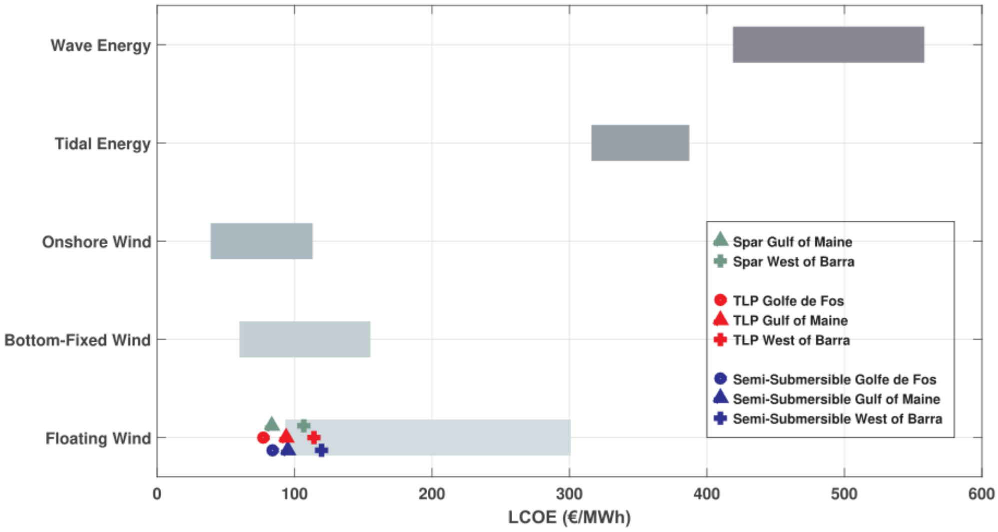

Figure 6: LCOE comparison between energy generation technologies. Calculated values of TLP in red, Semi-submersible in blue and Spar in green[8]

Next to indicating competitiveness for floating wind, the results showed that in principle all available concepts can provide cost competitive solutions. At this stage of research, it appears that the fundamental differences between the concepts are levelled out after all advantages and disadvantages are monetized. This is important, as it was also found that the key contributors to the LCOE are largely concept independent (such as the discount rate, turbine and substation cost). Thus, the decision process during the selection of a substructure designer may not be driven by the concept they represent, but rather other characteristics (e.g. proven track record). Scaling and learning effects, as well as standardization, also in terms of bankability and insurability, may increase the relative importance of the technical soundness of a concept.

5.1.4 Main influences on platform costs

Based on large scale sensitivity studies across various concepts, it was found that next to concept/developer specific items and independent of the same, several key influences on floating wind platforms in general could be identified. This includes in particular the discount rate, which is expected to decrease with reduced financial risks as more experience is included in the market. Also, parameters related to the power cable have shown high impact on the overall LCOE. The decommissioning costs did not show significant impact on overall LCOE for floating wind.

5.2 Innovation Needs

5.2.1 Procedures for Holistic Design Optimization including all Lifecycle Stages

A methodology for the global evaluation of floating wind systems/farms was introduced in LIFES50+ that allows detailed and comparative evaluation between fundamentally different concepts. At this stage, technical KPIs are evaluated only as part of a feasibility check. Furthermore, the three evaluation categories LCOE, LCA and risk were evaluated independent of each other. However, it is clear that technical performance, LCOE, LCA and risk are closely interdependent. For example, results from LIFES50+ have underlined that manufacturing considerations have significant influence on the overall LCOE. Future research needs to bridge the present gaps between the different disciplines by

[8] "*Sensitivity analysis on the levelized cost of energy for floating offshore wind farms*", Lerch, De-Prada-Gil, Molins, Benveniste, Sustainable Energy Technologies and Assessments, 2018

providing feasible methodologies to identify and quantify relevant influences between them. This ultimately leads to design optimizations which consider all the relevant influences from LCOE, LCA and risk perspective, considering all major components of the system, including components which are typically not considered in optimization loops at this stage, such as wind farm layout, wind turbine, station keeping system and electric cabling.

As this requires an increased understanding of the interdependencies within the system, this will lead to more efficient design procedures by knowledge of key components and margins for variation, reduced risk through better prediction of the performance and reduced costs through new means for optimization.

5.2.2 Development of Power Cables for Large Wind Farms

During the cost assessment of large floating wind farms with 10MW units, it became clear that a lack exists with respect to available power cables. The trend towards bigger turbines requires further development and verification of dynamic cables with higher power capacities and the corresponding electrical connectors.

5.2.3 Provision of Floating Substations

The application of floating offshore wind farms in deep waters requires the use of floating substations. In LIFES50+, the focus has been on the development and upscaling of floating substructures for large offshore wind turbines. There is a research and development need regarding substructures for offshore substations in order to comply with environmental loads, standards and certifications.

5.2.4 Definition of Recyclability Requirements

Regarding the end of life management, steel floating substructures could benefit from a greater recyclability, whereas concrete substructures may benefit from their longer lifetime and potential reuse. However, further investigation is required on the recyclability and reuse of offshore concrete structures.

5.2.5 Availability of Public datasets for LCOE and LCA assessment to support research and development of standardized procedures

In order to define standardized procedures for LCOE and LCA assessment, reference problems which build on detailed, realistic and public data sets are key to verify and continuously improve different methodologies. Furthermore, they allow transparent evaluation of cost drivers and sensitivities of the industry, which is valuable information in many different areas of the design process.

LIFES50+ provided unique opportunities to assess LCOE and LCA of large floating wind farm projects in a very detailed way. While this was made possible by close interaction with participating designers, the possibility of publishing reference values for different types of assets is very limited. A particular challenge was the limited data available for the DTU RWT, regarding cost of various components as well as considerations of fabrication, installation and decommissioning. Furthermore, the definition of vessel day rates has been challenging since limited public information is available and the rates are subject to volatility and fluctuations.

For the concepts design and evaluation, manufacturing, transport and installation stages were critical in terms of costs. It was possible to get realistic figures and information about available means at some places, but several assumptions were made for others. There’s a lack of public information to produce a common framework for the evaluation of different concepts and provide LCOE figures based on comparable conditions. Floating offshore wind LCOE is being compared with bottom fixed and it is expected to achieve a similar cost reduction in a much shorter time, but it is difficult to provide realistic figures with a large variability of the main cost drivers.

In the future, a stronger focus should be put on the provision of public data sets. These could be assessed by (anonymous) public domain questionnaires or setting up collection web sites where data can be submitted anonymously[9].

5.3 Related Publications, Available Online

The following documents related to the abovementioned findings may be found online for additional reading:

LIFES50+ Deliverable 2.2: LCOE tool description

Multi-criteria assessment tool for floating offshore wind power plant, Lerch, Benveniste, Berque, Lopez, Proskovics, WindEurope, 2016

A simplified model for the dynamic analysis and power generation of a floating offshore wind turbine, Lerch, De-Prada-Gil, Molins, International Conference on Renewable Energies, 2018

Collection Grid Optimization of a Floating Offshore Wind Farm using Particle Swarm Theory,

Lerch, De-Prada-Gil, Molins, DeepWind, 2019

Sensitivity analysis on the levelized cost of energy for floating offshore wind farms, Lerch, De-Prada-Gil, Molins, Benveniste, Sustainable Energy Technologies and Assessments, 2018

[9] Similar to 4C Offshore or the collaborative online database Numbeo.

6 Experimental evaluation

The main objective of WP3 led by SINTEF Ocean and with supported by Politecnico de Milano was to verify the feasibility, safety, and performance of two selected substructures out of the four designed in the first work package.

Three secondary objectives were:

1) Increase of the reliability of existing experimental techniques for floating offshore wind turbines.
2) Generate model test results for calibration of numerical models (done in WP4).
3) Define how wind tunnel and ocean basin tests can be combined in an optimal way to validate substructure concepts efficiently and more accurately than today.

The key findings related to the main objective are described in WP2, where a second optimisation of the concepts was performed, based on the additional results obtained through the model tests (WP3) and numerical simulations (WP4).

The main findings related to WP3 are about the advances made in the hybrid / hardware in the loop (HIL) model testing technique and the combination of wind tunnel and ocean basin tests.

The WP was organised with an ocean basin test, followed by wind tunnel tests. Since the real-time hybrid model tests in the ocean basin relied on the Aerodyn software by National Renewable Energy Laboratory (NREL), Boulder, US, for the numerical simulations, it was necessary to validate this before the experiments in the ocean basin. For the wind tunnel tests, a new model scale rotor had to be designed due to the large difference in Reynolds number between model scale and full scale. A 6DOF actuator, positioned under the wind turbine, was used in the HIL wind tunnel tests to apply the platform motions. This actuator had to be designed and constructed.

After performing the ocean basin and wind tunnel tests, the results were compared and an optimal verification method was described where use is made of both types of facilities.

6.1 Findings, Results & Recommendations

6.1.1 Aerodynamic Model Performance Compared to Wind Tunnel Tests

Aerodyn is the numerical simulation tool that was used during the real-time hybrid model tests in the ocean basin for the real-time computation of the aerodynamic loads. Validation of Aerodyn for floating wind turbines was necessary since the motions of the rotor can cause the rotor to operate close to or in its own wake.

Specific wind tunnel tests were performed, where a model scale rotor connected to a 2DOF (surge and pitch) actuator was tested at different wind speeds. The tests were done with motions with a range of frequencies including wave frequency ranges and with different amplitudes. The dynamic test results represent a reference database for AeroDyn validation.

All experimental tests were simulated in FAST 8.10/AeroDyn 14. A good agreement is evident between experiments and computations. As a first observation, two different behaviours can be seen: below-rated and above-rated wind velocity, implying different hysteretic aerodynamic responses. AeroDyn is able to properly identify them but was not able to precisely predict them.

This hysteresis, due to unsteady aerodynamics, should be investigated more thoroughly accounting for the variation of the angle of attack as well as the wake characteristics.

6.1.2 Provision of a Scaled Wind Turbine Model for use in Experimental Studies

A model scale wind turbine of a 10MW turbine was designed and built for the HIL wind tunnel tests. A redesign of the blades was necessary due to the large difference in Reynolds number between model scale and prototype scale. The model was built with the aim to match the model scale mass, but this was proven impossible due to the mass of the sourced equipment. Furthermore, the rotor was equipped with an individual blade pitch control.

The design methodology was new in the sense that the model scale wind turbine was designed to model correctly both thrust and the blade first bending mode. The main challenges found during the design process were achieving a representative rotor torque and achieving the scaled mass of the rotor-nacelle assembly.

Figure 7: PoliMi 10 MW Wind Turbine Model in the Atmospheric Boundary Layer test section of PoliMi tunnel (GVPM)

6.1.3 Provision of a Hexafloat Robot to Simulate Wave Induced Motions in Wind Tunnel

A 6DOF actuator, called Hexafloat robot, was designed and constructed to impose the simulated motions to the wind turbine during the HIL wind tunnel tests. Off-the-shelve actuators were not available due to the space limitations under the wind tunnel where the robot is to be installed, requiring the development of novel actuators.

The complete design methodology is described in detail in the deliverable and can be reused for the design of actuator for HIL testing.

6.1.4 Performance of Real-Time Hybrid Model Tests in an Ocean Basin

The real-Time hybrid model test method used in the Ocean Basin permitted to test a floating wind turbine under combined wind and wave loading. The hybrid method helped us overcome the limitations encountered when testing with physical wind and a physical rotor, which are:

- Froude-Reynolds scaling issued requiring a redesign of the rotor
- Wind generation of reduced fidelity and precision compared to wave and current generation
- Difficulty to achieve the model scale mass of the RNA

A cable driven parallel robot was used for the actuation of the aerodynamic loads during the model tests. A new design of the robot allowed us to simulate wind from all directions without needing to make any change, and also test extreme conditions such as gusts with direction change

The bandwidth of the system was increased such that the structural responses of interest, that were correctly modelled, ranged from 0 Hz and up to the tower first fore aft eigenfrequency.

6.1.5 Performance of HIL Model Tests in the Wind Tunnel

The HIL methodology together with the Hexafloat robot permitted to test a floating wind turbine in realistic conditions in a wind tunnel. A real-time simulation tool was developed for the simulation of the platform motions.

The experiments where unique in its kind, and the main challenges that were overcome are related to:

- Correction of larger model mass by subtracting physical inertial loads and addition of simulated inertial loads
- Notch and low pass filtering of frequencies related to tower vibrations
- Design of a model scale controller giving representative motions. A methodology to design a model scale rotor to match closely the prototype behavior was also presented.

Figure 8: The experimental setup for hybrid/HIL wind tunnel tests

6.2 Innovation Needs

From the work presented in this work package, specific subjects have been identified, which are of interest for future research.

6.2.1 Further Validation of Aerdodynamic Models

For the validation of Aerodyn, a comparison of the experimental results and FAST 8.10/AeroDyn 14 showed good agreement. Two different behaviours were seen: below-rated and above-rated wind velocity implies different hysteretic aerodynamic responses. AeroDyn is able to properly identify them but was not able to precisely predict them. The hysteresis cycles observed, due to unsteady aerodynamics, should be investigated more thoroughly accounting for the variation of the angle of attack as well as the wake characteristics.

Finally, the Influence of turbulent wind on the validation process needs to be tackled further on.

6.2.2 Uncertainty Quantification in Experimental Testing

Experimental testing of a FOWT will have some uncertainty associated with the process. There will be systematic and random uncertainties associated with the wave excitation, the test specimen and the response. These need to be quantified for the real-time hybrid model tests in the Ocean Basin as well as for the Hexafloat HIL model tests in the wind tunnel

6.3 Related Publications, Available Online

LIFES50+ Deliverable 3.1: AeroDyn validated model

LIFES50+ Deliverable 3.2: Wind turbine scaled model

LIFES50+ Deliverable 3.5: Hexafloat robot

Multiple-Degree-of-Freedom Actuation of Rotor Loads in Model Testing of Floating Wind Turbines Using Cable-Driven Parallel Robots.
Chabaud, V., Eliassen L., M. Thys, and T. Sauder. Journal of Physics: Conference Series 1104, no. 1 (2018): 012021. https://doi.org/10.1088/1742-6596/1104/1/012021.

Real-Time Hybrid Model Testing of a Semi-Submersible 10MW Floating Wind Turbine and Advances in the Test Method.
Thys, M., V. Chabaud, T. Sauder, and L. Eliassen. In Proceedings of the ASME 2018 1st International Offshore Wind Technical Conference, 11. San Francisco, California, USA: ASME, 2018

Wind Tunnel Tests on Floating Offshore Wind Turbines: A Proposal for Hardware-in-the-Loop Approach to Validate Numerical Codes.
Bayati, I., M. Belloli, A. Facchinetti, and S. Giappino. Wind Engineering 37, no. 6 (November 18, 2013): 557–68. https://doi.org/10.1260/0309-524X.37.6.557.

Aerodynamic Design Methodology for Wind Tunnel Tests of Wind Turbine Rotors.
Bayati, I., Marco B., Luca B., and Zasso A. Journal of Wind Engineering and Industrial Aerodynamics 167 (August 1, 2017): 217–27. https://doi.org/10.1016/j.jweia.2017.05.004.

A Wind Tunnel/HIL Setup for Integrated Tests of Floating Offshore Wind Turbines.
Bayati, I., Alan F., A. Fontanella, H. Giberti, and M. Belloli. Journal of Physics: Conference Series 1037 (June 1, 2018): 052025. https://doi.org/10.1088/1742-6596/1037/5/052025

Control of Floating Offshore Wind Turbines: Reduced-Order Modeling and Real-Time Implementation for Wind Tunnel Tests.
Fontanella, A., I. Bayati, and M. Belloli. In Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering, V010T09A081. Madrid, Spain: ASME, 2018. https://doi.org/10.1115/OMAE2018-77840.

Linear Coupled Model for Floating Wind Turbine Control
A. Fontanella, I. Bayati, and M. Belloli. Wind Engineering 42, no. 2 (April 2018): 115–27. https://doi.org/10.1177/0309524X18756970.

Wind tunnel 2-DoF hybrid/HIL tests on the OC5 Floating Offshore Wind Turbine
I. Bayati, M. Belloli, A. Facchinetti, 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim (Norway), 2017, OMAE2017-61763

A formulation for the unsteady aerodynamics of floating wind turbines, with focus on the global system dynamics
I. Bayati, M. Belloli, L. Bernini, A. Zasso, 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim (Norway), 2017, OMAE2017-61925

Scale model technology for floating offshore wind turbines
I. Bayati; M. Belloli; L. Bernini; H. Giberti; Zasso, A. IET Renewable Power Generation, 2017, DOI:

10.1049/iet-rpg.2016.0956 IET Digital Library

On the aero-elastic design of the DTU 10MW wind turbine blade for the LIFES50+ wind tunnel scale model
I. Bayati, M. Belloli, L. Bernini, R. Mikkelsen, A. Zasso, Journal of Physics Conference Series 753(2), October 2016. DOI: 10.1088/1742-6596/753/2/022028

On the functional design of the DTU10 MW wind turbine scale model of LIFES50+ project,
I. Bayati, M. Belloli, L. Bernini, E. Fiore, H. Giberti, A. Zasso,Journal of Physics Conference Series 753(5), October 2016. DOI: 10.1088/1742-6596/753/5/052018

7 Numerical evaluation

The WP4 focused on the qualification of numerical models and their rational use in design optimization and design verification. A multi-fidelity approach was utilized, centered around state-of-the-art aero-elastic modelling, which is nowadays used for design verification; simpler, efficient models which are turned into an optimizing pre-design tool, and advanced models at component level that predict physical load effects associated with large floaters beyond state-of-the-art. Schematically, these three levels of models are placed along the diagonal in the accuracy-CPU time diagram and the work package focuses on the increased efficiency of and accuracy potential associated with the combination and validation at models at all levels.

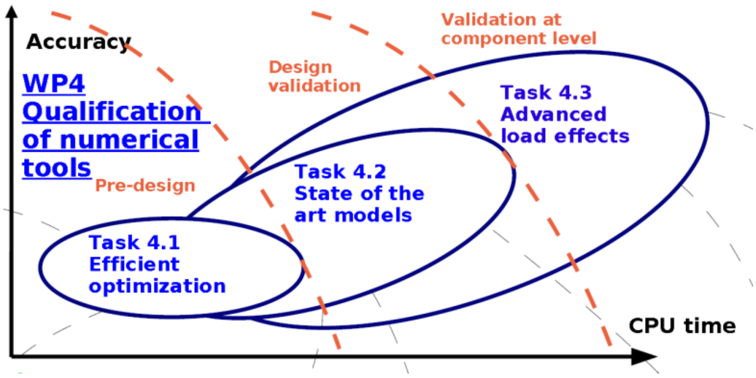

Figure 9: The WP4 setup with three levels of model fidelity in the Accuracy-CPU time diagram.

Close collaboration between WP4 and WP7 (design practices) was part of LIFES50+. Related results from WP7 are also included here, which are related to the topic of numerical evaluation of floating platforms.

7.1 Findings, Results & Recommendations

7.1.1 Verification of Simple Numerical Models for Early Conceptual Design

For early stage optimization of floating wind turbines, efficient numerical tools allowing for large simulation studies and sensitivity analysis are beneficial. In this deliverable, the frequency-domain model QuLAF[10] by DTU and the time-domain multibody model SLOW by USTUTT are introduced. The two models feature high computational efficiency, which is beneficial for early conceptual design calculations.

The simplified models are compared to the state-of-the-art numerical code FAST. This includes system identification, fatigue and extreme load cases according to the LIFES50+ design basis document as found in deliverable D7.2. For the study, a conceptual, generic concrete semi-submersible platform[11] is used together with the DTU10MW reference turbine[12].

Furthermore, a conceptual controller was developed to simulate the whole operational range of the turbine. It includes a common nonlinear state feedback below rated conditions and for above rated-

[10] Jurado, Borg, Bredmose, *"An efficient frequency-domain model for quick load analysis of floating offshore wind turbines"*, Wind Energy Science, 2018

[11] F. Lemmer, J. Azcona, F. Amann und F. Savenije, „*INNWIND.EU D4.37 Design Solutions for 10MW Floating Offshore Wind Turbines*,“ INNWIND.EU, 2016.

[12] C. Bak, F. Zahle, R. Bitsche, T. Kim, A. Yde, L. Henriksen und A. Natarajan, „*The DTU 10-MW Reference Wind Turbine*,“ Danish Wind Power Research, Fredericia,Denmark, 2013.

wind speeds, which are critical for floating wind turbines, a proportional-integral controller with gain scheduling.

Through this work, it is found that both the frequency-domain model QuLAF by DTU and the time-domain multibody model SLOW by USTUTT show good agreement with the reference model in terms of natural frequencies, steady-state simulations and irregular wave simulations. The fatigue loads in operational conditions agree well and thus proves the usability of the models in the conceptual design stages. For extreme loads, however, notable deviations occur due to strong nonlinearities in the aerodynamic and hydrodynamic loads, as well as in the response.

7.1.2 Public Definition and FAST Implementation of two LIFES50+ 10MW Floater Concepts

This work shares the design information for two floating substructures carrying the DTU10MW floating wind turbine. The substructures are the public versions of a four-column steel semi-submersible NAUTILUS-10 by Nautilus Floating Solutions S.L. and the three-column concrete OO-Star Wind Floater Semi 10MW by Olav Olsen A/S. The purpose of the public versions is to be used in physical model tests and numerical model research. The concepts were designed for the Gulf of Maine site, previously described in the Design Basis of the LIFES50+ project as in deliverable D7.2. For each concept, details are given for the tower, floating platform, hydrodynamics, mooring system and wind turbine control system.

Figure 10: The two LIFES50+ 10MW floater concepts. The OO-Star Wind Floater Semi 10MW by Olav Olsen A/S and the NAUTILUS-10 by Nautilus Floating Solutions S.L.

The contribution of this work in D4.5 was mainly the creation of two publicly available FAST models based on the two floating wind turbine concepts. These models served as reference numerical models for the project partners and provide a realistic reference for researchers outside of the project. The implementation of the DTU 10MW Reference Wind Turbine mounted on the LIFES50+ OO-Star Wind Floater Semi 10MW and the NAUTILUS-10 floating substructure is described. The floating substructure and turbine configuration is based on D4.2. Attention in the modelling has been given to the controller, tower structural properties, floating substructure hydrodynamics and the mooring system.

7.1.3 Optimization Framework and Methodology for Optimized Floater Design

The focus of this work was the optimization process in the design of the floating wind turbine in terms of cost and dynamic behaviour. Before the optimization algorithm was laid out, a design space exploration was performed. This helped define the free variables and their boundaries, the cost function and the subsystem design assumptions. A selection procedure of an optimizer was also presented, where a meta model (based on an artificial neural network fit) was used to find an appropriate optimizer with the least necessary number of iterations.

The optimization process presented includes the optimization of the hull shape while adapting the wind turbine controller in every loop. Of especial interest is the incorporation of the model-based controller design with a linear model, and then a nonlinear model for the time-domain calculations.

The optimization loop also included several simulation codes and design scripts. For the hydrodynamics a parametrized panel code was included and a simplified coupled floating offshore wind turbine model (SLOW) carried out the time-domain simulations of the defined power production load cases.

The optimization methodology showed that for a given set of free variables of a semi-submersible platform, one can arrive at a design which significantly reduces the response amplitude for the given environmental conditions. The trade-off in this case is the additional cost of the materials.

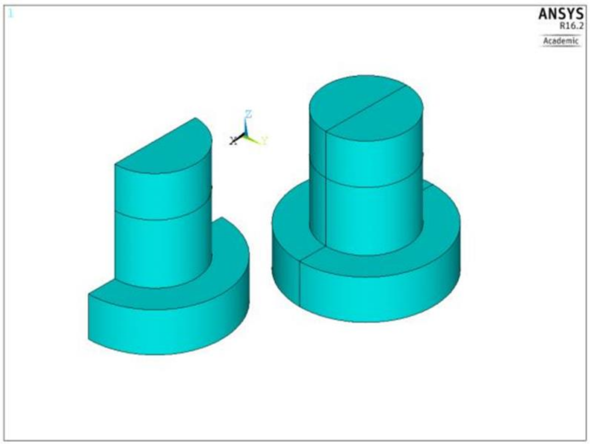

Figure 11: Example of floater design, optimized for low fatigue.

7.1.4 Identification of Challenges and Development Needs in FOWT Conceptual Design

In D4.4 an overview of the state-of-the-art modelling theoretical background for floating wind turbines was documented. It also outlines and compares numerical tools used within the consortium for the design optimization stage of the support structure. Through a survey among the consortium partners, a detailed methodology of the conceptual design of a floating wind turbine is given. The first step in the conceptual design is the static analysis to evaluate the stability and equilibrium states. Then, through dynamic analysis of the substructure, usually in the frequency domain, natural frequencies and response-amplitude operators are computed. Finally, time-domain simulations for a simplified set of load cases is performed, followed by the concept evaluation and possible iteration of the design process.

Challenges identified during the design when progressing to more advanced design phases included:

- automating the process of transitioning from one analysis type to the next
- establishing optimal techno-economic target design criteria to accelerate the design process
- mapping of loads from aero- and hydrodynamic engineering force models to more detailed structural models
- improving computational efficiency

Future numerical modelling activities and improvements needed were also identified. These included:

- more efficient integrated numerical tools
- integration of numerical tools and optimization within the design process
- cascading of design tools from different levels of modelling
- improved treatment of nonlinear wave forcing
- improved calculation of sectional loads in the floater and floater flexibility
- improving the reliability of design tools

7.1.5 Validation of Simple and State-of-the-Art Models against Experiments

For the verification of the design of a floating wind turbine, numerical tools are to be benchmarked against physical test. Thus, for the work in D4.6 the LIFES50+ wave basin tests of the two floating wind turbine concepts, are used for the benchmarking. The two state-of-the-art FAST models of the OO-Star Wind Floater Semi 10MW and the NAUTILUS-DTU10 are compared to experimental data from the wave basin tests performed at SINTEF Ocean. The two FAST models use different hydrodynamic modelling approaches in order to analyse different options.

First, the OO-Star FAST model presented in D4.5 is adapted and compared to experimental results of DLC 1.6 and 6.1. The model uses the Newman approximation for the second-order loads. It was found that the model with decay-tuned global linear and quadratic damping matrices is not sufficient to reproduce load cases with waves. Hence, as a next step, a global linear damping matrix is calibrated for each sea state to match the motion response observed in the physical tests. The results show that this approach is viable and generally yields predictions within 10% error at the 95% percentile of the response's exceedance probability for the full test duration. This is thus a viable approach to reproduce the platform motions when test data is available.

Furthermore, the OO-Star state-of-the-art model is used to benchmark the simplified frequency-domain model, QuLAF. It was found that for the validation of QuLAF against this FAST model, the largest discrepancies were observed for severe wave climates and for turbine operation around rated wind speed. This was linked to three main causes, namely (i) under-prediction of hydrodynamic loads in severe sea states due to the omission of viscous drag forcing; (ii) difficulty to capture the complexity of aerodynamic loads around rated wind speed, where the controller switches between the partial- and full-load regions; and (iii) under-prediction of the coupled tower natural frequency and over-prediction of the aerodynamic damping on the tower.

The validation process showed that the QuLAF model can be used as a tool in the preliminary design stages of a floating substructure for offshore wind. The comparisons were based on time series, power spectra and exceedance probability plots. A big advantage is that the computational speed in QuLAF is between 1300 and 2700 times faster than real time.

Additionally, validation of the NAUTILUS-DTU10 FOWT numerical model with wave tank tests is performed. The state-of-the-art FAST model of D4.5 is adapted and compared to model basin test results of DLC 1.6 and 6.1. The model includes viscous effects of the platform through Morison elements, for which their coefficients of drag are tuned for decay tests. Results show that the low-frequency motion response for irregular waves is generally under-predicted.

From the validation study of the NAUTILUS-DTU10 against wave basin tests it is seen that the model with a decay-tuned Morison drag elements in FAST is not sufficient to reproduce load cases with waves. Possible modelling improvements could be made to the mooring model, the damping representation and the applied Newman's approximation for the second order forcing.

The NAUTILUS-DTU10 FAST model is further compared to a SLOW model. SLOW is a frequency-domain simplified model, which includes constant added mass and parameterized actuator-disc aerodynamics. Results for two irregular sea states in terms of time series and power spectral density show very good agreement with the FAST model in surge, heave and pitch.

For the SLOW model presented of the NAUTILUS-DTU10, it was shown that the reduced-order model is well able to capture the eigenfrequencies of the platform and the tower, including the mooring system. Good agreement is found for the comparison of SLOW with FAST, suggesting that it is possible to use computationally more efficient, simplified models for an assessment of the early design stages.

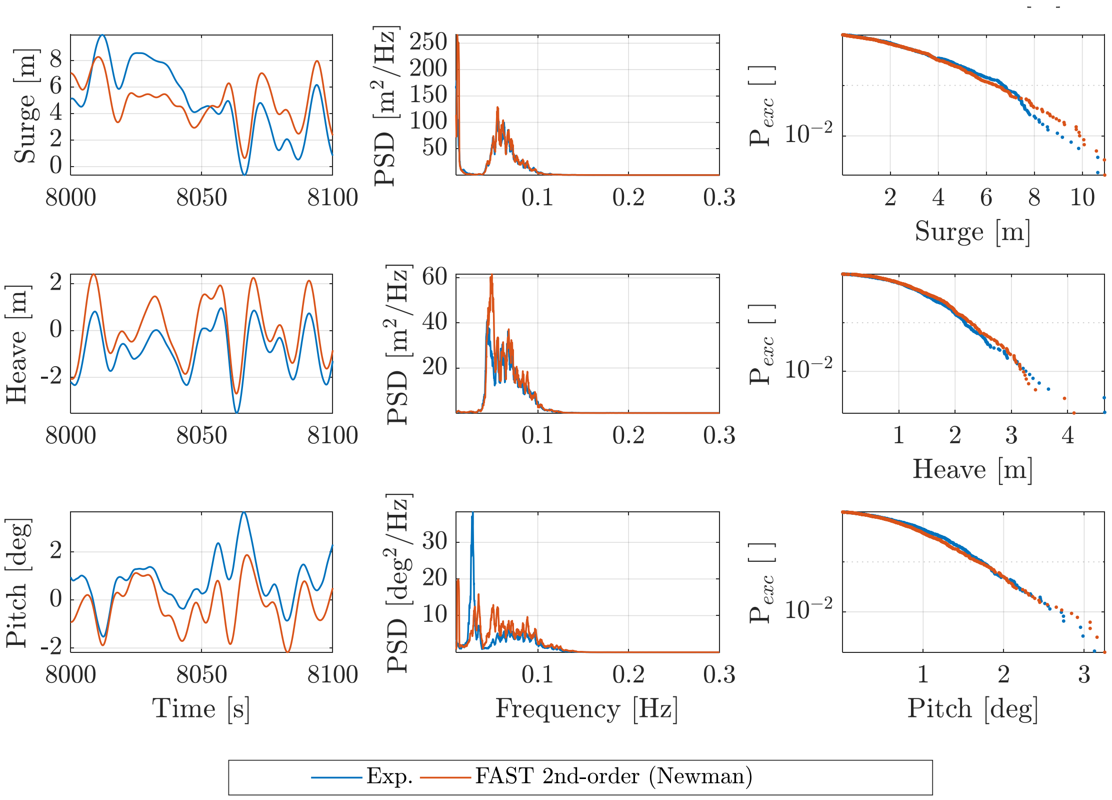

Figure 12: Example of comparison between FAST and experiment for the OO-Star Wind Floater Semi 10MW (DLC 6.1 with $H_s = 9.4$ m, $T_p = 16$ s). Left: Time series. Mid: Power spectra. Right: Exceedance probability plots.

7.1.6 Consideration of Advanced Models

In deliverable D4.7, the development of advanced models for advanced load effects and loads at component level used during the detailed design stages of floating wind turbine design process is shown. Advanced models are advantageous since they help reduce the uncertainty in the design. The five advances in the models presented focus on the model development and initial verification. The advances and the main findings from the work include:

1. Inclusion of floating platform elasticity in dynamic substructure response calculation with a case study of a triple spar platform

   Main findings: For the inclusion of floating platform flexibility, it is shown that the flexible properties can lead to global natural modes with associated frequencies that are within the wave excitation frequency region. From the demonstrated extreme waves, this can result in larger tower-top accelerations and side-to-side tower bending moments.

2. Inclusion of second-order and fully nonlinear wave forcing in FAST8 for the reproduction of wave tank tests of a tension leg platform floating wind turbine

   Main findings: For the presented study of second order and nonlinear wave forcing, it was found that from the different modelling approaches, there was no clear best model to reproduce the tests of the platform tested in the wave basin. For test comparisons, it is recommended to create first-order wave kinematics from the measured signal data, otherwise to use nonlinear kinematics.

3. Validation of an OpenFOAM(R)-based CFD solver for added mass, damping and excitation loads

   Main findings: A good match is found for the comparisons of the added mass and damping for various simulations with varying frequencies and amplitudes of regular wave in OpenFOAM CFD and WAMIT. For heave motions, and likely due to the heave plates, the added mass and damping of the WAMIT simulations compared to CFD are larger and smaller respectively.

4. Description of the fluid-multibody coupled solver (Simpack and ANSYS CFX) for high-fidelity hydrodynamic analysis with an example of the IDEOL floating platform

   Main findings: For the coupling of the CFD CFX solver to SIMPACK, details on the coupling technique for rotor load calculations are given and the approach to wave generation is detailed.

5. Development of a free vortex method for aerodynamic load calculations and comparison to the blade element momentum model

   Main findings: For the implementation of a free vortex method (ECN aeromodule AWSM), a good match with the blade element momentum model is found for the simulations at low frequencies when comparing the thrust during sinusoidal platform motion. At higher frequencies, a much larger hysteresis loop is found with the free vortex method.

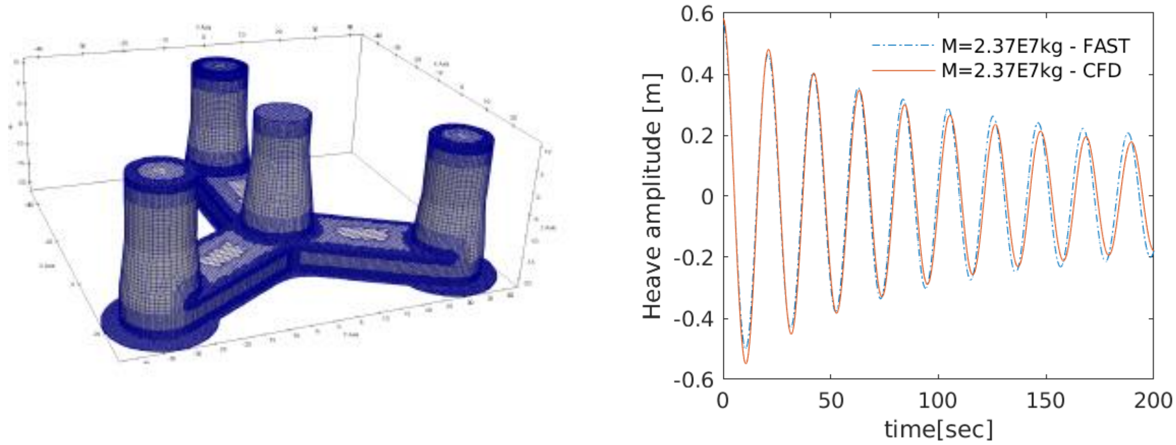

Figure 13: CFD mesh of the OO-Star Wind Floater Semi 10MW floater and decay test for heave compared to the FAST model.

7.1.7 Validation of Advanced Models

The deliverable D4.8 focuses on the validation of advanced models developed within WP4. It gives examples of cascading (application) of results from the advanced models into lower-fidelity models. The work concentrates on the validation within 7 subjects. They are mentioned below along with the contributions from the work.

1. The dynamic response calculations of a numerical model in HAWC2 with elastic modes against experiments

   Main Contribution: The presented validation of the elastic substructure modes inclusion into the HAWC2 aero-elastic model shows that the approach allows calculation of sectional load in the substructure.

2. A second-order FAST model of the OO-Star Wind Floater Semi 10MW with full second-order wave loads and calibrated modal damping, against wave basin tests

   Main Contribution: The presented validation of the second-order FAST model for the OO-Star Wind Floater Semi 10MW with full QTF showed a good agreement between the model and experiment platform motions when sea-state dependant viscous damping calibration was applied.

3. An OpenFOAM CFD hydrodynamics model of the OO-star Wind Floater Semi 10MW

   Main Contribution: Extending the results from D4.7, the validation against experiments for the Open-Foam hydrodynamics model of the OO-star Wind Floater Semi 10MW showed good comparisons for the surge in the high- and low-frequency range, although with some under-prediction of the heave motion. The numerical method in OpenFOAM, though, suffers from well-known instabilities.

4. A second-order FAST model of the NAUTILUS-DTU10 floating wind turbine with full second-order wave loads and calibrated damping, against wave basin tests

   Main Contribution: The presented validation of the second-order FAST model for the NAUTILUS-DTU10 with full QTF showed the need for load-case dependant Morison drag coefficients. However, the methodology was not able to properly reproduce all drift motions for the low-frequency range (especially in extreme wave tests), motivating the need for further investigation.

5. An ANSYS CFX hydrodynamics model coupled to a multibody solver SIMPACK of the NAUTILUS-DTU10 floating wind turbine

   Main Contribution: For the ANSYS CFX – SIMPACK coupled numerical model, comparisons of the radiation damping with potential-flow results show that in the heave direction, the potential-flow solution is much smaller, especially for smaller oscillation periods. This is foreseen as the viscous effects are neglected by the potential flow solution. In general, it is also found that natural periods are better approximated by the MBS-CFD approach even with a coarse mesh and medium size time step than damping.

6. Application of Operation Modal Analysis (OMA) for damping detection

   Main Contribution: For the investigation into the usage of Operational Modal Analysis (OMA) to estimate damping ratios, the OMA damping estimates from experimental data were found to be acceptable when used in the numerical model for the mild pink-noise sea states, while they needed significant re-calibration for the severe sea states with Pierson-Moskowitz spectra. The under-prediction of the response with the OMA damping ratios could be due to the neglected first-order motion effects in the applied second-order inviscid loads, the neglected third-order viscous effects and over-prediction of the mooring-induced damping.

7. The free vortex aerodynamic model against wind tunnel test of the scaled 10MW DTU reference wind turbine

Main Contribution: For the validation of the aerodynamic tools Aerodyn, ECN BEM and ECN AWSM, with experimental data, it was shown that ECN AWSM delivers better agreement with measurements, for sinusoidal motions of the rotor in the pitch or surge directions. In for the surge sinusoidal motions, neither Aerodyn nor ECN BEM provided accurate results, most likely due to the dynamics inflow model failure under such conditions. For pitch sinusoidal motions, all tools were not able to produce comparable results.

7.1.8 Numerical Sensitivity Analyses for FOWT

Global sensitivity analysis (GSA) based on analysis of variance (ANOVA) was identified as a useful tool to identify the most relevant environmental conditions within a given load cases. Next to providing a large-scale robustness check of the numerical model and the design itself, numerical GSA based on chi-square tests or Sobol's indices helped to quantify and rank the impact of environmental conditions on system component loading. Figure 14 shows exemplarily the results of a simulation study which was performed in order to investigate the different impacts of wind speed, wave height and wave period on the FOWT system. Relevant results for the concepts and site under consideration were:

- Wind speed (mean and standard deviation), wave height and wave period of major importance as compared to current, water depth, wind shear and yaw misalignment[13]. Directionality of wind and waves may be of significant influence, when wind-wave-misalignment is considered. The peak load direction is found depending on the substructure geometry.
- Impact of wind speed and wave period is not monotonic, hence special care is to be taken if a binning or reduction of these environments is considered.
- Interactions of wave periods and the wind turbine dynamic behaviour are likely to be of importance for highest loading from wave periods.
- Variation of peak enhancement factor is of minor influence.
- The influence of marine growth on mooring lines may influence the loading significantly, but the origin of influence is concept specific.

[13] However, it is noted that the evaluation of significance may change when considering increased variation of the environmental variables.

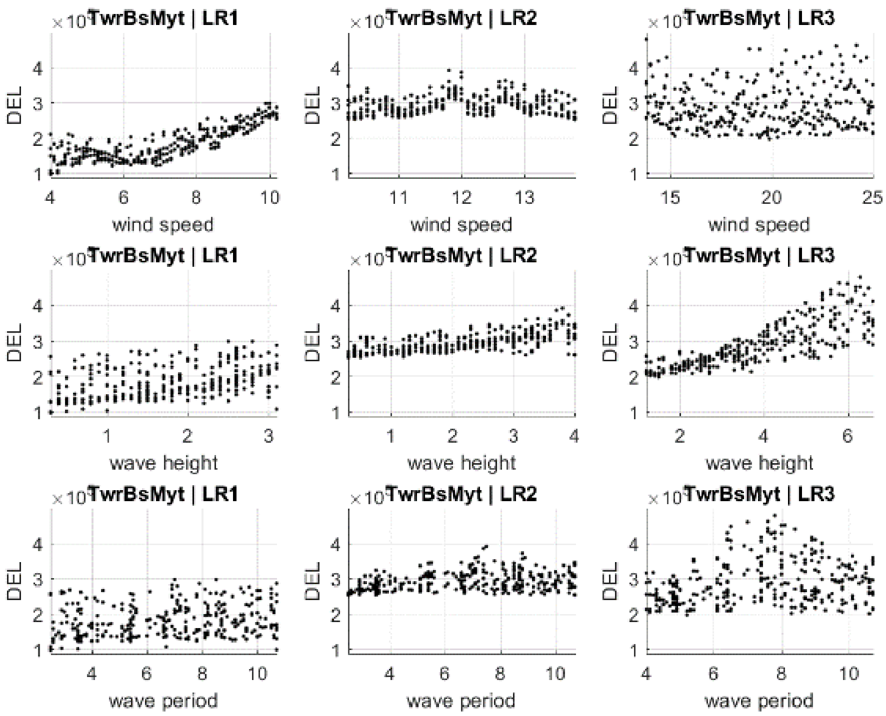

Figure 14: *LIFES50+ OO-Star Wind Floater Semi 10MW* Tower base fore-aft bending moment scatterplots of sensitivity analysis simulations considering variation of wind speed, wave height and wave period for three different load ranges (LR1: below rated, LR2: around rated, LR3: above rated).

7.1.9 Methods for Probabilistic Design of FOWT

The applicability of a large variety of tools and methodologies was investigated as part of the numerical efforts in LIFES50+. The resulting framework includes sampling strategies using Sobol's sequences, automated environmental model definition applying either Nataf and Rosenblatt transformations, which provide probabilistic design conditions for both FLS (scattered data) and ULS (environmental contours), sensitivity calculations building on chi-square or Sobol's indices, and surrogate models using linear or nonlinear regressions. An additional methodology which was found helpful is the bootstrap methodology for uncertainty assessment based on a limited stochastic data set.

7.1.10 Extended Simulation Requirements for FOWT

Sensitivity studies on several floater types performed within LIFES50+ demonstrate consistently that the load simulation of FOWT today is far away from a standardised and uniform process. The varying site-specific environmental conditions and the differences in floater and station keeping design concepts require an individual analysis of each concept and a careful load case setup in order to meet the FOWT concept peculiarities. This leads to comprehensive statistical considerations with high computational efforts in terms of data volume and calculation time. The convergence studies performed for FLS and ULS simulations point out that for achieving an accuracy of +-5% of the calculated load requires a remarkable amount of simulations. Some of the concise results are:

- 500 to 1000 seconds run-in-time in advance of every load case to exclude transient effects (initial operational parameters already predefined, otherwise 2000 s might be required)
- 3 hours simulation time for all components with significant impact of sea states to design loads or split of the 3 hours into shorter simulation packages with different seeds.
- 24 wind-wave misalignment combinations at least in case of sensitivity of the floater type to directionality. A special focus is to be put on the platform geometry in the selection of the directions.

- Resolution of the environment:
    - Wind speed: 2.0 m/s wind bin size at least, additionally include controller-specific wind speeds
    - Wave height: 1.5 m wave height bin at least
    - Wave period: 2.0 s wave period bin at least
- The full spectrum of wave periods of each wave height bin to be considered with special focus on interaction with low frequency floater motions

7.1.11 Requirements for Reduction of Considered Load Cases

A complete load setup for a FOWT according to one of the referenced certification standards requires at least the double amount of load case variations than for of a comparable sized bottom fixed offshore wind turbine. A reduction of load cases and parameter variations are only possible when detailed knowledge about the dynamic interaction of the floater type with environmental conditions is present. A known sensitivity for instance regarding specific, critical wave periods or wind wave misalignment angles could reduce the load setup significantly.

Some detailed potentials for reducing load case variations could be identified in the project:

- For calculation of RNA loads on FOWT 10 minutes simulation time appears sufficient
- For known floater behaviour regarding wind waves directionality a reduced setup could be the conservative application of unidirectional wind and waves, 180° misalignment or design specific misalignments such as 60 or 90°.

7.2 Innovation Needs

7.2.1 Simple Numerical Models

The simplified numerical models SLOW and QuLAF, were in limited agreement with the state-of-the-art FAST model when comparing extreme conditions. This is attributed to differences in loads, control, damping and mooring system models within the simplified numerical design tools, and the needed changes should be explored in future work.

Finally, it was found that introducing viscous hydrodynamic forcing and proper calibration of the damping against a state-of-the-art model could result in improved accuracy, but at the expense of lower CPU efficiency and less generality in the model formulation.

7.2.2 Numerical Optimization Frameworks

For the optimization framework of the FOWT outlined in this WP, while the general findings are considered valid, further studies could include:

- A higher-fidelity study in the subsequent design phases, including other load cases and ultimate loads, to prove the results and to proceed with the detailed subsystem design (e.g. detailed structural design, mooring design, etc.).
- Side-side dynamics and wind/wave misalignments to make the control design process more realistic, accounting for resonances or bandwidth limitations of the actuators
- On the hydrodynamics side, finer meshing and verified damping numerical models as well as second-order forcing for the verification of mooring design
- A more complex cost function that seeks an optimal solution in terms of system engineering including all lifecycle stages of a FOWT system inside a wind farm.

- Investigations into whether the inclusion of the wind turbine controller alters significantly the results compared to results of only using linear frequency-domain methods (panel code) of a rigid body
- Include optimization of more system components, like mooring lines, wind turbine tower, controller and even the complete substructure.
- Include a sensitivity analysis as a primary step of the optimization procedure to determine the design driving environmental conditions and load cases.

7.2.3 Quantification and Reduction of Uncertainties in Common Numerical Models Used for FOWT Load Assessment

After the outline of the numerical tools used for the substructure design by the consortium partners (D4.4), it is identified that the tools are qualified to some extent for use in the design of floating 10MW wind turbine substructures, as they present reasonable agreement with measurements for normal operating conditions. However, in transient and more adverse conditions they do not satisfactorily predict extreme loads as shown in[14]. Also fatigue estimates can vary somewhat for different components across many operating conditions. This motivates further investigation into the quantification and reduction of uncertainties in the model predictions.

7.2.4 Improvements of Advanced Models

During the investigation into nonlinear wave forcing, the following was found: for the inclusion of second-order and fully nonlinear wave forcing in FAST for the reproduction of wave tank tests of a tension leg platform floating wind turbine, investigation into a more detailed, non-constant, customizable user-defined numerical damping for the compared models is recommended.

Furthermore, ongoing OpenFOAM validation and developments includes implementation of detailed mooring systems (dynamic/quasi-static), response of the floater in more realistic waves including irregular and phase-focused waves and quantification of turbulence models (especially for higher sea states/focused waves).

7.2.5 Further Validation Needs for Advanced Models

The deliverable D4.8 is divided into different sections or topics that deal with the validation of advanced models. Different findings are highlighted in the following paragraphs.

For the presented validation of the elastic substructure modes inclusion in an aero-elastic numerical model, further validation for a floating structure with a natural frequency within the wave excitation frequencies would be desired.

Regarding validation with CFD, current field of research in OpenFOAM should focus on the numerical method´s well known instabilities, some of which are cause by the weak coupling between the fluid and the motion solver. Furthermore, for future use of CFD, quantifying the effects of turbulence on wave breaking to better understand such flows is of high interest.

For the presented validation of the second-order FAST model for the NAUTILUS-DTU10 with full QTF, the difficulties of validation of the damping for the different load cases showed the need for investigation and possible incorporation of the dependencies of the coefficients of drag of the platform and the mooring lines on non-dimensional parameters such as the Reynolds number and the Keule-

[14] A.N. Robertson, J.M. Jonkman, F. Vorpahl, W. Popko, et.al, "*Offshore code comparison continuation within IEA wind task 30: phase II results regarding a floating semisubmersible wind system*". 33rd International Conference on Ocean, Offshore and Arctic Engineering, San Francisco, USA, 2014

gan–Carpenter number. Additionally, investigation into the scaling effects on the motions and loads is of interest for future developments in floating wind turbines

Finally, for the validation of the aerodynamic tools Aerodyn, ECN BEM and ECN AWSM, experiments with sensors for visualising the flow field and CFD calculations are expected to help to better understand the occurring phenomena. Additionally, dynamic stall effects should be analysed in more detail for creating more accurate input conditions for simulations.

7.3 Related Publications, Available Online

7.3.1 Publications on simplified models

LIFES50+ Deliverable 4.1: Simple numerical models for upscaled design

LIFES50+ Deliverable 4.3 Optimization framework and methodology for optimized floater design

An efficient frequency-domain model for quick load analysis of floating offshore wind turbines.
A. Pegalajar-Jurado, M. Borg, and H. Bredmose Wind Energy Science 3, pp 693-712 2018.

Iterative Frequency-Domain Response of Floating Offshore Wind Turbines with Parametric Drag
F. Lemmer, W. Yu and P.W. Cheng (2018) J. Mar. Sci. Eng. 2018, 6, 118.

Multi-level hydrodynamic modelling of a 10MW TLP wind turbine
A. Pegalajar-Jurado, H. Bredmose and M. Borg (2016), Energy Procedia 94, pp 124-132. Proceedings from EERA DeepWind 2016

Parametric Wave Excitation Model for Floating Wind Turbines
Lemmer, F., Raach, S., Schlipf, D., and Cheng, P. W. (2016). Energy Procedia 94, pp 290-305. Proceedings from EERA DeepWind 2016:

Control design methods for floating wind turbines for optimal disturbance rejection
Lemmer, F., Schlipf, D., & Cheng, P. W. (2016). J. Phys. Conf. Series 753. Proceedings from Torque 2016

Optimization of floating offshore wind turbine platforms with a self-tuning controller
F. Lemmer, K. Müller, W. Yu, D. Schlipf and P.W. Cheng (2017). ASME 2017. Proceedings from OMAE 2017

The TripleSpar Campaign: Validation of a reduced-order simulation model for floating wind turbines
F. Lemmer, P.W. Cheng, Y. Wei, A. Pegalajar-Jurado, M. Borg, R.F. Mikkelsen and H. Bredmose (2018). ASME 2018, Proceedings from OMAE 2018.

7.3.2 Publications on public models at state-of-the-art level

LIFES50+ Deliverable 4.2 Public definition of the two LIFES50+ 10 MW floater concepts

LIFES50+ Deliverable 4.4 Overview of the numerical models used in the consortium and their qualification

LIFES50+ Deliverable 4.5 State-of-the-art models for the two LIFES50+ 10MW floater concepts

LIFES50+ Deliverable 4.6 Model validation against experiments and map of model accuracy across load cases

State-of-the-art model for the LIFES50+ OO-Star Wind Floater Semi 10MW floating wind turbine
A. Pegalajar-Jurado, H. Bredmose, M. Borg, J. G. Straume, T. Landbø, H.S. Andersen, W. Yu, K. Müller and F. Lemmer (2018). J. Phys. Conf. Series. 1104 2018. DeepWind 2018

7.3.3 Publications on advanced models

LIFES50+ Deliverable 4.7 Models for advanced load effects and loads at component level

LIFES50+ Deliverable 4.8 Validation of advanced models and methods for cascading into simpler models

Floating substructure flexibility of large-volume 10MW offshore wind turbine platforms
M. Borg, Hansen and H. Bredmose (2016). J. Phys. Conf. Series. 753 2016. Proceedings of Torque 2016

Elastic deformations of floaters for offshore wind turbines: Dynamic modelling and sectional load calculations
M. Borg, Hansen and H. Bredmose (2017). Proceedings from OMAE2017

Effect of second-order and fully nonlinear kinematics on a TLP wind turbine in extreme wave conditions
A. Pegalajar-Jurado, M. Borg, A. Robertson, J. Jonkman and H. Bredmose (2017). Proceedings from OMAE 2017

A CFD model for the LIFES50+ OO-Star Wind Floater Semi 10MW
H.S. Chivaee, M. Borg, A. Pegalajar-Jurado and H. Bredmose (2018). Proceedings from EERA DeepWind 2018

CFD Simulations of a Newly Developed Floating Offshore Wind Turbine Platform using OpenFOAM
Sarlak Chivaee, H., Pegalajar Jurado, A. M., & Bredmose, H. (2018). 21st Australasian Fluid Mechanics Conference, Adelaide, Australia 2018

8 Concept industrialization

A major challenge for the floating wind industry remains the definition of standardized, industrialized design processes. Reaching a comparable efficiency as the processes employed for state-of-the-art monopiles is expected to lead to significant cost reductions of the overall floating industry. This was one of the pronounced goals of LIFES50+ and hence was addressed in WP5.

The work considering industrialization work flows and methodologies investigated all lifecycle phases with respect to potential improvements to reach mass production capabilities. This included focal research in the areas of preliminary mooring line design as well as design and process optimization considering fabrication and installation requirements for platforms made of both steel and concrete.

8.1 Findings, Results & Recommendations

8.1.1 Consideration of New Technological and Computational Challenges

Building on the experiences from O&G as well as bottom fixed offshore wind in particular, a roadmap was provided, which describes how an industrialized design process for FOWT can be achieved. Compared to fixed bottom offshore, the results of the evaluation show that while some aspects of floating wind design show less complexity (e.g. geotechnical analysis for catenary mooring systems or individual designs within a wind farm), significant differences are to be expected with respect to (1) **new components** (mooring lines, umbilical, anchors, floating substructure) and those requiring **requalification or -design** (tower, RNA, controller), (2) **numerical models** (higher fidelity of hydrodynamics, importance of coupled models), (3) **new procedures for installation, operation and maintenance** (in-/on-/offshore installation and O&M, vessel requirements, workability), (4) **new design load cases**, including new fault cases and directionalities and misalignments.

Considering the design tools for industry-based design, the requirements are related to increase efficiency of the overall concept evaluation procedure. This includes capabilities for **automated pre- and post-processing modules,** which are implemented in accordance to design standards and enable the designer to assess and interpret results as swiftly as possible. This also encompasses automated generation of load case tables based on available met-ocean data. Also, **automated and parallel execution of multiple computations** in the time domain is important to accommodate for the increased demands for computation (increased number of load cases) due to e.g. fatigue load assessment or design optimization studies. To allow the latter, fast and extensive model parameter variations are required, and **advanced optimization algorithms** may be applied. These should account for longer iteration times (3h instead of 1h for full statistics, more complex numerical models, etc.) and embedded optimization loops which also require data transfers between dedicated models and software tools.

An aspect of primary importance is the **data exchange between wind turbine manufacturer and substructure designer**. This has been highlighted in different areas of the project and also plays an important role for industrialization. Different ways for interaction have been evaluated. The proposed methodology should always be a full exchange of all necessary data to enable integrated time-domain load calculations with state-of-the-art aero- servo- elasto- hydrodynamic simulation tools as well as model tank testing. This is considered to significantly drive down both costs and risks of the system design instead of interactions with limited and reduced data exchange.

8.1.2 Preliminary Mooring Line Design

Available standards[15] for the design of station keeping systems, which are also relevant for floating wind systems, only indicate design procedures for detailed designs, referring to a detailed set of load cases, including fatigue design. To enable early design loops and optimization of possible mooring configurations, as part of LIFES50+ a conceptual mooring design procedure was introduced in D5.2 for semi-submersible substructures. The same procedure was applied to determine relevant influences and performance criteria of the mooring system.

The approach builds on a quasi-static design methodology with a focus on a limited number of load cases: two ULS (parked and operating at rated wind speed) and one ALS (mooring line failure added to ULS parked). From experience, fatigue loads may be neglected in the majority of preliminary mooring line designs, which is why they are neglected in this procedure[16]. Floater motions are calculated considering steady wind loading (including aerodynamic drag of the tower), 1st order hydrodynamic forces and 2nd order drift forces (slowly-varying and mean) and current-induced viscous drag forces. **Current drag force as well as second-order wave loads and drift forces on the floater may be significant and must be considered already in early phase of mooring design.** For selection of environmental conditions, the contour line method was applied, using 50-year environmental contours for significant wave height and peak wave period (based on 3D contour plane at rated wind speed for ULS during operation). Resulting loads are multiplied by safety factors as provided in DNVGL-OS-E301. The approach was found to provide robust and fast solutions in the early stages of the design, when various setups with varying materials are to be compared.

For a preliminary design, the mooring line system may be parametrized by the **input parameters** chain/rope diameter, chain/rope lengths, anchor radius, clump weights/buoyancy modules (including position). The **design space boundaries** are considered to be set by the limits of maximum tension in the mooring lines, uplift angle at the anchor, maximum floater offset (due to dynamic cable limitations) and no synthetic rope in contact with sea bed or water exchange area. In preliminary evaluation, the **performance** can be evaluated based on more or less quantitative measures like robustness towards uncertainties of weather or installation, installation procedure, recycling, redundancy and material costs.

8.1.3 Material Considerations

Both steel and (reinforced) concrete are used as materials in existing floating wind substructures, making the choice of material one of the primary characteristics of a platform concept. Regarding concrete in particular, in-situ concrete is considered to be the state-of-the-art solution. The advantages and disadvantages of material choice regarding fabrication considerations were evaluated as part of LIFES50+ and are summarized in Table 2.

[15] See, e.g. DNVGL-OS-E301

[16] While fatigue loads are expected to be of higher relevance for FOWT than in traditional O&G projects, early experiences showed that the ULS based approach is still considered to provide valuable primary designs which are close to the final design which includes FLS consideration.

Table 2: Advantages and Challenges of Material Choice in the Fabrication Process[17]

	Advantages	Disadvantages

Steel	• Established in the offshore wind industry:
	  ○ Know-how existing
	  ○ Proven solutions and standards exist to avoid issues related to corrosion due to saltwater and salty air, wind turbine load, etc.
	• Assembly can be executed relatively fast if components are pre-fabricated (consists of welding operations and positioning of the parts only)
	• Potential of automated pre-fabrication
	• Lighter substructures are possible (compared with concrete)
		• Large dimension components/parts:
		  ○ Need to be built at rare large-scale steel mills, typically not at construction site, which is a challenge for mass production
		  ○ Heavy/large parts need to be transported to construction site, suitable access (road, railways, waterways) required
		  ○ Suitable storage area at port required
		• Expensive material, price fluctuating, planning difficult
		• Specialized equipment (e.g. large-scale welding machines and cranes with sufficient lift capacity) required, shipyard preferable

Concrete	• Concrete supply and formula adaptable to local conditions and project requirements:
	  ○ Ready-mix concrete
	  ○ Mobile batching plant
	  ○ Installation of a stationary batching plant at the construction site
	• Local content is ensured (local workforce, local supply chain)
	• No specialized equipment, like large scale welding machines, required (construction at lower costs)
	• Low costs of concrete as a raw material
	• Adjustments simple to apply due to variability of:
	  ○ casting process at construction site
	  ○ Ready-mix concrete only: less storage area required (no raw material has to be stored for batching at port)
	• Robust to external conditions compared to steel and long life-time
		• Limited use in offshore wind industry, resulting in less experience with production steps, O&M, decommissioning procedures and pre-casting
		• Large dimensions of concrete floaters require large construction area for mass production
		• High weight of concrete floaters (restrictions for construction site selection due to the bearing capacity and space)
		• Concrete cannot bear tension loads, therefore additional procedures (e.g. pre-tensioning, avoiding of upending actions) necessary
		• Wide range of weather restrictions for construction process (e.g. no construction during frost or heavy rain)
		• Mixing process at the construction site possibly more inaccurate (additional quality assurance necessary)
		• Curing times restrict scheduling and transportation

8.1.4 Fabrication Considerations

The choice of an adequate construction site highly interdepends with the target FOWT design. Within LIFES50+, the options and constraints involved in defining the fabrication procedures (assembly of prefabricated parts) were assessed and evaluated. The construction site should be in proximity of the port, and thus the two key considerations are the choice of a suitable construction port as well as the available infrastructure at/near the port. While many tasks of the fabrication procedure are individual to the design or to the target location (and the accompanied weather), a particular focus of the work were general considerations that are to be taken into account.

Key port characteristics are

- The size of the port and possibility to establish an assembly line with parallel construction of multiple units
- The accessibility of the port by rail & road (cargo vessels not considered to be a problem since requirements for floating wind substructures should be stricter)
- The ports' capabilities to perform float out procedures
  - Dry dock (considered ideal, but often not available to fit dimensions of floating substructures)
  - Construction barge (submersible)
  - Construction site near harbor basin

Considerations with regard to the equipment include

- A sufficient number of cranes of required height and lifting capacity

[17] Updated version of table as presented in "*Fabrication and installation constraints for floating wind and implications on current infrastructure and design*", Matha, Brons-Illig, Mitzlaff, Scheffler, Deepwind, 2017

- Storage capacities for construction parts and finished units
- Availability of SPMTs, and space for handling if finalized substructures need to be transported within port.

Due to the new requirements specific to floating wind regarding the size and number of units to be constructed, it should be expected that an expansion of the infrastructure of a suitable port is required for floating wind projects, including project specific modifications.

8.1.5 Basic Fabrication Methodology for Large Scale Manufacturing

From the results of the Manufacturing Readiness Level (MRL) questionnaire, it was found that the manufacturing readiness for FOWT substructure manufacturing lags behind the Technology readiness. The Manufacturing readiness still lingers at MRL 2 when the Technological maturity has already reached TRL 4 for the selected steel and concrete floating concepts. A manufacturing proof of concept was needed to enable further maturity, especially for large-scale manufacturing of floaters. The LIFES50+ deliverable concentrates solely on establishing a proof of concept and recommending industrial best practices for the large-scale manufacturing of 50 floaters. The results from this study will have major implications towards the reduction of overall CAPEX and eventually lower the LCOE. The basic methodology is as depicted below.

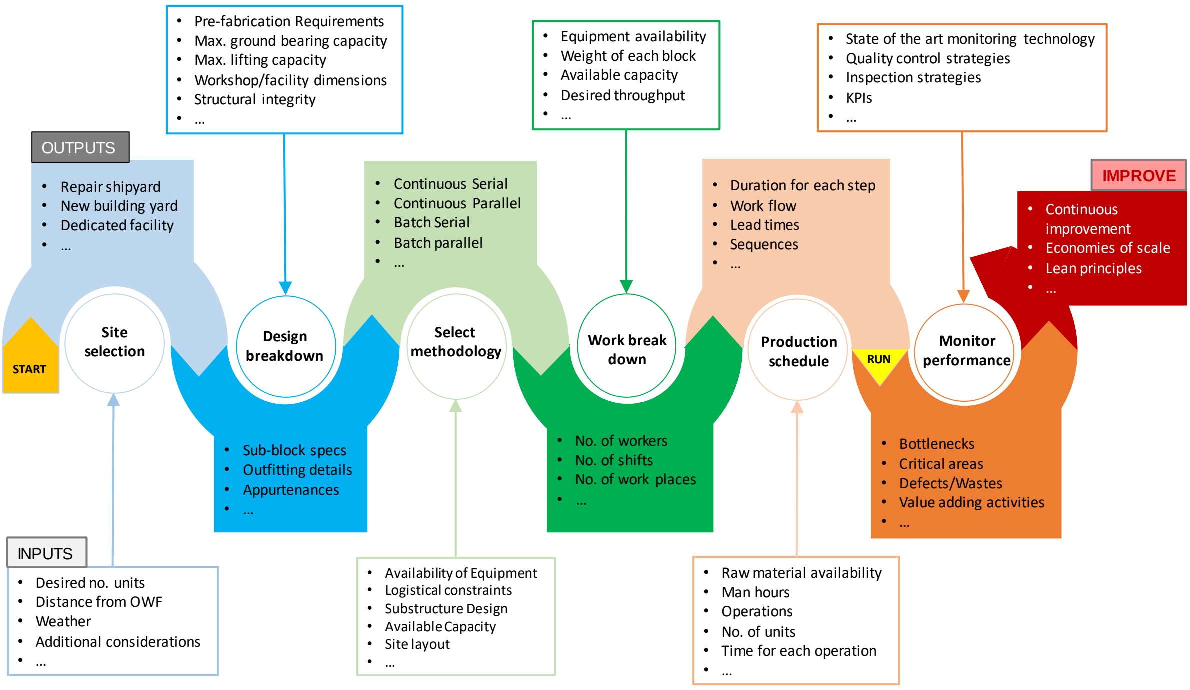

Figure 15: Generalized production methodology for floater manufacturing

The MRL assessment also revealed few key areas, which need to be assessed for increasing the manufacturing process maturity. Areas such as quality control, process capability and control and manufacturing management were found to be key aspects of fabrication and assembly that need attention and research. These areas were addressed during the manufacturing study as well. In addition to that, critical areas were identified and key performance indicators useful for monitoring the manufacturing process have been recommended.

8.1.6 Design for Manufacturing and Assembly (DFMA)

Adaption of the design for simpler manufacturing and assembly is of importance. A set of guidelines on achieving a simplified design, known as the DFMA guidelines is mentioned. The importance of following DFMA principles is underlined by the fact that about 70% of manufacturing costs (cost of materials, processing, and assembly) are determined by design decisions, with production decisions responsible for only 20%. Moreover, the participation of the manufacturer at the earlier stages of design, i.e. before the design is virtually frozen, is recommended and holds enormous potential for cost savings. To achieve this, the establishment of an interactive design loop between design and manufacturing experts is advisable.

8.1.7 Installation Considerations

The installation procedure of a floating wind turbine is highly dynamic and involves a large number of subsequent tasks that need to be organized efficiently, in order to keep the costs as small as possible. Contrary to the fabrication, the implementation of an installation process is not governed by its general feasibility, but rather the efficiency with which it can be performed. Compared to bottom fixed offshore installation, some challenges are mitigated due to possibility of performing important operations at the harbor. This also leads to less restrictions with respect to wind speed and the wave height generally becomes the most critical environmental parameter. However, the increased distance to shore also adds new challenges. The installation of a single floating wind unit may take more than 5 days and interruptions of the installation procedure are not possible (no jack up vessels possible for higher water depth). This adds significant sensitivity towards the weather and its predictability.

In LIFES50+, installation process scenarios were evaluated for large-scale wind farms. This meant the performance of case studies for the three LIFES50+ reference locations, including port selection and evaluation. The workflow for this evaluation is summarized in Figure 16 and builds on the categorization of the major installation processes of float out, transit, installation, cable installation, termination and return. For large wind turbines with high towers, an assembly at port is considered to be the only feasible option, as this implies constraints towards the lifting height that cannot be met by available vessels.

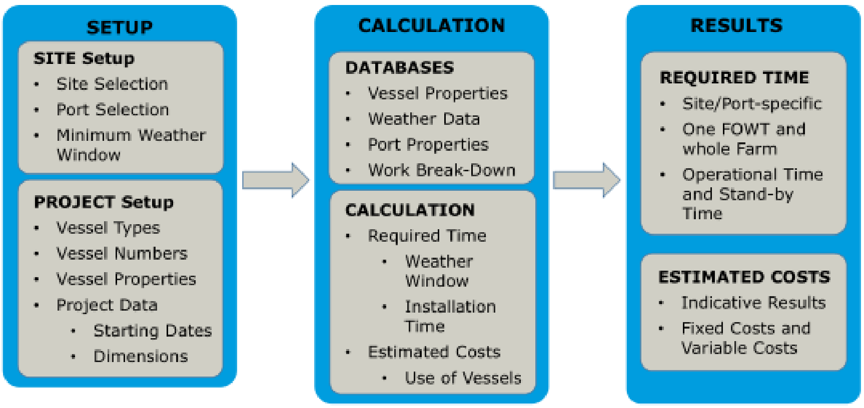

Figure 16: Workflow for determining challenges and bottlenecks in the installation process

For the evaluation of floating wind installation procedures, it is recommended to describe the process depending on its three major influences:

Port: There are two major requirements with respect to the port infrastructure. These are the depth of the harbor basin and wet storage space (areas, where readily assembled floating platforms can be stored). The driving factor for installation procedures is the distance from port to the wind farm site. This has a substantial impact on the transit time and thus the sensitivity of the overall process on weather windows. To reduce the distance, different ports may be considered for fabrication and installation of the substructure. Fabrication and installation do not necessarily have to be performed at the same port, although this is preferable. Temporary layup locations outside the port may be used for storage.

Weather: For floating wind structures, significant time is required for installing a single unit while, at the same time, the procedure has to be performed without interruption. Even though mainly the wave height is a constraint for the installation procedure, the prediction accuracy of the natural environment is of high importance to achieve a reliable schedule. This includes both the assessment of weather windows in the planning phase as well as short-term predictions in the installation phase. Weather constraints for operations can result in bottlenecks of the installation, if available weather windows are to short and/or required installation time too long.

Vessels: The setup of the fleet for the installation procedure is largely influenced by the mooring configuration, the location of the port, the availability of different vessel types as well as the target weather constrains defined by the weather at site. A variation of vessel types is required during the installation procedure, such as tug boats, anchor handling vessels and cable lay vessels. The weather constraints for an operation may be mitigated by choice of more robust vessels. The vessel costs are expected to significantly influence the cost of the overall operation. These are comprised of costs for charter, personnel and equipment, which all largely depend on weather and port. In addition, price uncertainty is to be expected due to the general limitation of available vessels.

The two major performance criteria are installation time and costs, which can be assessed based on the overall setup defined by a combination of port, weather and vessels. The installation time per FOWT unit is influenced primarily by the port distance, the vessel speed and the performance speed of installation tasks. The costs can be categorized into fixed costs (largely made up by the number and type of vessels, the port selection and the duration of the overall procedure) and variable costs (here items such as the legal situation in the country and the fuel costs are seen as significant).

8.1.8 Marine Operations

Since the design of floating wind platforms is under larger economic pressure than those applied in offshore O&G, marine operations need to be optimized to make floating wind more feasible.

8.2 Innovation Needs

8.2.1 Reduction of Uncertainties and Risks

Floating wind is still a novel industry with significant experiences to be made until mass production of floating wind farms becomes a reality. To support this, uncertainties in the design process (numerical and experimental methods) have to be made quantifiable by validations building on full scale data from demonstration and pre-commercial projects. Considering the later lifecycle stages, the first steps towards industrialization can be and have been made by building on existing knowledge and supply chains from bottom fixed offshore wind and O&G. However, due to the fundamental differences between fixed and floating, it is important that new and relevant procedures are introduced for floating wind as well. To carefully implement new procedures, with the least possible risk and uncertainty, experience from fixed offshore wind may certainly be helpful as well. Ultimately, clearly defined constraints, parameters and performance indicators have to be defined for fabrication, installation and O&M procedures to allow a strategic reduction of uncertainties and risks and subsequently allow for optimization of these procedures. In order to allow for a wide spread development of these procedures, public databases (e.g. from publicly funded projects) are key to support the definition of standardized methods and benchmark problems based on which future industry can grow.

8.2.2 Involvement of Supply Chain in Early Design Stages

The results of LIFES50+ clearly highlight the significance of later lifecycle phases on the overall design. In order to reduce the number of design iterations (and related calculations), key influences from fabrication and installation procedures on the design and related performance indicators need to be identified and included in a parametrized way in early optimization procedures. This may lead to application of multi-objective optimization schemes, if indicators are not of the same dimension. The focus should not, for example, be on mass optimization only, but serial production, production speed, market and supply chain considerations, logistics, installation, OPEX among other are all equally or more important when looking at the overall LCOE.

8.2.3 Reliable Weather Models

Floating wind is facing more severe weather conditions, longer times for single-unit installations and higher sensitivity towards weather restrictions considering the complexity of the installation task and available equipment. Accurate forecasting is relevant for installation procedures and any lack of accuracy leads to significant uncertainty of the costs of the overall task. To support reliable installation schedules, improvements in probabilistic weather forecasting are continuously important as well as their consideration into the design process of FOWTs in order to support a reliability-based design of the installation task.

8.2.4 Existing Manufacturing Facilities Need Upgrade

From the manufacturing study conducted by Ramboll, it was found that the manufacturing readiness lags behind that of the technology readiness. Shipyards in general are not well equipped for large scale floater fabrication and extra manufacturing capacity or investment in automation is expected. Shipyards and manufacturing yards capable of handling large standalone projects do exist, but they are currently not well equipped to manufacture floaters in large numbers in a continuous manner. Upgrading existing facilities is an important requirement to achieve the economies of scale.

8.2.5 Simulation Models for Manufacturing, Assembly and installation

Due to the dynamic nature of these integral processes, models for recreating the process of fabrication and assembly need to be developed. These models must be capable to simulate large scale production scenarios and must represent various site conditions and their capacities. Model independent variables must be identified, and a sensitivity analysis may be required to evaluate their usefulness. Existing models from other industrial sectors may be adapted to FOWT technology. Recreating the actual production scenario using simulation models will help detection of critical areas and bottleneck processes during the fabrication, assembly and installation of the floater. This can also be considered as a cheaper alternative compared to the pilot-scale demonstration of floaters.

8.3 Related Publications, Available Online

The following documents related to the abovementioned findings may be found online for additional reading:

LIFES50+ Deliverable 7.1: Review of FOWT guidelines and design practice

LIFES50+ Deliverable 7.2: Design basis

LIFES50+ Deliverable 7.4: State-of-the-Art FOWT design practice and guidelines

LIFES50+ Deliverable 7.5: Guidance on platform and mooring line selection, installation and marine operations

LIFES50+ Deliverable 7.6: Framework for LCOE, uncertainty and risk considerations during design

LIFES50+ Deliverable 7.7: Identification of critical environmental conditions and design load cases

LIFES50+ Deliverable 7.8: Required numerical model fidelity and critical design load cases in various design phases

LIFES50+ Deliverable 7.9: Guidance and recommended methods for HIL/SIL-based FOWT experimental testing

LIFES50+ Deliverable 7.10: Recommendations for platform design under considerations of O&M, logistics, manufacturing and decommissioning

Comparative Analysis of Industrial Design Methodologies for Fixed-Bottom and Floating Wind Turbines
Matha, Pérez Morán, Müller, Lemmer, OMAE, 2016

Industrial Design Considerations for Floating Wind Turbines
Matha, Mitzlaff, Wehmeyer, Pérez Morán, Müller, Lemmer, WindEurope, 2016

Fabrication and installation constraints for floating wind and implications on current infrastructure and design
Matha, Brons-Illig, Mitzlaff, Scheffler, Deepwind, 2017

9 Uncertainty and risk management

Assessing the uncertainties and risks of floating substructures can be critical to understand the operational capabilities and overall viability of a given design. A key target of LIFES50+ was the development of a generalized risk assessment methodology for deep-water floating wind substructures, which did not exist prior to project initiation. Thus, specific areas of risk associated with the development of FOWT substructures and wind farms were addressed. Four major risk categories were identified. These were:

1. Technology risks
2. Commercialisation risks
3. Health, safety and environment risks
4. Manufacturing risks

Considering the overall process of risk management, the work of LIFES50+ focused in particular on the task of risk identification and assessment. The developed methodologies enable the designers to assess a full profile of risks associated with their concept, for all lifecycle phases from design to decommissioning.

9.1 Findings, Results & Recommendations

9.1.1 Definition of a Generalized Methodology for Risk Management of Deep Water Substructures

A general methodology for risk assessment within the four categories of risks was established. The methodology is set up so that it is flexible enough to be viable for different risk categories and substructure typologies. This is found to be important for global risk evaluation, where risks are first assessed separately and then combined. The developed methodologies build on state-of-the-art approaches for risk management, including HAZID for qualitative identification of potential hazards and risk assessment (consequences and probabilities of hazards) summarized by risk scores to describe the relevance of all identified hazards. Maintaining an overview of all possible hazards is important for risk assessment. In this way, to define taxonomies or other means of classification or organization within the different risk categories and lifecycle phases, the following procedures are considered as viable:

- Technological risk category: Functional composition analysis (rather than structural decomposition) was found to be the most feasible approach to detect and evaluate technological novelties as there can be large differences between different substructures (e.g. typology and primary material). The use of categorisation helps to generate a structured view of a concept and shed light to relative novelties of all functional elements. The risk assessment is then performed focussing on the novel elements of the technology.
- Commercialisation risk category: Employing the concept of Commercial Readiness Index (CRI), which links commercial readiness and TRL and supports the derivation of relevant risks that developers face on the road towards commercialisation.
- Health, Safety and Environment (HSE) risk category: The proposed methodology includes both standard parts of the technology lifecycle as well as standard types of HSE. The Source-Pathway-Receptor (SPR) and Source-Pathway-Receptor-Consequence (SPRC) concepts are proposed to be used to identify the link between hazard and risk.
- Manufacturing risk category: The proposed methodology builds on the concept of Manufacturing Readiness Level (MRL). The resulting framework also includes socio-economic risks.

Considering lifecycle phases in a risk taxonomy, the O&M phase should be split into (1) minor repairs and inspection and (2) major repairs, which may be split further into subsequent stages indicating hazards for individual tasks to be performed.

9.1.2 Technological Risks

As mentioned above, the technological risks were assessed based on the functions of different FOWT components. Considering this, the majority of identified technological risks are considered to be within the remit of the substructure designers and are considered as being of low novelty. The most important risks are associated with connection and disconnection of electrical components for operation and maintenance, risks associated with cabling and finally the required adjustment of the controller for the floating system.

9.1.3 Mostly Known HSE Hazards in Floating Wind

The identification of newly added hazards of floating wind compared to established industries regarding HSE was a pronounced goal of the risk related efforts of LIFES50+.

Of all lifecycle phases, O&M was identified as the phase with the most unique challenges to floating wind. Manufacturing has no unique hazard to floating wind, due to the fact that steel and concrete constructions have a long track record in other industries. Installation hazards that are expected for floating wind are similar to those in bottom fixed offshore wind, oil and gas, shipbuilding and other related industries. Finally, if decommissioning is considered to be a reversal of the installation process, it can be assumed to exhibit similar, known challenges.

Even for O&M, the majority of hazards are not unique to the industry. Compared to fixed-bottom offshore wind, the main difference is the motion characteristics of floating platforms. However, the motion of FOWT introduces four major novelties compared to bottom-fixed platforms, namely the more complicated access and egress, an increased likelihood of motion sickness of working personnel, an increased difficulty of performing O&M work, which can influence the quality and/or speed of work, and finally an increased likelihood that hazards become real due to potentially performing hazardous activities more often.

9.1.4 Risks of Manufacturing Readiness

The primary risk for the commercial realization of floating concepts at a given site is considered to be the capability of mass production due to time and space restrictions. The availability and capability of cranes at the manufacturing yard poses additional risks.

9.1.5 Commercial Risks beyond Technology

Risks related to achieving an overall status were determined based on readiness indices (such as manufacturing or commercial readiness levels). A particular focus of LIFES50+ was set on assessing commercial risks of novel floating wind turbine substructures. This ultimately was interpreted as the risks towards reaching a reference level of the Commercial Readiness Index (CRI). Linked to this, seven distinctive topics with related risks were identified to enable a CRI which enables industry scale production of the considered system. These are (1) stakeholder acceptance, (2) environmental/local acceptance, (3) supply chain/manufacturability, (4) substructure and wind turbine compatibility, (5) technical performance, (6) financial performance and (7) market opportunity.

As part of the evaluation, each risk topic is assigned with a relative likelihood score between 1 and 5. The scoring results in a global overview of commercial risk of the platform under consideration, describing how likely it is to achieve commercialisation. A total risk score was not implemented due to varying levels of impacts of the different influences from location, country and design.

From results of LIFES50+, key differences between designers were identified that provide insight to the commercial risks of other stakeholders or the overall industry. Importantly, these are not only items which are related to the technical performance of the concept, but rather the experience and network of the concept designer with respect to finance and supply chain of all lifecycle stages.

- The implemented level of collaboration between substructure designers with OEMs and key component suppliers (e.g. mooring lines, umbilicals, etc.), including coupled numerical analysis
- Having a partner with a large balance sheet as part of the designer's stakeholder portfolio, who can provide a wide range of guarantees to a possible project (such as providing less expensive insurance)
- The designer's experience in raising and organising finance and the availability of resources to execute a commercial scale project
- The designer's financial exposure towards price fluctuations, resulting from installation, key components, and weather risk
- The designer's track record of operational performance
- The design's technical flexibility to address a wide range of possible implementation scenarios (e.g. wind turbines, water depth, seabed conditions)
- The design's ease for serial production, transportation and installation

Additionally, the ability of a platform to perform major repairs at port was found to be of potential value to drive down O&M costs of the system.

9.1.6 Influences on Sustained Growth and Continuous Competition

Independent of the designer or the design, there are important risks towards the overall floating wind industry in major markets that were identified as part of LIFES50+. These are policy-based in the way that potential locations may have limited track records with offshore constructions in general, which complicate the setup of consenting schemes (in particular emerging markets). Additionally, in most countries no clear pathway can be found towards commercialisation of the floating wind industry, possibly supported by subsidy schemes, in order to enable growth of local industries and maintain international competition in the still early stages of the industry.

The challenges that floating wind will face in the midterm future are related to establishing large scale projects while maintaining a competitive environment to enable a variety of concepts. Projects have to be large in order to be of continuous interest for turbine OEMs and project developers and to realize them without government support, they will have to be commercially viable. Large scale projects make better use of some costs (e.g. project development, substations, cables), which makes them potentially more cost efficient. Large scale projects are more difficult to achieve when new (technically promising) entrants with less experience are involved due to higher risk penalties. For large projects, the required supply chains for a target location may be underdeveloped or non-existing, leading to a required balancing between the creation of local content (establishing supply chain and production near-site) and external supply from centralized production ports which may be more cost efficient. Significant impacts (and related risks) on project timelines may result from stakeholder groups of the site under consideration (e.g. fishing community, military, aviation, recreational and environmental groups).

9.1.7 Risk Management as an Iterative Procedure in the Design Process of FOWTs

The developed procedures can be applied to highlight the readiness of critical and innovative items of a given concept, not only regarding the applied technologies, but also commercialisation. In this way, an iterative risk assessment and evaluation with increasing detail level for the various risk categories is considered of substantial support in the evaluation of viability status of floating wind turbines.

9.2 Innovation Needs

9.2.1 Risk Evaluation and Risk Treatment

Risk evaluation and -treatment are also part of the complete risk management, which were not considered as part of LIFES50+. These two items are very dependent on the different designer's risks tolerance and strategy. Future work should address these follow up steps with a special focus to allow for wholesome and standardized risk management procedures for floating wind systems.

9.2.2 Component and Process Innovations

As part of the risk assessment activities in LIFES50+ it was found that improvements in various components and involved processes are of particular importance for the future development of the industry. Some of the experiences may be transferred from bottom fixed offshore wind, albeit unique challenges in the floating industry exist.

In particular, it was found that future innovation and standardisation of equipment and processes related to the power transmission present an important chance to drive down both costs and risks of floating wind. Also, innovations for dynamic cables are considered as a requirement to reduce the failure risk to a feasible level. As this is expected to be driven by the supply chain, a positive market outlook for the floating wind industry is a necessity. Finally, looking at manufacturing processes, FOWT-specific innovations & investments in cranes and ports is crucial to enable commercial deployments in the first place as well as reducing related risks and uncertainties.

The source of financing for new technologies is difficult to realize. Generally, the supply chain is willing to invest in product development if a constant flow of projects is guaranteed. On the other side, governments require the supply chain to invest in product development prior to providing subsidies for next-generation innovations. Clearly, any incremental gain in innovation is achieved only by either side choosing to take a risk.

9.2.3 Related Publications, Available Online

The following documents related to the abovementioned findings may be found online for additional reading:

LIFES50+ Deliverable 6.1 Risk Management for Deep Water Substructures

LIFES50+ Deliverable 6.6 Publication and presentation of the research performed in the Work Package

Methodology for Risk Assessment of Floating Wind Substructures
Proskovics, Hutton, Torr, Scheu, DeepWind, 2016

Challenges in using Risk Assessments in Offshore Wind Asset Management
Scheu, Matha, Hohrath, Proskovics, ISOPE, 2016

Multi-criteria Assessment Tool for Floating Offshore Wind Power Plants
Lerch, Benveniste, Berque, Lopez, Proskovics, WindEurope, 2016

Results of a Comparative Risk Assessment of Different Substructures for Floating Offshore Wind Turbines

Proscovics, Scheu & Matha, DeepWind 2017

An Introduction to Risk in Floating Wind - Key risks and how to mitigate them
Proskovics, 2017

10 Application of findings: Design optimization of public concept(s)

10.1 Introduction

The task of this section is to apply the optimization techniques introduced in D4.3[18] to both, the steel design NAUTILUS-DTU10 and the concrete OO-Star Wind Floater Semi 10MW design that are studied in LIFES50+. The optimization task of LIFES50+ D4.3 focused on the optimization of the floating wind turbine dynamic behavior in wind and waves. Thus, the focus is on the physical dynamic behavior with the understanding that a smooth response behavior leads to reduced loads, which in turn, yields lighter structures and a smaller cost of energy. In order to demonstrate the versatility and the effectiveness of the proposed method and understand the influence of platform design on the overall dynamic properties of the floating wind system.

At the beginning of this section, optimization tools, variables and the design space will be briefly introduced. Afterwards, two optimization loops are set up. In the first loop, the brute-force searching method is employed to investigate the sensitivity of harmonic response to the platform design. The harmonic response is a useful indicator, which was developed in the course of the project. Next to the modal analysis, it provides an understanding of the response behavior of a floating turbine to wind and wave loads of different sinusoidal frequencies. With this information, a good overview of the load distribution and power fluctuation can be obtained.

In the second loop, a full system optimization incorporating combined wind and wave loads, and the turbine controller, is carried out. Finally, the results will be further discussed, and conclusions will be drawn.

10.2 Optimization tools

The optimization of substructures for floating offshore wind turbines is a multidisciplinary problem, which integrates structural dynamics, hydrodynamics, aerodynamics, control and optimization algorithm. Correspondingly, in this work multiple software/subroutines are integrated/implemented by the mathematical programing platform Matlab for the pre-processing/processing/post-processing of the optimization loop.

An important task in the conceptual/preliminary design phase is to maximize the exploration of design space, which indicates that simplified models rather than the complex high-fidelity models should be used considering the limited computing resources and analysis time. That means less important factors, for example the directionality effects of external loads, will not be considered in this stage. The dynamic model used in this work is the reduced-order multibody dynamic simulator SLOW[19], in which five degree of freedom (DOF) is considered: platform surge x_p, heave z_p and pitch displacement β_p, tower-top fore-aft displacement relative to tower base x_t and the rotor speed Ω. Figure 18 shows a sketch of the exemplary mechanical model of SLOW. SLOW is not only able to capture the nonlinear transient dynamic behaviors of the system in time-domain, but also able to linearize the system around a specific steady state, working as an efficient frequency-domain model. In this study, these two modules will be applied to the full-system optimization and the harmonic-response brute-force searching respectively, which will be introduced in the following subsections.

[18] Lemmer, F., Müller, K., Yu, W., Faerron Guzmán, R., Kretschmer, M., Lifes50 plus: D4.3 Optimi-zation framework and methodology for optimized floater design. 2016.

[19] Lemmer, F., Lower-order modeling, controller design and optimization of floating offshore wind turbine. Ph.D thesis of University of Stuttgart. 2018.

Matlab provides a powerful optimization toolbox. Based on the comparison of five optimization algorithms in the previous study (D4.3), the Pattern Search Algorithm is selected as the optimizer of the full-system optimization process.

The 3D solid model is parameterized and established in the CAD software CATIA (as shown in Figure 17) and the structural properties e.g. the platform mass, center of gravity (CoG) and moment of inertia are extracted with the aid of the interface subroutine between CATIA and Matlab. The parameterization implies that the results shown in this chapter are interpretations of the original designs NAUTILUS-DTU10 and OO-Star Wind Floater Semi 10MW, made by USTUTT independently of the platform designers.

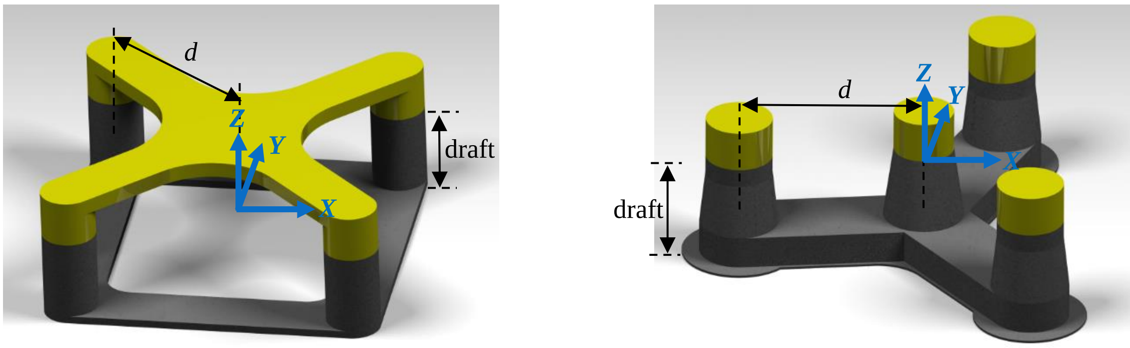

Figure 17: 3D CAD model of the steel (left) and the concrete (right) platform

Concerning the hydrodynamics, the frequency-dependent added mass, radiation damping and excitation forces are calculated by the potential flow solver Ansys Aqwa. The excitation loads are then transferred to time domain through Inverse Fourier Transform, serving as wave load input to the dynamic model. In addition, the viscous drag forces are also considered by using the quadratic term of Morison's equation. The approach introduced in the literature[20] is used to determine the drag coefficient for each section of structural components.

Aerodynamics are simplified by an application of a rotor-effective wind speed at hub height, which is a weighted average of the three-dimensional turbulent wind field on the entire rotor plane[21] . Combined with the thrust and power coefficient look-up tables, the resulting thrust force and aerodynamic torque acting on the rotor are calculated and served as wind load input to the dynamic model.

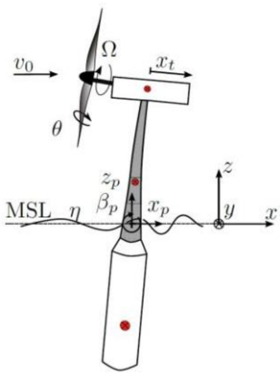

Figure 18 Topology of SLOW FOWT model showing degrees of freedom and main inputs

[20] Robertson, A., et al., Definition of the semisubmersible floating system for phase II of OC4. Offshore Code Comparison Collaboration Continuation (OC4) for IEA Task, 2012. 30.
[21] Schlipf, D., D.J. Schlipf and M. Kühn, Nonlinear model predictive control of wind turbines using LIDAR. Wind Energy, 2013. 16(7): p. 1107-1129.

10.3 Optimization variables and design space

Instead of fully parameterizing the platform configuration, the centreline column spacing and the draft are selected as free variables (as shown in Figure 17) and other dimensions are kept constant. These variables are selected because they are two of the dimensions that are most correlated to the dynamic responses according to the sensitivity study in D4.3. Besides, it is easier to visualize the design space and how the cost function varies along with free variables, which will be beneficial to make a clear understanding of the optimization process. The height of the upper structure above SWL, column diameter, pontoon width and height are the same as in the original design. Note that for the original design, structural components like stiffeners and bulkheads are arranged inside the platform, whereas they are not included in the 3D hull model for the sake of simplification. For consistency, the wall thickness of pontoons, columns and upper structures are tuned to match the mass, CoG and moment of inertia of the original design. Once the wall thickness is determined, it is kept constant throughout the whole optimization process. With regards to ballast, its weight is determined by the equilibrium between the hull displacement and the total weight of the system (turbine, platform, ballast and mooring pretension). The range of the optimization variables which makes up the design space of the optimization process is presented in Table 3.

Table 3 Optimization variables

Free variables	Unit	Range of value Steel platform	 Concrete platform
Centreline column spacing	[m]	[18:1.4: 53]	[20:2:54]
Draft	[m]	[10:2:65]	[10:2:65]

It can be seen that a large range of variables is used in this work. Obviously, not all the designs meet the fundamental requirements of floating structures and it is necessary to discard the unfeasible designs before the optimization loop starts. Four constraint conditions are used to further narrow down the design space: the average pitch motion under rated wind condition, the platform heave and pitch natural period and the differences between them, which can be calculated by the following equations:

$$\beta_p = \frac{T_{rated} H_{hub}}{C_{55}} \leq 10^{\circ}$$

$$T_{33} = 2\pi \sqrt{\frac{m + A_{33}}{C_{33}}} \geq 17\ s$$

$$T_{55} = 2\pi \sqrt{\frac{I + A_{55}}{C_{55}}} \geq 20\ s$$

$$|T_{55} - T_{33}| \geq 3\ s$$

Where T_{rated} is the rated wind thrust; H_{hub} is the hub height; C_{33} and C_{55} is the sum of hydrostatic and mooring stiffness for the heave and pitch DOF respectively. The linearized mooring stiffness matrix around the undisplaced position is used here. The restoring forces are calculated by quasi-static code and linearized by the least square fitting; m and I is the total mass and moment of inertia of the system; A_{33} and A_{55} is the added mass for the heave and pitch DOF. Note that the moment of inertia and the added mass are defined at the CoG of the whole system.

The design space of the steel and concrete platform is shown in Figure 19. The yellow region denotes the potentially feasible designs, while the other areas represent the infeasible designs that violate the constraints above.

The figure shows that the steel designs with extremely large column spacing are infeasible if the pontoon dimensions and column diameter are kept constant (which is not the case according to the Concept Designer pre-sizing procedures). The main reason is that the large deck structure will significantly increase the height of CoG without relevant increase in the CoB, in the displacement and in the moment of inertia of waterplane area, with implies a reduction in GM (metacentric height), leading to a small hydrostatic stiffness to resist the wind tilting moment. Besides, having a large column spacing for the concrete floater will also imply increased pontoon dimensions and thus increase the cost, at some point resulting in an unfeasible concept. It will also cause fabrication challenges as the structure grows in size. The overlap of heave and pitch natural period will increase the risk of structural failure and it mainly occurs in oversize region, which again demonstrates that extremely large column spacing/draft should be avoided.

The same occurs with the constraint of the heave period. In all the steel designs it has been assumed that the water plane area remains constant. Consequently, the unique way to increase the heave period is increasing steel mass and heave added mass. By varying the draft or column spacing, the steel mass increases, but to a lesser extent than in the concrete design. Therefore, it is necessary to extent the pontoon width for moving more volume of surrounding fluid as it moves in the heave DoF. However, this can cause that the restriction of pitch period not be fulfilled. So, it will be necessary to adapt the height of the pontoon, so that the design would not have excessive displacement.

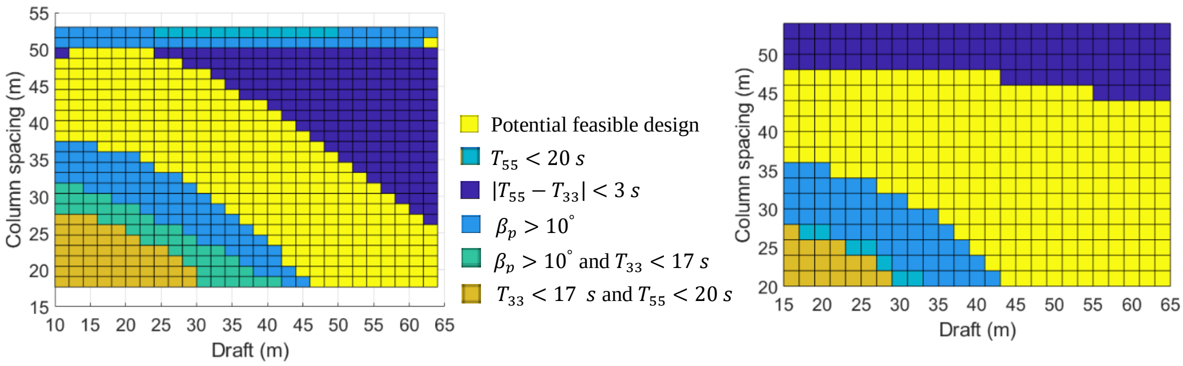

Figure 19: Design space of the steel (left) and concrete (right) platform

10.4 Brute-force searching: harmonic response

The harmonic response to wind and wave loads, namely Response Amplitude Operator (RAO), is an important assessment criterion for the dynamic performance of floating structures. Floating wind turbines are composed of rigid platform and flexible tower/blade. The interactions between the rigid and flexible components will result in some unique phenomena which cannot be observed in the rigid body case. To evaluate these special phenomena, it is necessary to pay more attention on the whole structure, rather than just focus on the rigid substructure (as the oil and gas industry typically do for the global design). As an example, Figure 20 presents the response amplitude along the centreline of a floating wind turbine to unit regular loads of different frequencies. The dimension of the floater would have a significant impact on the motion mode of the turbine, further influencing the power production as well as the fatigue loads. Due to its importance, the harmonic response modes of the steel and the concrete platform are investigated in this subsection.

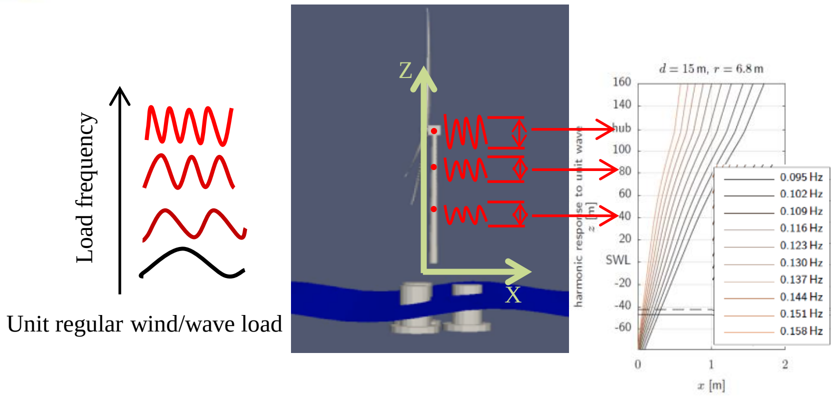

Figure 20: Harmonic response along the centreline of a floating wind turbine to unit regular wave of different frequencies

The amplitude of harmonic response is obtained by using the linearized SLOW module. To provide the steady state information (mean platform motion, rotor speed and blade pitch) for the linearization process, time-domain simulations under steady wind condition (the harmonic response at 13.9 m/s wind speed) are carried out. Owing to the high computational efficiency of the linear SLOW model, the harmonic responses for all the variable combinations within the design space are calculated for the given design load case. Unit regular wind/wave of 10 frequencies ([0.010:0.007:0.073] Hz for wind and [0.095:0.070:0.158] Hz for wave) which cover the main energy range are used in the analysis.

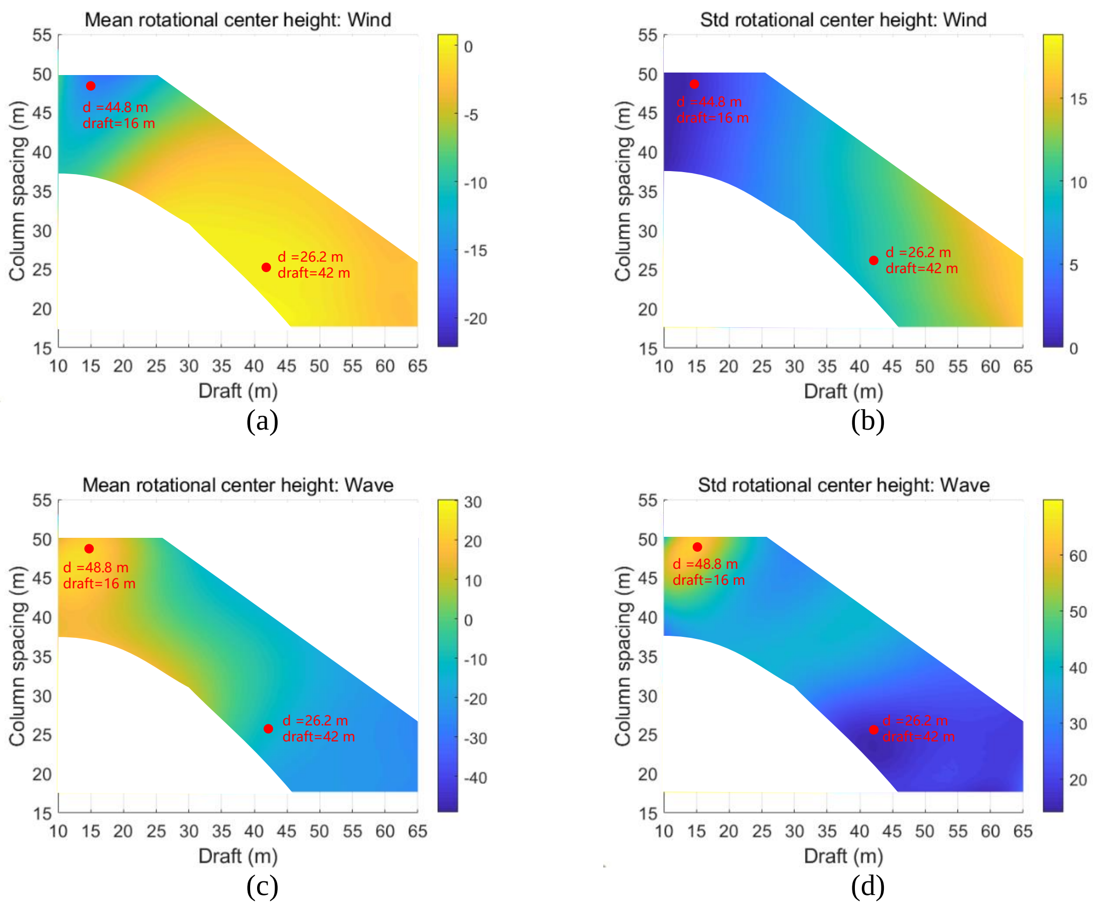

Figure 21: Contour of the rotational center height for the steel platform: (a) mean and (b) standard deviation value of rotational center subjected to unit regular wind loads of 10 frequencies; (c) mean and (d) standard deviation value of rotational center subjected to unit regular wave loads of 10 frequencies

The instantaneous center of rotation, which is defined as the position with the smallest harmonic response along with the turbine centreline with respect to the still water level, is employed to characterise the motion mode of the floating system. It should be noted that the rotational center varies with the load frequency. The mean and the standard deviation value along with load frequency are used to describe its sensitivity. Note that in some circumstances the system has a purely translational response. For these cases the rotation center is omitted.

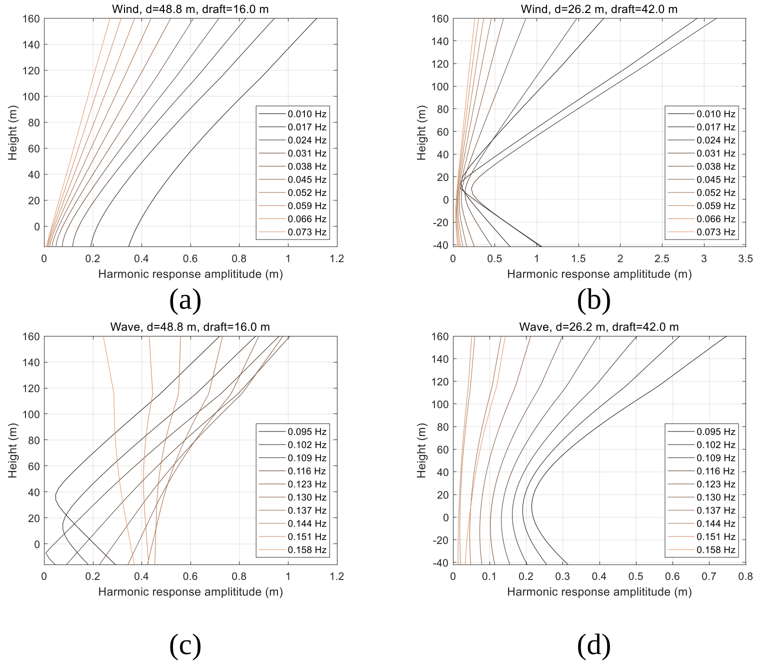

Figure 22 Amplitude of harmonic response along the centreline for two steel designs subjected to unit wind (a)-(b) and wave (c)-(d) loads of 10 frequencies respectively

The contours of the rotational center height for the steel platform are presented in Figure 21. It is obvious that the rotational center subjected to unit wind load is mainly dependent on the platform draft. The design with small draft has a lower rotational center, which potentially indicates a large tower top harmonic response. In this case the rotational center varies little with the wind frequency. However, a completely different phenomenon can be seen when it turns to a deep draft design: the rotational center moves to the higher position and becomes much more sensitive to the wind frequency. The harmonic response plots of two “extreme” designs (marked by the red points) shown in Figure 22 (a)-(c) provide a clear view of the trend described above.

The figures of the wave-induced harmonic response present an opposite trend throughout the design space: large mean rotational center height with high sensitivity to the wave frequency is seen in the low-draft cases, while small mean and standard deviation values are seen in the large-draft region. Interestingly, two typical motion modes are observed in a low-draft design (d=44.8 m, draft=16 m), as shown in Figure 22 (d). At the low wave frequency, the floating system pitches around a relatively low point and significant displacement occurs at the tower top, which hereafter refers as to the “backward mode”. However, as the frequency increases, the tower top motion decreases relative to the substructure and finally becomes a component that excites least to the wave loads along the turbine centerline, which hereafter refers as to the “forward mode” (also called counter-phase pitch response). Obviously, compared with the backward mode, the forward mode is beneficial to improve the power production and reduce fatigue of the tower caused by wave response. Figure 22(e) show that the backward mode dominates the large-draft designs.

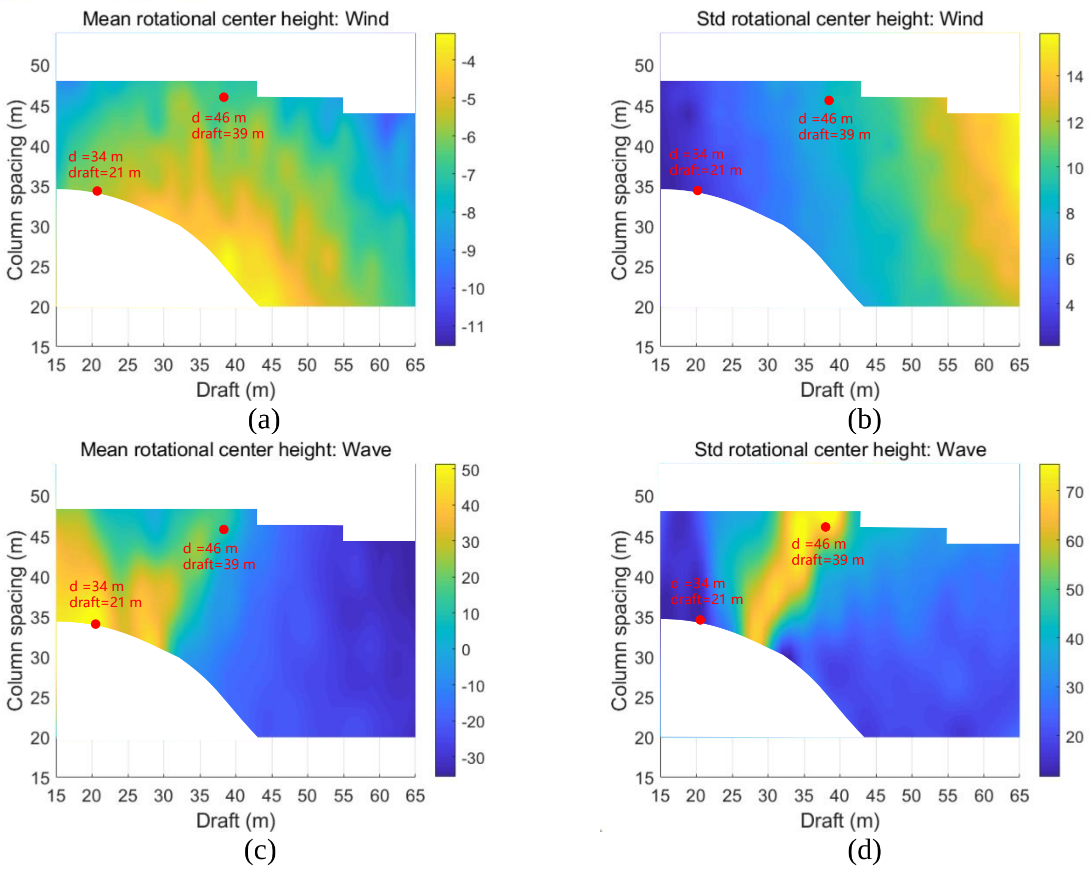

Figure 23 Contour of the rotational center height for the concrete platform: (a) mean and (b) standard deviation value of rotational center subjected to unit regular wind loads of 10 frequencies; (c) mean and (d) standard deviation value of rotational center subjected to unit regular wave loads of 10 frequencies

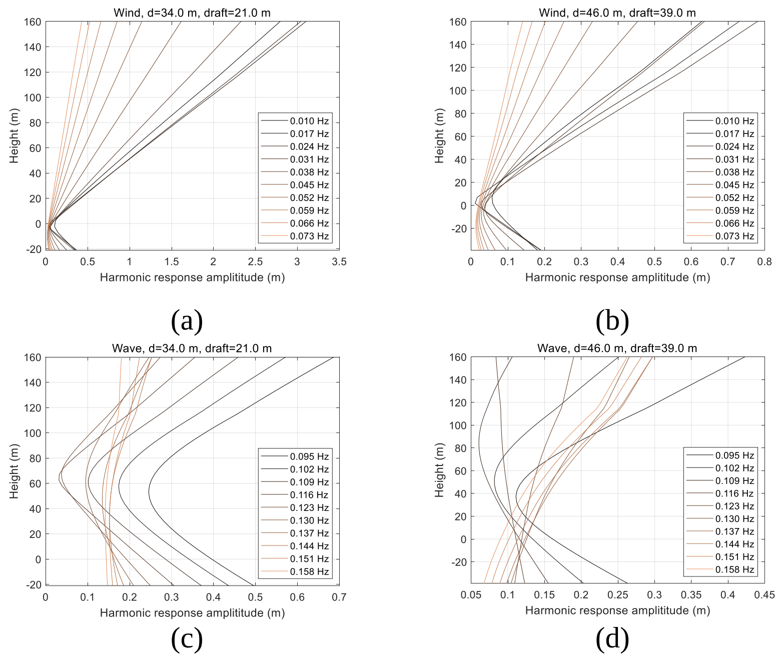

Figure 24 Amplitude of harmonic response along the centreline for two concrete designs subjected to unit wind (a)-(b) and wave (c)-(d) loads of 10 frequencies respectively

Figure 23 shows the rotation center data of the concrete platform. The trend for the wind-induced harmonic response is similar to the steel case and the turbine tower moves in the backward mode throughout the design space, as Figure 24(a)-(c) show. In terms of the wave-induced motion, the forward mode is also observed in the low-draft cases, but the sensitivity to the load frequency is a little bit less significant than the steel design. However, there are still some regions that vary a lot to the frequency, e.g. d = 46 m, draft = 39 m.

10.5 Full system optimization

The optimization procedure described in the D4.3 document (as shown in Figure 25) is applied to the full system optimization. Based on the given geometrical parameters, the 3D solid model is first set up and the structural properties, hydrostatic coefficients and the production cost of the floating system are calculated. The feasibility of the design is checked by the constraint conditions before the dynamic's assessment activities start. Subsequently, the panel code Ansys Aqwa is called to calculate the hydrodynamic coefficients of the platform, serving as input to the SLOW model. Afterwards, the time-domain nonlinear SLOW model is employed to estimate the overall dynamic performance. The cost function is calculated by combining the production cost and the dynamic performance. The above procedures are repeated until the optimizer finds out the optimal design.

For each loop, stochastic environmental conditions for DLC 1.2 (extracted from D7.2[22]) listed in Table 4 are simulated. The indicator used for dynamic assessment is the sum weighted standard deviation of tower top displacement, namely:

$$\sigma_{TTdsp} = \sum_{i=1}^{N_{\mathrm{DLC}}} \sigma_{TTdsp,i} \cdot p_i$$

Where $\sigma_{TTdsp,i}$ is the standard deviation of tower top displacement at the ith load case; p_i is the occurrence probability of the ith load case; N_{DLC} is the number of load cases.

Table 4 Environmental conditions employed in the full system optimization loop

V_{hub} (m/s)	H_s (m)	T_p (s)	Probability
5	1.38	7	49.9%
7.1	1.67	8	21.6%
10.3	2.2	8	19.1%
13.9	3.04	9.5	7.5%
17.9	4.29	10	1.7%
22.1	6.2	12.5	0.2%
25	8.31	12	0.02%

In the aspect of production cost estimation, more details are considered compared with the D4.3. The D2.2 document reports that the total manufacturing cost of the floating substructures includes the material cost, the labour cost and the overhead cost[23]. In this work, the material cost is estimated by multiplying the total mass of platform by the material price. For steel substructures, the labour cost is mainly related to the welding length and the painting area[24]. The welding length depends on the size of the raw steel plate, which is estimated based on the steel industry standard as well as the limitation of the transportation vehicle dimension. The cost of concrete substructures can be simply estimated based

[22] Krieger, A., Ramachandran, Gireesh K. V., Vita, L., Alonso, P. G., Almería, G., Berque, J., Aguirre, G. Lifes50 plus: D7.2 Design Basis. 2015.
[23] Benveniste, G., Lerch, M., Prada, M., Kretschmer, M. Lifes50 plus: D2.2 LCOE tool description, technical and environmental impact evaluation procedure. 2016.
[24] Farkas, József, and Károly Jármai. Optimum design of steel structures. Heidelberg: Springer, 2013.

on a statistic that for the same weight, the manufacturing cost of 1-ton reinforced concrete = 84% × the cost of 1 ton of steel[25]. Aligned with the D2.2 document, the overhead cost is approximated as 27 % of the total manufacturing cost.

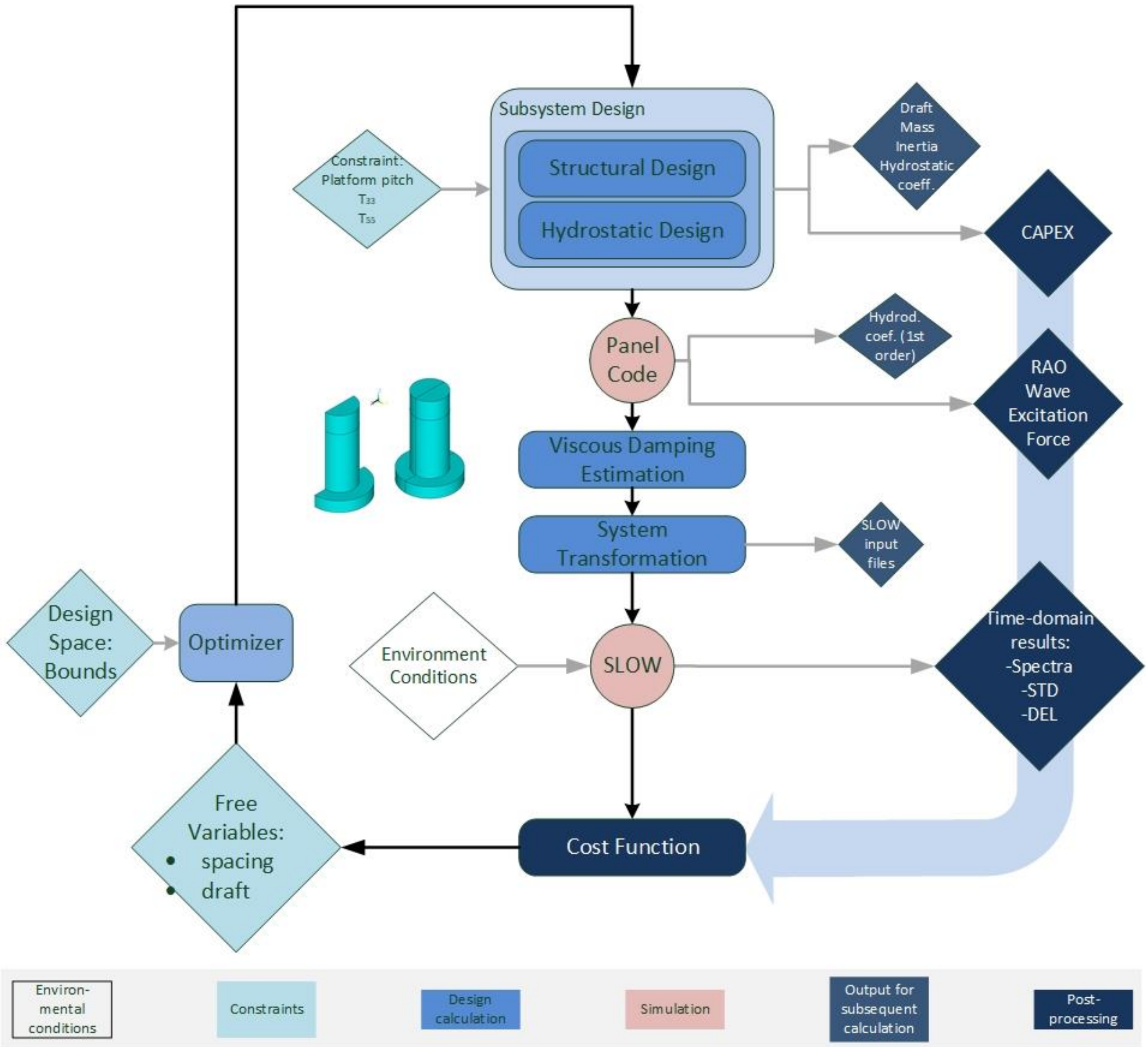

Figure 25 Workflow of the optimization process

The cost function is written as follows:

$$J = 0.788\frac{\sigma_{TTdsp} - \sigma_{TTdsp,min}}{\sigma_{TTdsp,max} - \sigma_{TTdsp,min}} + \frac{c - c_{min}}{c_{max} - c_{min}}$$

Where c is the platform manufacturing cost. The minimum and maximum values of the dynamic response and cost are the results of the 50 example designs which are randomly selected within the design space. The weighting factor of 0.788 is the Pearson-correlation of cost over tower top displacement (see D4.3).

In order to make a clear view on how the assessment indictors vary with the hull dimension, the contours of the tower top displacement standard deviation, the manufacturing cost and the cost function

25 Pérez Fernández, R. and M. Lamas Pardo, Offshore concrete structures. Ocean Engineering, 2013. 58: p. 304-316.

are presented in Figure 26. The red points are the simulated designs during the optimization loop and the contours are obtained by using the Blind Kriging interpolation technique[26].

Figure 26(a)(d) show that the large draft designs tend to oscillate less at tower top since lower CoG provides a better stabilization. However, simply increasing the size of the platform cannot guarantee the improvement of dynamic performance. Although the designs with large column spacing and draft have a good hydrostatic stability, they also suffer from large wave excitation since their geometrical dimensions get close to the incident wave length.

As Figure 26(b)(e) shows, the platform manufacturing cost is also highly correlated with the draft dimension. One reason is that columns are the major/largest components for semisubmersible platforms. Increasing the column length will not only greatly increase the amount of construction material and labour, but also increase the amount of ballast that is needed to achieve the target draft.

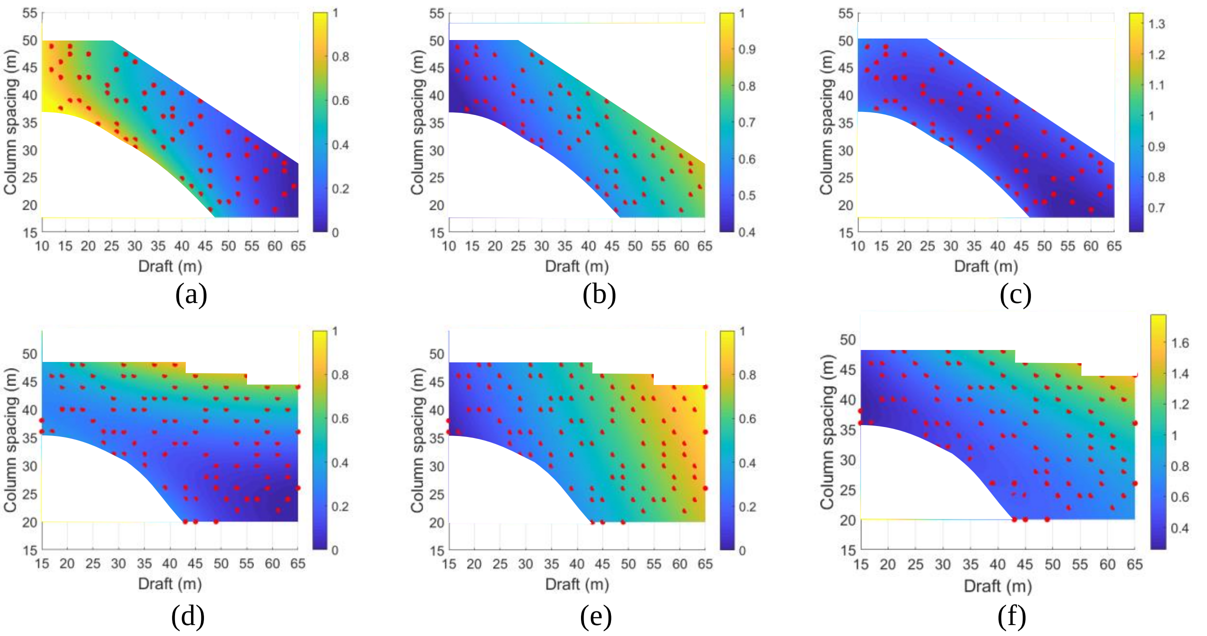

Figure 26 Contour of normalized tower top response, manufacturing cost and cost function for the steel (a), (b), (c) and the concrete platform(d), (e), (f)

As for the cost function results, Figure 26(c)(f) shows that the cost function works differently in different platform optimizations. In the steel case, the cost function bias more on the dynamic performance of the system, thus the optimization program regards the “spar” design (d=20 m, draft=60 m) as the optimum design. On the contrary, it is partial to the manufacturing cost in the OO-Star case and the optimizer indicates the low-draft design is the optimum design. In fact, it is not easy to trade off the assessment indictors in a perfect way by using a straightforward cost function. To avoid impractical bias, attention should not only be paid on the design with the lowest cost function value, but also to the similar level of designs.

10.6 Conclusions

In this work, the optimization technique developed in D4.3 is applied to two public concepts: the four-column steel and the three-column concrete semisubmersible platform, in order to make a clear understanding of the influence of platform design on the overall dynamic performance of floating wind sys-

[26] Joseph, V. Roshan, Ying Hung, and Agus Sudjianto. "Blind kriging: A new method for developing metamodels." Journal of mechanical design 130.3 (2008): 031102.

tem. From the investigation on harmonic response, it is found that the draft dimension has a significant impact on the motion mode of floating wind system. The backward mode tends to occur in the large-draft designs, while the forward mode occurs in the small-draft designs. The full system optimization results show that increasing the draft dimension is helpful to reduce the tower top response, however, it will also significantly increase the manufacturing cost.

In summary, this study shows that a system-level parametric study/optimization can lead to designs which behave more steadily under met-ocean conditions of a given site. Tools like the presented one can be applied for site adaptations or upscaling of a design concept. The reduced-order model is able to represent the main system dynamics. This means that the design process can start with coupled simulations, already in the preliminary design stage, instead of decoupled simulations. This will help to arrive at a more straightforward and efficient design process, not only for new designs but also for design adaptations.

11 Summary List of Key Findings, Recommendations and Needs

Below are listed all key findings, results, recommendations and innovation needs as found in the project. The listed items are addressed in the topic-related chapters in this document.

Concept Development and Optimization (Chapter 4)

Key Findings, Results and Recommendations

- Definition of three benchmark sites
- FAST model for the DTU10MW RWT for use on FOWTs
- Design basis for benchmark sites
- Requirements for upscaling FOWT substructures
- Specification of manufacturing strategies and marine operations
- Considerations in the design of FOWT substructures
- Critical environmental conditions
- Technical comparison methodology

Innovation needs

- Improvements in wind turbine modelling and turbine rating
- Framework for controller design
- Detailed reference sites with design basis for substructure classification
- Availability of public datasets to support research and development of standardized procedures

Concept evaluation (Chapter 5)

Key Findings, Results and Recommendations

- Probabilistic LCOE calculation as part of the design process
- Global evaluation measures for FOWT concepts
- Evaluation of cost competitiveness of FOWT
- Main influences on platform costs

Innovation needs

- Procedures for holistic design optimization including all lifecycle stages
- Development of power cables for large wind farms
- Provision of floating substations
- Definition of recyclability requirements
- Availability of Public datasets for LCOE and LCA assessment to support research and development of standardized procedures

Experimental evaluation (Chapter 6)

Key Findings, Results and Recommendations

- Aerodynamic model performance compared to wind tunnel tests
- Provision of a scaled wind turbine model for use in experimental studies
- Provision of a Hexafloat robot to simulate wave induced motions in wind tunnel
- Performance of real-time hybrid model tests in an ocean basin
- Performance of HIL model tests in the wind tunnel

Innovation needs

- Further validation of aerodynamic models
- Uncertainty quantification in experimental testing

Numerical evaluation (Chapter 7)

Key Findings, Results and Recommendations

- Verification of simple numerical models for early conceptual design
- Public definition and FAST implementation of two LIFES50+ 10MW floater concepts
- Optimization framework and methodology for optimized floater design
- Identification of challenges and development needs in FOWT conceptual design
- Validation of simple and state-of-the-art models against experiments
- Consideration of advanced models
- Validation of advanced models
- Numerical sensitivity analyses for FOWT
- Methodology for probabilistic design of FOWT
- Extended simulation requirements for FOWT
- Requirements for reduction of considered load cases

Innovation needs

- Simple numerical models
- Numerical optimization frameworks
- Quantification and reduction of uncertainties in common numerical models used for FOWT load assessment
- Improvements of advanced models
- Further validation needs for advanced models

Concept industrialization (Chapter 8)

Key Findings, Results and Recommendations

- Consideration of new technological and computational challenges

- Preliminary mooring line design
- Material considerations
- Fabrication considerations
- Basic fabrication methodology for large scale manufacturing
- Design for manufacturing and assembly (DFMA)
- Installation considerations
- Marine operations

Innovation needs

- Reduction of uncertainties and risks
- Involvement of supply chain in early design stages
- Reliable weather models
- Existing manufacturing facilities need upgrade
- Simulation models for manufacturing, assembly and installation

Uncertainty and risk management (Chapter 9)

Key Findings, Results and Recommendations

- Definition of a generalized methodology for risk management of deep-water substructures
- Technological risks
- HSE hazards in floating wind
- Risks of manufacturing readiness
- Commercial risks beyond technology
- Influences on sustained growth and continuous competition
- Risk management as an iterative procedure in the design process of FOWTs

Innovation needs

- Risk evaluation and risk treatment
- Component and process innovation