LIFES50+

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

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Definitions & Abbreviations

ACP	Actuator Point Model
BEM	Blade Element Momentum
CE	Cummins Equation
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
DLC	Design Load Case
DLL	Dynamic Link Library
DOF	Degree of Freedom
DS	Dynamic Stall
FD	Frequency Domain
FEM	Finite Element Model
FVM	Free-wake Vortex Model
GDW	Generalized Dynamic Wake
GSM	Global Stiffness Model
IFE	Institute of Energy Technology
KoM	Kick off Meeting
MBS	Multi-Body System formulation
MD	Morison Drag term
ME	Morison Equation
MIT	Massachusetts Institute of Technology
NMBU	Norwegian University of Life Sciences
OC3	Offshore Code Comparison Collaboration
OC4	Offshore Code Comparison Collaboration Continuation
OC5	Offshore Code Comparison Collaboration Continuation, with Correlation
PT	Potential flow Theory
QSM	Quasi-Static Model
RAO	Response Amplitude Operator
RB	Rigid Body
SM	Simulink-MATLAB interface
TD	Time Domain
UD	User Defined

Symbols

a	Axial induction factor
a'	Tangential induction factor
A	In-plane cross section area
$\bar{\bar{\mathbf{A}}}$	Added mass matrix
$\mathbf{B}$	Structural damping matrix
$\mathbf{C}$	Structural stiffness matrix
$\bar{\bar{\mathbf{C}}}$	Hydrostatic stiffness matrix
c_D	Drag coefficient

c_m	Added mass coefficient
C_d	Profile local drag coefficient
C_l	Profile local lift coefficient
C_n	Profile local normal coefficient
C_t	Profile local tangential coefficient
D	Sectional characteristic length
dF	Modified differential Morison force
dF_{mor}	Differential Morison force
$\vec{F}$	Global force vector
$\bar{\mathbf{F}}_{exc}$	External forcing vector
$F_{surface}$	Surface point force
g	Acceleration due to gravity
$\bar{\bar{\mathbf{K}}}$	Radiation retardation kernel
$\vec{M}$	Global moment vector
$\mathbf{M}$	Inertia matrix
$\bar{\bar{\mathbf{M}}}_{RB}$	Mass matrix
$\vec{n}$	Body surface normal vector
Q	Torque
$\vec{r}$	Distance vector
r	Blade element radius
S	Wetted surface
t	Time
T	Thrust
$\dot{u}$	Water particle acceleration
u	Water particle velocity
u_t	Time derivative of the water particle velocity
u_x	Spatial derivative of the water particle velocity in the x-direction
u_z	Spatial derivative of the water particle velocity in the z-direction
V_{rel}	Induced relative velocity
V_∞	Free-stream velocity
w_z	Spatial derivative of the z-wise particle velocity
$\ddot{X}$	Structure acceleration
$\dot{X}$	Structure velocity
α	Angle of attack
β	Local twist angle
η_x	Spatial derivative of the surface elevation in the x-direction
ρ	Air density
ρ_w	Water density
ϕ	Flow angle
Φ	Velocity potential
Φ_d	Diffraction velocity potential
Φ_r	Radiation velocity potential
Φ_w	Incident velocity potential
ω	Turbine rotational speed

Executive Summary

The report provides an overview of the numerical tools used by the consortium in the preliminary design and optimization of floating wind turbine substructures. A state-of-the-art review of floating wind turbine coupled modelling was conducted, with a focus on substructure modelling, highlighting current challenges in this area. Particular areas identified include nonlinear wave kinematics and force modelling on large-volume substructures; hydrodynamic viscous forcing; substructure flexibility; and, large rotor aerodynamic damping.

A questionnaire was distributed to consortium partners concerning numerical tools used during the preliminary design and optimization of floating substructure concepts, as well as initial "pre-design" methodologies employed. Consortium partners use either WAMIT or AQWA for carrying out hydrodynamic analysis, largely in the frequency domain. A range of aero-hydro-servo-elastic numerical tools are then used for carrying out coupled dynamic simulations of the floating system, with FAST being the most prevalent, followed by OrcaFlex, SIMA, Bladed, Flex5, HAWC2, Simpack Wind and SLOW.

These aero-hydro-servo-elastic numerical tools have similar engineering models implemented: variants of the momentum balance aerodynamic model; combinations of time domain hydrodynamic potential flow and Morison equations; a mixture of finite element methods, multibody formulations and shape response structural representations; and both quasi-static and dynamic mooring line models. The verification, validation and qualification of these tools are defined and presented, with the majority of tools being similarly qualified for the preliminary design and optimization of floating wind turbines.

Consortium partners use preliminary design methodologies similar to those used in the offshore oil and gas industry. Initiating with a static design constrained by a small number of design criteria and variables, designers then carry out a static analysis to evaluate static stability and equilibrium states. Dynamic analysis of the floating substructure follows, normally in the frequency domain, identifying natural frequencies and response amplitude operators. Finally, designers perform time-domain coupled simulations for a restricted set of environmental conditions. This is followed by a concept evaluation and if necessary, the process is repeated considering feedback from the previous cycle. Some partners also include intermediate concept evaluations between static design, static analysis, dynamic analysis, and coupled simulation analysis.

A number of challenges were also identified that design engineers face when going through this process and progressing to more advanced design phases. These include: 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; and improving computational efficiency.

The results from the questionnaire responses and state-of-the-art review also provided an outlook on future numerical modelling activities and areas where model improvements are needed. The major topics of interest identified were: more efficient integrated numerical tools; integration of numerical tools within the design process; cascading of design tools from different levels of modelling; and improving the reliability of design tools.

Contents

1 Introduction

1.1 Context within LIFES50+

This report summarises the initial work in Work Package 4 related to improving state-of-the-art design tools for large floating wind turbine substructures. The aim of this report is to provide an overview of current tools, modelling background and design methodologies used by consortium partners, and identify the current challenges in advancing numerical design tools that may be addressed within LIFES50+. A questionnaire was sent out to all consortium partners, found in Appendix A, to gather such information and the gap analysis carried out in the formulation of LIFES50+ was also utilised.

1.2 Report structure

This report first presents a brief overview of state-of-the-art modelling activities and theoretical background for coupled analysis and design of floating wind turbines in Section 2, with particular focus on floating substructure modelling. Section 3 then outlines and compares numerical tools currently in use within the consortium for the design optimisation phase of floating wind turbine support structures. Section 4 then details the conceptual design methodologies currently implemented by partners and the role of the numerical tools in this process. Specific challenges in this stage of design are also highlighted. This is followed by Section 5 where an outlook on future modelling activities is presented. Finally Section 6 provides some conclusions and recommendations.

2 Environment & Subsystem modelling state-of-the-art

2.1 Hydrodynamics modelling

2.1.1 Wave kinematics models

A variety of wave kinematic theories and models exist. These include the linear Airy wave theory, Stokes' 2nd and 5th order theory, and Stream function theory, where all are restricted to wave motion at constant depth and the latter two are further restricted to regular waves. The applicability of these theories is thus dependent both on the desired wave climate and nonlinearity, and the force model in use.

Application of more complex wave kinematics models for such structures would then require abandoning the velocity potential linearization process and evaluating the nonlinear potential flow field in the time domain. A number of different approaches have been developed, with examples including high-order spectral methods (Ducrozet, 2012) and fully nonlinear solvers (Engsig-Karup, 2009). Whilst the former is formally weakly nonlinear method, the iterative solution to the nonlinear wave potential has proved reliable in many practical applications.

2.1.2 Force models & equations of motion

2.1.2.1 Slender structures

The Morison equation (Morison, 1950) has been extensively used to represent hydrodynamic loading due to its versatility to cover a range of slender and multi-member structures. Whilst the validity in theory is limited to transverse forces on infinitely-long slender cylinders, in practice it has shown to produce promising results for a typical floating wind turbine semi-submersible in comparison to model scale measurements (Robertson, 2013). Eqn. (1) presents the Morison equation in a form that includes the relative motion between structure and fluid particles.

$$dF_{mor}(z,t) = \left\{\rho_w A c_m(\dot{u} - \ddot{X}) + \rho_w A \dot{u} + \frac{1}{2}\rho_w c_D D(u - \dot{X})|u - \dot{X}|\right\} dZ \tag{1}$$

Here ρ_w is the water density, A is the in-plane cross section area, c_m is the added mass coefficient, $\dot{u}$ is the in-plane water particle acceleration, $\ddot{X}$ is the in-plane structure acceleration, c_D is the drag coefficient, D is the sectional characteristic length (the diameter in case of a cylinder), u is the in-plane water particle velocity and $\dot{X}$ is the in-plane structure velocity. Orientation of the velocities are illustrated in Figure 1.
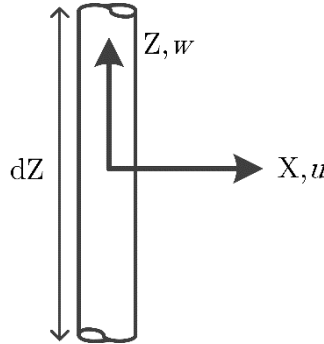

Figure 1 - Morison equation coordinate system

Modifications to Eqn. (1) have been made by Rainey (Rainey, 1989; Rainey, 1995) to account for nonlinear effects, Eqn. (2). Firstly, the fluid particle acceleration is now the Lagrangian acceleration rather than the Eulerian derivative of the wave velocity. Further, additional terms are considered to account for the finite length of the body, and the change in kinetic energy of the flow around the body at the intersection between the water surface and body (Eqn. (3)), which shows the special case of a vertical cylinder.

$$dF(z,t) = \left\{\rho_w A c_m(\dot{u} - \ddot{X}) + \rho_w A \dot{u} + \frac{1}{2}\rho_w c_D D(u - \dot{X})|u - \dot{X}| + \rho_w A c_m w_z(u - \dot{X})\right\} dZ \tag{2}$$

$$F_{surface}(t) = -\frac{1}{2}\rho_w A c_m \eta_x (u - \dot{X})^2 \tag{3}$$

Here $\dot{u} = u_t + u u_x + w u_z$, w_z is the spatial derivative of the z-wise particle velocity, and η_x is the spatial derivative of the surface elevation in the x-direction. In addition, Faltinsen et al. (Faltinsen, 1995) proposed a theory that accounts for up to third-order effects on a surface-piercing cylinder which has a diameter of the same order of magnitude as the wave amplitude. This theory, now known as the FNV model, relies on applying potential flow theory to solve the diffraction problem.

2.1.2.2 Large-volume structures

In engineering models describing the dynamics of a floating body, the six degree of freedom (DOF) motion of the body is usually represented by a set of coupled second-order differential equations. The approaches in which interactions with the marine environment are determined vary, depending on the body geometrical properties and prevailing environmental conditions.

As floating substructures will increase in size to accommodate larger wind turbine units, relative length scales approach those of offshore oil and gas floating substructures where other hydrodynamic effects, namely diffraction and radiation, become more prevalent and are not inherently captured by

the Morison approach. Thus, the adoption of another approach is needed, with the most common being potential flow theory coupled with boundary element methods.

Classically solved in the frequency domain, potential flow panel models provide the necessary information to investigate diffraction and radiation forces. Inherent to potential flow methods, viscous forcing and viscous damping are not included and hence are usually incorporated through empirically-determined coefficients or by adapting parts of the Morison equation.

Current practices linearize the potential flow solution assuming an equilibrium position for the floating body and a general harmonic solution to the velocity potential such that the necessary first-order quantities can be derived. The linearized boundary conditions are illustrated in Figure 2 and the Laplace equation concerning the velocity potential given by Eqn. (4) is applied to establish the velocity potential within the fluid domain and the pressure at the surface of the floating body.
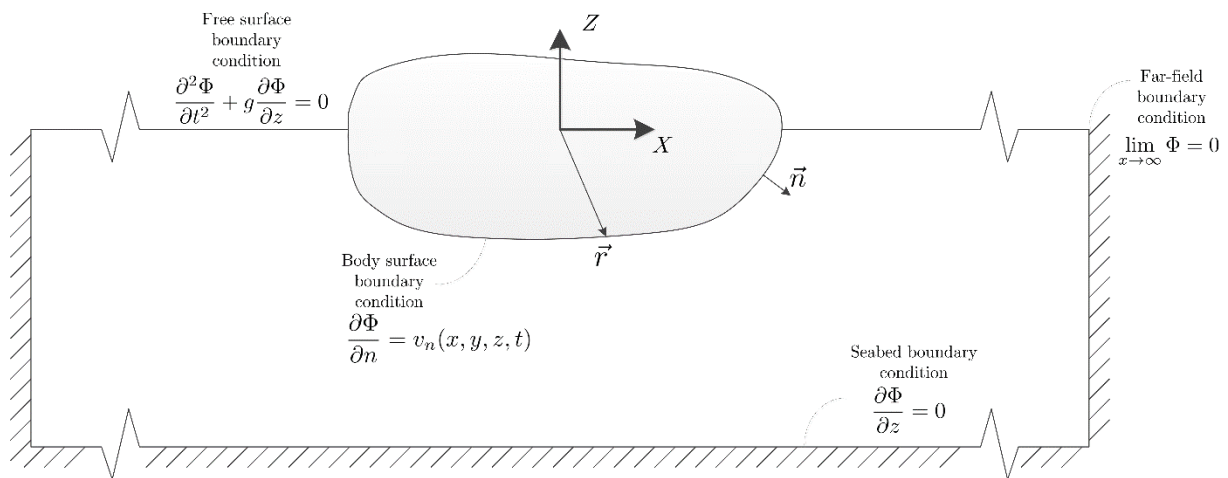

Figure 2 - Boundary conditions for the linearized potential flow problem

$$\Phi(x, y, z, t) = \ \Phi_w + \Phi_d + \Phi_r \tag{4}$$

$$\nabla^2 \Phi = 0$$

As the velocity potential is decomposed into a number of components representing the incident (Φ_w), diffracted (Φ_d) and radiated (Φ_r) wave fields, the global force $\vec{F}$, and moment, $\vec{M}$, contributions for each of these can be computed, Eqns (5) and (6):

$$\vec{F} = \rho_w \iint_S \left(\frac{\partial \Phi}{\partial t} + gz \right) \vec{n} \cdot dS \tag{5}$$

$$\vec{M} = \rho_w \iint_S \left(\frac{\partial \Phi}{\partial t} + gz \right) (\vec{r} \times \vec{n}) \cdot dS \tag{6}$$

Here S represents the wetted surface of the structure in the equilibrium position, g is the acceleration due to gravity, z is the vertical coordinate from the mean sea level, $\vec{n}$ is the body surface normal vector, and $\vec{r}$ is the corresponding distance vector from the reference coordinate system origin. The orientation and reference point of $\vec{F}$ and $\vec{M}$ is the origin of the reference system.

Application of these results in the time domain is done through the Cummins equation (Cummins, 1962; Oglivie, 1964), as is done in the coupled numerical tools used in the consortium:

$$\left(\bar{\bar{\mathbf{M}}}_{RB} + \bar{\bar{\mathbf{A}}} \right) \ddot{\mathbf{x}}(t) + \int_{-\infty}^{t} \bar{\bar{\mathbf{K}}}(t - \tau) \dot{\mathbf{x}}(\tau) d\tau + \bar{\bar{\mathbf{C}}} \mathbf{x}(t) = \bar{\mathbf{F}}_{exc}(t) \tag{7}$$

Where $\mathbf{M}_{RB}$ is the mass matrix, $\bar{\mathbf{A}}$ is the added mass matrix, $\bar{\mathbf{K}}(t)$ is the radiation retardation kernel, $\bar{\mathbf{C}}$ is the hydrostatic stiffness matrix, $\mathbf{x}(t)$ is the rigid body displacement vector and $\mathbf{F}_{exc}(t)$ is the external forcing vector. It should be noted that additional external forcing terms may be added to the equation to represent mooring forces and wind-induced forces.

Apart from first-order potential hydrodynamic loading, second-order effects have an important role in the design and response of floating systems. Second-order hydrodynamic effects are a combination of both coupled first-order terms as well as the second-order potential. Pinkster (Pinkster, 1980) classified these effects by the following decomposition into five contributions:

  A. First order relative wave elevation relative to the static waterline
  B. Pressure contribution from first order velocities squared in the Bernoulli equation
  C. Products of the gradient of the first order body motions and first order pressure
  D. Rotation of the first order fluid force relative to the body axes
  E. Second order potential

The relative importance of the individual components depends on the platform geometrical and inertial configuration, as well as flow regimes around the submerged floating body (Matos, 2011). To date, floating wind turbine studies investigating second-order hydrodynamic effects have focussed on the so-called difference- and sum-frequency forces, associated with the difference and sum of pair-wise interacting first-order frequencies (e.g. (Duarte, 2014)). This is due to the potential resonant conditions that may transpire in both catenary- and taut-moored structures, including excitation of turbine eigen-modes. In fact a number of studies for spar-type substructures (Karimirad, 2013; Roald, 2013), tension-leg-platforms (Bachynski, 2014), and semi-submersible type substructures (Gueydon, 2014) found configuration-dependent significance of difference- and sum-frequency hydrodynamic excitation. For spar-type floating wind turbines Roald et al. (Roald, 2013) found that there are not significant second-order effects on the system, whilst Karimirad (Karimirad, 2013) indicated that second order difference-frequency forces may induce resonant heave responses. In the case of some tension-leg-platforms Bachynski (Bachynski, 2014) concluded that sum-frequency hydrodynamic forces can have a significant impact on load calculations. Gueydon et al. (Gueydon, 2014) highlighted that for large-volume semi-submersible substructures difference-frequency hydrodynamic forces have a large impact on global performance due to coupling with natural frequencies of the moored system.

2.1.3 Viscous forcing considerations in potential flow implementations

Hydrodynamic viscous effects need to be explicitly incorporated within the equations of motion, in particular to realistically predict substructure motion close to and at resonant conditions. As described by Borg et al. (Borg, 2015), different approaches are possible based on available data and model complexity. A first approach is to construct a global linear damping matrix, proportional to the substructure bulk motion, based on measured data or typical values for similar structures. In light of the large-amplitude motion in the range of first order wave frequencies seen for floating wind turbine substructures, a global quadratic damping matrix can supplement or replace this linear approach. The quadratic damping matrix would be constructed either from measured data or by assimilating an equivalent representation from a discretized substructure Morison drag force model. In both cases the viscous damping force is dependent on the platform bulk motion and does not usually consider the local variations in relative fluid kinematics.

An improvement on the global damping matrices approach, and as is now being done in most numerical tools, is to construct a distributed substructure model consisting of the Morison drag term and evaluating the local hydrodynamic drag forces based on instantaneous local relative fluid kinematics

in the time domain. This approach improves substructure global motion predictions (Robertson, 2013), however selection of appropriate drag coefficients is not trivial and contributes to uncertainties (still requiring a degree of calibration against measured data).

The type of calibration based on measured data has as yet still to mature, with a number of different approaches in use based on linear and nonlinear free decay measurements analysis, e.g. (Coulling, 2013), and platform response measurements analysis, e.g. (Aksnes, 2015).

2.2 Mooring system modelling

The main function of the mooring lines to maintain the position of the floating system, and in the case of tensioned lines to maintain stability, can be represented by models classified as static, quasi-static and dynamic. The static type in its simplest form consists of calculating the mooring restoring forces through a linearized global stiffness matrix. The shortcomings of this approach is the restriction to small-amplitude motion, no information on individual mooring line behaviour and the inability to capture nonlinear and dynamic mooring line characteristics (van den Boom, 1985).

In any case this approach is usually dependent on a model description of the individual mooring line geometry that is quasi-static – that is, at each time step the mooring line is assumed to be in static equilibrium. Hence it is advantageous to directly solve the quasi-static model of individual mooring lines during coupled time-domain simulations, resulting in a nonlinear model whereby the instantaneous position of mooring fairleads are considered when calculating mooring forces. This is the approach implemented by most coupled numerical tools within the consortium. As is inherent to quasi-static models, the exclusion of mooring line velocity and acceleration infers that hydrodynamic forcing is not considered.

Some of numerical tools have now also progressed to adopting more advanced numerical representations of mooring systems that capture the dynamic characteristics and interactions with the surrounding environment. This is achieved by discretizing the mooring lines either with a multibody formulation or finite element method. Whilst these dynamic models are more computationally intensive, they provide more of an improvement on numerical predictions particularly in adverse operating conditions (Hall, 2014) – the larger loads and large-amplitude motion in these conditions induce dynamic effects in mooring lines that are not captured by quasi-static models. In this regard, Hall et al. suggest that mooring line modelling complexity not only affects mooring line load predictions but also blade loads predictions. Dynamic models are particularly relevant to tensioned moorings – Bachynski (Bachynski, 2014) concluded that linear frequency-domain mooring models did not provide adequate results for tension leg platforms, and dynamic finite element mooring models with second-order hydrodynamic substructure forcing were important for extreme and fatigue response calculations. It can be concluded that dynamic mooring line models are recommended when carrying out design and optimization beyond preliminary system sizing.

2.3 Structural modelling

The simplest structural representation of a wind turbine and the substructure is by assuming they are a set of rigid bodies. This is useful during initial conceptual design. However, the flexibility of the structures would need to be included to derive eigen-modes and sectional loads for dynamic design. This is normally done through the discretization of the system components into a number of elements.

The desired numerical accuracy and related level of discretization form a trade-off in numerical tools in optimizing computational speed and the level of detail in results. Hence structural models used in state-of-the-art coupled numerical tools range from modal representations over to multibody formula-

tions and to finite element models (FEM). The underlying basis for all three approaches is the same – the second order dynamic equation of motion:

$$\mathbf{M\ddot{x} + B\dot{x} + Cx = F} \tag{8}$$

Here $\mathbf{M}$ is the inertia matrix, $\mathbf{B}$ is the structural damping matrix, $\mathbf{C}$ is the structural stiffness matrix, $\mathbf{x}$ is the structural deformation vector and $\mathbf{F}$ is the external forcing vector.

The FEM approach can require thousands of nodes to accurately describe the structural behaviour of a wind turbine system (resulting in a large DOF system), and this has a significant impact on the computational performance on the numerical model. A solution to this is to linearize the problem and assume the structure deforms by a linear superposition of a subset of the response shapes of the system. This is often referred to as the modal representation, Figure 3, although the response shapes do not need to be natural mode shapes, e.g. (Øye, 1996). By describing the nodal deformations in terms of shape deformations, the number of degrees of freedom (DOFs) of the system are greatly reduced, thereby simplifying the computational issue.

The downfall of a modal model is the inherent nature of the approach – linearization. This assumption limits the validity of the model to small amplitude deformations and there is some loss of nonlinear interactions. However the linearization can be made on local elements (e.g. tower, drivetrain, blades) such that the global deflections of, for example, the blades, are not linear. Further, loads are normally computed at the instantaneous position of e.g. the blades. This can be interpreted as nonlinear loading and in turn the structure response is not truly linear. As is the case with wind turbine implementations, beam models are typically used so deformations of the cross section are typically not captured.
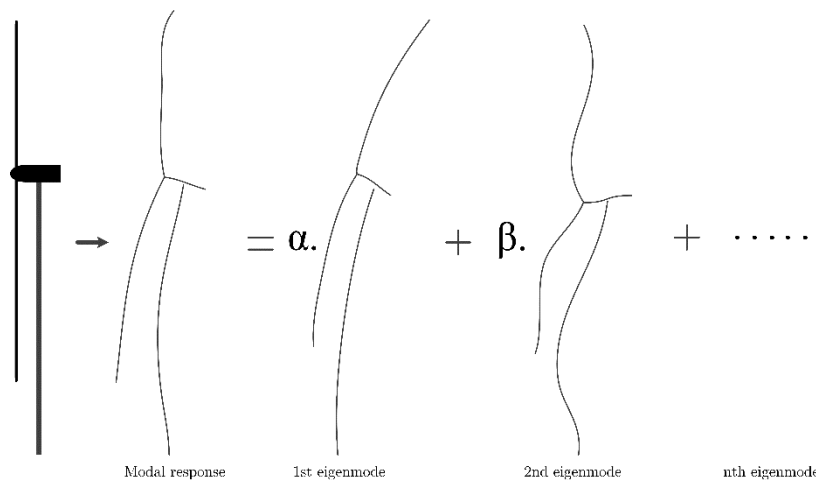

Figure 3 - Illustration of modal representation

An approach which bridges the gap between modal representations and FEM is the multibody formulation, Figure 4. Essentially the multibody formulation uses a smaller number of elements than FEM to represent the system structure, and in some cases reduced element. This is the formulation that coupled numerical tools are now adopting (detailed in Section 3.1).

The modal approach has produced good results, even in the range of conditions where its range of validity is in doubt (Jonkman, 2010). However the current state-of-the-art structural modelling is placed in multibody and FEM approaches. The large amplitude and nonlinear motion of floating wind turbines coupled with the lack of full scale measurements requires these levels of fidelity to more accurately predict responses. However qualification of these models is still needed, as they may not be

accurate in all situations. In the wind turbine domain, current model development is focusing on in-cluding three-dimensional beam theories that capture the nonlinear coupled behaviour of novel struc-tural configurations involving anisotropic materials and structural control systems (Branner, 2012).
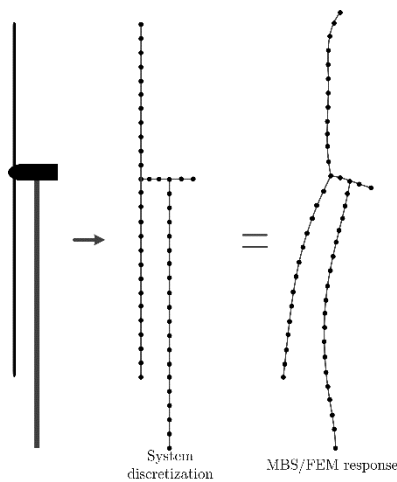

System
discretization   MBS/FEM response

Figure 4 - Illustration of multibody and FEM representations

Structural damping would preferably be obtained through deterministic modelling of the structure. However this is typically difficult and hence a simplified damping model is often used to establish the structural damping matrix. This model is based on a linear combination of the mass and stiffness ma-trices, and is typically referred to as Rayleigh damping. Calibration of this model is ideally done against physically measurements, but when this is not possible sensitivity studies need to be carried out prior to design optimization for suitable structural damping to be selected (DNV GL, 2013).

Inclusion of flexible motion in the modelling of floating substructures has to date remain somewhat unexplored – both due to the limitations imposed by hydrodynamic force models and relatively rigid substructures typically adopted from the offshore oil and gas industry. With the transition to larger substructures for larger turbines, coupled with the shift from offshore oil and gas design practices to reduce costs, substructure flexibility – even in the case of large-volume substructures – can become an issue to be considered during design and optimization coupled numerical simulations. Adopting a purely Morison force model approach allows for the substructure to be readily modelled with the same approach as the wind turbine. However when utilising potential flow force models this is not as straightforward, as hydrodynamic forces are typically derived as bulk loads for the global rigid floater motion, rather than distributed forces.

Bulk loads for flexible shapes, however, are possible to include in the calculations. Further, incorpora-tion of substructure flexibility coupled with potential flow hydrodynamic force models in time-domain numerical tools can follow methodologies developed for the design and analysis of very large floating structures (Fu, 2007; Taghipour, 2008; Wang, 2008).

2.4 Aerodynamics modelling

The current state-of-the-art models evaluating aerodynamic loading on wind turbines is a modified form of the Blade Element Momentum (BEM) theory (Matha, 2011; Sørensen, 2011; Hansen, 2015). Essentially BEM equates the loss of momentum of the flow through the turbine rotor (represented as a permeable actuator disk) to the loads imparted on the rotor blades (represented by a 2D strip ap-proach), Figure 5. Assuming a one-dimensional flow, applying the law of conservation of momentum

and energy equation, the induced relative velocity, V_{rel}, and angle of attack, α, at an arbitrary blade element can be derived:

$$V_{rel} = \sqrt{\left(\omega r(1 + a')\right)^2 + \left(V_\infty(1 - a)\right)^2} \tag{9}$$

$$\alpha = \tan^{-1}\left(\frac{V_\infty(1-a)}{\omega r(1+a')}\right) - \beta \tag{10}$$

Where ω is the turbine rotational speed, r is the blade element radiaus, a is the axial induction factor, a' is the tangential induction factor, V_∞ is the free-stream velocity and β is the local twist angle. By adopting a differential approach to deriving the blade loads as a function of rotor radius, the elemental torque, $\frac{dQ}{dr}$, and thrust, $\frac{dT}{dr}$, can be calculated (c.f. Figure 5):

$$\frac{dQ}{dr} = \frac{1}{2}\rho V_{rel}{}^2 c C_t r, \qquad C_t = C_L \sin\Phi - C_D \cos\Phi \tag{11}$$

$$\frac{dT}{dr} = \frac{1}{2}\rho V_{rel}{}^2 c C_n, \qquad C_n = C_L \cos\Phi + C_D \sin\Phi \tag{12}$$

where ρ is the air density, c is the local blade chord, C_L is the local lift coefficient, C_D is the local drag coefficient, and $\Phi = \alpha + \beta$. The flow angle Φ is composed of the angle of attack α and blade twist angle β. The local force coefficients are related to the α-dependent airfoil profile coefficients through Φ.
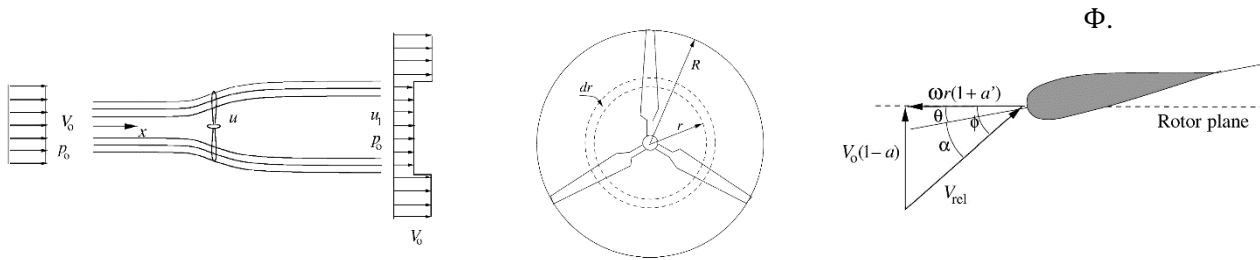

Figure 5 - left: 1D idealized flow through a rotor; centre: annular discretization of rotor plane; right: local blade element velocity triangle. Images adapted from (Hansen, 2015)

This allows for calculation of distributed and global aerodynamic loads on the wind turbine blade. Furthermore, modifications and corrections to the classical BEM theory have allowed for the inclusion of the dynamic stall and inflow phenomena, blade tip losses, finite number of blades, skewed flow, hub effects and tower effect e.g. (Moriarty, 2005; Hansen, 2015).

Through the design process it is necessary to consider the turbulence naturally present in the wind flow. In the timescales of coupled simulations short-term wind speed spectral distributions are considered as specified by recommended practices and design standards, e.g. (DNV GL, 2010b) and (IEC, 2005), with the Kaimal spectrum (Kaimal, 1972) being widely used. Realizations of three-dimensional wind fields following these spectra are commonly done through the application of the IEC coherence model, the von Karman coherence model (Saranyansoontorn, 2004) or the Mann model (Mann, 1998).

An alternative model to BEM is generalized dynamic wake (GDW) theory (Moriarty, 2009). Also known as the acceleration potential method in the helicopter industry, this approach solves the Laplace equation for calculating pressure distributions over the rotor plane. The advantage of GDW over BEM is that it inherently captures dynamic and three-dimensional effects. However the GDW solution does not implicitly include wake rotation and can break down with heavily loaded rotors and in low wind speeds. Overall, BEM is a more widely used model than GDW in coupled simulations.

More advanced aerodynamic models that have seen very limited use in coupled floating wind turbine simulations are fixed/free vortex methods and computational fluid dynamics methods. These models allow for capturing rotor-wake interactions and more detailed viscous effects, aspects that momentum-based models cannot currently simulate. One phenomenon known as the vortex ring state is of particular interest for floating wind turbines as it may be induced by substructure motion when operating at high tip speed ratios (Sebastian, 2013). This phenomenon comes about as the turbine pitches back and forth due to platform motion, different sections of the rotor blades experience different flow regimes to the extent that outboard blade sections alternate between 'windmill' and 'propeller' states. This occurs when the turbine has a damping influence on the floating substructure and is exchanging some kinetic energy with the air flow. When in the 'propeller' state, the blades induce what is sometimes referred to as negative damping – that is, the bulk motion of the system is exacerbated through a reinforcing feedback loop. This phenomenon obviously violates the slipstream condition of momentum-based engineering models, and as yet model modifications still need to be identified.

In conjunction with the vortex ring state phenomenon, the influence of radial flow on blade loading and wake evolution for large floating wind turbines has not yet been investigated. Micallef et al. (Micallef, 2011; Micallef, 2013) found that radial flow is significant for the inboard and outboard sections of a wind turbine blade, but to a much smaller degree in the blade mid-section. The radial flow at the blade tip section can significantly influence shed tip vortices that subsequently will influence local blade loading, altering extreme and fatigue load estimates. Further to this when a floating wind turbine is in operation with the rotor tilted due to the steady pitch offset of the floating substructure, a component of the incident wind would traverse radially along the blade. This has the potential to exacerbate the influence of radial flows in the rotor plane and subsequent load effects. Substructure motion in a lateral direction to the wind may also contribute to augmented radial flows. This contribution would be most significant in scenarios where wind and wave misalignment exists. Whether these scenarios will actually have a markedly noticeable impact on the floating wind turbine subsystem loads is yet to be quantified.

3   Brief description of numerical tools used by consortium

The consortium partners use a range of numerical tools in the preliminary design and optimization of floating support structures for wind turbines. The questionnaire mentioned previously was used in collecting this information. Table 1 indicates the software tools used by the relevant partners. Note that ORE Catapult and IREC are not included, as these partners do not carry out activities related to the design and simulation of floating wind turbines.

Both WAMIT and ANSYS AQWA have approximately equal usage by consortium partners for the evaluation of hydrodynamic characteristics of floating support structure designs. In the case of time-domain integrated tools, FAST is the most used code followed by BLADED, OrcaFlex and SIMA (SIMO/RIFLEX). In the case of concept developers, FAST and OrcaFlex are most used. A brief description of the capabilities of each code is provided below.

	WAMIT	AQWA	FAST	BLADED	OrcaFlex	3DFloat	Flex5	HAWC2	SIMA (SIMO/ RIFLEX)	Sesam/ Wadam	Simpack Wind	SLOW
DNVGL	X			X								
DTU	X		X				X	X				
IBER		X	X									
IDEOL		X	X		X							
MARINTEK	-*								X			
OO	-*					X	X		X	X		
TECN		X	X		X							
USTUTT		X	X	X							X	X
POLIMI		X	X									
*WAMIT data is incorporated in the software tools SIMA, Sesam/Wadam and 3DFloat												

Table 1: Numerical tools usage within the consortium

WAMIT: a commercial numerical tool originally developed at MIT and now licensed by WAMIT, Inc. for analysing wave-structure interaction for offshore and ship structures (WAMIT, 2015). It is based on potential flow theory and solves wave-structure interactions problems in the frequency domain, although transformation of results into the time domain is also possible. WAMIT is capable of evaluating second order potential flow hydrodynamic forces and allows for the modelling of complex submerged geometry and flexible substructures.

ANSYS AQWA: a commercial numerical package developed by ANSYS, Inc. for analysing wave-structure interaction of offshore and marine structures (Ansys, 2015). Similar to WAMIT, AQWA solves for the potential flow solution within the frequency domain with the possibility to transform results for time-domain simulations. Dynamic mooring line models are also included along with the evaluation of second-order hydrodynamic forces, with the capability of transferring distributed pressure loads to structural models from other ANSYS products.

WINDOPT: a proprietary numerical package developed by MARINTEK (MARINTEK, 2012) consisting of a number of programs – WAMOF3, MIMOSA and NLPQL – that evaluate the hydrodynamic load coefficients, platform motions and mooring line forces, and contain efficient optimization algorithms, respectively. The objective of this tool is the conceptual optimization of floating wind turbine support structures, mooring system and power cable for a given cost function and set of design constraints.

FAST: an open-source integrated numerical tool developed at the National Renewable Energy Laboratory (NREL). It integrates engineering models for aerodynamics, structural dynamics, hydrodynamics and control theory to carry out aero-hydro-servo-elastic time-domain simulations of the whole wind turbine system (Jonkman, 2005). Aerodynamics are modelled using BEM or GDW models. The wind turbine structure is currently represented through a modal representation (with a finite element implementation under development), slender and large-volume structure hydrodynamic force models are implemented and typical dynamic equations model the drivetrain. In the pursuit of increased model use and management, NREL have recently enhanced the modularity of FAST to facilitate easier implementation of new modules, whilst also increasing the code numerical robustness and performance.

BLADED: a commercial integrated tool developed by Garrad Hassan, now part of DNV GL, primarily for the wind industry manufacturers (DNV GL, 2015). It is an integrated software package for the design and certification of both onshore and offshore wind turbine structures, and has undergone extensive validation against model- and full-scale measurements. Similar to FAST, it integrates the same level of engineering models to represent aerodynamics, hydrodynamics, structural dynamics and control dynamics.

OrcaFlex: a commercial numerical package for the dynamic analysis of offshore marine systems developed by Orcina (Orcina, 2015). Originally developed for the analysis of mooring and riser systems, the software has also been interfaced with FAST to simulate floating wind turbines. With the same aerodynamic and wind turbine structural and control modules as FAST, OrcaFlex has in-house capability of calculating Morison-based hydrodynamic forces as well as importing potential flow information from other software such as WAMIT and ANSYS AQWA. OrcaFlex also contains detailed dynamic mooring line models.

3DFloat: an integrated tool developed by the Institute for Energy Technology (IFE) and the Norwegian University of Life Sciences (NMBU). It computes the dynamic response of flexible structures subjected to wind and wave loading in the time domain (De Vaal, 2015; Myhr, 2015). It is based on a nonlinear FEM framework allowing large deflections and flexibility in model configurations being simulated. The aerodynamic loads on the rotor are computed by BEM with dynamic inflow and corrections for yaw errors. The hydrodynamic loads are computed by a combination of Morison elements and linear potential theory bodies (import of WAMIT/WADAM) results.

Flex5: an integrated tool developed by Øye (Øye, 1996) at the Technical University of Denmark to simulate the aeroelastic response of wind turbines. Utilising BEM with dynamic stall and dynamic inflow for aerodynamic load calculations, the wind turbine dynamic response calculations are done with a set of static or modal deformation shapes chosen for each structural element. Wind turbine control is achieved through user-defined routines and floating substructure loads are calculated through the Morison equation alone or combined with the Cummins equation, and quasi-static mooring line models are implemented.

HAWC2: an integrated tool developed by DTU Wind Energy (Larsen, 2015) for calculating wind turbine system responses in the time domain. The aerodynamic model is based on BEM, however this has been modified to include dynamic wake, wake expansion and swirl, along with other correction models pertaining to wind turbines. The wind turbine system is structurally represented with a multibody formulation, allowing for a large flexibility in system configurations that can be modelled. Similar to the other integrated tools, hydrodynamic loads can be modelled by either the Morison equation or potential flow solution (when imported from WAMIT), or a combination of both.

SIMA (SIMO/RIFLEX): a proprietary numerical package developed by MARINTEK (MARINTEK, 2009; MARINTEK, 2011) and licenced by DNV GL. The BEM aerodynamic model with dynamic wake is implemented, and allows for the coupled analysis of floating wind turbine systems in the time domain. SIMO bodies are employed for large-volume hydrodynamic calculations based on a combination of frequency-domain potential flow data and distributed Morison elements, while RIFLEX computes the structural response to all environmental loading with a finite element approach (including Morison drag loading on flexible elements). The hydrodynamic formulation also includes 2nd order wave loading (second order wave kinematics, or second order force and moment QTFs from the potential flow solution).

DNV SESAM – Wadam: Wadam, which forms part of the SESAM package licenced by DNV GL, is a numerical tool for the assessing wave-structure interactions of offshore structures and is largely based on WAMIT results (DNV GL, 2010a).

Simpack Wind: Simpack Wind is an extension to the general-purpose multibody-dynamics software developed by SIMPACK AG, allowing for integrated simulations of offshore wind turbines. Aerodynamic and hydrodynamic loads are calculated using the same modules as in FAST, which are inter-

faced to the multibody wind turbine structural model in SIMPACK. SIMPACK Wind has been used in the analysis of different floating wind turbine systems by (Matha, 2011; Beyer, 2013).

SLOW: SLOW is a numerical tool developed at the University of Stuttgart primarily for carrying out integrated conceptual system simulations of offshore wind turbines (Sandner, 2012). A simplified aerodynamic model based on power and thrust coefficients is interfaced with a reduced DOF multibody dynamics structural model to compute the dynamic response of the system subject to environmental conditions. Hydrodynamic loading is calculated either with the Morison equation or based on frequency-domain potential flow model data. There is also the possibility of SLOW to interface with higher-fidelity subsystem and force models. One of the primary uses of SLOW is in controller design during conceptual design stages.

3.1 Summary of tools capabilities & usage

Table 2 summarises the overall capabilities of all the numerical tools used within the consortium for substructure preliminary design and optimisation. As is evident, the vast majority of integrated tools utilise BEM aerodynamic models with corrections. A similar trend is also seen for hydrodynamics and associated floating body modelling, where either the Morison equation or the combination of Cummins equation and the Morison equation are used, with the Cummins equation relying on hydrodynamic coefficients generated by potential flow programs such as WAMIT or AQWA.

In representing the structural flexibility of the turbine, most integrated tools adopt a trade-off between computational effort and numerical accuracy – the multibody system formulation. In the case of FAST and BLADED, a modal approach is also possible that allows for a large increase in computational speed with associated reduction in numerical accuracy for certain operating conditions. 3DFloat, HAWC2 and SIMA (SIMO/RIFLEX) also tend towards FEM representations of the turbine. In the case of the substructure flexibility, the representation is dependent on hydrodynamic force models selected. In the case of the Morison equation being used in the 'strip theory' fashion, the substructure flexibility may be included in a similar approach as blade flexibility. In the case of the Cummins equation, where hydrodynamic coefficients and forces are derived to represent hydrodynamic loading, the substructure is considered to be rigid as these quantities are evaluated at a single point of reference. Whilst it is possible to go further and incorporate distributed hydrodynamic pressure loads from the potential flow codes, to date the inherent rigidity (and hence high natural frequencies) of substructures to comply with safety level requirements has not warranted the exploitation of such capabilities in existing integrated design tools.

In capturing the influence of the mooring system, all time-domain state-of-the-art integrated tools use quasi-static or higher-fidelity (multibody or FEM) models. These higher-fidelity models are either based on the multibody system formulation or finite element method. Lastly, wind turbine controller modelling is largely identical across the numerical tools – the use of a Dynamic Link Library (DLL) or user-defined subroutine allows for proprietary controllers from wind turbine manufacturers to be included as 'black boxes' within coupled time-domain simulations. For more research-oriented tools, such as FAST and SLOW, interfacing with the MATLAB Simulink environment is also possible.

3.2 Verification, validation & qualification

In the context of this work, verification refers to the comparison of a numerical model to another numerical model of similar or higher fidelity; validation refers to the comparison of a numerical model to measurements from model- or full-scale physical realisations of the system; and qualification refers to the synthesis of the verification and validation in the context of the design process. For example, sim-

plified numerical models are qualified to carry out preliminary sizing of the system, but are not quali-fied for the analysis of the final system design.

The momentum-based aerodynamic models in use by the majority of numerical tools listed in Table 2 have long been used by the onshore and fixed-foundation offshore wind industry. Significant verifica-tion exercises have been done of codes that have been used in the design and analysis of commercial wind turbines (Boorsma, 2014) and are also being carried out specifically for very large (10-20MW) rotors, e.g. AVATAR project (Schepers, 2015). However in the case of aerodynamic models of rotors undergoing support structure motion, preliminary comparison of momentum-based models with CFD has been done (e.g. (Sivalingam, 2015; Lin, 2015; Wu ,2015)), but validation still needs to be carried out – which will be addressed in Work Package 3 through model-scale experiments.

	Aerodynamics	Hydrodynamics	Structural dynamics	Mooring line dynamics	Controller modelling
WAMIT	N/A	FD PT	RB or Modal	GSM	N/A
AQWA	N/A	FD PT or TD CE+MD	RB or FEM (TD)	GSM or QSM or FEM	N/A
WINDOPT	N/A	FD PT	RB	QSM or FEM	N/A
FAST	(BEM or GDW) + DS + DI	TD ME or TD CE + MD	Modal or MBS	GSM or QSM or FEM	DLL or UD or SM
BLADED	BEM + DS + DI	TD ME or TD CE + MD	Modal or MBS	GSM or QSM or FEM	DLL
OrcaFlex	Coupled to FAST	TD ME or TD CE + MD	Coupled to FAST	GSM or QSM or FEM	Coupled to FAST
3DFloat	BEM + DS + DI	TD ME or TD CE + MD	FEM	GSM or FEM	DLL or UD
Flex5	BEM + DS + DI	TD ME or TD CE + MD	FEM/Modal/Shape	QSM	UD
HAWC2	BEM + DS + DI	TD ME or TD CE + MD	MBS/FEM	GSM or QSM or FEM	DLL or UD
SIMA (SIMO/ RIFLEX)	BEM + DS + DI	TD ME or TD CE + MD	MBS/FEM	GSM or QSM or FEM	DLL or UD
Sesam/ Wadam	N/A	FD PT + ME	RB	GSM	N/A
Simpack	(BEM or GDW) + DS + DI or FVM or CFD	TD ME or TD CE + MD	MBS	GSM or QSM or MBS	DLL
SLOW	ACP	Reduced TD CE or ME	Modal or MBS	GSM or QSM	SM

Aerodynamics BEM – Blade Element Momentum GDW – Generalised Dynamic Wake (induction model) DI – Dynamic Inflow DS – Dynamic Stall CFD – Computational Fluid Dynamics FVM – Free-wake Vortex Model ACP – Actuator Point Model *Hydrodynamics* FD – Frequency Domain TD – Time Domain PT – Potential Flow CE – Cummins Equation MD – Morison Drag term ME – Morison Equation	*Structural & mooring line dynamics* RB – Rigid Body MBS – Multi-Body System formulation FEM – Finite Element Method GSM – Global Stiffness Model QSM – Quasi-Static Model *Controller Modelling* DLL – Dynamic Link Library UD – User Defined SM – Simulink-MATLAB interface

Table 2: Summary of tools capabilities

The hydrodynamic models used in the numerical tools here are the standard used by the offshore oil and gas industry for similar substructures. In the context of floating offshore wind turbines, the majori-ty of the numerical hydrodynamic models have been verified through the OC3 project for a spar type

structure (Jonkman, 2010), and through the OC4 project for a semi-submersible type structure (Robertson, 2014). Further to this, a large number of experimental campaigns have been carried out in wave and ocean basins for validating these hydrodynamic and coupled models, most notably the DeepCwind project (Robertson, 2013) for a 5MW turbine and more recently through the INN-WIND.eu project for a 10MW turbine (Sandner, 2015; Bredmose, 2015). In the case of all partners, verification and validation of the hydrodynamic models for most operating scenarios has been carried out, although models can suffer in accuracy, typically in more adverse extreme environmental conditions.

The theoretical basis for wind turbine structural models has long been implemented in various industries and research areas. In particular for large wind turbine blades that undergo large elastic deformations, models from the aerospace industry have been adapted. Aero-elastic responses predicted by these models have been the key point of interest for verification and validation. In the case of floating wind turbines verification of such responses have been verified in the OC3 and OC4 projects, (Jonkman, 2013; Robertson, 2014) but validation is still an activity that needs to be carried out. In terms of fixed-foundation wind turbines, validation efforts have been made in the OC3 and OC4 projects and are being done for very large rotors as part of the AVATAR project (Schepers, 2015). Some numerical tools have also been validated against measurements from large scale fixed/foundation turbines, e.g. (Kim, 2014).

With regards to mooring system model representations, not much dedicated effort in validation has been carried out except in the case of global performance mentioned previously (Azcona, 2014). However, the mooring line models used within the consortium have been tried and tested by the offshore and marine industry, qualifying them for use in the design of floating wind turbine support structures station-keeping systems.

The verification, validation and qualification of coupled models that integrate all the separate engineering models are not as straightforward. As each of these separate modules was originally developed independently, the influence of other modules on the performance and validity of the individual model is put into question. One example is the aerodynamic model – momentum-based implementations assume steady-state flow through the rotor, although this is not necessarily the case with a floating substructure. This is alleviated when dynamic inflow is included. Model modifications are implemented to account for some dynamic effects; however, in the case of a floating wind turbine rotor, they have not yet been validated. Collaborations to date - namely OC3 and OC4 (Robertson, 2013) – have attempted to verify coupled models through 'code-to-code' comparisons. These exercises have proved to be beneficial in identifying errors in model implementation and identifying pitfalls present throughout all codes. However, verification exercises are limited by the fact that when comparing numerical models only the soundness of model implementation is being assessed and not the match to reality.

Hence to date validation attempts have focused on the global performance of the system – designing experimental campaigns to provide realistic measurements for substructure motion and forces. The focus was shifted away from turbine performance in favour of these due to the conflict between the different scaling laws that are applicable to these subsystems.

All partners have taken steps to validate the global performance of their coupled design tools through ocean basin experiments, Table 3; however predictions of variables such as tower and blade loading are yet to be validated against either model- or prototype-scale measurements. It should be noted that whilst the LIFES50+ project aims at advancing floating support structures, it is imperative that codes

also adequately capture the turbine loads as this will form part of the basis on which the support structures are evaluated.

3.2.1   Results from the OC4 comparison

Here a brief summary is provided of some results relevant to the coupled dynamics numerical tools from the OC4 comparison project (Robertson, 2014). The floating system considered consisted of the NREL 5MW wind turbine installed on a tri-column semi-submersible. The project compared a total of nineteen numerical tools, however here only selected results for the numerical tools that are used by the consortium partners are shown. Figure 6 presents results for a regular wave load case, with an incident wave height of six metres and period of ten seconds, and no wind.

In surge, it was found that there are some differences between the numerical tools for both mean and oscillatory components. In particular, differences in mean surge values between the numerical tools were due to whether drift forces were incorporated in the hydrodynamic load model. Differences in oscillatory surge motion were mainly due to the underlying approach for determining the hydrodynamic viscous damping. There is better agreement in pitch due to the absence of significant nonzero
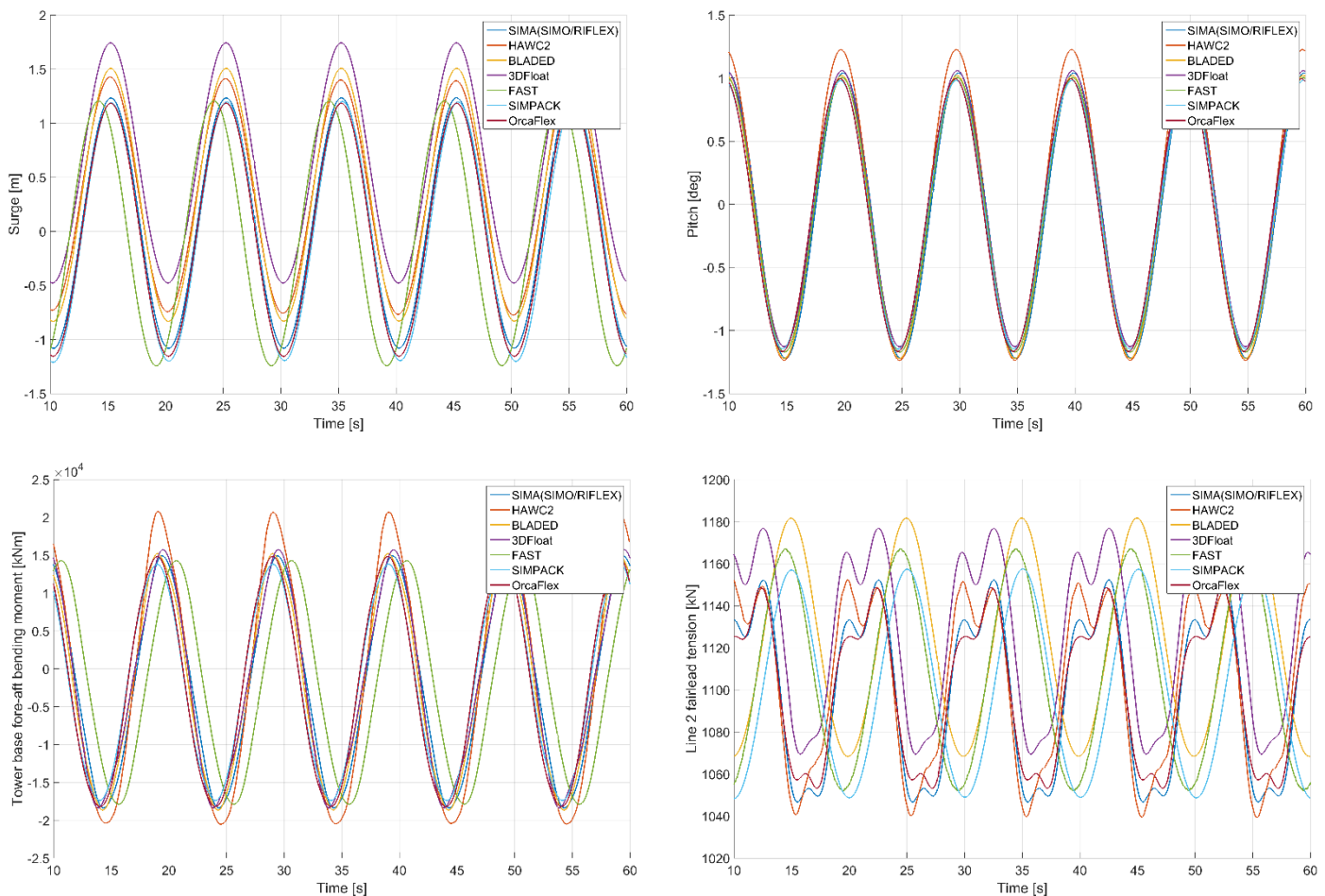
mean wave moments and a smaller influence of hydrodynamic viscous damping as compared to surge.

Figure 6 – Results for a regular wave load case (LC2.1, wave height = 6m and wave period = 10s). Clockwise from top left: surge motion; pitch motion; mooring line 2 (aligned with wave direction) fairlead tension; and, tower base fore-aft bending moment.

The differences observed in the fairlead tension of the mooring line aligned with the wave direction can be attributed to both the type of mooring line model used and the differences in surge motion between the numerical tools. As indicated by Robertson (2014), there are two distinct groupings of the predicted fairlead tensions that relate to whether a quasi-static or dynamic mooring line model is implemented. The tools with a dynamic mooring model predict tensions with a wider range of frequency content and phase difference compared to the tensions predicted by tools with a quasi-static mooring model.

On the basis of the extended set of load cases detailed by Robertson (2014), it is clear that there are still noticeable differences between the results of different numerical tools, with a need for experimental validation of these design tools which can guide the further development to enhance their representation of the underlying physics. Recommended practices for validating these numerical tools also need to be established in the near future.

DNVGL	OC3, OC4, OC5 and against measurements
DTU	OC3, OC4, OC5 and against measurements
IBER	Global model compared against wave tank experiments
IDEOL	Global model compared against wave tank experiments
MARINTEK	OC3, OC4, OC5 and comparison against wave tank experiments
OOL	OC3, OC4, OC5 and comparison against wave tank experiments
TECN	OC5 and comparison against wave tank experiments
USTUTT	OC3, OC4, OC5 and against measurements
POLIMI	OC4 and OC5

Table 3: Partner verification and validation achievements

4   Initial "pre-design" methodologies

The design of floating support structures for wind turbines to date has largely followed the methodologies established in the offshore oil and gas industry, e.g. Collu et al. (Collu, 2010; Collu, 2014). This methodology is loosely illustrated in Figure 7, derived from Collu et al. (2014), where for given site conditions a preliminary static design is established based on required buoyancy and pitch hydrostatic stiffness. With an established platform geometrical and inertial layout, a static and dynamic analysis is performed to capture the equilibrium state(s) and dynamic performance of the support structure for the given site. Note that traditionally dynamic analyses are normally done within the frequency domain. With the support structure performance known, an evaluation of the design is carried out; including cost considerations and the process is iterated until a design satisfying all requirements is obtained. For more details regarding the preliminary design approach in the offshore oil and gas industry, refer to Patel (Patel, 1989), Clauss (Clauss, 1992) and Chakrabarti (Chakrabarti, 2005).

Following the questionnaire responses from project partners, it was seen that a similar methodology is followed, illustrated in Figure 8. All participants initiate the design process with a parametric tool that carries out preliminary sizing of the support structure based on static stability and in some cases also some cost considerations. Some partners have automated this process whilst others carry out a manual preliminary sizing.

This preliminary design is then fed into a frequency-domain hydrodynamic analysis to establish global platform eigen-modes and Response Amplitude Operators (RAOs) that are subsequently utilised to derive the response spectra and performance of the support structure for given site conditions. At this stage there is an intermediate evaluation of the design and if necessary the process is iterated before proceeding to further analyses.

Once this is done, the initial design is then assessed with time-domain aero-hydro-servo-elastic models for a restricted set of design load cases (DLCs). This restricted set of DLCs covers ultimate and fatigue limit states in normal operating conditions as well as ultimate limit states in parked survival conditions. At this stage a more detailed assessment of subsystem loads and responses is also carried out. Some partners at this stage also feedback results to the preliminary sizing stage and iterate until achieving the desired requirements.
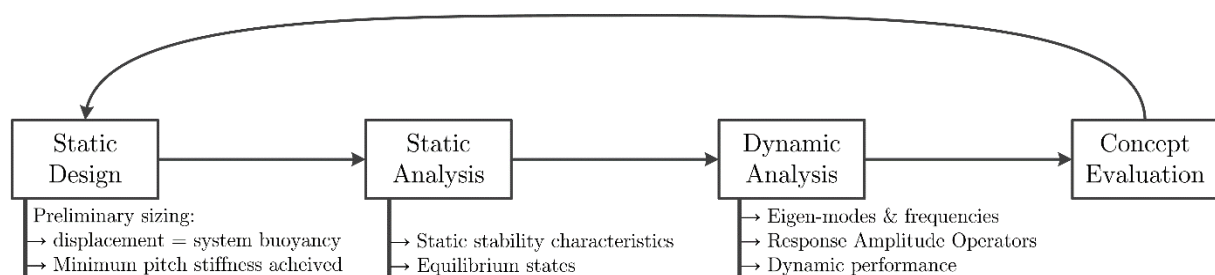

Figure 7 - Generic conceptual design process in the offshore oil and gas industry, adapted from Collu et al. (2014)
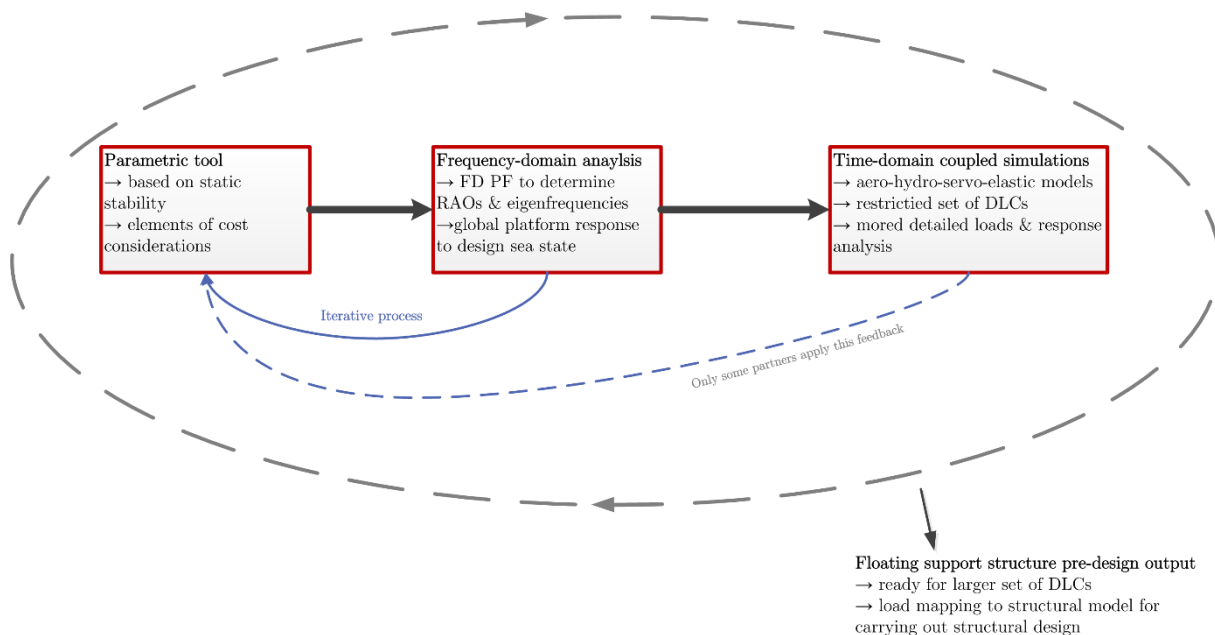

Figure 8 - Overview of conceptual design process utilised by members of the consortium

The above nested iterative cycles are carried out until a satisfactory global design of the floating support structure is achieved. This design is then assessed for a more thorough set of DLCs covering a wider range of transient and stochastic conditions, and this is also followed by a detailed structural design of the floating support structure. The implementation of numerical tools in this design process for each relevant partner is illustrated in Table 4.

Partner	Static Design & Analysis	FD Dynamic Analysis	Feedback cycle to design	TD Coupled dynamic analysis	Feedback to design
DTU	-	WAMIT	Y	HAWC2/Flex5	N/A
IBER	In-house parametric tool	AQWA	Y	FAST	Y
IDEOL	In-house parametric tool	AQWA	Y	FAST-OrcaFlex	Y
MARINTEK	WINDOPT	WINDOPT	Y	SIMA (SIMO/RIFLEX)	N/A
OOL	In-house parametric tool	WAMIT*	Y	3DFloat	Y
TECN	In-house parametric tool	AQWA	Y	FAST-OrcaFlex	N
USTUTT	-	AQWA	Y	SLOW, Simpack Wind, FAST	Y
*OOL use Sesam/Wadam which contains WAMIT					

Table 4 - Summary of numerical tool usage in the design and optimisation process

4.1 Current challenges

There are some challenges in improving the effectiveness and efficiency of these design methodologies to consolidate and accelerate the overall design process.

Automation of process: In many cases the pre-design process detailed above is largely manually executed by design engineers, lengthening durations of design iterations and potentially not reach an optimal design. Automating the pre-design process is one challenge design engineers are currently facing, with particular issues such as transfer of information from different codes/stages, and implementation of robust optimisation algorithms to investigate the whole design space.

Target design criteria: Establishing a set of target design criteria such that the pre-design is a good representation of the final detailed system is not trivial. With multiple – often conflicting – criteria from different subsystems, balancing the relative importance of all is a challenge and may sometimes lead to biased designs. Establishing the right mix of technical and economic criteria, potentially looking beyond the immediate static stability criterion can reduce the number of design iterations both in pre-design and detailed design phases – hence reducing engineering development costs.

Efficient load mapping: One challenge faced by some design engineers is the mapping of loads from aerodynamic and hydrodynamic engineering models to more detailed structural models – particularly when shifting from the pre-design phase to the next design phase. The main issue is that the majority of force models in this preliminary design phase provide sectional point loads, where information on sectional pressure distribution is not readily available or lost, and thus mapping these point loads to distributed loads in physically correct manner is challenging.

Computational efficiency: An ever-present challenge to design engineers is maximising computational efficiency of numerical tools to accelerate the design cycle. As numerical tools are initially developed by engineers rather than software developers, efficient code implementation is sometimes an issue. Investing in software development and moving towards code parallelization would address this challenge somewhat – however it is important to maintain desktop PC usability or computational resources that are readily available to design engineers.

5   Numerical modelling outlook

Following the questionnaire responses and literature survey of current state-of-the-art numerical modelling for the design and optimisation of floating wind turbine substructures, topics of interest have been identified to advance numerically modelling techniques and improve design cycles.

5.1   Integrated numerical modelling

Approaches to developing integrated numerical tools have historically begun with a numerical tool either from the onshore wind industry or from the offshore oil and gas industry. In attempting to simulate floating wind turbines, code developers developed interfaces to separate numerical tools, resulting in occasionally unstable and computationally inefficient tools mainly due to the method of data transfer between the different codes. Examples include HAWC2 coupled with WAMSIM (Kallesøe, 2011), and FAST with TimeFloat (Cermelli, 2010).

To address this challenge, alternative approaches were needed to overcome the computational downfalls. On one hand, changing the approach to model development would minimize communication bottlenecks – developing a framework whereby the numerical tool is modularized as far as possible with standardized interfaces, as is currently being done with the FAST tool (Jonkman, 2013). By establishing a single numerical integrator governing the execution of the simulation, the instabilities seen in the examples mentioned previously are largely eliminated. On the other hand, fully exploiting the computational resources available to design engineers can drastically accelerate the overall design process. Parallelizing both individual and multiple simulations with GPUs and CPUs would maximize use of computational resources and reduced simulation times (Muskulus, 2010; Schafhirt, 2015).

The majority of consortium partners are interested in developing more efficient integrated numerical tools, and the two aspects detailed above pave the way for concept developers to accelerate their design cycle with faster computations and easier integration of specialised and/or proprietary numerical modules within modular coupled tools.

5.2   Integrating numerical tools in the design process

As a floating wind turbine design progresses from conceptual and preliminary design stages to more detailed design stages, a different range of numerical tools are used to deal with the varying requirements of modelling detail. Transferring design and loads information from one set of tools to the next may be a cumbersome, time-consuming and/or error-prone process.

One method to minimize such challenges is the adoption of a systems engineering approach. This allows for a holistic approach to designing, organising and managing the design process for a floating wind turbine system and is particularly suited to multi-disciplinary engineering problems. An initiative implementing this is a collaborative project between NREL and DTU Wind Energy called FUSED-Wind (FUSEDWind, 2015). By defining a framework for the interaction of different numerical and cost models, a more streamlined design process is established.

5.3   Cascading design tools

One main common outlook from consortium members was the desire to further improve the numerical accuracy of various components of integrated numerical tools that are used during design and optimization. From a numerical standpoint this may be achieved by using more advanced tools than state-of-the-art coupled models to gain a better understanding of the physics and processes that are occurring. The benefit of carrying out these advanced loads studies would be a cascading of results to the state-of-the-art numerical tools in the form of proposed model modifications that would increase accuracy whilst maintaining computational efficiency. Particular areas where this approach would be suitable

are in transient and extreme events, substructure flexibility, unsteady aerodynamic scenarios and viscous hydrodynamic damping.

5.4 Improving reliability of state-of-the-art design tools

The uncertainty in numerical engineering models has always required measurement data to identify the regions of model validity, quantify such uncertainties and increase confidence in numerical model predictions. Significant efforts have already been made in numerical model validation, e.g. Robertson et al. (Robertson, 2013), with good agreement between predictions and measurements for most operating conditions. However in transient and extreme events, there have been discrepancies between predictions and measurements that will be addressed in Work Package 3 in LIFES50+.

6 Conclusions

A wide range of numerical tools are used for floating substructure design and optimization by consortium partners. This report presented an overview of these tools and current practices in implementing these tools within the design process. The state-of-the-art models used by consortium members largely make use of the same type of engineering models to describe the aerodynamic and hydrodynamic loading on the floating wind turbine and its structural response, having comparable levels of accuracy in their analysis.

The verification, validation and qualification of these numerical tools were presented, with the majority of tools reaching satisfactory levels from a global standpoint. However, there are still needs for further validation of modules within these integrated numerical tools. The numerical tools are qualified to some extent for use in the design of floating 10MW wind turbine substructures – in general they are in reasonable agreement with measurements for normal operating conditions, however in transient and more adverse conditions they do not satisfactorily predict extreme loads (Robertson, 2014). Also fatigue estimates can vary somewhat for different components across many operating conditions. This motivates activities in LIFES50+ of quantifying and reducing uncertainties in model predictions to enable more optimal and cost-effective designs to be achieved through experimental campaigns (Work Package 3) and advanced numerical studies (Work Package 4).

On the basis of consortium partner responses to the distributed questionnaire and a literature survey, current challenges in improving the design and optimization cycle and tools used within were identified, as well as an outlook on the focus of further modelling development activities. In particular, significant interest lies in the integration of different tools in the design process as well as improving the reliability of the state-of-the-art design tools. The main drivers for this activity in LIFES50+ will be the use of experimental campaigns to map the accuracy of numerical models, and the cascading of results from advanced models to state-of-the-art models – Figure 9 illustrates this within the CPU time-accuracy domain and forms the template for model cascading within LIFES50+.
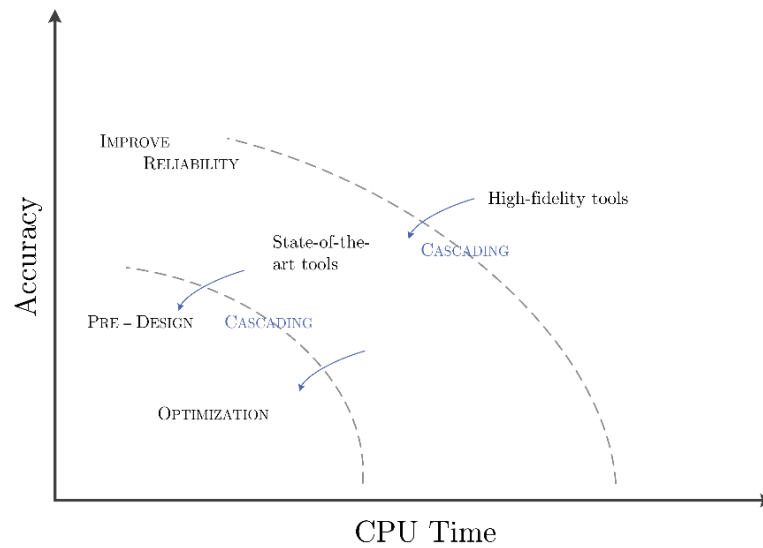
Figure 9 - Generalized CPU time-accuracy graph illustrating the concept of cascaded results and knowledge from high fidelity models to preliminary design and design optimization tools

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8   Appendix A – Consortium Questionnaire

Questionnaire related to Deliverable 4.4: Overview of the numerical models used in the consortium
and their qualification.

Dear LIFES50+ Consortium member. As part of Deliverable 4.4 "Overview of the numerical models used in the consortium and their qualification" we would like to ask for your feedback to the below questionnaire. We'd be grateful if you would answer briefly and bring it to the KoM meeting. We will then talk to you there, to detail some of the points further.

Once the questionnaires are analysed, we will come back and probably ask for detailed information on some of the models.

Best regards

Michael Borg and Henrik Bredmose

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 Partner Name:

Name and email address of contact person:

A. Platform design

Which models do you use for initial pre-design:

Are they solved in time domain or frequency domain?

To what level do you optimize the platform design? Manually? Automated? In simplified design space with few parameters? Please specify.

B. Coupled modelling of full WT system

Do you run a coupled tool for the full WT system?

    If yes, which model do you apply?

How do you incorporate the wind turbines controller?

Which load cases do you consider?

Do you apply optimization of the floater design on the basis of these coupled simulations?

C. Modelling of the mooring system

How is the mooring system modelled? Which model tool?

Are hydrodynamic forcing of the mooring lines included?

Are inertia effects of the mooring system included? (or quasi-static?)

D. Hydrodynamic modelling details

Which wave theories are implemented in the modelling tool?

What is the basis of calculating the global motion of the floating structure (e.g. Cummins equation)?

Which wave force model(s) are considered (e.g. Morison, potential flow)?

Is second-order wave excitation considered? Or higher order?

How is the hydrostatic force calculated during simulations?

Are viscous effects included? How?

How is hydrodynamic damping included?

E. Structural modelling of the platform

What is the basis of the floating platform structural model?

Do you regard the flexible motion of the platform as important?

To what level of detail is hydro-elasticity considered?

F. Model validation

To which extent have the included models been validated. Please specify for each tool. E.g.

"Wamit model checked against wave tank experiments", "Coupled model checked in OC4":

G. Modelling Outlook

Where do you see gaps in modelling abilities relative to your concept?

In which aspects of your modelling tool do you envisage the greatest need for development in terms of accuracy?

In which aspects of your modelling tool do you envisage the greatest need for development in terms of computational efficiency?

H. Detailed questions on aerodynamic and wind turbine modelling

Which induction model is used, and please provide details on any modifications applied?

Have considerations for dynamic effects been included (e.g. dynamic stall, dynamic inflow, etc.)? Please provide details.

Have considerations for additional effects been included (e.g. finite aspect ratio, tip effects, skewed flow, etc.)? Please provide details.

In the case of reduced-order force models, can you provide the source of aerodynamic profile coefficients used in modelling?

Is the influence of the tower included in blade load modelling?

Is the tower drag considered during simulations?

Are wake models employed in simulations? If yes, please provide details.

Please specify the incident wind profile and turbulence models available in your modelling tool.

What level of detail is achieved in modelling the drive train and generator system?

What level of detail is achieved in modelling the electrical system and interaction with the electrical grid/substation?