Behavioural Model Specification

ELEMENT

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Contents

1 Introduction

A Funding Grant was awarded from the European Union's Horizon 2020 research and innovation programme to develop and validate an innovative tidal turbine control system, using the tidal turbine itself as a sensor, to deliver a step change improvement in the performance. This will demonstrate Effective Lifetime Extension in the Marine Environment for Tidal Energy (ELEMENT), driving the EU tidal energy sector to commercial reality. This was in response to the call LC-SC3-RES-11-2018: Developing solutions to reduce the cost and increase performance of renewable technologies.

This document is produced for Work Package 6 (WP6) Behavioural Modelling and is submitted to satisfy deliverable D6.1 Behavioural Modelling Specification of the ELEMENT project. This is a working document, and the specification will be further developed during the project design phase.

In WP6, the STRA team are tasked to *build a holistic model of turbine behaviour and optimise the control system using existing data from operational tidal turbines*.

The behavioural model integrates models of the following: tidal flow (INNO &OREC); blade-fluid interaction (NOVA, informed by results from the EnFAIT project); support structure (INNO); and turbine design (NOVA) with the control system (NOVA & STRA). This behavioural model can be utilised for controller design and performance assessment for the ELEMENT project.

In the ELEMENT project, the model development and controller design are considered to be undertaken in three stages.

In the first stage, the work will be focused on the initial behavioural model from NOVA and the existing controller used in their current system. A comprehensive understanding of the system behaviour, controller performance and available tools, etc. will be developed from the work in this stage.

In the second stage, the focus will be moved to the development of the advanced behavioural model to include new elements such as the collision detection model and the collision risk model. Advanced behaviour controller will need to be developed to address the increased control tasks. Data-driven techniques will be employed to enhance the control system performance.

In the final stage, the task is to refine the developed (advanced) behavioural model and its controller to incorporate prototype test results and findings from emerging research; continue to refine the test framework and validate the model.

Following this roadmap, a set of terms are introduced as follows:

- IBM, initial behavioural model; IBC, initial behavioural controller (in T6.2)
- ABM, advanced behavioural model; ABC, advanced behavioural controller (in T6.3)
- RBM, refined behavioural model; RBC, refined behavioural controller (in T6.4)

Please note the three controllers are introduced here mainly to distinguish their use at different stages of the project for different purposes. They should all be developed under the same framework. For example, ABC will be developed from IBC through optimal parameter tuning and enhanced by data-driven approaches; RBC is refined from ABC through parameter tuning.

The output of WP6 will include behavioural system models, predicted turbine loads and yield, and will be used to optimise turbine design to achieve the overall lifetime cost of energy (LCOE) reduction target.

2 Task Description

Behavioural model specification (M1-3)
This document provides a high-level specification for the ELEMENT behavioural model, and an outline testing and validation plan. It also includes a review of available modelling techniques.

The STRA team leads this work (T6.1) in the ELEMENT project. Other partners including NOVA, INNO, WOOD, OREC, DNV and ABB will provide advice on model design when consulted. Further detail will be developed as the project progresses.

3 Behavioural Modelling – Sub-Models and Interconnectivity

A behavioural model can be thought of as an open, interconnected modelling framework formed of several subsystems with shared variables, interconnections and constraints. A behavioural approach to model such systems is based on defining the interaction architecture, modelling the behaviour of each subsystem and defining interaction constraints. Such an approach is systematic, modular and adaptable to computer-assisted implementation [1,2].

Key requirements include the following:

- Requirement Specification – a description of who will use the model and what they need. There are several approaches to reaching this description, a common approach is to describe the "FURPS", that is the Functionality, Usability, Reliability, Performance and Supportability of the model.
- Interface Definition – a description of the inputs required by the model, outputs generated from the model, as well as the format of the data at those input and output signals.
- System Architecture – a description and representation of a system, organised in a way that supports reasoning about the structures and behaviours of the system. This is commonly described using a block diagram, with different blocks describing the different sub-components of the model.
- System Functionality – a description of what various users might "observe" when interacting with the model or sub-parts of the model. For the latter, this would describe what each block in the block diagram "does".
- Test Specification – a description of how the behavioural model and its sub-component models can be tested, how it is supported by theory, real world data or results from other models.

The above requirements will be outlined here in order of their appearing in Deliverables 6.2-6.4. In each case the existing models will be introduced and their interactions with the other components of the overall model discussed.

A set of high-level requirements are presented in Section 3.1 and are given to make clear what the aims of the behavioural model are. These very high-level requirements are then refined into specifications for the initial behavioural model (IBM) in Section 3.2 and the advanced behavioural model (ABM) in Section 3.3.

A general review on modelling techniques – related to the concept of behavioural modelling – for tidal energy is included in Appendix 0.

3.1 Requirements

The requirements for the initial behavioural model are to:

1. Use the outputs of a model of the far field hydrodynamics as an input to the IBM;

2. Model the turbine, its controller, and the structural support to inform energy yield and damage models;
3. Use the outputs of the developed models to enhance the controller and hence improve LCOE.

In addition to the above requirements, several enhancements are considered for the advanced behavioural model:

1. Improve or replace the turbine's controller with an advanced state of the art controller
    a. The controller should have better basic performance than the existing controller and be capable of adapting its operation based on the inputs from the ABM including a collision risk and collision identification model.
2. Supply the advanced controller with data driven control enhancements to:
    a. Ensure the controller is optimised for the operating conditions;
    b. Ensure the controller adapts to changes in the turbine dynamics over time (e.g. biofouling).

A high level FURPS description of the requirements for the behavioural model is given in Table 1.

Table 1: Description of requirements

Quality Attribute	**Sub-quality**	**Defined Requirements**
Functionality	**Capability**	The initial behaviour model (IBM) should be capable of using the outputs of a model of the far field hydrodynamics as an input to the IBM, modelling a turbine, its controller (IBC), and the structural support to inform energy yield and damage models, using the outputs of the developed models to estimate LCOE. In addition to the IBM, the advanced behavioural model (ABM) should incorporate the collision detection model and the collision risk model. The advanced behavioural controller (ABC) should be designed to improve the energy yield and reduce loads. The ABC should be capable of adapting its operation based on the inputs from the ABM. Data-driven techniques will be employed to ensure the control system is optimised for the operating conditions and the controller adapts to changes in the turbine dynamics over time (e.g. biofouling). At the late stage of the project, the ABM should be refined to incorporate prototype test results and findings from emerging research. The refined behavioural model (RBM) will be used for controller parameter retuning.
	Reusability	The three behavioural models, i.e. IBM, ABM and RBM, developed at different stages, should be reusable for modelling different tidal turbine systems, in different locations, with different support structures.
	Security	Certain elements of the behaviour models – such as the turbine and controller – should be able to be encrypted while still allowing the overall behaviour model to still work. A "user" should be able to interact with the behavioural model without damaging the underlying model.
Usability	**Human Factors**	The behavioural models are intended for use by tidal turbine design teams. These are typically engineers with experience of common engineering and numerical modelling packages. The

		behavioural model interfaces should share the principles of the user interface of those tools.
	Aesthetics	The aesthetics of the user interface are determined by the design of the sub-components. The behavioural model is not intended for commercial release, so the aesthetics are less important than the underlying functionality. Aesthetic design should take heed of visual impairment requirements.
	Documentation	The behavioural models should be documented for the "user" explaining how to interact with the model. This should include documentation describing the sub-components. An additional element should describe the architecture of the behavioural models, written for future model developers.
Reliability	**Availability**	The behavioural models should be available for the user except when an updated model is being installed.
	Predictability	The behavioural models should give repeatable results when consistent inputs are applied.
	Accuracy	The behavioural models' sub-components should be benchmarked against test/real world data.
Performance	**Speed**	The behavioural model should run at a satisfactory speed for the purposes of the users. This minimum speed is to be established by consulting with the future users.
	Scalability	The behavioural models should be capable of being scaled up to full tidal turbine arrays and interactions between turbines in the future.
Supportability	**Flexibility**	The behavioural models should be modular in nature to allow for sub-component models to be swapped.
	Installability	The behavioural models should be installable on a standard Windows computer, specified for engineering design functions.

3.2 System Architecture, System Functionality and Interface Definition for the Initial Behavioural Model (IBM)

The purpose of the IBM is to allow for simplified analysis of various aspects of tidal device operation and control in order to begin investigating avenues for reduced LCOE through improved yield and reduced loads, leading to extended operational lifetimes. This initial model will also serve as a basis for enhancements made in WPs 6.3 and 6.4. Fig. 1 shows a system overview of the IBM which will be developed in the first stages of ELEMENT WP6. As well as improving the basic controller, the IBM can be used to optimise and improve the design of the tidal turbine.

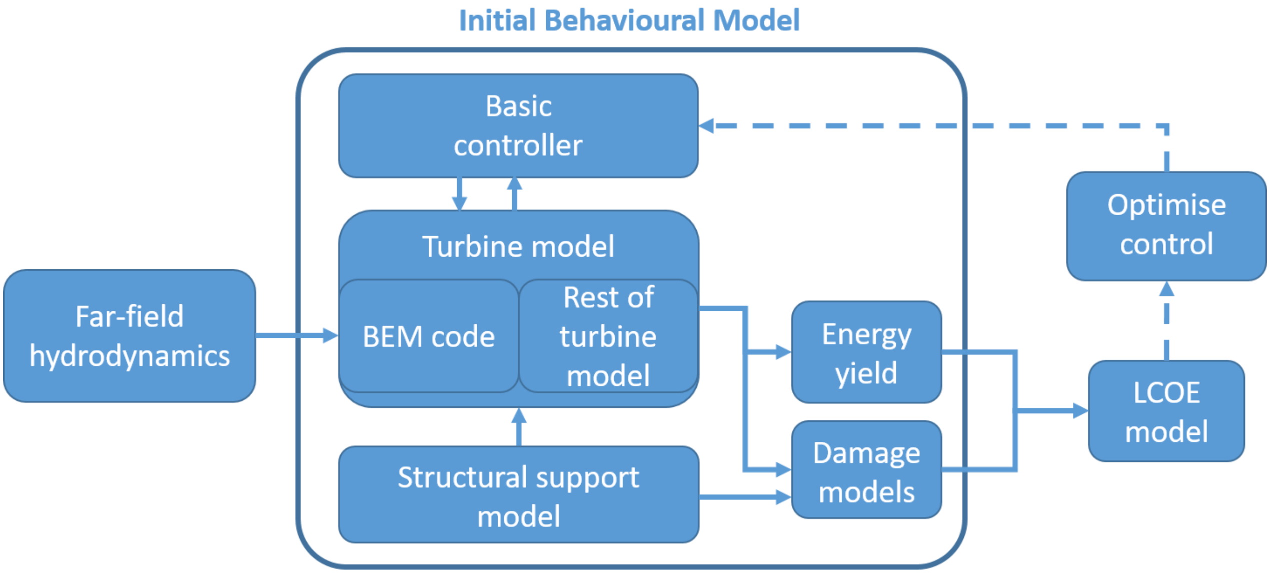

Figure 1: System overview of the **Initial Behavioural Model (IBM)**

The following subsections summarise each of the IBM sub-models, with the following information presented in each case:

- A brief description of the sub-model
- The software the sub-model is based in (where there are several options the likely candidates are listed)
- The data required by the sub-model to run
- The outputs of the sub-model
- The other sub-models that the sub-model interacts with

3.2.1 Far-field Hydrodynamics

These models, combined with field measurements, capture the flow at a tidal energy site often independently of a turbine being present, allowing for flow characteristics such as flow speeds, shear profiles and turbulence characteristics to be determined. Two far-field hydrodynamic models will be used in ELEMENT. The first was developed for the Shetland site as part of the EnFAIT project, the second is for the Étel site and is to be supplied by INNO. They form an input to the behavioural models in the form of these site characteristics. The numerical model themselves are 2D, which means that they provide current velocity values averaged over the water column and therefore no information regarding the current shear profile. Also, these models typically estimate the tidal resource over long durations (of the order of months to years) and this can only practically be achieved by using a coarse spatial and temporal resolution compared to what is needed as an input to the turbine model for dynamic simulations. The output of these models will therefore be combined with field measurements (typically obtained from Acoustic Doppler Current Profilers or ADCPs, at a high temporal and vertical resolution) to provide high-resolution flow characteristics input (flow speed, velocity shear profile, turbulence characteristics, etc.) to the Tidal Bladed software (see **turbine model** below).

Software: Danish Hydraulic Institute (DHI) Mike 21 for the Bluemull Sound (Shetland) site and TELEMAC 2D for the Étel site.

Required data: None for the Bluemull Sound (Shetland) site as the model has already been developed by a third party and the site has already been the subject of field measurements. It therefore has no input dependencies within the ELEMENT project. For the Étel site, the model will be developed by INNO and will require bathymetric and boundary conditions data as well as field measurements for calibration and for producing the fine resolution flow input.

Outputs: The numerical models themselves will provide the three components of depth averaged flow velocity at a spatial resolution of 15-20m or better and at a temporal resolution of 5 min or better. The ADCP measurements will provide velocity profiles across the water column with a vertical resolution of the order of the metre and a temporal resolution of the order of the second.

Interactions: This model feeds into and informs the flow field generation aspect of the **turbine model** (see below).

3.2.2 Turbine Model

The turbines themselves will be modelled in hydro-elastic numerical simulators which are based on Blade Element Momentum (BEM) theory. Such programs allow for the efficient simulation of turbines in turbulent spatiotemporal flows. The turbine itself is represented as an interconnected set of elastic and rigid bodies and these models include all the turbine's main components such as: rotor, drivetrain, support structure and the turbine control strategy.

Two such software tools might be used in ELEMENT. The first, and principal one, being DNV-GL's Tidal Bladed. This is a comprehensive turbine modelling software and has been validated as a tidal turbine design tool. In addition to modelling the turbine itself, Tidal Bladed also allows for the generation of unsteady 3D turbulent flows as inputs to the simulations themselves. These can be generated such that the flow characteristics conform to those identified by the **far-field hydrodynamic models** for each site (outline previously). A Tidal Bladed model of the NOVA M100 turbine has previously been implemented in the EnFAIT project and this will form a basis for the models developed in this work. In order to ensure the correct frequency domain characteristics of this **turbine model**, a consideration which is crucial for control, a spectral analysis will be performed for operational field data from each of the turbines being modelled. This will ensure good agreement between the simulated and real-world turbines. Additionally, structural frequencies identified in the dynamic **structural support models** are also required for the same reason.

As part of the ELEMENT project the NOVA RE50 turbine will be tested on a floating platform. Therefore, it will also be necessary to model and understand the impact that moving from a fixed to floating support structure will have on tidal turbine behaviour and control requirements. For this portion of the work it is necessary to use software which allows the physical behaviour of the floating platform to be included. Such a piece of software is FAST, which was developed by the National Renewable Energy Laboratory in the USA. It has the capability to couple with existing open-source hydrodynamic load packages which allow for a floating platform and its interactions with the flow field and waves to be included in simulations.

It should be noted that the inclusion of a floating platform into these models is non-trivial and represents a significant time-allocation in terms of resources. As such, research priority will be given to the fixed bottom turbine models in Tidal Bladed to ensure good results within the specified timelines of these work packages. Modelling of the floating platform will be undertaken, including a study of dynamic and control impacts, however, it should be noted that the extent of these particular areas of investigation will depend on the availability of time and resources as a trade-off between this and the other requirements of the work package.

Software: Tidal Bladed, FAST

Required data: Structural dimensions, drivetrain properties, blade profiles, real operational data for harmonic frequency determination, structural harmonics from the FEA structural support model (below). For validation measured data from turbines in the field will be used if available. If such data is not available (for newer turbine types for example) then data from testing may be used.

Outputs: Time varying outputs under realistic operational conditions for all turbine channels and loads. This includes power, rotational speed, torque, blade loads, hub loads, tower loads.

Interactions: The turbine modelling software (Bladed/FAST) will generate 3D turbulent flow fields based on the outputs of the **far-field hydrodynamics models**. The **turbine models** themselves will be controlled by the **basic controller** (see below) throughout simulations in these turbulent flows. Loading experienced by the support structure during these simulations will then serve as an input to the dynamic **structural support models** (see below) which will assess the impact operational loads have on the turbine structure in more detail than is possible with the simplified structural representations used in Bladed and FAST. Power and load outputs are then used as inputs to the **energy yield** and **damage models**. There may be outputs from the turbine model to the **collision risk model** in the ABM.

3.2.3 Structural Support Model

In order to understand loading, flow interactions and potential damage for the tidal turbine support structures, INNO will develop high-fidelity finite-element (FE) models in ANSYS software. These will be used to a) perform structural frequency domain analyses in order to identify structural harmonic frequencies (important for control considerations as mentioned above); and b) assess structural responses to the loading imparted to the structure by the flow and turbine interactions. This will allow for resulting loads and stresses throughout the support structure to be analysed and the damage imparted by fatigue cycles and peak loads to be characterised for this portion of the turbine. Time series loads imparted to the support structure, outputted from the BEM based **turbine model** simulations outlined above, will be used as the inputs to the **structural support models** for each turbine and support structure type considered.

Software: ANSYS or similar finite-element model code

Required data: Structural dimensions and material properties of the support structures to be modelled. Load time series outputted from the **turbine models** in turbulent flows.

Outputs: Structural harmonic frequencies, stress response distributions throughout the support structure as a result of imparted loading.

Interactions: The **structural support model** will be used in conjunction with loads calculated from the **turbine models** to characterise the response of, and stress distributions within, the support structures of modelled turbines. Stress distributions within the supports will be used to inform the **damage models** used to assess probable component lifetimes.

3.2.4 Initial Behavioural Controller (IBC)

Before concentrating on advanced control and machine-learning concepts, it is first necessary to demonstrate the validity of the models being used to represent real-world tidal turbine systems. As such, it is necessary to initially implement the existing operational control structures into the **turbine models**, making a comparison of real-world and simulated data meaningful. Additionally, this will allow for the parameters of the current proportional integral (PI) control approach to be optimised, providing the best possible baseline against which to compare more advanced control concepts to be developed later in the project.

Software: C, with the controller itself most likely taking the form of a dynamic link library (DLL).

Required data: The control parameters for each turbine to be modelled.

Outputs: Control outputs fed into the dynamic models in turbine simulation

Interactions: The basic controller will dynamically control the **turbine models** during simulations, in turn this will impact the loading, damage and yield of the modelled turbine.

3.2.5 Energy Yield

The behavioural model will allow for energy yield of the modelled turbines to be predicted for the sites at which they will be located. This can be done by taking simulated results in given flow conditions and combining with distributions which represent the annual flow speeds and turbulence levels etc., and which will be sourced from the far-field hydrodynamics model. This will allow for annual energy yield to be predicted and, importantly, for increases in energy yield due to improved turbine control to be quantified. Where applicable, the IEC standards and guidelines for tidal turbine technologies will be used as the basis for the energy assessment [10]. Where the standards for tidal turbines may not suffice, IEC standards for wind turbines [11] can be adapted for the marine case.

Software: Bladed, Excel and MATLAB

Required data: Simulation outputs for power generated under a range of flow conditions, distributions representing the annual occurrences of given conditions at the sites under consideration.

Outputs: Predicted annual energy yield for given turbines at given sites.

Interactions: The energy yield outputs will form an important and impactful input to the overall LCOE model.

3.2.6 Damage Model

During operation, fatigue and peak loads contribute to damage to a device and a large focus of ELEMENT is reducing this damage in order to improve reliability and extend operational lifetimes for these devices. In order to quantify improvements made to turbine life through load reductions achieved using improved control, NOVA will incorporate an automatic, predictive model of turbine damage estimation into the behavioural model. This will be informed by detailed knowledge of the turbines and their components, with loading inputs to these damage models provided by **turbine model** simulations, subsequent analysis using the **support structure models** and rainflow counting methods.

Software: Excel (current) or MATLAB

Required data: Load time series across turbine components from simulations of the **turbine models** and **support structure models.** It may be necessary to use time-series of non-mechanical variables.

Outputs: Damage accrued by different turbine components during operations in a range of conditions. Expected times to failure for those structural components due to fatigue damage accumulation.

Interactions: The **damage models** receive inputs directly from the **turbine models** and **structural support models**. Damage outputs then provide input to the **LCOE model** and will have a significant bearing on the calculated LCOE.

3.2.7 LCOE Model

The LCOE model developed in ELEMENT will be based on that created during the EnFAIT project. It will be used to assess the overall impact of the control system on the overall goal of the ELEMENT project, this being to reduce overall LCOE by 17%. The LCOE model will provide a means to explore the trade-offs between improved control allowing for changes to yield, loads, CAPEX and OPEX in optimising lifetime costs. As LCOE requires that scheduled and unscheduled maintenance is incorporated, the relevant data for deployed turbines will be used as a baseline for maintenance.

Software: Excel (current) or MATLAB

Required data: Outputs from **yield** and **damage models** generated as part of the behavioural modelling program.

Outputs: LCOE of the turbine as predicted by the behavioural model with a given set of design and control parameters.

Interactions: The LCOE is the overall ‘cost’ function being optimised during behavioural modelling, as such it will have important implications for each part of the model which can be adjusted to change the turbine performance.

3.2.8 Control Parameter Optimisation

As has been outlined above, the IBM mainly serves to validate the modelling approach being used, by demonstrating agreement with the turbine data which correspond to those being modelled. However, it will also be an important opportunity to ensure the best possible configuration is found using the initial design and control structure (before implementing more advanced control and learning concepts). Therefore, after the validation exercise has been carried out, an optimisation will be performed which looks to assess how yield and loads/damage may be adjusted in order to minimise LCOE through optimal tuning of the current controller parameters within the IBM.

3.3 System Architecture, System Functionality and Interface Definition of the Advanced Behavioural Model (ABM)

Having developed the IBM and validated against turbine data for each of the modelled turbines, T6.3 then looks to develop an Advanced Behavioural Model. As shown in Fig. 2, this will involve enhancing the IBM with state-of-art control concepts, in some cases taken from the wind energy industry and adapted to the tidal turbine case.

This section will outline these additional sub-models along with their input requirements and interactions.

3.3.1 Advanced Behavioural Controller (ABC)

STRA will develop state-of-the-art controllers for the **turbine models** investigated in this work. This will draw from years of experience working with wind turbines in a similar context. The new controllers will be built around the standard PI architecture while also incorporating filters to remove structural harmonics from the systems and scheduling of controller gains as appropriate.

Development of the controller will be through one or more of MATLAB Simulink, DNV GL Bladed, and FAST. The controller will be designed to provide the rated power output at the rated flow speed whilst minimising loads. Below the rated flow speed the controller will maximise power capture within the turbine rotor speed limits whilst minimising the loads on the critical structural components, particularly the rotor blades and the tower/support structure.

The synergies between wind turbine control and tidal turbine control will be utilised to ensure that the controller is at the cutting edge of technology. The controller will also need to be compatible with the data driven control enhancements (see Section 3.3.2) with parameters able to be quickly and easily tuned based on the suggested optimisations.

Software: C based DLL, MATLAB Simulink, DNV GL Bladed, and FAST

Required data: **Turbine model** design parameters, operational turbine data for identification of harmonics requiring filtering.

Outputs: Control commands for the turbine model during simulations

Interactions: The new controller will directly control the **turbine model** during simulations. This will in turn impact energy yield, loads/damage and also LCOE.

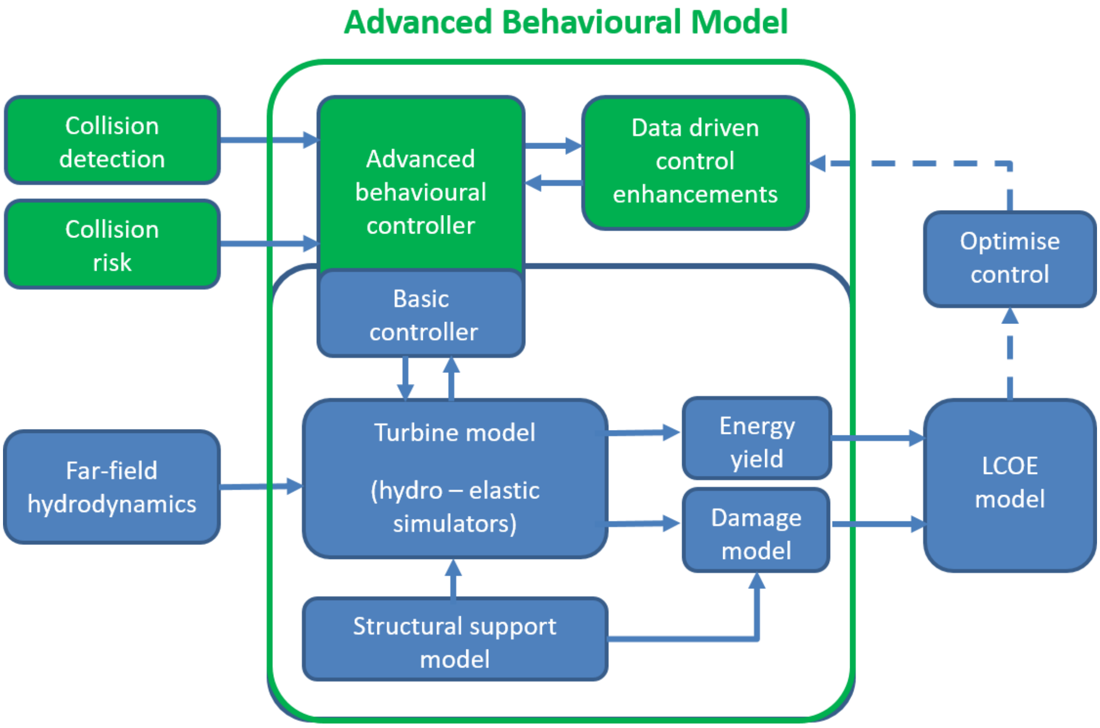

Figure 2: System overview of the **Advanced Behavioural Model (ABM)**

3.3.2 Data Driven Control Enhancements

The STRA control group have developed a range of data driven techniques to enhance real-time controllers by using the turbine as a sensor and learning dynamic information during operation to inform control decisions. The two techniques identified as having the highest potential impact on tidal loading, yield and LCOE are Gaussian process (GP) dynamics identifications and detection of anomalous conditions in the flow field by using Extended Kalman Filtering (EKF). Both methods can use existing or inexpensive measurements on the turbines to extract information relevant to control. The EKF further requires a model of the flow field to detect flow anomalies such as gusts in the measured data. Learning then takes place as the turbines operate and new data is fed to the learning algorithms. In turn these techniques feed information back to the controller which will signal that a certain control action is necessary, e.g. after the detection of a large turbulent eddy moving towards the turbine. In addition to these identified techniques, the STRA team have experience with a wide range of other similar methods which might also provide LCOE improvements. Therefore, in order to ensure the best possible outcomes, once the IBM has been developed and validated a joint review process will be undertaken between NOVA and STRA to assess the data and measurement/testing capabilities available at that time in order to identify the best possible techniques to apply for control enhancement.

Software: MATLAB

Required data: Turbine outputs from both real and simulated turbines. Access to 'correct' results of a learning algorithm, e.g. turbine Cp curve in the GP case. This may be direct by STRA being given this information, or indirect by NOVA performing comparisons and feeding back accuracy results to STRA rather than the answer itself.

Outputs: Improved control through a range of possible avenues depending on which learning algorithms are selected as being optimal.

Interactions: The data driven control enhancements will communicate directly with the state-of-the-art turbine controller developed in this same work package.

3.3.3 Collision Detection Model

NOVA will review existing methods for detection of marine fauna and estimation of collision risks. The selected model will then be implemented in the ABM.

Software: TBC

Required data: Estimation of animal/bird density.

Outputs: Assessment of risk of collision with marine fauna in real-time. This signal can then be interpreted and used to automatically shut down the turbines if necessary.

Interactions: The collision model will need to interact with the turbine control system for automated shutdowns to be possible.

3.3.4 Collision Risk Model

Whereas the collision detection model acts in real-time to identify potential collision events, the collision risk model will look to quantify the likelihood of collisions happening given the locations, environments and operation of these tidal turbines. This will allow for the behaviour of marine fauna at sites where tidal turbines maybe placed to be taken into account, and for the assumptions used when performing collision risk modelling to be assessed and improved. Project findings during ELEMENT will feed into this risk assessment work, with the result being a wealth of data allowing for evidence-based risk reductions. This will in turn give greater confidence to assenting authorities regarding the environmental impacts of these devices. It should be noted the development of collision risk model in outside of the scope of WP6.

Software: ERM, CRM or maybe ETPM.

Required data: Estimation of animal/bird density.

Outputs: High level collision risk model, driven by observations and field data.

Interactions: The collision risk model will be informed by some operational parameters for the turbine such as rotational speeds and the flow speed range across which it is operational.

3.3.5 System Optimisation

Having developed and included a range of advanced concepts in the ABM it will be necessary to enhance the control system using data-driven learning techniques and optimise the design for an overall minimum in LCOE through yield increase and load decrease trade-offs.

4 Behavioural Modelling – Outline Development, Testing and Validation Plan

In this section the plan for developing, testing and validating the IBM and ABM is presented. The plan is broken down by task as per the proposal. The work to be completed is summarised in Table 2 from T6.2 to T6.4. For each task the sub-models within the behavioural model that require development are broken down in turn.

Table 2: Description of work

#	Description of work	Lead	Month	Role of other partners
T6.1	Produce a high-level specification and test plan for the behavioural model. Include a review of available models and their suitability for use in this project.	STRA	M1-3	NOVA, WOOD, OREC, DNV, INNO: advise on model design
T6.2	Develop initial behavioural model: develop a basic initial model to use in the ELEMENT control system design. Develop a test framework and validate the model.	NOVA	M4-12	STRA, INNO, WOOD: advise on basic model design and implementation
T6.3	Develop advanced behavioural model: learning from work conducted on the basic model, develop advanced models of flow, rotor, drivetrain, Extended Kalman Filters and Gaussian Process, incorporating findings from system design and emerging results from prototype testing. Continue to refine the test framework and validate the model.	STRA	M4-24	NOVA, INNO: develop model components WOOD, DNV: advise on basic model design and implementation
T6.4	Refine behavioural model: refine the behavioural model to incorporate prototype test results and findings from emerging research. Continue to refine the test framework and validate the model	STRA	M25-36	NOVA, WOOD, ABB, NRTK, OREC, INNO: supply test results; advise on model design and implementation

4.1 IBM Tasks, Timeline and Validation/Testing Methodology (Task 6.2)

The lead project partner for the initial behavioural model is NOVA, with much of the modelling work based on models developed under previous work. STRA will be required to assist with the linking of the various model components and will need to learn the detail of each model in order to inform their development of the ABM.

4.1.1 Far-field Hydrodynamics

Far-field hydrodynamic models will be required for two sites, one in Shetland to be supplied by OREC and one in Étel, to be supplied by INNO. The Shetland model is already available as it was developed as part of the EnFAIT project. The tasks required for this sub-model are therefore:

Task	Lead	Other partners
Obtain EnFAIT model and ADCP data	NOVA	-
Obtain Étel model and ADCP data	INNO	-
Share hydrodynamic models with relevant partners	NOVA/INNO	STRA
Test and compare hydrodynamic model outputs	STRA	NOVA/INNO
Produce test-site data	STRA	NOVA/INNO

By the end of the tasks outlined above the far-field models will be well known to the relevant partners and far-field flow data for the chosen IBM site(s) will be easily generated by the appropriate partners. The far-field flow models have been tested and validated in previous projects.

4.1.2 Initial Behavioural Controller (IBC)

The initial behavioural controller is currently in use on the NOVA machines. It will need to be adapted for use in the turbine model (see Section 0), perhaps including re-coding of the controller. Whilst NOVA will lead on this task, it is expected that the STRA will support heavily as they have deep experience of writing controller code for Bladed. To interact with inputs from other sub-models of the IBM, the IBC may also need some additions and/or alterations. These alterations may be added at any point in the controller development as some required changes may only be identified when developing other parts of the IBM. Once re-coded the IBC will need to be tested using the turbine model. With testing completed, the controller can be re-tuned if required to improve performance whilst keeping the same controller architecture. The tasks, along with lead and other partners are presented below:

Task	Lead	Other partners
Re-code the controller for use with Bladed	NOVA	STRA
Test the controller with the turbine model and compare results with measured data (**Validation**)	NOVA	STRA
Re-tune the controller to improve performance	NOVA	STRA
Adaptations to the controller for IBM functionality	NOVA	STRA

4.1.3 Turbine Sub-Model

For the IBM the turbine sub-model will be a DNV GL Tidal Bladed model that incorporates all the dynamic aspects of the rotor, tidal flow and (simple) substructure. The Tidal Bladed model has been previously developed by NOVA, however, it may require adaptation for use in this project. It is noted that the dynamics of stall are not well modelled in Bladed, and so a separate Simulink based stall model is used. The model will require to be updated to reflect any recent design changes by NOVA before it is combined with the IBC (see Section 4.1.2) and simulation tests conducted. The results of the simulation tests will be compared to measured data from the installed turbines and the model adapted where possible to account for differences. Time will be required to be spent considering if any additional dynamic aspects require to be modelled for use within the wider IBM. If additional aspects are identified then these will need to be modelled, implemented and tested.

Task	Lead	Other partners
Update Bladed model to reflect any recent changes to the design of the turbine	NOVA	STRA
Test the turbine model and controller and compare outputs to measured data (**Testing**)	NOVA	STRA
Adapt model to more accurately reflect measured data (**Validation**)	NOVA	STRA
Identify any dynamics not currently modelled that may be required for the IBM	STRA	NOVA
Add in any additional dynamic models required	STRA	NOVA
Document the turbine model including a guide on using the model	NOVA	STRA

Note on validation: During the validation process some differences between the model and measured data may be due to the flow field and so careful consideration and assessment will be required to ascertain the root cause of any differences identified such that the turbine model is not erroneously altered. It is particularly important that the model has similar properties to the physical turbine in the frequency domain and so frequency analysis will be required. Variables that are key for validation are: rotor/generator speed, rotor thrust, blade root bending moment. The spectra of these variables should match well with any available measured data.

4.1.4 Structural Support Sub-Model

The structural support sub-model uses the outputs of the turbine model as its input. The support structure modelled will be a sea-bed fixed support structure. INNO will lead the development of this sub-model and use Ansys as the software. It is important that the primary structural modes of the model are the same as the actual support structure and this is a good measure to validate the model. If measured stresses/strains on the structure are available, then these should also be compared to the model to help validate.

Task	Lead	Other partners
Develop initial FE model of support structure	INNO	NOVA
Use inputs generated from the turbine model and compare loads against measured stresses/strains (**Testing**)	INNO	NOVA
Adapt model to more accurately reflect measured data (**Validation**)	INNO	NOVA
Document sub-model including instructions on the use of the model	INNO	NOVA

4.1.5 Energy Yield Sub-Model

Energy yields can be calculated using the outputs of simulations using the turbine model. Also required are the far-field model to provide information on the long-term conditions of the site. By using the appropriate standards, the model validation becomes less onerous as standard methods can be considered validated already. Once coded the model can be tested by using measured data from a limited set of measured data and extending to a larger data set and comparing against the measured output over the larger data set.

Task	Lead	Other partners
Assessment of relevant standards from which to base the energy yield model	STRA	NOVA
Identification of items missing from the relevant standards	STRA	NOVA
Written outline and justification of the energy yield model	STRA	NOVA
Coding of the energy yield model	STRA	NOVA
Documentation of energy yield sub-model	STRA	NOVA

4.1.6 Damage Sub-Model

To create the damage model the types of damage and the critical components that can be damaged will need to first be assessed. The assessment of which components to model will be based on NOVA's learned experience so far and STRA's experience from both tidal and wind turbine projects previously conducted. With the critical components identified, the type of damage (fatigue or extreme loads) that could affect the component should be identified. Using this information, models of critical components can be created that estimate the impact on life of the simulations conducted using the turbine model. Validation of the damage model is particularly difficult due to limited data and the nature of fatigue loads in particular whereby no damage can be seen until near to failure. As such, well validated techniques should be used where possible and estimation of the uncertainty of the damage sub-model should be provided.

Task	Lead	Other partners
Identification of critical components	NOVA	STRA
Identification of mechanisms of damage for each component	NOVA	STRA
Modelling of damage based on turbine sub-model inputs	NOVA	STRA
Documentation of damage sub-model including uncertainties	NOVA	STRA

4.1.7 LCOE Sub-Model

An LCOE sub-model was developed in a previous project and so the model will not need to be designed from scratch. Instead, the existing model can be updated to reflect new data.

Task	Lead	Other partners
Amalgamation of maintenance data from deployed turbine(s)	NOVA	STRA
Adaptation of LCOE model to reflect lessons learned and new data acquired since previous projects	NOVA	STRA
Documentation of LCOE sub-model	NOVA	STRA

4.1.8 IBM Creation and Optimisation

With each of the sub-models designed, tested, and validated the components can be linked together to create the IBM. In order to test the IBM, the controller will be optimised using the IBM to minimise the LCOE. Changes to the controller and/or other components of the real system can then potentially be applied on the real turbine to validate the IBM. Note that validation testing would take place in other work packages of the project, i.e. WP8 for onshore testing, WP9 for tow testing, WP10 for estuary testing, and WP11 for offshore testing.

Task	Lead	Other partners
Collect all sub-models and documentation and ensure that all models can be run individually	STRA	NOVA
Use IBM to adapt the controller and/or other components to reduce the LCOE (quantify LCOE reductions and compare against targets)	STRA	NOVA
Document IBM in IBM report for deliverable D6.2	STRA	NOVA

4.2 ABM Tasks, Timeline and Validation/Testing Methodology (Task 6.3)

The ABM builds upon the IBM, enhancing the controller with advanced control methodologies to create a **state-of-the-art controller**. The controller can be adapted over time through **data-driven control enhancements**. A **collision detection system** is incorporated to prevent collisions with foreign objects and animals whilst a **collision risk model** reduces the chances of collisions occurring by adjusting the operational strategy of the turbine in order to minimise collision risk.

The IBM focussed on the sea-floor fixed design of the M100 turbine. In task T6.3, the ABM will build upon this model to enhance the performance of the same turbine. During development, care will be taken to ensure that the ABM will also be applicable to other turbines.

4.2.1 Advanced Behavioural Controller (ABC)

The IBC will be enhanced/replaced with a state-of-the-art controller. The development of the advanced behavioural controller (ABC) under task T6.3 will mainly revolve around using advanced control techniques within the control architecture to minimise the loads on the turbine whilst maintaining high energy capture and also putting in place the functionality for the controller to adapt to the data-driven approaches. The tuning and testing procedure will need to encompass all operating conditions and include extreme load conditions.

Task	Lead	Other partners
Enhance initial behavioural controller, improving ABC architecture to adapt to ABM.	STRA	NOVA
Tune and test ABC.	STRA	NOVA
Add functionality to adapt the ABC based on data-driven approach(es)	STRA	NOVA
Document the advanced behavioural controller.	STRA	NOVA

4.2.2 Data-driven Control Enhancements

In task T6.3, initial data-driven control enhancements will be developed. It will be key to identify the enhancements most likely to deliver the largest reductions in LCOE, particularly the LCOE model will be very useful in this regard. Once the enhancements most likely to reduce LCOE greatly have been identified the techniques will require development. Many of the possible methodologies (e.g. Gaussian processing) will require significant research and development. As each enhancement is developed it will require initial software testing to make sure the results produced are as expected. Once fully tested the control enhancements can be made ready for application on the operational turbine. Note that the testing on an operational turbine is outside of the scope of this work package.

Task	Lead	Other partners
Identify control enhancements with most likely benefits for LCOE.	STRA	NOVA, WOOD, INNO, DNV
Develop control enhancements with the use of data-driven techniques.	STRA	NOVA
Test control enhancements in simulation environment and quantify improvements to LCOE	STRA	NOVA
Prepare control enhancements for real world application	STRA	NOVA

4.2.3 ABM Creation and System Optimisation

With each of the sub-models designed, tested, and validated the components can be linked together to create the ABM. In order to test the impact of the ABM, the controller (ABC) will be optimised using the ABM to minimise the LCOE. Changes to the controller and/or other components of the real system can then potentially be applied on the real turbine to validate the ABM. Comparisons can also be made between software simulations using the IBM and simulations using the ABM. Note that validation testing would take place in other work packages of the project, i.e. WP8 for onshore testing, WP9 for tow testing, WP10 for estuary testing, and WP11 for offshore testing.

Task	Lead	Other partners
Collect all sub-models and documentation and ensure that all models can be run individually	STRA	NOVA
Use ABM sub-models to adapt the ABC and/or other components to reduce the LCOE (quantify LCOE reductions and compare against targets, also compare to IBM results)	STRA	NOVA
Document ABM and summarise the main outcome in deliverable D6.3.	STRA	NOVA

4.3 Refined Behavioural Model (RBM) Tasks, Timeline and Validation/Testing Methodology (Task 6.4)

In T6.4 the ABM model will be refined to incorporate prototype test results and findings from emerging research. Adaptations to the turbine model and, potentially, the structural support model, will allow the RBM to be applied to the RE50 floating tidal turbine.

4.3.1 Refined Behavioural Controller (RBC)

The advanced behavioural controller from T6.3 will be further enhanced based on the lessons learned over the project and adapted to a floating platform. Floating platforms introduce significant additional dynamics to the system that the controller needs to take into account, including moorings, the effect of waves, and far lower effective structural frequencies.

Task	Lead	Other partners
Refine the ABC for a floating platform	STRA	NOVA, INNO
Tune and test the refined behavioural controller (RBC)	STRA	NOVA
Compare performance to IBC and ABC, and quantify improvements	STRA	NOVA, WOOD
Document RBC	STRA	NOVA

4.3.2 Turbine Model

In order to apply the ABM to a floating tidal turbine an entirely new turbine model will require development. DNV-GL Tidal Bladed is not well suited to modelling floating platforms and so FAST will be used instead. FAST allows easy addition of user defined modules and so a floating platform module would require design and integration with the model.

Task	Lead	Other partners
Develop FAST model of the non-floater components	STRA	NOVA
Develop model of floater	STRA	NOVA
Integrate floater model with turbine model	STRA	NOVA
Test model and validate against any available test data	STRA	NOVA, WOOD

4.3.3 Data-Driven Control Enhancements

The data-driven control enhancements will be further developed based on new data generated from other work packages in the project and for assimilation with the floating turbine model. It is difficult at this stage to state exactly what features may or may not be included in the control enhancements, a clearer picture will be possible after the delivery of the IBM, with further clarification on the delivery of the ABM.

Task	Lead	Other partners
Identification of ABM enhancements	STRA	NOVA
ABM enhancement development	STRA	NOVA
Implementation and software testing of ABM enhancements	STRA	NOVA
Quantification of impact on LCOE of ABM enhancements	STRA	NOVA, WOOD
Plan for implementation of ABM enhancements on physical system	STRA	NOVA, WOOD
Documentation of ABM enhancements	STRA	NOVA

4.3.4 RBM Creation and System Optimisation

With each of the sub-models designed, tested, and validated the components can be linked together to create the RABM. In order to test the impact of the RABM, the controller will be optimised using the RABM to minimise the LCOE. It is unlikely that the RABM will be tested on physical systems within the project due to time limitations, however simulations using the RABM can be conducted for a floating tidal turbine and also for the fixed tidal turbine. Comparisons of the LCOE of the fixed turbine baseline, the fixed turbine RABM and the floating turbine RABM can be made.

Task	Lead	Other partners
Collect all sub-models and documentation and ensure that all models can be run individually.	STRA	NOVA
Use RBM to adapt the controller and/or other components to reduce the LCOE (quantify LCOE reductions and compare against baseline, IBM, ABM, and floating against fixed).	STRA	NOVA/WOOD
Document RBM in the final behavioural model report for deliverable D6.4.	STRA	ALL

5 Overall Deliverable Timeline

It is noted that at this stage of the project it is difficult to outline the tasks to a high resolution as the project is likely to adapt and change as it progresses. As such, whilst the plan presented here is as complete and in depth as possible, it will be regularly updated by the STRA team throughout the project.

Appendix A. Generic Review of Tidal Energy Numerical Modelling Techniques

This section provides a review of the various types of numerical models available for the different components of behavioural model. The numerical models retained for each component of the behavioural model are detailed in the main body of the report.

A.1 CFD Models

The most complete computational model of a full-scale tidal turbine is developed by solving the Navier-Stokes equations, with some kind of turbulence model, using CFD. Blade resolved CFD modelling relies on a digitised format of the blade geometry and a moving mesh to account for blade rotation. It is quite challenging to generate a mesh with sufficient resolution close to the blade surface, easy convergence and low memory and CPU usage. Furthermore, difficulties may appear at the moving boundary of the mesh which can manifest itself as a pressure discontinuity. A widely used solution is the generation of a hybrid mesh: structured mesh for the boundary layers and unstructured mesh elsewhere [3]. In tidal turbines, turbulent fluctuations arise on the full frequency range as follows [4]:

- low frequency waves;
- low to medium frequencies approaching flow turbulence;
- high frequency eddies due to blade-generated turbulence and fixed frequency cycle effects from onset mean-velocity shear, influence of support structure (tower) and surrounding boundaries.

Large eddy simulation (LES) models turbulent fluctuations by retaining large eddies and ignoring small eddies in solving Navier-Stokes equations. Addressing only cyclic fluctuations with unsteady Reynolds-averaged Navier-Stokes equations (RANS) turbulence models is more common as it requires less finer meshes. Typical RANS models used in wind/tidal turbines are $k-\varepsilon$, Spalart-Allmaras and, the most common in 2D and 3D hydrofoils, $k-\omega$ SST. It should be however noted that RANS models have also been found to fail on accurately modelling stalled flow in high angles of attack [3].

Computational speed and reduce memory usage can also be improved by discretisation of the Navier-Stokes equations by using discretisation methods such us finite-volume method (FVM), finite-element method (FEM) and finite-difference method (FDM). A further model simplification can be attained by [5]. Representation of the blades can also be simplified by using line actuator models.

A.2 Blade Element Momentum (BEM) Models

In its simplest form, BEM is a computationally efficient approach to model flow/turbine interactions. It is essentially an analytical method that provides an acceptable level of approximations to the asymmetric distribution of inflow and loads found when the turbine is unyawed, with respect to the oncoming flow, and under no dynamic stall effects [6]. To overcome these limitations the following empirical corrections can be introduced in the model, see [3] and references therein:

- tip loss correction factor to account for the effects of vortices shedding from the blade tip on the induced flow velocity;
- correction of flow speed behind the blade when the turbine blade gets into turbulent wake state (operation at high tip speed ratios);
- compensation by dynamic inflow model of the rotor-diameter-dependent and flow-speed-dependent time delay caused between the wake and the inflow when the inflow changes;
- dynamic stall and time delay corrections when the hydrofoil quickly changes the angle of attack of the rotating blade;
- radial flow correction on hydrodynamic loads; and

- skewed wake correction when the turbine is yawed.

BEM models are usually combined with structural dynamic models of the turbine blade and rotor to produce powerful aero-elastic tools. Such an approach is also applicable to produce hydro-elastic tools.

A.3 Other Turbine Modelling Techniques

Other approaches to model unsteady wake dynamics, besides dynamic inflow models, are vortex models and actuator disc type models. Vortex models are able to represent the strengths (circulation) and spatial location of the vortex elements, which are trailed by the blades and converted into the downstream wake, as vortex filaments from which the induced velocity field can be determined through the application of the Biot-Savart law [6]. In actuator disc models the Euler or Navier-Stokes formulations are solved using FVM or FDM without resolving the geometry of the blade. Instead, the surface of the blade is replaced by distribution forces acting on the incoming flow. Both vortex and actuator disc models are more computationally intensive than BEM with dynamic inflow, nonetheless they produce a better insight into the flow development and wake dynamics [3].

A.4 Turbine Structural Modelling

Structural modelling can be roughly classified as 3D finite element model FE models and 1D equivalent beam models. In a 3D FE model, the hydrodynamic shape and structural layout of the turbine composite blades are modelled as 3D composite shell elements which is capable to represent composite layer characteristics throughout the shell thickness. 3D FE models are usually coupled with CFD to perform aero-elastic modelling at a high computational cost. A FE-BEM approach is more computationally efficient [7]. In 1D beam models the largest dimension of a slender blade structure is defined as the beam axis and the cross-sectional geometry of the blade is considered to vary along the span of the beam in a perpendicular axis. The two most used beam models are the Euler-Bernoulli model and the Timoshenko model. Both models deal with slender beams subjected to extensional, torsional, bending loads, and assumptions of small deflections. The Timoshenko model also accounts for shear deformation effects. To deal with large blade deflections and geometric nonlinearities, nonlinear models are required. The discretisation of the blade modelled as a series of 1D beam elements can be carried out using the modal approach, the multi-body dynamics (MDB) approach and the 1D FE model approach [3]. The 1D beam models also require cross-sectional properties of the blade such as mas per unit length and cross-sectional stiffness which can be obtained from a cross-sectional analysis using 3D FE, 2D FE models or classical lamination theory.

A.5 Large-scale Coastal Models

Both BEM and CFD are mainly suited to model the interactions between flow and turbine at a fine temporal and spatial resolution (sub-second and sub-metre respectively). Flow and resource modelling at regional scale is associated with coarser resolution (of the order of minutes and of tens of meters) to render practical modelling of large geographical areas over long durations (typically years). Regional coastal area models can be used to predict changes in the far-field. Coastal area models usually consider the reduction in momentum, leaving the turbulence generated by the turbine unmodelled and thus reducing the accuracy in the simulation of wake recovery. In order to investigate resource availability or impact of energy extraction due to array and inter-array turbine scenarios on the wider environment, the tidal energy dissipation associated with the presence of tidal turbines may be approximated by adding one of the following corrections [8]:

- Bottom friction source term in depth-averaged 2D models. This approach is not suitable for 3D models.
- Sink term to the momentum equation in 3D models to represent the loss of momentum due to the energy extraction.
- Turbulence correction terms can also be added on 3D models to accurately represent wake recovery.

Modelling complications such as failing to model the angle between the flow and the turbine's heading in strong bidirectional flows, failing to represent the turbine thrust coefficient as a function of flow speed, and failing to represent turbines wake interactions as well as low resolution grids to represent such interactions are still open research topics.

One main constraint of the above modelling approaches on representing the coupled nature of the tidal turbine system is the multiple time scales of the problem. A schematic of the different scales for a similar system is presented in Fig. A1 [9].

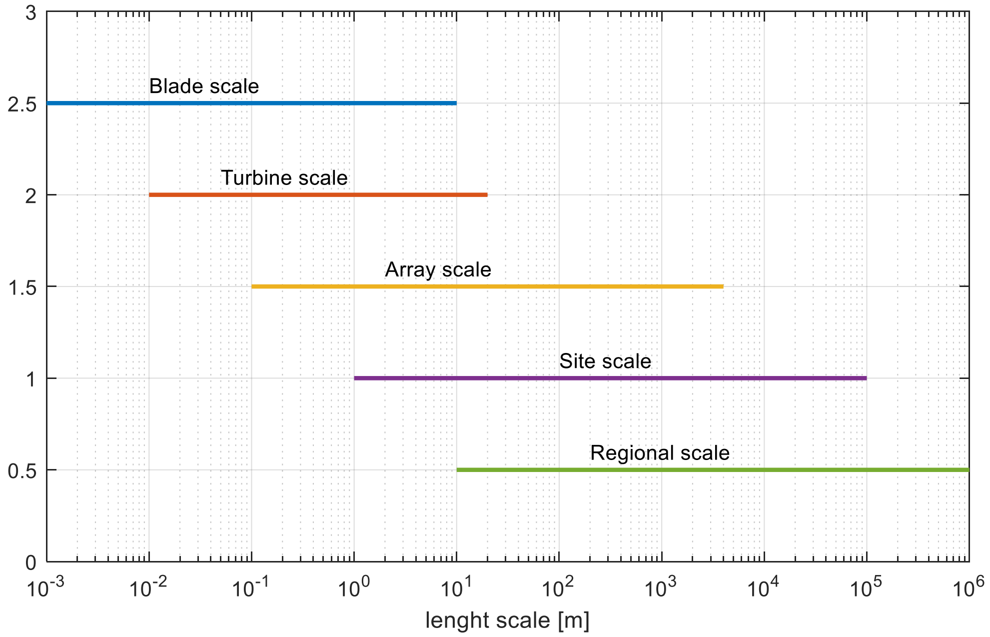

Figure A.3. Different scales of hydrodynamic modelling for tidal turbines

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