University of Exeter coursework header sheet

ECMM102 Group Project (Meng) (A, TRM1+2 2015/6)

010553

1019569

620015740

Coursework: G2

Submission Deadline: Thu 28th Apr 2016 12:00

Personal tutor: Professor Gavin Tabor

Marker name:	G Tabor
Word count:	6295

G2 Report: Wind Farm Modelling

Ben Ashby, Matt Howard, Louis Hudson, George Hyde-Linaker, Ben Johnson, Harry Liu, Tom March, James O'Leary, Ben Withams

2016

4th year MEng Group Project

I certify that all material in this thesis that is not my own work has been identified and that no material has been included for which a degree has previously been conferred on me.

Signed: , , , , , , ,

Ben Ashby, James O'Leary

College of Engineering, Mathematics, and Physical Sciences
University of Exeter

G2 Report

ECMM102

Title: Wind Farm Modelling

Word count: 6295

Number of pages: 20

Date of submission: Wednesday, 27 April 2016

Student Name: Matthew Howard

Programme: MEng Mechanical Engineering

Student number: 620015740

Candidate number: 010553

Supervisor: Professor Gavin Tabor

Table of contents

1. Introduction

Offshore arrays of wind turbines are a major source of sustainable and renewable energy and are a vital aspect of the evolving energy generation sector. One main issue regarding wind energy is that a significant amount of wind farms currently in operation produce less energy than predicted prior to their construction. This is predominately due to the complex aerodynamic behaviour of turbines being difficult to predict. The majority of current modelling techniques use either Computational Fluid Dynamics (CFD) using simple Actuator Disk Models (ADMs) or Engineering Wake Models (EWMs) to simulate the approximate behaviour of wind turbines.

2. Group objectives and deliverables

The aim of this project was to research the current techniques used for predicting the performance of wind farms and to lay the foundations for development of improved modelling techniques. These aim to achieve better approximations of wind farm power yield and narrow the gap between predicted and observed wind turbine behaviour. These objectives identified a clear and well defined structure for the group, with one team evaluating the existing modelling techniques, while the other addresses the development of future approaches. This formed the overarching system by which work packages within the group were devised and allocated. The main objectives and deliverables of the project are summarised in the following sections.

Figure 1 outlines the aspects of wind farm modelling studied within the project. The links with the commercial SWEPT 2 project allow any proposed improvements identified within this project to be utilised and further developed within a commercial project; these improvements are proposed in the conclusion. The Centre for Modelling and Simulation (CFMS) was used as a contact throughout this project.

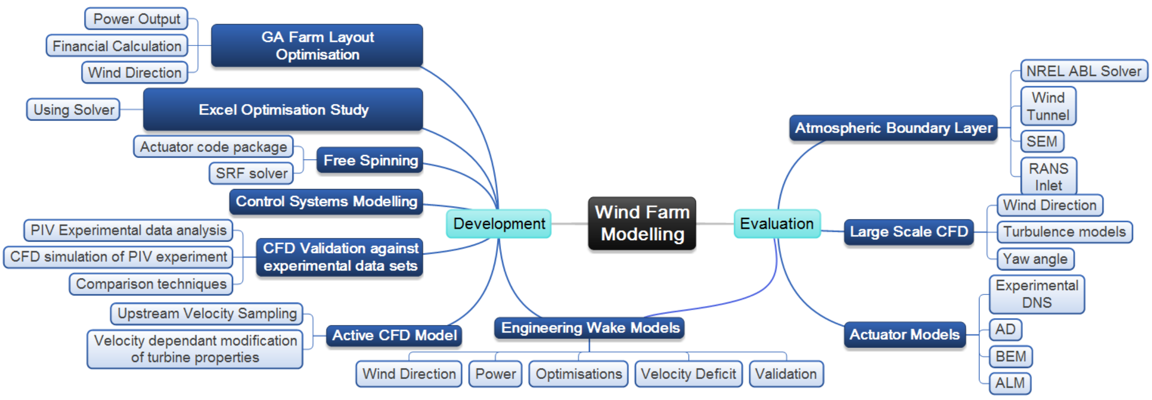

Figure 1: Breakdown of Project Structure

2.1 Evaluation of Current Methods for wind farm analysis

The evaluation aspect of the project was focussed on investigating the current techniques used to predict dynamic behaviour and power yield from wind turbines; these included CFD simulations and EWMs. This hoped to identify the causes of inaccuracies of current modelling techniques, highlight areas for future development, and evaluate the potential of these approaches for future use in industrial applications.

This work required the delivery of full implementations of pre-existing modelling techniques and assessments of the model behaviour. Extensive comparisons of the models with one another and with validation data allowed the key shortcomings of each model to be identified.

2.2 Development of Techniques for wind farm analysis

The main objectives of the development aspect of the project were to propose improved functionality of pre-existing modelling techniques and to lay the foundations for new ones. This would deliver implementations of the new techniques or functionality as well as assessments of the improvements and limitations that these offer. From this platform, further investigations into the developed methods can continue from this project.

3. Work programme – individual work packages

The following section details the aims and objectives of the individual work packages.

3.1 Tom March

Title	**An investigation into the effect of different wind directions and turbulence models on CFD simulations for Wind Farms**
Aims	• To use an ADM [1] within CFD to find the power losses over different wind directions and yaw angles • To compare different turbulence models evaluating their efficiency, accuracy and suitability for this application • To collaborate with the group using the findings found within this project to identify find where the discrepancies lie within current wind farm evaluation techniques
Deliverables	• Set-up a 20 turbine wind farm incorporating the ADM method within OpenFOAM • Run simulations over different wind directions and yaw angles to find significant power losses • Simulate the wind farm using different turbulence models • Compare and validate the simulations run as part of the project with sources found as part of the literature review and values found by other members of the group

3.2 Ben Ashby

Title	Development of CFD turbine model to respond to variation in flow velocity.	Methods for comparison of CFD results and large experimental datasets.
Objectives	• Modify ADM to set characteristics according to local wind velocity • Set solver to match power curve of the Siemens SW-2.3-93 wind turbine • Enable better modelling of arrays by setting each turbine according to flow speed at each point in array	• Recreate results of Particle Image Velocimetry (PIV) experiment investigating wake behind a submerged hull using CFD • Identify methods for the comparison of large datasets which can be transferred to future work comparing wind farm models with site data
Deliverables	• Implement patch to sample speed upstream of turbine • Modify solver to update thrust and torque for the next time-step according to sampled velocity • Compile and test modified solver	• Accurate CFD model of case using LES modelling • Validated collection of statistical and graphical data comparison methods

3.3 Ben Withams

Title	Investigating and validating current wake models for use in predicting the power output and optimising the layout of Offshore Wind Farm Arrays
Aims	• Identify discrepancies between Engineering Wake Models and observed effects • Create useable and editable mathematical model for use in future research
Deliverables	• Identify and evaluate most commonly used wake models • Identify wake summing methods • Set up robust and customisable mathematical models • Create basic optimisation algorithm • Compare gathered data to other group members, including performance of mathematical models to CFD and optimisation techniques

3.4 George Hyde-Linaker

Title	Modelling and assessing the effect of the turbulent Atmospheric Boundary Layer (ABL) on ADM
Objectives	• Approximate the velocity profile of an offshore ABL via wind tunnel experimentation • Compare differing approaches for generating the turbulent ABL in OpenFOAM • Produce Solver for the simultaneous modelling of the ABL and actuator disk wind turbine model using Large Eddy Simulation (LES)
Deliverables	• Dataset and method of modelling an ABL profile via small-scale wind tunnel experimentation • Proposed inlet condition for an offshore ABL and method of incorporating eddies into flow via the Synthetic Eddy Method (SEM) • Solver which models turbulent eddies and actuator disks simultaneously • Comparison between use of a turbulent ABL and constant uniform velocity inlet for wind turbine modelling of ADM

3.5 Ben Johnson

Title	**Development of free-spinning wind turbine representations for CFD.**
Objectives	• Create a free-spinning moving geometry CFD solver and test its viability • Develop a free-spinning actuator representation of a wind turbine and implement it as a CFD solver package ready for further investigations into the discrepancies between free and prescribed angular velocity representations of wind turbines
Deliverables	• A free-spinning single-reference frame (SRF) solver in OpenFOAM • A flexible actuator package for OpenFOAM incorporating a free-spinning Actuator Line models (ALM), ADMs, control systems and a polymorphic structure capable of having additional models and control systems written in

3.6 Matt Howard

Title	**Investigating the potential of actuator modelling for accurate power yield prediction from wind turbines.**
Objectives	• Compare various forms of actuator models, assessing their accuracy and potential for industrial use • Validate the models against experimental data
Deliverables	• Implement a range of actuator models with increasing complexity in force distribution methods • Predict the behaviour of a particular turbine case with each model and complete in depth comparison • Use the geometry dependent models to recreate a well-researched experimental case for the purposes of validation

3.7 James O'Leary

Title	**Study of the use of Microsoft Excel for offshore wind farm development**
Objectives	Determine the suitability of Excel as a tool to help offshore wind farm developers make design decisions regarding: • Turbine positioning decisions given array cable costs and wake effects. • Offshore substation positioning • Investment Appraisal of Offshore Wind Farm development projects.
Deliverables	• Development of cash flow forecast and net present value calculation for Offshore Wind Farms • Identify turbine locations which minimise cost and maximise power generation in different scenarios using linear programming techniques.

3.8 Louis Hudson

Title	**Investigation into the modelling of wind turbine control systems and the development of a wind turbine controller**
Objectives	• Develop a pitch and yaw control simulation models based on the Controls Advanced Research Turbine (CART3) system • Validate the model simulation results against CART3 control results • Develop control strategies for performance optimisation
Deliverables	• Developed a full turbine model using Simulink which considered the aerodynamic aspects modelling the control systems in as "ideal" subsystems. • Using different dynamic models to optimise control performance and to validate against CART3 model • Produced a range of control strategies for integration into future models

3.9 Harry Liu

Title	**Wind farm layout optimisation using Genetic Algorithm (GA)**
Objectives	• Develop multi-objective GA for wind farm layout optimisation • Implement the Jensen-Katic [2] wake model and a summing method to calculate wake loss • Design and implement capital and operation and maintenance cost models • Identify, adapt and implement computation cost reduction methods
Deliverables	• Objective fitness functions for testing and improvement • Computation cost reduction methods testing • Identify Pareto front of farm layouts with customisable parameters • Compare optimised layout of small farm to expected layout

4. Methodology

This section aims to briefly explain the work carried out by each member, it has been split up into the Evaluation and Development sections as justified previously.

4.1 Evaluation of Current Methods for wind farm analysis

Matt Howard: Evaluation of Actuator models

A number of actuator methods were implemented in OpenFOAM that used methods of increasing complexity for distribution of blade forces over the actuator region. These included a uniform distribution representing the Rankine-Froude actuator disk, a Goldstein optimum distribution representing an ideal turbine operating at the Betz limit. Also a blade element coupled distribution representing the true forces based on local rotor geometry, and an actuator line approach which distributes the same blade element forces on lines through the domain to represent the individual blades.

A case study of a theoretical full-scale offshore wind turbine as described by the National Renewable Energy Laboratory (NREL) [3] was used to compare the models. All models were used to predict the behaviour of this turbine in consistent conditions and data regarding simulated power yield, near and far wake profiles and computational expense was collected and compared. A case study involved using the more complex geometry dependent models to predict the results of the Model rotor Experiments in Controlled conditions (MEXICO Experiments) [4] to validate the models and compare them to true observed turbine behaviour.

Ben Withams: Analysis of Engineering Wake Models

Current industry standards focus on using EWMs, which describe how the wake deficit recovers downstream of a turbine and how the wakes expand. This allows the power output for a wind farm to be calculated. The three EWMs that were chosen were the Jensen-Katic [2], Frandsen [5] and Larsen [6] models, these were set up in a spreadsheet and validated against previous studies. Furthermore the spreadsheet was used to analyse the power output from a wind farm of any layout of 20 turbines and from any wind direction. This work was validated against results from the literature and can be used as a reference for other work carried out in this project.

Tom March: Analysis of Wind Directions and Turbulence Models

To analyse the effect of changing wind directions and yaw angles, simulations were run from 0 to 30 degrees in 5 degree increments. For comparing yaw angles, the simulations were run twice; first ensuring the turbines were facing the wind direction and second keeping the turbine angle fixed. This gave 7 different wind directions and yaw angles. Simulations were run to compare 5 different turbulence models, these included three Reynolds Average Navier-Stokes (RANS) models, Detached Eddy Simulation (DES) and LES. Graphs were then drawn up to compare the simulated power output of the different yaw angles with theoretical calculations, the power distribution across the farm over different wind directions and finally the power output and distribution of the different turbulence models.

George Hyde-Linaker: Modelling and Assessing ABL

The solver *EddiesAndActuatorDiskPisoFoam (EAADPF)* was implemented in OpenFOAM for LES modelling of the turbulent eddies within neutral ABL flow, the behaviour of the actuator disk wind turbine model, and the interaction between them. The produced solver is a modified SEM, which introduces turbulence into the flow by imposing eddies of a prescribed length scale onto a time-averaged flow. This technique has been largely developed by Jarrin et al. [7]. In order to generate a close approximation to the ABL flow at offshore wind farm locations, wind tunnel experimentation of an induced boundary layer were conducted to replicate the profile of the ABL. Incorporating these results into OpenFOAM as an inlet condition, used in conjunction with *EAADPF*, produced the profile of a turbulent offshore ABL whilst accounting for the behaviour of the ADM. A constant uniform inlet was compared with the generated turbulent ABL of the EAADPF, to investigate the possible effect of ABL flow on the power discrepancy of current modelling methods, which often use uniform velocity inlets.

4.2 Development of Techniques for wind farm analysis

Ben Johnson: Development of free-spinning techniques

To develop free-spinning techniques the torque must be found, as it is related to the angular acceleration by the moment of inertia. The angular acceleration is then numerically integrated for the angular velocity, which can then be used for the solver calculations. The equation of the torque on a mesh patch for a moving geometry simulation was derived and written into OpenFOAM's SRFPimpleFoam solver, along with the numerical integration to create the free-spinning SRF. For the free-spinning ALM the torque is found from the Blade Element Method (BEM), the angular acceleration is then numerically integrated twice to get the rotation angle of the blades. The actuator package was written in OpenFOAM and C++, therefore using polymorphism and object-orientated programming techniques.

Ben Ashby: Development of Active ADM

The ADM used to represent the turbine [1] was modified to introduce a sampling patch upstream of each turbine. The averaged velocity across this patch was used to set the thrust and torque values for the model using a lookup table of values, found to correspond to the power curve of the Siemens SW-2.3-93 wind turbine. These solver modifications were used in the class descriptor file for the solver, meaning that these changes apply to each turbine object initialised in a case. For a more detailed description of this work please see the corresponding individual report.

Ben Ashby: CFD Validation against Large Experimental Datasets

Recreating the results of the PIV hull wake experiment in CFD required careful meshing and set up. The hull and flume were reproduced in a domain that included sufficient spacing from the outlet and inlet to minimise errors. This domain was meshed using Pointwise, using a fully resolved boundary layer mesh around the hull and a refined area at the sample region. The case was tested using the k-Epsilon turbulence model before being run using LES to recreate the transient behaviour of the wake structure. Once the CFD had completed, the data was imported into MATLAB, where it was compared to the PIV data using a number of statistical and graphical approaches.

Louis Hudson: The development Wind Turbine model controllers

To develop ideal pitch and yaw control systems, a complete turbine model was created which had the specifications of a real turbine. The controller was developed to efficiently control rotor speed, pitch and yaw at constant and variable wind speeds, based on a set of given parameters taken from the CART3 system, developed by the NREL. A turbine state machine was developed and integrated to allow the system to run using different operating conditions.

Various case studies, developed using the CART3 system, were used for validation of performance as well as system characterisation tests. Additionally, step input tests were ran for detailed model realisation. Finally, a range of control strategies were outlined for the integration of more advanced models which consider more advanced blade and actuator control strategies.

Harry Liu: Development of a GA for wind farm layout optimisation

A three objective GA was designed and implemented in MATLAB with fitness functions to represent power, capital, and operation & maintenance cost, to optimise wind farm layout. Archive reduction methods are analysed and adapted to minimise the computation cost.

Objective functions and archive reduction methods were individually tested, using a farm layout that emphasised the results of each function. Pareto front layout results of small farms were analysed to show optimised layout. Whereas Pareto front results of large farms were analysed to determine relationships between cost and power.

James O'Leary: Study of the use of Excel for offshore wind farm development

This study looked to determine the suitability of Excel as a tool to help offshore wind farm developers make design decisions, for example, where to position turbines. Since profitability depends on the power generated and the cost of producing that power, designers are required to make trade-offs between cost centres and performance drivers. To identify whether Excel could be used to help make such trade-off decisions, a mathematical equivalent of an offshore wind farm was created in Excel and different designs were optimised subject to design constraints such as minimum separation and cost. This optimisation was achieved through the use of linear programming techniques in conjunction with the Simplex algorithm and a GA within the Excel Solver.

Ben Withams: Creation of mathematical models incorporating EWMs

The creation of the mathematical model which incorporates EWMs for the evaluation sub section can be further implemented in the developmental section. Currently there are multiple programs that are used in industry to calculate the wake deficits and power outputs within wind farms. By creating the model within Excel, a program which is far simpler to use and easily editable has been created. The model can be used to simulate any wind farm layout up to 20 wind turbines including different wind directions. A basic optimisation technique has also been implemented that uses a random number generator to find the optimum layout for a set of turbines.

5. Results and analysis

5.1 Evaluation of Current Methods for wind farm analysis

Matt Howard: Evaluation of Actuator models

It was observed that the simpler forms of actuator models were able to recreate the velocity deficit in the far wake region almost as well as the complex forms. In the near wake however, their predictive capabilities were lacking. The more complex forms of ADM, such as BEM, were more capable in the near wake region. However only the ALM approach was able to simulate complex flow structures such as root and tip vortices, as visualised with Q-criterion in **Figure 2**. The ALM was shown to be very complete in its simulation of turbine flows and predicted the results of the MEXICO Experiments [4] well.

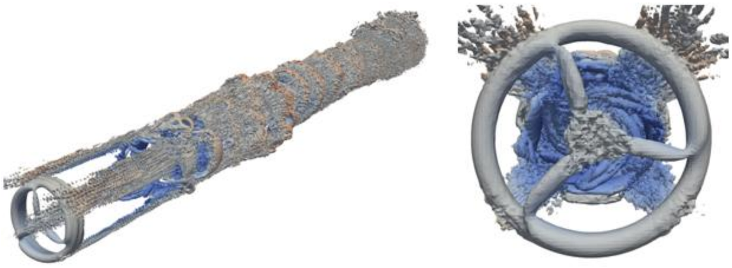

Figure 2: Q-criterion coloured by velocity for the ALM used

Actuator models were shown to have good potential for future commercial use. The level of complexity in the force distribution methods increased the computational expense of the solver. Thus an appropriate model can be chosen, given the output requirements for a specific case. However, the simpler methods were shown to remain capable of approximating the far wake velocity profiles and the rotor power yield over time. More complex models may only be necessary if the simulation of transient near wake effects and vortex formations is specifically desirable.

Ben Withams: Analysis of Engineering Wake Models

The single wake cases for the 3 most used EWMs in industry have been validated against a range of previously carried out studies. The variation in prediction of wake expansion between these EWMs has been identified as the primary cause of discrepancies between the power outputs of the various models. This occurs because a difference in wake expansion will result in a difference in wake interactions between turbines.

A wind direction study has also been carried out, differences were found between the predicted power outputs due to the issues with expansion detailed previously. However all of the models showed increases in power output for non-zero wind directions. It was also shown that a wind direction of approximately ± 10 degrees resulted in the optimum power output across all of the EWMs.

Tom March: Analysis of Wind Directions and Turbulence Models

Resulting from the simulations run over different yaw angles, it was concluded that changing the yaw angle of an ADM is not an accurate or true representation of a real turbine. Through simulations of varying wind direction, it was found that changing the wind angle can vary the power by up to 20%. Following the turbulence model simulations it was clear that the k-ω SST model was the most suitable RANS model. LES and DES showed far more accurate representations of complicated flow structures. However, LES modelling was far more computationally expensive. The turbulence models showed differences of power by up to 48%. **Figure 3** shows the varying power distribution of the different turbulence models by row.

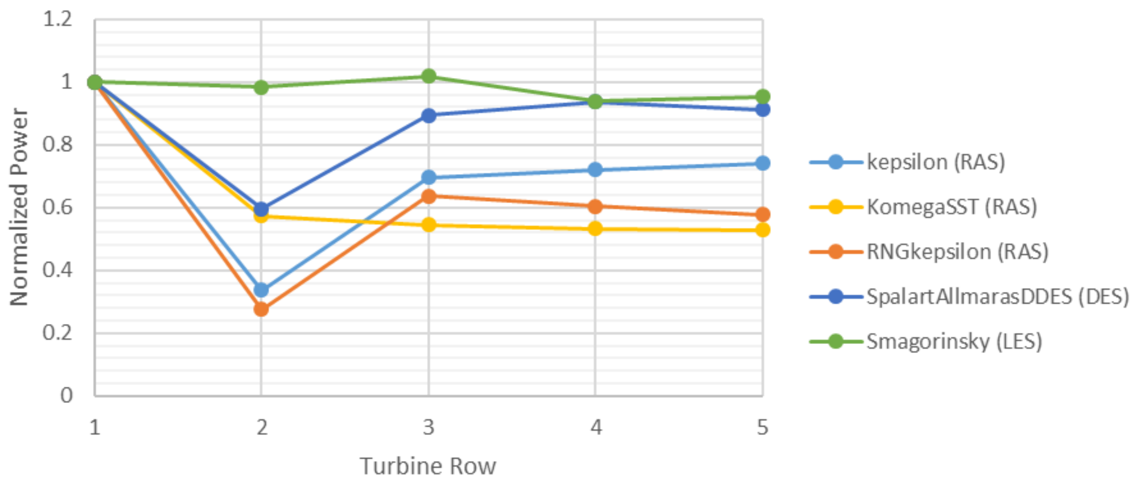

Figure 3: Power generated as a function of turbine row for a wind farm using different turbulence models

George Hyde-Linaker: Modelling and Assessing ABL

The *EAADPF* has the capability of modelling actuator disks and introducing eddies of a prescribed length scale into the flow. *EAADPF* was implemented and combined with the data obtained from wind tunnel experimentation to produce an approximation of the aerodynamic interaction between the turbulent ABL and the ADM. The effect of using *EAADPF* for modelling the complex aerodynamic interactions between the turbine model and the atmospheric airflow was then compared with using time-averaged inlet velocities. These two approaches can be visualised in **Figure 4**. From sampling and using a control volume, the main conclusions from the project were that for the studied turbine at a height of 100m:

- Average velocity airflow exposed to turbine can be ~15% higher when considering the freestream velocity of atmospheric airflow as airflow speed at a turbine height.
- The power predicted to be generated by the ADM is largely dependent on the mean flow exposed to the turbine and the velocity fluctuations have little impact.
- The airflow velocity downstream of turbine is significantly less and more unpredictable using turbulent ABL, which is important for downstream modelling.

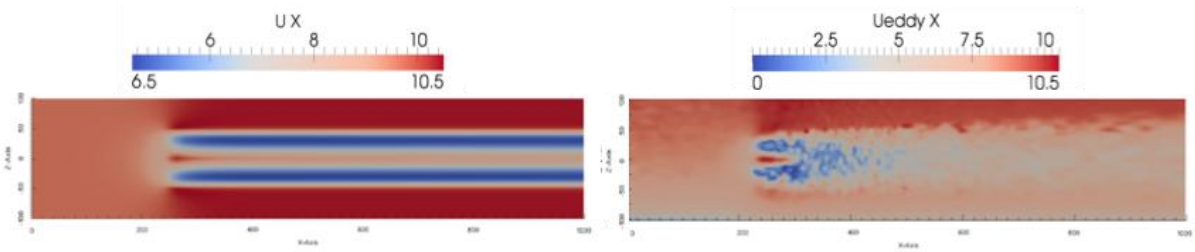

Figure 4: Velocity profiles obtained using uniform and turbulent ABL conditions

5.2 Development of Techniques for wind farm analysis

Ben Johnson: Development of free-spinning techniques

The free-spinning SRF solver was successful in the basic test case but was found to be too computationally expensive to be viably used for a full investigation, when tested on a wind turbine geometry. The actuator package was structured as shown in **Figure 5**, the solid lines represent the inheritance of classes from the abstract base classes used for polymorphism. The red dotted lines represent the dependency of classes, in this case this is cyclic dependency managed by member pointers to the classes. This structure allows any model to be easily added in with little rewriting of the code and allows for run-time selectability. The actuator package was tested and was found to be highly efficient. It allows for any combination of models and has no limit on the number of turbines. The control systems have been implemented with an architecture that allows them to fully manipulate the actuator model, although only a basic system has been currently implemented. The free-spinning ALM implemented in the package passed the test cases and showed great potential for a full investigation into the discrepancy between prescribed and free-spinning simulations.

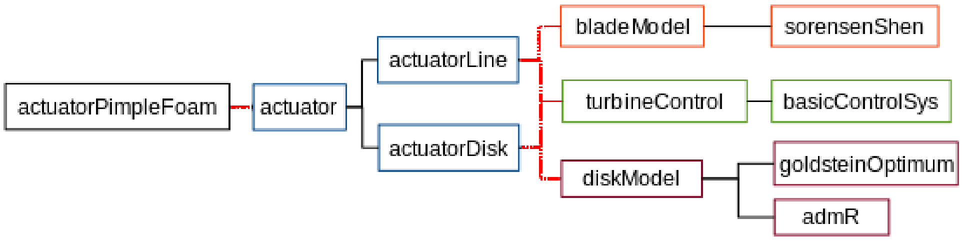

Figure 5: Code structure showing inheritance (solid) and dependence (red-dotted), coloured by class groups

Ben Ashby: Development of Active ADM

A modified solver that uses sampled flow velocity to set turbine thrust and torque was achieved in this work. This solver compiled successfully and a simple test case showed that the thrust and torque were altered in response to changing flow velocity. However this solver proved to be highly computationally expensive, so further work would need to streamline the solver algorithm before this method can be applied to more complex cases.

Ben Ashby: CFD Validation against Large Experimental Datasets

The results of the PIV experiment were successfully replicated in OpenFOAM for both RANS and LES turbulence modelling. The correlation between the PIV and CFD datasets was high, with the RANS model giving a correlation of 0.991 when compared to the time averaged PIV data. A search function was constructed to find the closest fit between the transient LES and PIV datasets, allowing corresponding datasets to be identified and compared, this function produces plots of the error distribution between the datasets and returns the sum of square residuals and correlation coefficient.

Louis Hudson: The development Wind Turbine model controllers

A pitch control system has been developed which effectively responds to variable wind input as shown in **Figure 6**. The model suffered from initial stabilisation and overshooting but managed to track pitch effectively.

The yaw control system has been developed that suitably responds to variable wind direction inputs shown in **Figure 7** with a maximum yaw rate of 0.5 deg/s. Any greater wind direction angle produced a yaw misalignment which impacted overall model power performance.

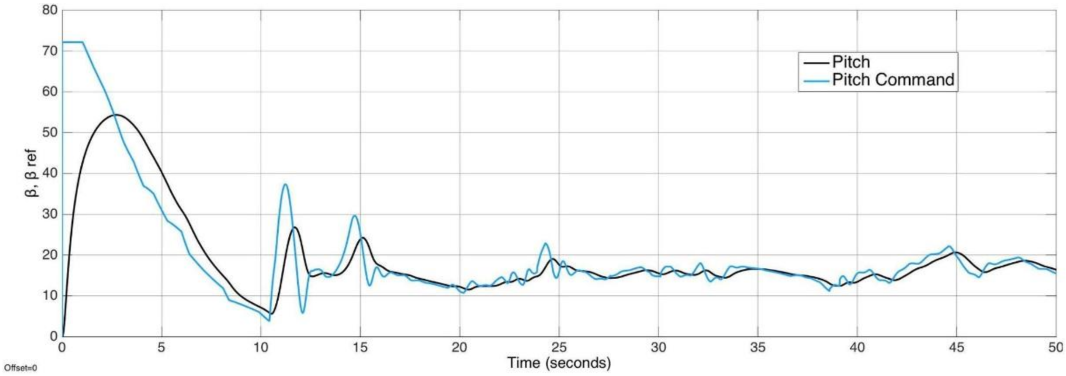

Figure 6*:* Designed pitch command and pitch angle

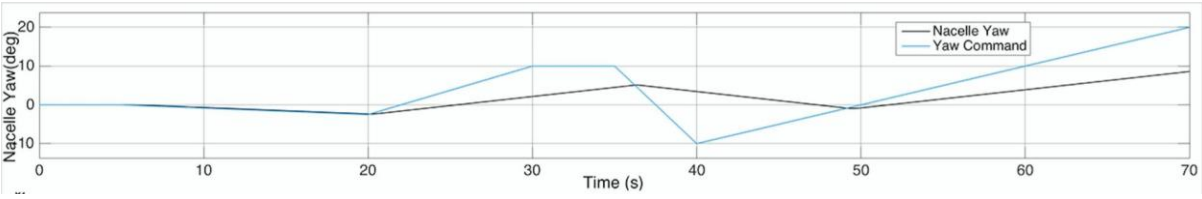

Figure 7: Designed yaw command and yaw angle

Harry Liu: Development of Genetic Algorithm

All fitness and archive reduction functions were tested separately with farm layouts or results that emphasise the effect of each function to show that all are working as expected.

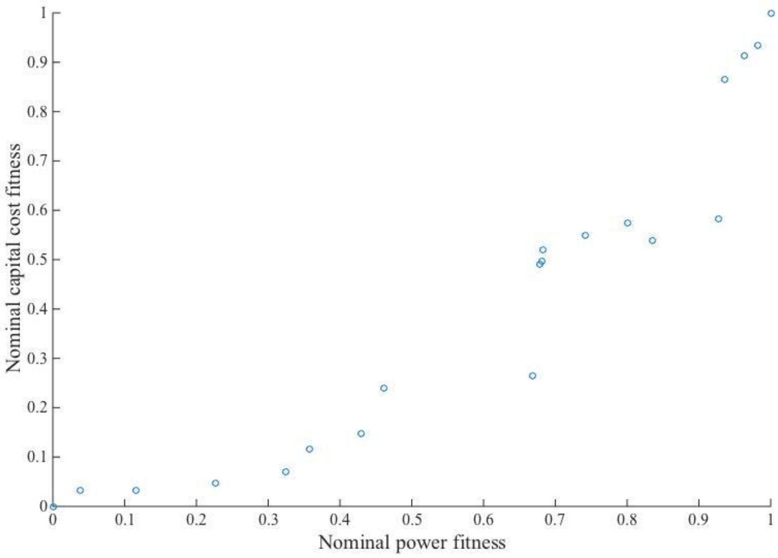

Figure 8: Pareto front presenting nominal power and cost fitness of optimised large farm layout

Figure *8* shows the Pareto front between power output and capital cost, it presents the nominal power and capital fitness of 20 layouts. The farm conditions used are 20 rotor diameters squared, and 3 rotor diameters separation distance. Detailed 3D Pareto front can be analysed using a curser, but analysis of Pareto result are done in pairs, as values are more easily read. The precise layout of each result on the Pareto front can be found in a separate file.

The optimised layout of small farms with small separation distance are analysed first, the results have shown that Pareto front of layout results are as expected. The Pareto front of large farm simulation shows the non-linear relationship between power and cost are as expected.

James O'Leary: Study of the use of Excel for offshore wind farm development

Excel's built-in 'Solver' tool allows users to identify optimal solutions to mathematical problems using one of three algorithms. In this project, the Simplex linear programming algorithm and a GA were used within 'Solver' to maximise power production and minimise cost for different designs. The optimal designs generated using this approach met all of the applied constraints and in doing so demonstrated that Excel can be used to help offshore wind farm developers make design decisions. However, further work would be needed to make this an industry standard approach.

Ben Withams: Creation of mathematical models incorporating EWMs

Three mathematical models that incorporate different EWMs have been successfully created, they can calculate the wake effects, subsequent velocity deficit and therefore power output of any wind farm of 20 or less turbines. This approach could be extended for use with more turbines if required. The EWMs in question have been validated against previous studies, as detailed earlier.

The optimisation study that was carried out was unsuccessful due to the random number generator which was used to place the turbines. The code was written such that the difference between possible locations could be as little as 10cm. This resulted in a layout that was too complicated and too computationally expensive to be justifiable.

6. Conclusion and Further work

This section summarises the group findings for the two main project areas. Finally recommendations for future work are also stated.

6.1 *Evaluation of Current Method for wind farm analysis*

Throughout this work a number of approaches to the modelling of wind turbines have been evaluated, including a range of CFD techniques and EWMs. A number of Actuator models have been used, including ADMs and ALMs. Simpler ADMs [1], showed reliable results in the far wake region at a low computational cost, while ALMs produced a better resolved near wake region.

The low computational cost of the ADM used throughout this project has enabled the investigation of a range of flow phenomena which impact turbine behaviour. The effect of yaw and turbulent wakes have been investigated using LES and DES, to simulate wake interaction in an array of turbines. This work showed that the interaction of wakes in a wind farm can be efficiently reproduced through the use of ADMs and DES turbulence modelling.

The influence of the ABL on turbine behaviour has also been investigated using LES modelling. Through the use of this ABL inlet it was found that the velocity exposed to the turbine was lessened by as much as 12%. This led to lower power generation of the turbines, also causing the wakes to be more turbulent and of lower velocity. This has highlighted a potential cause of calculated power discrepancies of wind farms. Further work is required to validate these findings.

EWMs were used as an alternative to CFD approaches, allowing for the quick simulation of wake behaviour in applications such as array optimisation. Discrepancies between power output predictions from EWMs have been mainly attributed to the differences in how they predict the wake expansion. The angle of wind direction has also been found to increase the power output for non-zero values up to 30 degrees as this was the range of values studied. A variation in predicted power output was also observed between the different EWMs in the wind direction study which can be attributed to different wake expansion rates. This can be compared to the CFD results for changing wind directions which illustrated the importance of wake expansion on results.

These results identify situations where each different technique is the most suitable and helps inform decisions on model selection based on the needs of the user.

6.2 Development of Techniques for wind farm analysis

Improved functionality of existing analytical approaches was sought in this work. MS Excel analysis of EWMs is developed; this work has been shown to perform well for arrays of up to 20 turbines, though this could be extended for use with arrays of any size. A different approach using the multi-objective GA was taken for layout optimization, to determine the Pareto front between power, capital cost and operation & maintenance cost. This approach was developed for one EWM, but is more versatile in terms of yaw angle and turbine number. Furthering this work, a more advanced financial model for the design of wind farms has been developed in Excel, which could be incorporated into the optimisation process. These approaches are efficient in generating optimal array layouts, with high predicted power yields and low financial costs, furthering techniques currently used in industry for wind farm design.

From the evaluation section of this work, a key issue identified in the CFD turbine simulations was the requirement to prescribe turbine operational parameters in the case set up. To counter this issue a range of new approaches and models have been implemented. The ADM used throughout this work has been modified to actively respond to the flow velocity received by the disk through the use of an upstream sampling patch. This allows for better power prediction for arrays where wake shadowing reduces the incident flow velocity for downstream turbines. For more complex ALMs, a free-spinning model was implemented in OpenFOAM, adjusting RPM for the turbine blades in response to dynamically changing flow conditions. To increase the ease of turbine modelling in OpenFOAM, and increase flexibility of model selection, a modular toolkit for turbine modelling has been implemented. This library includes a free-spinning ALM, ADMs and control systems. An ideal model of a turbine control system has been implemented in Simulink with a view to maximising turbine power yield and optimising rotor speed through the control of pitch angle – maximising the power coefficient. This control system has the potential to be integrated into the turbine modelling OpenFOAM toolkit, increasing the model sophistication.

In order to quantify the performance of the turbine modelling approaches used throughout this work, from EWMs to the various actuator models used, validation against an experimental dataset for a real world turbine would be needed. At the onset of the project it was planned to validate these models against a LiDAR dataset gathered from the Rødsand II wind farm in Denmark. To this end, a series of data comparison techniques have been established, taking the results of a PIV experiment to develop a validation procedure for the large datasets involved. However, the LiDAR dataset was not made available within the duration of this project.

6.3 Future Work

This project proposes that a control strategy to develop the turbine state machines for a more practical situation is sought, ensuring improvement of pitch controller using a real-time 'Tip Speed Ratio optimiser' and 'improvement of yaw controller' using LiDAR vector prediction. Additionally, a control strategy to incorporate a segmented aerodynamic load model could be pursued in future work.

Layout optimization can be improved through the addition of more complex cost models, and the inclusion of more detailed control systems, which better optimise blade pitch angle, β. More detailed models would raise computation cost but would more accurately predict power and cost, thus better determining the optimal layout.

The OpenFOAM actuator toolkit that has been produced can be expanded to include the more complex control systems, the local velocity sampling techniques and the implementation of the ABL that have been developed by this project. This extended functionality would better serve future projects by enabling more accurate simulations and widening the breadth of research that could be done on actuator models and free-spinning ALMs.

7. Project Management

7.1 Management Overview

To ensure project aims and objectives were met, a group Gantt chart was constructed (see **Figure 9**) and weekly team meetings were used to review progress and organise future actions. Project supervisor Gavin Tabor and postdoctoral researcher Steven Daniels attended the meetings to assist with any issues. To ensure that the workload was shared, the roles of Chair and Secretary of meetings were rotated on a weekly basis.

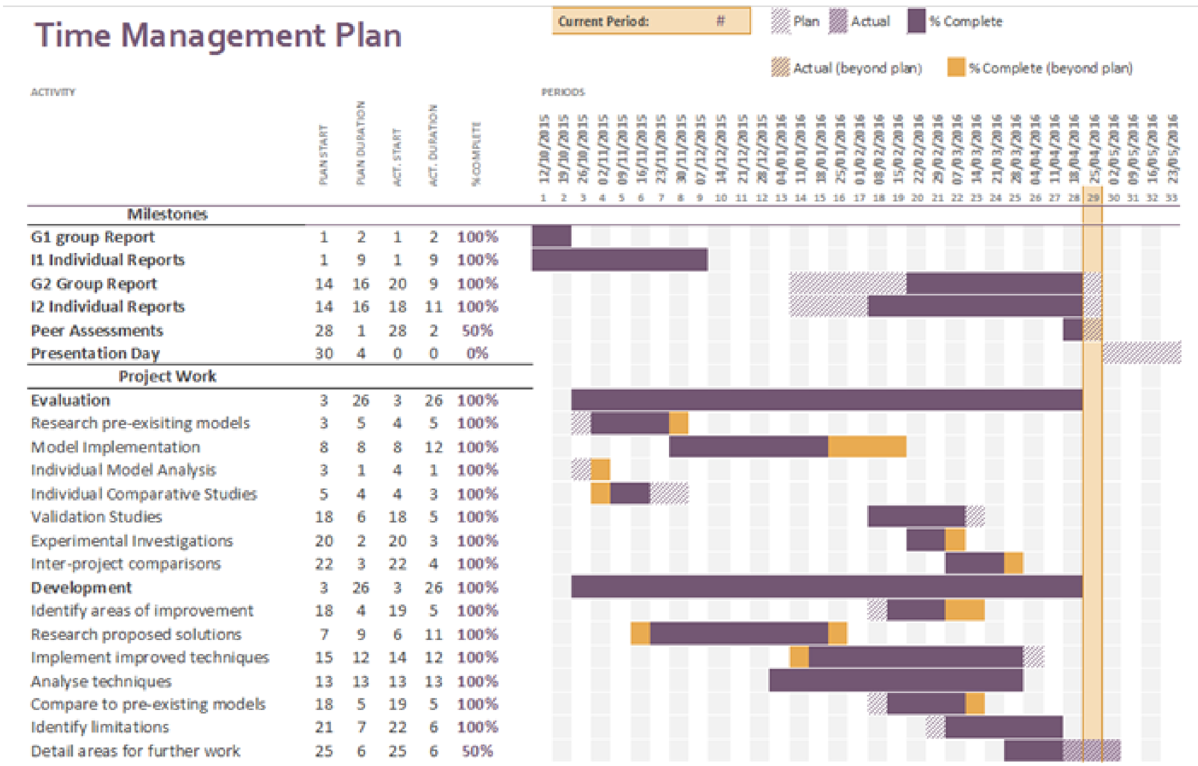

Figure 9: Gantt chart utilised throughout project

In addition to this, meetings were arranged between individuals with overlapping work packages in order to aid collaboration. Online platforms, such as Google Drive and MS Word Online, allowed work to be shared throughout the group and reports to be written in unison. All necessary resources were provided by the Engineering College and so none of the £800.00 allocated budget was spent.

Over the course of the project the direction of several of the individual projects evolved in response to circumstances out of the group's control, specifics of this can be found in the group I2 reports. This was managed through a combination of weekly meetings and assessment of the risks to project success (see **Table 1**). The risk assessment and Gantt chart were used to identify the primary risks to the project so that they could be monitored and mitigated as they progressed.

Table 1: Assessment of risks to project success

Risk Item	Effect	Cause	Chance (0/4)	Severity (0/4)	Importance(0/16)	Action to minimise risk
Computing Power Insufficient	Excessive Simulation run times	Computational resources	1	4	4	Use cloud resources and or partners super computers if necessary
Wind Tunnel	Risk trapped fingers/hair/clothing from fan in wind tunnel, eye damage	Moving parts and strong winds	2	4	8	Wind tunnel is designed to limit access to moving parts. Precautionary measures should be taken, hair should be back and ties tucked in.
LiDAR data not available	Planned project work package not possible	Data not made available by 3rd party	4	3	12	Have a contingency plan if this dataset is not available so that the data comparison techniques study is still possible
Loss of data	Delay of project completion	Corruption of files and user error	1	3	3	Properly backing up all data

7.2 Health and Safety

Health and safety guidelines for office computational work were considered during all stages of the project following the government guidelines [8]. For the wind tunnel analysis conducted in the ABL individual project, the health and safety aspects are covered in the associated I2 report. The PIV experiments were carried out by trained lab technicians due to hazards of the class 4 laser.

7.3 Economic and environmental factors

Cloud computing was used when primary resources where insufficient to share computing power resources. Additionally, the use of efficient code and modelling practices largely reduced the run-time of High Performance Computing, thus saving a higher amount of energy whilst keeping down running costs. The project made use of computational modelling and simulation. This allowed for rapid modification and testing of design without the need for physical prototyping/experimentation.

References

[1] Svenning, E. "Implementation of an actuator disk in OpenFOAM," CFD with open source software, Chalmers University, 2010.

[2] Katic, I., Højstrup, J and Jensen, N O. "A simple model for cluster efficiency." European Wind Energy Association Conference and Exhibition. 1986

[3] Jonkman, J, Butterfield, S, Musial, W and Scott, G. “Definition of a 5-MW Reference Wind Turbine for Offshore System Development,” National Renewable Energy Laboratory, 2009.

[4] Schepers, J.G. and Snel, H. “Model Experiments in Controlled Conditions,” Energy Research Centre of the Netherlands, 2007.

[5] Frandsen, S. et al. “Analytical modelling of wind speed deficit in large offshore wind farms.” Wind Energy. 2006;9(1-2):39-53. doi:10.1002/we.189.

[6] Larsen, G.C. “A simple wake calculation procedure.” Roskilde, Denmark: Risø National Laboratory, 1988.

[7] Jarrin, N, Benhamadouche, S, Lawrence, D and Prosser R. “A Synthetic-Eddy Method for Generating Inflow Conditions for LES,” International Journal of Heat and Fluid Flow, vol. 27, pp. 585-593, 2006.

[8] Working with display screen equipment (DSE). (2013). [online] Health and Safety Executive. Available at: http://www.hse.gov.uk/pubns/indg36.pdf [Accessed 19 Apr. 2016].