University of Exeter coursework header sheet

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

032596

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Coursework: I2

Submission Deadline: Thu 28th Apr 2016 12:00

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Word count:	12591

I2 Report

Wind Farm Modelling

Thomas March

2015

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...

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

I2 Report

ECMM102

Title: An investigation into the effect of different wind directions and turbulence models on CFD simulations for Wind Farms

Word count: 12591

Number of pages: 40

Date of submission: Wednesday, 27 April 2016

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Abstract

This project has been completed as part of a group aim to find sources of power losses in wind farms. The project aims to use an actuator disk model within OpenFOAM to simulate a 20 turbine array over varying conditions. Including changing the wind direction, yaw angle and turbulence models.

The changing wind direction and yaw angles are simulated using a steady-state solver with an O-mesh. The power of the farm is calculated from the simulations and plotted for comparison between the different angles and theoretical data. Three Reynolds-averaged simulation (RAS) turbulence models are evaluated along with LES and DES to find any difference in power prediction. These are compared and recommendations of the most suitable turbulence models are made.

The project finds that simulating yaw angle using a simple actuator disk is not valid. This is due to the method not taking into account any turbine blade geometry. The efficiency of the wind farm can be greatly increased by changing the wind direction. It was also found that DES provides the greatest accuracy without sacrificing computational expense and the most suitable RAS model was the k-ωSST.

The project was not able to find sufficient data to validate the findings. Therefore it is recommended that the work completed for this project is taken further. Firstly to validate the findings and secondly to further evaluate the different wind directions using DES.

Keywords: Wind Farm Modelling, Actuator Disk, LES, DES, Wind Directions

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1. Introduction and background

This project aims to use computational techniques to analyse the wake effects and power outputs of a wind farm over varying conditions. This report outlines the individual project efforts that have been completed as part of the group's aims and objectives. The wind farm that has been simulated as part of this project is a generic 20 turbine farm with rows of 4 turbines. The format was used due to the inability to gain access to real wind farm data and coordinates. The layout of the farm has been chosen due to its high wake to wake interactions without introducing unnecessary complications.

This project has been completed to find out why the actual power output of wind farms are far lower than estimated. It has been stated that the wakes of upstream turbines are causing efficiency losses of 10-20% [1]. The wakes are the most significant causes of power losses for wind farms. The project aims to investigate the discrepancies present within the current techniques used to estimate the wake effects of wind farms.

The project will use an actuator disk (AD) method [2] (as explained within the I1 report) within computational fluid dynamics (CFD) to calculate the power outputs from each turbine within the wind farm. The power is calculated using equations related to the actuator disk method. The CFD will be completed using OpenFOAM an open-source CFD software package. The project compares the results from simulations over different wind directions, yaw angles (the angle at which the turbine face is to the wind direction) and turbulence models in an attempt to find any discrepancies of power when compared with group results.

1.1. *Project Aims*

This section outlines the project aims. This is a list of the tasks that the project aims to complete in order to reach the overall objectives of the individual and group project.

- To use an AD model within OpenFOAM 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 help find where the discrepancies lie within current wind farm evaluation techniques

1.2. Project Objectives

The aims of the project outlined above will be completed using the following objectives:

- Set-up a 20 turbine wind farm incorporating the AD 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 external data found as part of the literature review and values found by other members of the group

1.3. Report Structure

The literature review completed as part of this project will be presented. The review provides a detailed account of the sources evaluated as part of the research for this project, including the key findings from those sources. The method and set-ups of the simulations will then be explained and outlined. Following on from this the results gained from this project will be shown, analysed and any comparisons will be made with external data, as well as comparisons between results found within the project. After the results have been shown, the conclusions will be discussed with any recommendations for future work. The report will conclude with an explanation of the project management techniques, an outline of a project risk assessment and evidence of how this project collaborated with other members of the group with an effort towards achieving the group's overall aims.

2. Literature review

A literature review has been carried out as part of this project. This review follows on from the one previously carried out earlier as part of this project, outlined in the I1 report. The previous review focussed largely on the simulation techniques that have been used so far to analyse the flows through a wind farm. It also focusses on turbulence models that have been used. Some of the sources that were used previously are used again in this review as they are still relevant. The project has become more focussed on particular aims and objectives, and so these topics reviewed include projects that have used different turbulence models, flow directions and yaw angles.

A literature review has been carried out to find previous studies on wind farm flows using

CFD and to identify different methods of analysis to aid decision making. The review will also identify projects that have been completed similar to this one mitigating any risk of overlapping previously completed work. The review is also important as it gives details on how different aims have previously been completed. This provides advice on boundary conditions, solvers and turbulence models that should be used and compared with one another. It can also be used to validate any findings from this project. The review will also find the most recent advances in this area, outlining the most accurate CFD simulations that have been carried out on wind farms.

This literature review will follow a subject structure, and is broken down into different sub-headings outlining different types of information that the papers contain. A paper can spread across different sub-headings if the content is relevant to more than one. A critical analysis of each source is also completed under the final sub-heading of the literature review.

1.1. CFD simulations of wind turbines/farms using an actuator disk

The first section outlines work that has been previously completed whereby an actuator disk has been used to simulate a wind turbine or turbines as part of a farm. This section is to provide an overview of how previous projects have been carried out and to find any relevant data that can be compared with.

The first paper that has been used is a review of the status of using CFD to analyse wind farms. The paper produced by B Sanderse, S P van der Pijl and B Koren in 2011 [3] gives a broad overview of techniques and models used within this field. This paper is relevant to a few different sub-headings within this literature review and so just the information regarding actuator disks will be analysed within this sub section.

The study suggests that the calculation of the thrust coefficient can be an issue when using an AD model. This is because the AD model needs an input of a thrust value for it to accurately simulate a wind turbine however the thrust value changes with the inlet velocity. As the inlet velocities of the turbines will be changing due to the wakes of upstream turbines this value can be very difficult to calculate and input into the simulation. The paper suggests two different techniques to achieve this. The first is based upon finding the velocity of the flow around the turbine. This technique can only be achieved through multiple simulations until the values have converged. Another proposed technique is to use disk averaging and time filtering techniques in an iterative process to find the inlet velocity of each of the turbines. This can only be completed using a time dependent solution and so will also be very time consuming especially for large turbine arrays and refined meshes. Emrah Kulunk [4] provides an alternative technique for calculating the thrust of the turbines, this is done simply by averaging the upstream velocity and the wake velocity to get the velocity through the turbine. This velocity can then be used to calculate the power and thrust provided by the turbine. These techniques all require a high computational cost as they must be completed in an iterative process. A starting value of the thrust will be determined and the technique proposed by Emrah Kulunk will be used for post-processing.

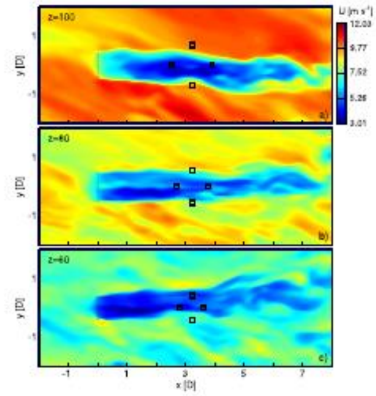
1.2. CFD simulations using LES, DES and RAS turbulence models

This sub section of the literature review is to analyse sources that have used large-eddy simulations (LES) or make comparisons between LES and Reynolds-Averaged Simulation (RAS) models. This is to gain an understanding on what the differences between LES and RAS should be and also to provide data to compare any simulated results with.

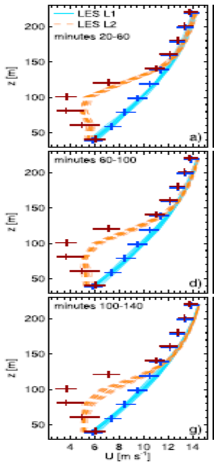
The paper provided by J Mirocha et al [5] gives simulations that use an actuator disk along with LES. The simulations only involve one turbine, so comparisons cannot be made using the whole array, however it can be useful to compare the flow structure of a single turbine. Figure 1 shows the picture produced from this paper of an actuator disk using LES for three different heights, z=80 is at the centre of the turbine.

The wake produced from the actuator disk is meandering, the wake is not steady state and the velocity is different throughout. Figure 1 shows graphs plotted within this paper, the graphs show the velocity profile of the flow upwind and downwind of the turbine where L1 is upwind. These graphs can easily be compared with data found from simulations run as part of this project.

Figure 1: Horizontal cross sections of velocity at three heights above the surface (a) and the velocity profile for a single turbine (b)



(a)

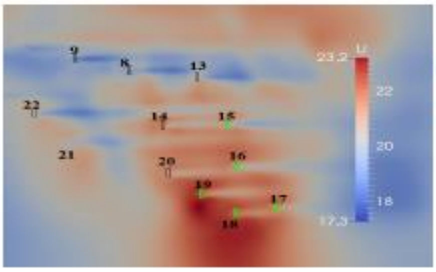


(b)

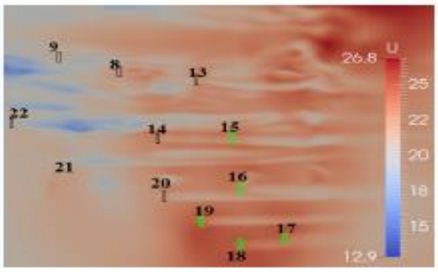
The next source provides a valuable comparison between LES and RAS simulations for wind farms. M Tabib, A Rasheed and T Kvamsdal [6] provide a clear comparison between the turbulence models for an onshore wind farm. The paper simulates the wake effects taking into account the effect of the terrain to calculate the turbine performance throughout the farm. As mentioned the paper provides comparisons between LES and RAS simulations, one comparison found from this paper can be seen in figure 2 which compares the velocity of the different models at a particular time.

Figure 2: A comparison made between RAS and LES for the velocity over the Bessaker wind farm

(a) RAS model



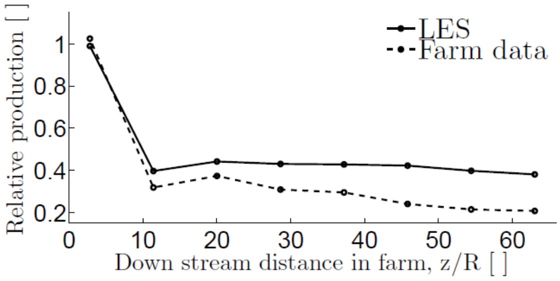
(b) LES model



As can be seen from figure 2 the LES model is expected to have far more rotating flows and the two different models show quite different results. The paper suggests that the RAS model shows between 8-10% more power production than the LES model. There are many other comparisons that are made within this paper including the difference in vorticity, turbulent kinetic energy and streamlines.

The paper provided by O Eriksson, J Lindvall, S-P Breton and S Ivanell [7] gives analysis on the downstream wake at the Lillgrund wind farm located in Sweden. It focusses on the far wake up to distances of 7 km. An actuator disk is used along with LES. This paper uses a weather research and forecasting model to determine the boundary conditions of the simulation, the information that it provides on the calculation and analytical techniques are very limited. The paper can mainly be used for data comparison with the LES simulations.

Figure 3: The relative power production of the Lillgrund wind farm in the seventh column



This study provides data on the relative production of the wind turbines depending on which row they are located in, therefore showing the power losses of the downstream turbines. The graph shown in figure 3 concludes that there are large losses at downstream turbines when compared with the upstream ones. The paper suggests that LES slightly over predicts the power production of the wind farm when comparing the data with the real values. This is interesting as it suggests that RAS models majorly over predicts power production as M Tabib, A Rasheed and T Kvamsdal [6] conclude that RAS models provide an 8-10% increase in power production of LES models.

The review completed by Sanderse B, Pijl S and Koren B [3] provides information on the use of LES and RAS models for simulating the wakes of wind turbines. The review gives advantages and disadvantages to LES over using RAS. The study states that LES can simulate turbulent flows with large-scale eddys more effectively than RAS models. This means that LES will provide a much more accurate simulation but will take far more time to simulate. The review states that the k-ε and k-ω RAS turbulence models result in very diffusive wakes that are not realistic and the velocity drops through the turbines are not sufficient. This is supported by [6] that states the RAS models over predict power production.

This paper suggests that one solution to the issue of the turbulence models is to use DES (Detached Eddy Simulation), which combines LES and RAS together to give a computationally inexpensive but more accurate result.

1.3. Analysing the effect of different yaw angles/flow directions

This sub section of the literature review is required to gain an understanding of the errors that can be found from different yaw angles, and to determine the effect that different flow directions has on the aerodynamics of a wind farm.

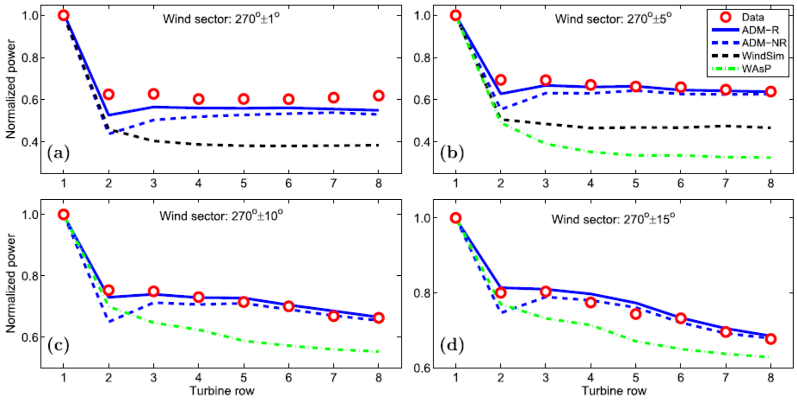
The first source written by Kragh K and Hansen M [8] provides no data to be compared with as simulations were not completed as part of the project. However it is very useful to gain an understanding of the importance of the yaw angle. The paper suggests that when a turbine is not facing the wind it experiences a yaw angle error which means that the production of the wind turbine is limited. The paper gives equations that can be used to calculate the yaw angle error and have been validated against experimental data. The formula for calculating the maximum power output including yaw error can be found below where k has been found experimentally as 1.8, ρ is the density of air, A is the swept area of the rotors, V is the wind speed, θ is the yaw angle and C_P is the coefficient of power.

$$(1)\ P = \frac{1}{2}\rho A(V\cos^k(\theta_E))C_P$$

The study conducted by Y-T Wu and F Porté-Agel [9] simulates the wake and power losses of the Horns Rev wind farm located off the coast of Denmark using LES. The simulations were run over four different wind directions to determine the wake effects while changing the yaw angle so that the turbine is facing in the direction of the wind.

Figure 4 shows the normalized power of each turbine row as the wind direction has changed. ADM-R in the legend refers to an actuator disk model including rotation, ADM-NR refers to one without rotation, WindSim, and WAsP are models that can be used to simulate wake effects. It can be seen from figure 4 that the actuator disk models match up well with the data that has been taken from the wind farm. It is clear that as the wind direction changes the power outputs are less consistent, however more of the turbine rows have a higher power.

Figure 4: A graph to show the effect of changing wind direction on the Horns Rev wind farm



Y-T Wu and F Porté-Agel conclude their study by suggesting that the models are well matched with the real data from Horns Rev wind farm but discrepancies can be found when the acute angles of wind are simulated.

1.4. Recent advances on CFD analysis of wind farms

It is important when carrying out a project to have a prior knowledge of the most recent advances within the field. This section will outline a small selection of examples of recent papers that have been published outlining advances of modelling wind farms.

A recent project has been carried out to design and evaluate a more efficient model of an actuator disk [10]. This study conducted by D Sturge et al. gives an example of a recent model that has been created which is called a hybrid actuator disk. The model combines the standard actuator disk technique with full rotor simulation. It proposes a much more accurate technique for simulating wind farms while not sacrificing computational expense.

There have also recently been advances within optimizing a wind farm using the FLORIS model which predicts the wake effects of the turbines [11]. P Gebraad et al. propose a way of combining optimization techniques, changing the yaw angle of each of the turbines in real time. This changes the angle and dispersion of the wake meaning that the wake effects can be minimized. This paper shows that recent simulations are not just focussing on the wake effects but also on optimizing the farm as the simulation is running.

The final example of recent advances within this field is how the simulations that are being run are introducing much more complicated factors to increase their accuracy for specific wind farms. F Castellani et al. [12] present a case whereby the complex terrain where the turbines are located is simulated. This is to analyse the effect of the undulating ground on the power output of the wind turbines. The terrain is generated using data supplied by supervisory control and data acquisition systems (SCADA). This project shows how the simulations are becoming more complex and introducing factors like terrain that have not been sufficiently simulated previously.

1.5. A critical review of the sources used

A critical review of all of the sources will now be carried out in order of mention. This is to evaluate how useful a source really is, checking whether the data is to be trusted and will be comparable to the point of validation. The final three sources which were used to evaluate the most recent advances in this field will not be critically reviewed as these will not be used further as part of this project.

The first paper that was mentioned within this literature review was a review conducted by Sanderse B, Pijl S and Koren B [3]. This paper was used in a few different sub headings as it provided information across different topics including turbulence modelling and actuator disk modelling. The paper is a review and so very little data is supplied and so there is little to be compared with. It should also be noted that the paper was published in 2011, this means that a lot could have changed in five years and some of the points and conclusions made within this paper may no longer be valid.

The next source to be used was J D Mirocha et al.'s [5] paper investigating near-wake flows of wind turbines using LES and an actuator disk model. This paper can be useful when comparing individual turbines in large arrays, but as the paper only simulates a single turbine the results might not be valid for an array and therefore not be comparable. This paper can be used to compare the form of the wake that the actuator disk produces as the pictures provided will be comparable.

The paper by M Tabib, A Rasheed and T Kvamsdal [6] supplies pictures comparing LES and RAS simulations for a wind farm over rough terrain. As the simulations carried out as part of this project will not take into account rough terrain as it is an offshore wind farm the results will vary when compared to this source. It is important to compare the differences between LES and RAS, this paper can provide some validation for that.

The source by O Eriksson, J Lindvall, S-P Breton and S Ivanell [7] supplied information on the use of actuator disks and LES for the use of analysing the downstream wake effects of wind farms. When comparing data with this paper it is important to realise that the setup of the cases might vary, the turbine layout will be very different and it will have an effect on the results. However the data can still be very useful for making comparisons as the results should follow a similar pattern where downstream turbines produce far less power.

The study conducted by K Kragh and M Hansen [8] gives information on the effect of the yaw alignment on the power production of a wind turbine. The paper also gives equations claiming that they are accurate and validated against experimental results. However these experimental results are not stated and so it cannot be proven that these equations do perform as expected. It is important to realise this when using these calculations as part of this project.

The paper written by Y-T Wu and F Porté-Agel [9] provides data found using LES of the Horns Rev wind farm over different flow directions. This data can be directly compared however it is important to realise that the turbine locations and boundary conditions will be different as they have not been specified within this paper. This means that although the data can be compared, the values found will vary, also the paper suggests that there are discrepancies present in some of the simulations which will affect the data comparisons.

3. Theoretical background and Method

This section will outline how this project was completed. This includes the equations that were used to calculate the power output of the turbines as well as the techniques that were used to analyse the effects of the changing wind directions, yaw angles and the different turbulence models.

For all of the simulations the turbines were positioned in the same way and the sizes of them remained constant. For each simulation 20 turbines were present, they were laid out in a symmetrical pattern consisting of 4 columns and 5 rows. The columns were distanced 500m away from each other with each row 800m apart. This meant that each turbine was 800m downstream from the previous one. These distances were chosen as they are within a standard range of distances at the Rødsand 2 wind farm located off the coast of Denmark. The turbines were also chosen to be 100m in diameter all with consistent thrust and torque values.

As this project contains three main objectives, this section will be split into three different parts, firstly an outline of the power equations as these are used for each section, followed by the set-up of the different flow directions and different yaw angle simulations. The final section will show the set-up of the different turbulence model simulations. These two sections will include how these models were set-up, the generation of the mesh including the mesh convergence study, and finally a description of how these models were evaluated.

3.1. Power Equations

The power, torque and thrust calculations were key to evaluating and setting up the simulations for this project. The power equations were used to evaluate the efficiency of the farm across the different simulations and so is key to the analysis performed within this project.

It is possible to set up control volumes within the simulations. These are virtual boxes whereby the flow in and out of the box is calculated which using the correct power equation can be used effectively. However early on within this project it became clear that this technique, though effective and accurate, is not suitable for the simulations run in this project due to the time consuming nature of this method. The problem with this method is that a control volume must be individually set up for each turbine and each simulation. As there are many turbines within each simulation this technique is too time consuming. This meant that a less time consuming method was necessary.

Unfortunately with a less time consuming method a less accurate result is obtained. It should be noted that the power equations within this project might not be accurate, however they can still be very useful as their relationships can be analysed to good effect. The power equation which was found in the study conducted by Emrah Kulunk [4] is stated below, where U_∞ is the freestream velocity entering the turbine, U_w is the velocity of the wake, and T is the thrust of the turbine.

$$(2)\ P = T\left({U_\infty + U_w}/{2}\right)$$

The equation above gives a far simpler way of calculating the power of each wind turbine as just the inlet and wake velocities need to be calculated during the simulation. The problem lies with finding a way of calculating these velocities. Therefore a decision was made to use probes. Probes calculate the velocity at a given point in the mesh. As it is the velocity in just one cell this value can be very unreliable especially within rotating flows. So three probes were positioned 100m in front of and behind each of the turbines. This was to ensure they were spread across the wake to gather the velocity at three different points. Figure 5 below shows an example of the code used to place the probes so that they gave the velocities as the simulation was running. This code is located within the controlDict of the case. This is the dictionary file whereby many of the necessary input parameters are set to run the simulation. The turbine for this example has a midpoint with coordinates (5750 7300 150).

Figure 5: The code used to position the probes in front of and behind the turbines

```
 Turbine_1
{
    type                          probes;
    functionObjectLibs            ("libsampling.so");
    enabled                       true;
    outputControl                 timeStep;
    outputInterval                100;
    fields
    (
        magU
    );
    probeLocations
    (
        ( 5700   7400 150 )
        ( 5750   7400 150 )
        ( 5800   7400 150 )
        ( 5700   7200 150 )
        ( 5750   7200 150 )
        ( 5800   7200 150 )
    );
}
```

3.2. Different Flow Directions and Yaw Angles

This section will discuss how the different flow directions and yaw angles simulations were set-up. This includes setting up the simulations and boundary conditions, designing and generating the mesh, and finally the method of analysis will be explained.

3.2.1. Simulation Set-Ups

Firstly how the simulations were set-up will be explained. Clearly the set-up of the simulations is one of the most important parts. The set-up must be correct to ensure that the simulations run as expected and they produce accurate and reliable results. Within this section many different simulations were set-up as 7 different wind directions and 6 different yaw angles were simulated. However there are many common parameters between the simulations, including the turbulence parameters, the solver and the boundary conditions used.

Every simulation within this section was run using simpleFoam. SimpleFoam is an OpenFOAM steady state solver. This means that the simulation converges after an amount of iterations, after which the solution is consistent and does not change, therefore the final iteration is the only important value in post-processing.

The mesh is extremely important to the accuracy and efficiency of the simulations, and will be discussed in further detail within the next section. The boundary conditions are necessary for the set-up of the simulation and are determined by the shape of the mesh. As the simulations were run over different flow directions the most suitable mesh was an O-mesh which is in the shape of a circle making it possible to run different flow directions using the same mesh. As the flow direction was changing the inlets and outlets need to self-determine whether the flow is entering or exiting at the boundary. An inletOutlet boundary condition was used, as this boundary condition acts as an inlet if the flow is travelling inside the domain and an outlet when the flow is travelling out of the domain. The base of the mesh was a stationary wall, and the top of the domain travelled in the same direction as the wind.

The magnitude of the velocity of the wind flowing through the domain was decided to be the maximum that a real wind turbine will experience. As real wind turbines cut out at around $13ms^{-1}$ this is the value that was used. To set up the different flow directions different velocity vectors needed to be calculated. As mentioned earlier 7 different flow directions were simulated starting from 0^o and ending at 30^o in 5^o iterations. The different directions were calculated using trigonometry and these values entered into the velocity initial conditions file for the simulations.

These simulation's environmental conditions must be consistent so that they can be compared with each other. This means keeping turbulence conditions consistent over all of the simulations. Turbulence conditions are necessary to predict the random movements of flow when it is turbulent. The k-ε turbulence model is a widely used and very robust model, and this model was suitable as the comparison of results is the most important thing.

To use the k-ε turbulence model, values for k and ε need to be specified beforehand, and the method of calculating these values can be found at CFD-online.com [13]. How to calculate k and epsilon is shown below where U is the velocity, Re is the Reynolds number, L is the inlet height and C_μ is a turbulence constant with a value of 0.09.

$$(4)\ k = \frac{3}{2}(UI)^2$$

$$(5)\ I = 0.016Re^{\frac{-1}{8}}$$

$$(6)\ \varepsilon = C_\mu \frac{k^{3/2}}{0.07L}$$

Combining equations 4 and 5 gives a value for k and equation 6 gives a value for ε. Inputting the values into these equations gives a value of 0.121 for k and 0.000494 for ε.

As mentioned in the previous section of this report, the power is calculated using 3 probes either side of the turbine. It is necessary to change the position of these probes depending on the flow direction so that they are placed in the wake of the turbines in each of the simulations. This is done using the equations found below. These equations were found online [14] and proved to be accurate. Xr and Yr are the rotated coordinates, Xc and Yc are the centre points, and θ is the angle at which the coordinates are rotated by.

$$(7)\ Xr = Xc + \cos(\theta) \times (X - Xc) - \sin(\theta) \times (Y - Yc)$$

$$(8)\ Yr = Yc + \sin(\theta) \times (X - Xc) + \cos(\theta) \times (Y - Yc)$$

To achieve analysis over different wind directions and yaw angles, simulations were run where the wind direction was altered but the turbine positions remained constant. This gave different yaw angles. To simulate different wind directions whereby the yaw angle is kept at 0^{o}, the turbine positions needed to be altered so that they faced the wind direction, this was done using the equations above also.

3.2.2. Mesh Generation and Convergence Study

The mesh is one of the most important factors of an accurate and robust simulation. As discussed earlier the most suitable mesh for this application was an O-mesh. The mesh was created in Pointwise meshing software for CFD, this mesh can be seen in figure 6.

Figure 6: The mesh generated to use for the different flow direction simulations

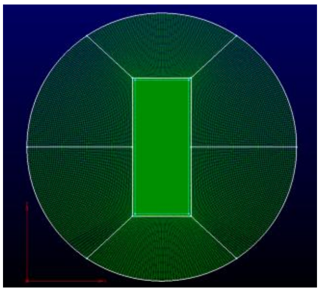
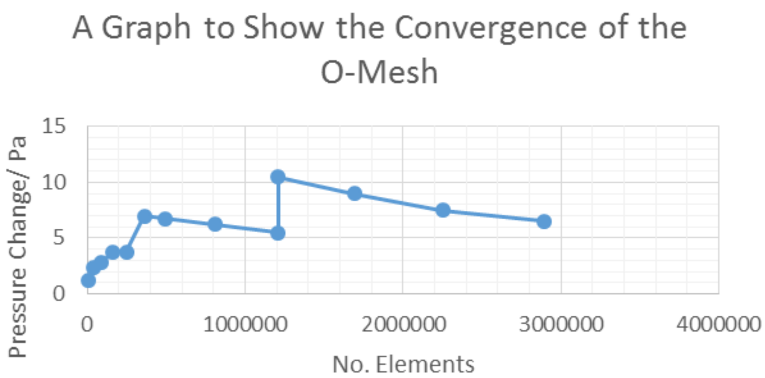


Figure 6 shows the mesh that will go through the mesh convergence study. The boundaries of the mesh are curved so that different flow directions can be specified using the same mesh. The most important part of the mesh is at the centre as this is the region for refinement therefore this is where the turbines were placed.

It is important for a mesh to go through a mesh convergence study to find an accurate mesh that is not too computationally expensive. A mesh convergence study is where simulations are run and a particular result is taken. This result changes as the mesh becomes more refined, however the result converges to a point when the mesh becomes refined enough. The mesh convergence study completed for these simulations was run with one turbine, and the pressure change across the turbine was taken as the data to compare with over the different meshes. The graph that shows the results of the mesh convergence study can be seen below.

Figure 7: A graph to show the convergence of pressure as the number of cells increases



The graph above shows a very strange mesh convergence. This is because the depth of the turbine has to be spread over more than one cell which meant that as the mesh was very coarse the turbine had to be far deeper. After each time that the turbine was made less deep the pressure change was altered and this can be seen at 250000 and 1210000 elements. At 1210000 elements the turbine was made 10m deep instead of 20m. It can be concluded from the mesh convergence study that the turbine that is 20m deep converges after 1210000 elements and the turbine that is 10m deep converges at more than twice that. It was then sensible to suggest a mesh containing 1210000 elements with a turbine depth of 20m was suitable for the simulations.

3.2.3. Method of Analysis

The analysis of these simulations is very important as it will be unknown whether the results gained from the simulations will be reliable and accurate. The results gathered from the simulations will be compared with the external data found as part of the literature review. The results will also be compared with other group member's results from similar situations. Their results were gathered through the use of wake models.

The power equations mentioned earlier within this report will be analysed using a spreadsheet. The creation of the spreadsheet is a very important part as each simulation contains 600 pieces of data. The spreadsheet will plot a chart and a graph. The chart will compare the total average power output of all of the turbines for each wind angle and the graph will compare the power output of each row. This will then provide a conclusion on the effect of changing the wind direction for the wind farm.

The calculated yaw angle error using equation (1) will be plotted using the power values obtained for a yaw angle of 0^{o}. These values will then be compared with the values that are obtained through the simulations of different yaw angles. This will give analysis on the effect of changing the yaw angle of the turbines and will prove whether the actuator disks are valid for changing yaw angles.

3.3. Different Turbulence Models

3.3.1. Simulation Set-Ups

The general set-up for these simulations was very similar to the different wind direction simulations stated in the previous section. The wind speed was equal to $13ms^{-1}$ again and so the calculation of k and epsilon were the same. The inlet and outlet boundary condition was similarly set-up however the shape of the mesh was different. Due to these simulations having a consistent wind direction the O-mesh was no longer needed, therefore a simpler cuboidal shaped mesh was more suitable. As the mesh was cuboidal, side walls were now present. These walls will have no effect on the flow and so they were classed as slip walls.

The simulations needed to be set-up as similarly as possible so that fair comparisons can be made between the different turbulence models. As LES and DES were used a transient solver was needed. PimpleFoam was used as it is a robust, transient solver. The actuator disk solver is a steady-state solver using simpleFoam so it needed to be altered to work with pimpleFoam. This involved combining the actuator disk solver with the pimpleFoam solver and compiling the new transient actuator disk solver.

As was mentioned previously these simulation set-ups were very similar to the previous section using the same inlet, outlet, bottom wall, top wall and turbulence parameters. However the different turbulence models needed to be set-up in slightly different ways. The k-ε model did not need any alteration over the different flow direction simulations and to use the RNGk-ε model the only change was that this model was specified in the RASProperties file, where the Reynolds averaged simulation turbulence model is specified. To use the k-ωSST turbulence model, the model again needs to be specified in the RASProperties file and also the value of ω must be calculated. This is done by dividing ε by k (ω=ε/k) which have been calculated previously in this report. The value of ω for this simulation was found to be 0.00408.

LES and DES is set-up in a slightly different way. Firstly LESmodel must be stated within the turbulenceProperties file to state that an LES model is being used. This tells the solver to look in the LESProperties file where the LES model is stated. Smagorinsky was the LES model specified in the LESProperties file and spalartAllmarasDDES was the DES model specified similarly in the same file.

A very important value when using transient solvers is the courant number. The courant number must be equal to or less than 1, as this makes sure that fluid does not travel through more than one cell over a single time step. The courant number formula is stated below and determines the size of the time step necessary to run the transient simulation where V is the velocity, t is the time step and x is the cell size.

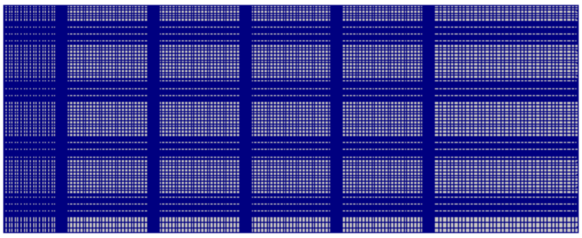
$$(9)\ C = \frac{V\Delta t}{\Delta x}$$

The next section will outline the mesh generation for these simulations and the mesh convergence study, once the final mesh was chosen the courant number could be calculated and the time step for these simulations chosen.

3.3.2. Mesh Generation and Convergence Study

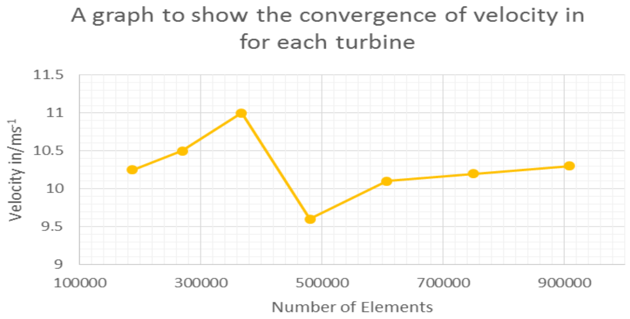
As mentioned previously, the generation of the mesh for the comparison between different turbulence models was far simpler than the O-mesh. This was because it was not necessary to create an O-mesh and so a cuboidal shape was sufficient. To view sufficient wakes of the final turbines the mesh needed to be 5000m long, and to fit all of the turbines, 2000m wide. It was extremely important to make use of refinement regions for this project. Refinement regions are areas of the mesh where the cell density is higher than other areas, as these areas can be placed in important areas for analysis and can cut down on simulation time. As the most important areas of the simulation were at the turbines and down the wake of the turbines these were the areas that needed to be refined.

Figure 8: An above view of the mesh used for the turbulence model simulations



The mesh was created in blockMesh which is a meshing utility that is built in to OpenFOAM, as can be seen in figure 8 (the wind will be flowing left to right). It is known that when using LES and DES, as the mesh refines, the result tends towards direct numerical simulation therefore a mesh convergence study was not strictly possible or necessary. A mesh refinement study was performed anyway, because the mesh needed to remain consistent throughout all of the comparisons. This meant a mesh needed to be sensibly chosen. A mesh refinement study gives a suitable mesh for the simulations and this mesh was used over all of the different turbulence models. The simulations for this refinement have been run using the k-ε turbulence model, simulating all 20 turbines within the mesh. The value that converged was the inlet velocity of a turbine in the final row. The graph showing the mesh convergence can be seen below.

Figure 9: A graph to show the change in velocity with number of elements



From the graph above after 600000 elements the value of velocity changes by very small amounts showing that the solution is converging to around $10.3ms^{-1}$. From the mesh convergence it can be concluded that the mesh of 900000 elements was suitable for these simulations.

Now that the mesh has been generated it was possible to calculate the courant number for these simulations. Using equation (9) the time step must be less than or equal to 1.4, so a time step of 1 was suitable for these simulations.

3.3.3. Method of Analysis

These simulations will be validated in a similar way to the different flow direction simulations and they will be compared with external pieces of data and also data collected from other members of the group. The same spreadsheet will be used to calculate the power output of the farms and a graph will be drawn for each simulation showing the power output from each of the turbine rows for each turbulence model. A chart will also be drawn comparing the average power output from the turbines for each of the turbulence models. Conclusions can then be drawn from these charts and graphs to find the most suitable turbulence model for simulating a wind farm.

The velocity plots will also be compared between the different turbulence models to show the major differences between them.

4. Presentation of results and analysis

This section will outline the results that were gathered through the completion of this project including both the different flow direction simulations and different turbulence model simulations. Firstly the results for the different flow directions and yaw angles will be shown.

This will be followed by the analysis of the simulations including comparisons with external data and theoretical calculations.

Following this, the results for the different turbulence models will be shown including some examples of the power distribution over the farm. These models will then be analysed again comparing the results with external data and also comparing them with each other.

4.1. Different flow directions and yaw angles

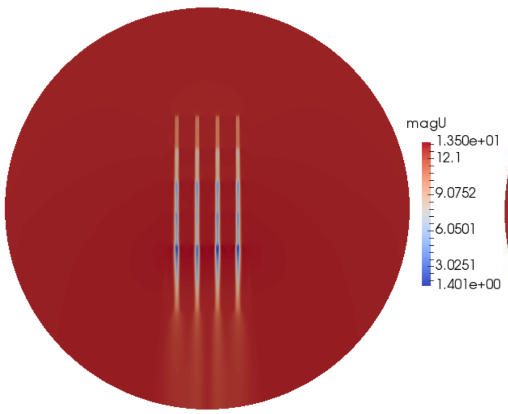
The results for the different flow directions and yaw angles will firstly be shown. This will include pictures of the velocity across the farm over different wind directions and will show a small selection of the power distribution over the farm. Following this, the simulations will be analysed, firstly comparing the different yaw angles to the theoretical calculations to determine validity, and then comparing the simulations with external data and analysing the effect of the changing wind direction.

4.1.1. Results

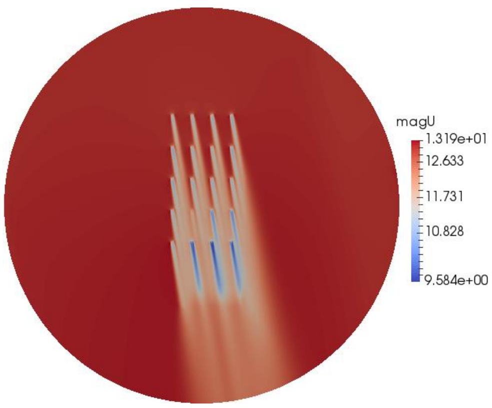
A selection of different figures that show the velocity throughout the farm will be shown. This includes four of the seven different flow directions and three of the different yaw angles. This is due to the figures looking largely the same and will give a broader outlook of the simulations run. Firstly the velocity of the different flow directions for 0, 10, 20 and 30 degrees will be shown in figure 10 and the different yaw angles 5, 15 and 25 in figure 11. For the different wind directions the turbine is kept facing the direction of the wind, whereas for the different yaw angles the turbines are always facing the same way.

Figure 10: The velocity of the flow throughout the farm for different wind directions

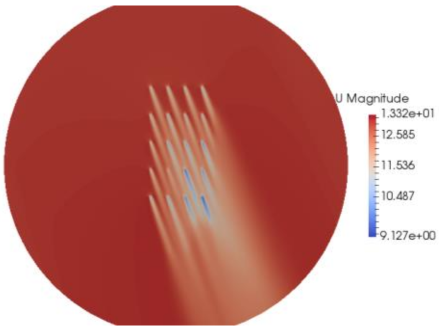
0 degrees



10 degrees



20 degrees



30 degrees

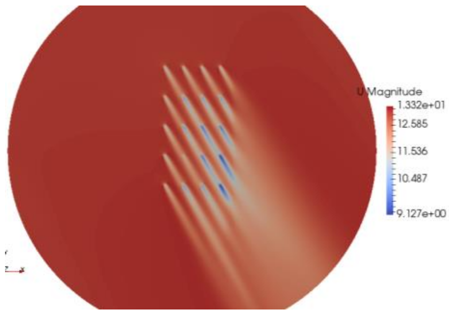
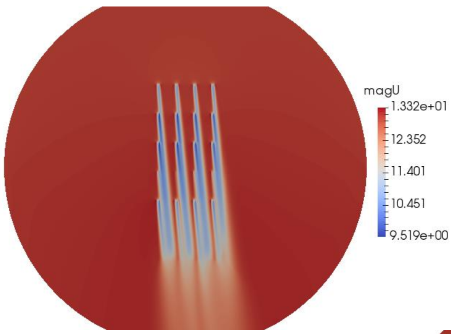
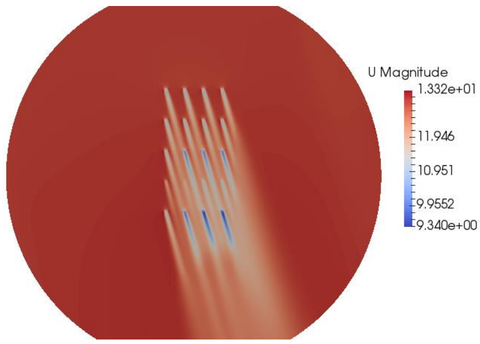


Figure 11: The velocity of the flow over different yaw angles

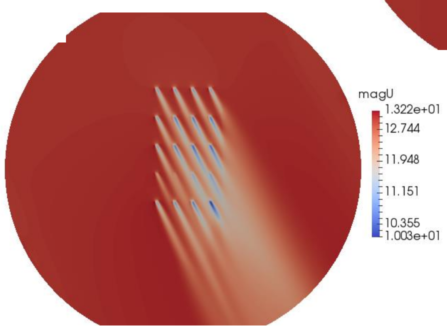
5 Degrees



15 Degrees



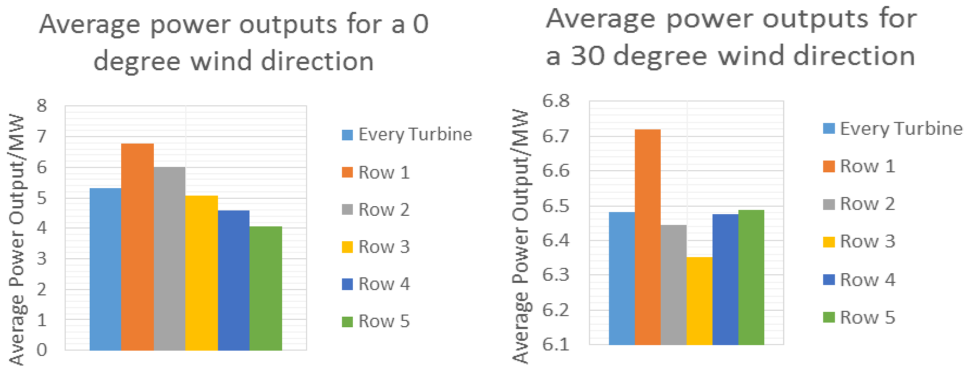
25 Degrees



From the above figures the red areas depict faster flow and the blue represents slower flow, therefore the wakes of the turbines can be seen in the blue areas of the figures. The layout of the turbines can be seen when viewing figure 10 at 0 degrees. Each time the flow slows a turbine is present, and this can be seen 20 times within that figure.

When inputting the data that was collected from the probes during these simulations into the spreadsheet many graphs and charts were created. The most valuable chart for these simulations shows the average power output of each of the rows as well as the total power output therefore this chart was created for every simulation run. Figure 12 shows the chart used for the 0 degree simulation and the 30 degree simulation where the yaw angle is equal to zero.

Figure 12: Two charts to show the average power output of the rows for a 0 and 30 degree wind direction



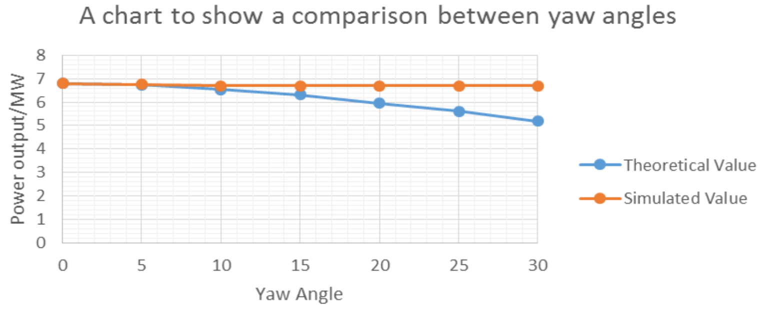
Unfortunately due to the volume of results and figures that were gained during these simulations not all of them can be shown within this report, however the most important and relevant figures have been shown and will be analysed.

4.1.2. Analysis

Firstly it is important to prove whether changing the yaw angle of the turbines within these simulations is valid. Clearly with a real life turbine the yaw angle will have a large effect as the blades are designed so that they are most efficient when they are facing the wind. An AD does not factor in any blade geometry and it just extracts energy from the flow and so it is unknown whether changing the yaw angle has any effect on the power extracted from the flow by the AD.

Equation (1) gives a theoretical method of calculating the power of wind turbines as the yaw angle changes. The angles simulated as part of this project start from 0^{o} finishing at 30^{o} in 5^{o} increments. The theoretical effect of the different yaw angles has been calculated using the values of power found from a 0^{o} yaw angle and these values are then compared graphically with the values found from applying a different yaw angle within the simulations. This graph can be seen below in figure 13; the power produced is the average of all the turbines.

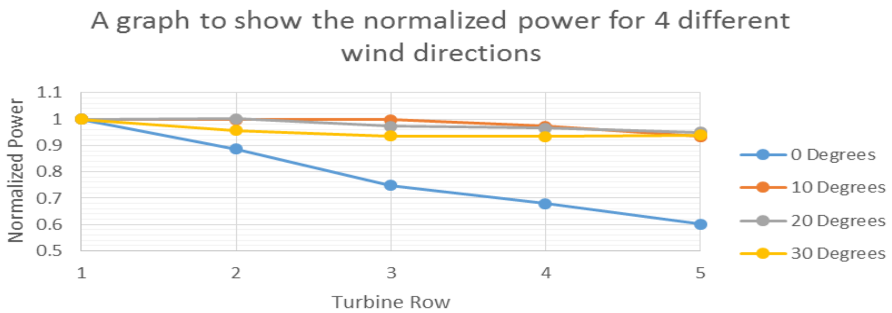
Figure 13: A graph to show the comparison between the theoretical and simulated effect of a changing yaw angle



The theoretical value plotted in figure 13 shows to be very realistic. As the yaw angle increases, the power decreases further each time. Figure 13 shows that the simulated value of the power does not change with yaw angle. This definitely does not represent what happens in reality and therefore it can be concluded that changing the yaw angle using an AD is not valid. This is due to the AD not taking into account any blade geometry, it just calculates an energy loss from the flow using set calculations. The only way that the yaw angle could be valid using an AD would be to set the yaw angle error within the programme, so that when the AD detects a yaw angle, it corrects its power to account for this. The yaw angle simulations will not be taken any further within this project as they are not valid.

Now that the changing yaw angles have been evaluated the simulations whereby the wind direction changes but the yaw angles stay consistent must also be validated. This is a very difficult task as there is very little data that these simulations can be validated against. Figure 3 and figure 4 are both graphs that can be used to compare the changing wind direction results with. They show the power distribution over the farm row by row. Figure 14 below shows the power production of the farm row by row in terms of the normalized power. The normalized power is the power of the rows as a factor of the first row, so the first row must always be equal to 1.

Figure 14: A graph to show the power distribution of the farm over changing wind directions



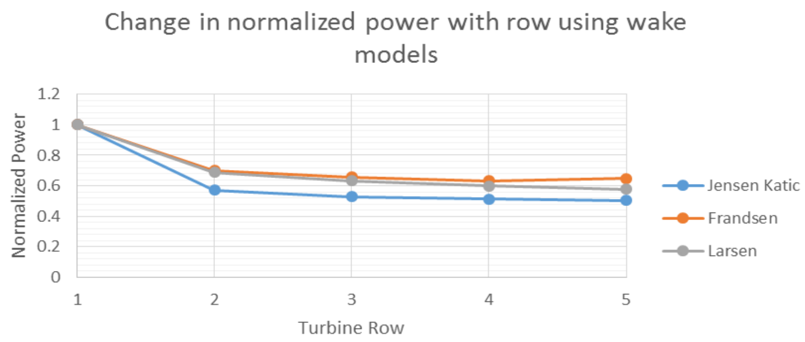
When comparing figure 14 at 0^{o} with figure 3 the values are quite different. Figure 3 shows a much lower power production at the second row of turbines and then the power production levels off with the rest of the turbines producing similar amounts of power. Figure 14 shows that at 0^{o} the power production lessens the further downstream the turbine is. This can be seen as realistic because the wake becomes more pronounced the more turbines it has flowed through. The difference between the two graphs could be down to many different factors, including different turbine layouts, torque and thrust values. Most importantly figure 3 is data collected from LES simulations and these values are clearly going to differ significantly from a simulation running the k-ε turbulence model.

Figure 4 shows the effect of changing the wind direction at the Horns Rev wind farm. The graphs show that actually as the wind direction changes the overall power production increases. This is also true with the simulations run as part of this project. Figure 14 shows that when the wind direction is not at 0^{o} all of the rows produce similar amounts of power. This is not necessarily true for each turbine but, as at least one turbine from each row receives clean air, the power production is far more evenly distributed. Again the values are different from figure 4 but, similar to when comparing with figure 3 many parameters are unknown and so it is likely that the simulations will differ.

It is clear that the power produced when the wind is travelling at 0^{o} is less than when it is at an angle due to the wakes of the upstream turbines having a much larger effect. This can be seen in figures 10 and 11 illustrating when there is an angle to the flow, the number of turbines that a wake affects is less.

This project has run alongside the group project and has involved a lot of interaction between the group members. One key interaction between the member's projects is the ability to make comparisons between results. The main results that can be compared with this project are provided by Ben Withams [15] as their results have been found using different techniques, but are directly comparable as the environmental conditions and turbine positions are consistent with this project. Graphs for comparison can be seen below.

Figure 15: Graphs to show normalized power of the wind farm using different wake models and wind directions [15]



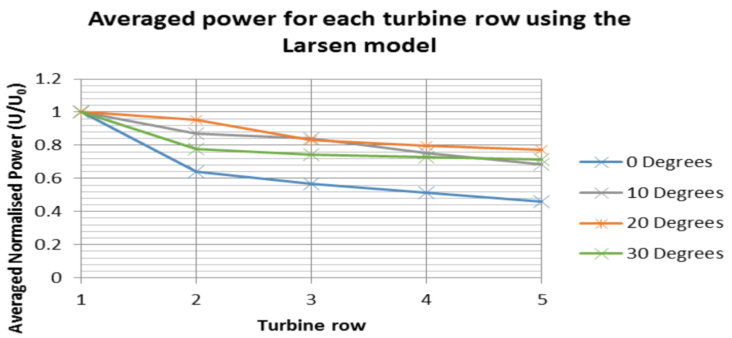
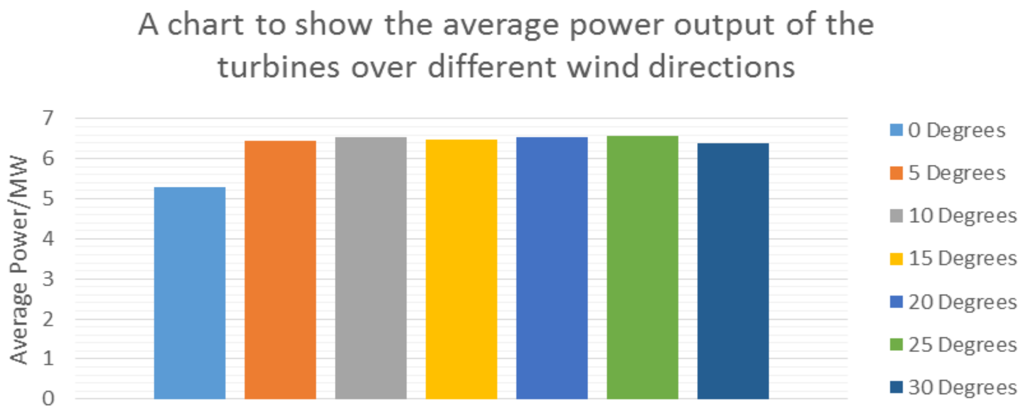


Figure 15 shows graphs produced from results gathered by Ben Withams. The first graph shows the normalized power of each of the turbine rows using different wake models. The wind direction is at 0 degrees without any yaw angle error. This graph can be compared with figure 14 at 0 degrees. There are some similarities here including how the power clearly drops from the first row. However how quickly the power drops is different between the two graphs. Figure 14 shows that the power drop is much less sudden, and the power keeps slowly dropping through the turbine rows. Whereas figure 15 shows that the power drop is sudden but after row 1 the power output of the rows stays consistent.

The second graph in figure 15 shows the normalized power across the farm over different wind directions. This is directly comparable with figure 14. When comparing with figure 14 it can be concluded that the two agree that the least efficient wind angle is at 0^{o}. However the results differ for the other angles. Figure 15 shows that the power still lessens considerably through the farm whereas figure 14 shows that this does not happen to quite that extent.

The final chart (figure 16) that has been created shows the average power of each of the turbines for the different wind directions. This gives an answer to which is the most efficient angle at which the wind is directed. This essentially gives the most efficient array out of the 7 that were simulated as the turbines could be set out permanently as if the wind was directed in a particular direction.

Figure 16: A chart to show the average power output of each wind turbine over different wind directions



The chart above shows that when the wind is travelling at 0^o the efficiency of the farm is at its worst whereas the rest of the angles show much the same result with just slight variations. This outcome is due to the high wake interactions with downstream turbines due to how they were laid out. This chart shows that as long as the turbines are not directly behind one another the result will be quite similar for 20 turbines arranged within this area. It can be concluded that if the turbines were laid out across a wider area the power output would be much larger due to less downstream turbines.

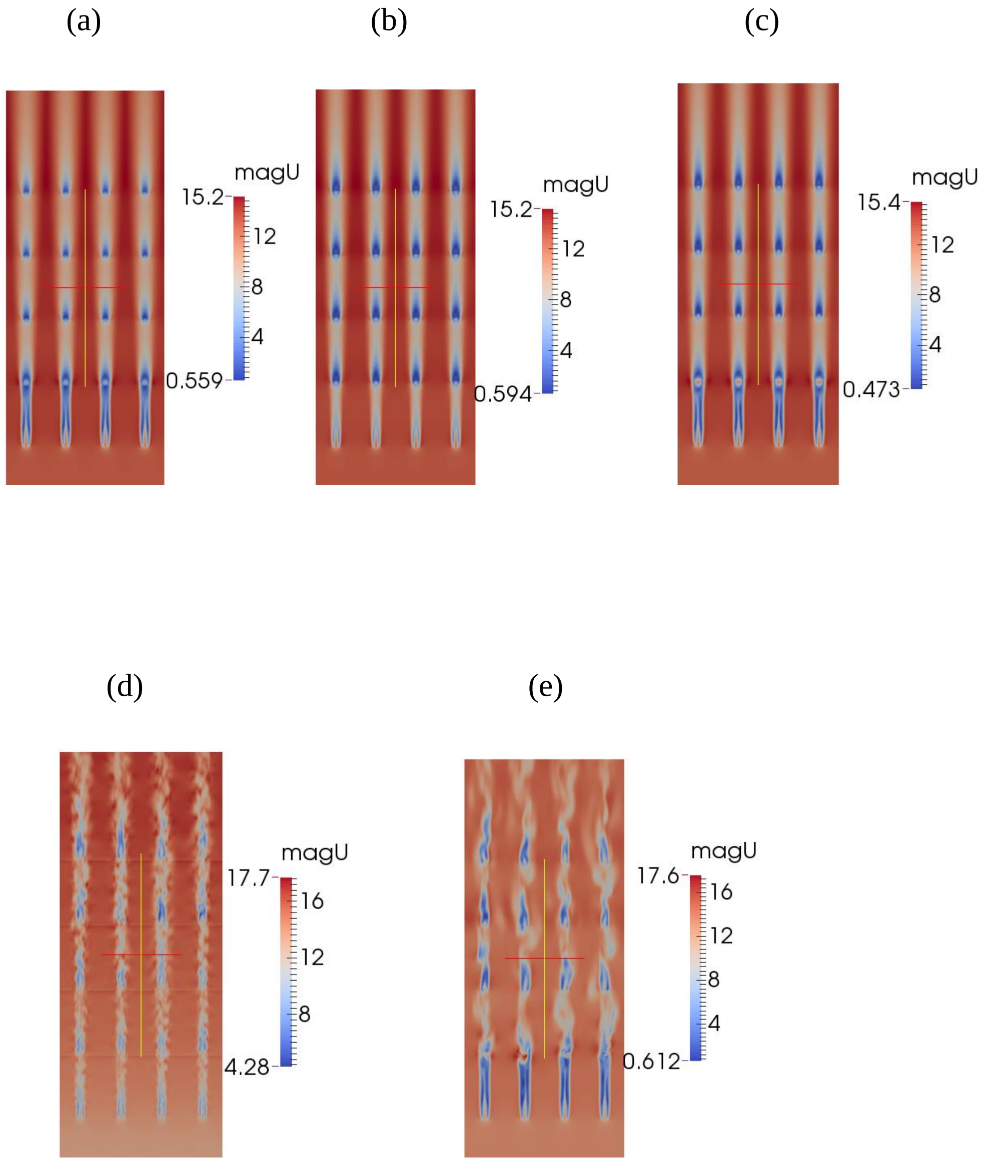
4.2. Different turbulence models

This section will be structured similarly to the previous, firstly showing the results that were gathered from the different turbulence model simulations. Following this, the results will be compared with external data and analysed to find the advantages and disadvantages of each of the models.

4.2.1. Results

The results shown will be the velocity plots throughout the domain, the turbines are laid out the same as within the different flow direction simulations with the direction of the wind being kept at 0^o for all of the simulations. It is important to note that the wind is flowing from bottom to top, not top to bottom for these simulations. Figure 17 shows all of the different turbulence models after 1000 iterations.

Figure 17: The velocity throughout the domain for the different turbulence models



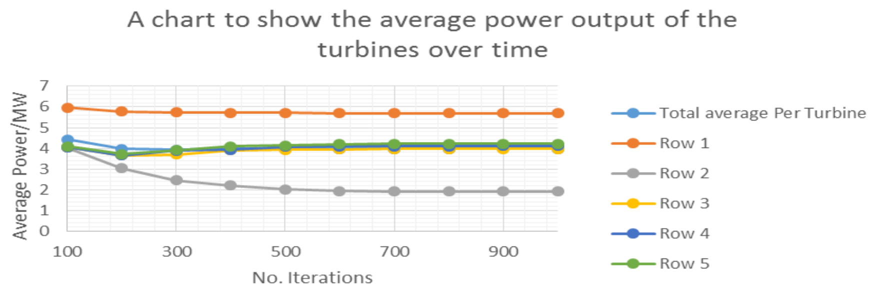
(a)= k-ε model, (b)= k-ωSST model, (c)= RNGk-ε model, (d)= smagorinsky (LES) model, (e)= spalartAllmarasDDES (DES) model

Figure 17 shows many very clear differences between running the different turbulence models. Briefly the LES shows much clearer, more complex flows in the wakes of the turbines and these wakes are actually flowing slightly faster than within the other models.

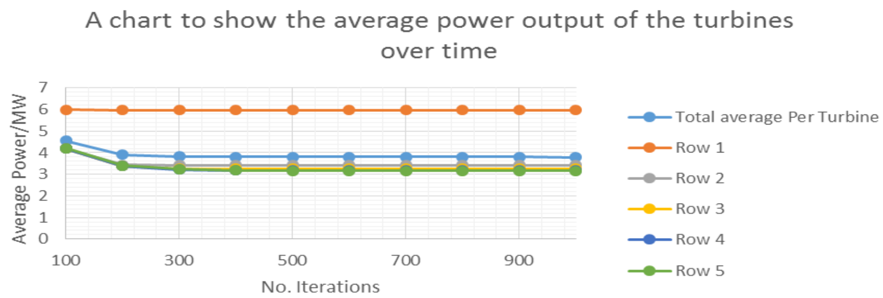
Graphs that show how the power output of the rows change with time will now be shown. These graphs are important in understanding how the flow develops for each of the different turbulence models.

<u>Figure 18: Graphs to show the power of the wind farm over time for the turbulence models</u>

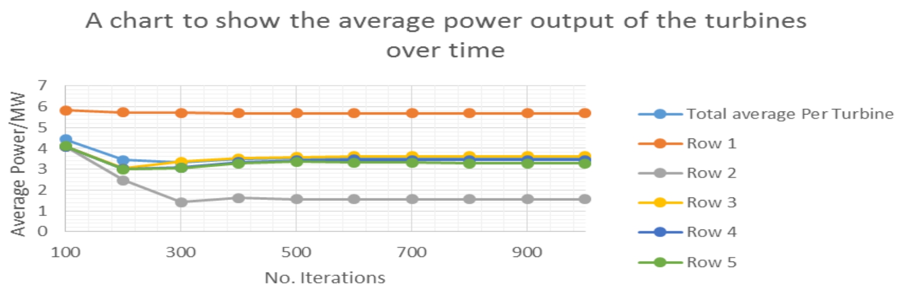
<u>k-ε Model</u>



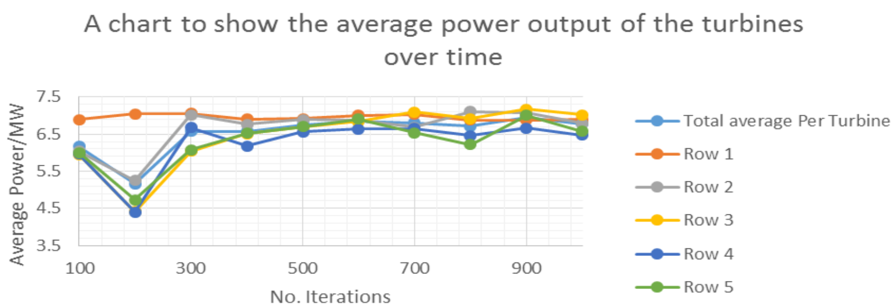
<u>k-ωSST Model</u>



<u>RNGk-ε Model</u>



<u>Smagorinsky (LES) Model</u>



SpalartAllmarasDDES (DES) Model

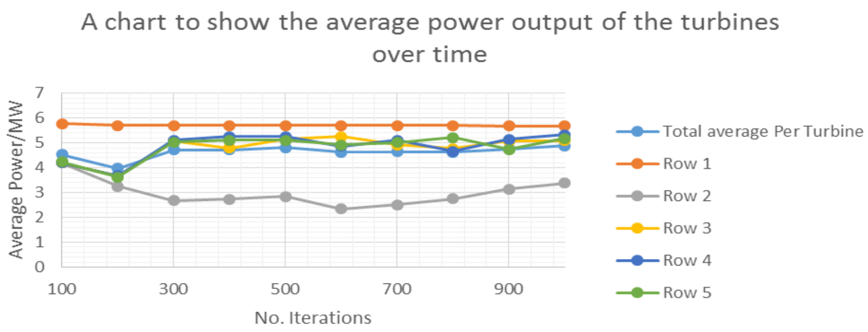
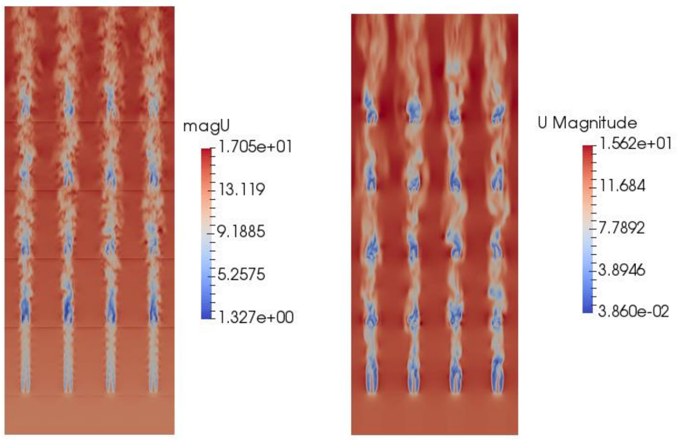


Figure 18 shows that the RAS models converge after 300 iterations however LES and DES do not. The k-ωSST and LES model show that each of the rows downstream from the first produce consistently less power however the rest of the models show row 2 produces the least.

It was clear when completing this project that the LES and DES simulations were the most interesting. The mesh density is also more crucial for these models so it was decided that these would be taken further, improving the mesh for each one. Figure 19 below shows simulations run for the LES and DES turbulence models with much more refined meshes. This will give a greater understanding of the advantages and disadvantages of each.

Figure 19: The velocity across the domain for the LES (left) and DES (right) models



The difference between the simulations in figure 17 and these simulations especially with the DES is quite considerable. These results will be key to analysing the difference between the models and which is the most suitable. The next section will analyse the results that have been shown here.

4.2.2. Analysis

Similar to the different flow direction simulations these simulations will be compared with external data in order to validate the findings and identify the differences. The turbulence models will then be compared with each other using the velocity figures above and also using graphs that show the distribution of power over the wind farm for the different turbulence models. Also the average power of the turbines will be compared.

Firstly all of the simulations can be compared with figure 3 within this report because they are all set up in the same way and so can all be fairly compared. The normalized power of the farm for all of the turbulence models is shown below in figure 20. This graph will show the change in power for each of the rows when compared with the first row.

Figure 20: A graph to show the normalized power of farms for different turbulence models

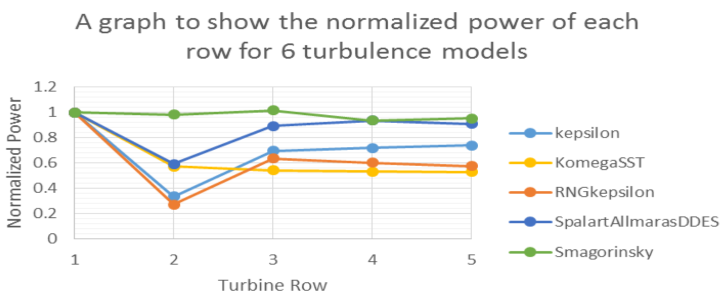


Figure 20 shows quite a difference from figure 3. Each of the turbulence models obtain different values and some propose different patterns of power distribution. The Smagorinsky (LES) model declares very little variation in power between all of the rows. This is very different when compared with figure 3 where the power is highest at row 1 and falls to around 0.4 for each of the following turbines. The other turbulence model that does not follow a similar pattern to the others is the k-ωSST turbulence model which follows a very similar pattern to figure 3. The only difference is that the power values are slightly higher making this very interesting as it is the only one that follows the pattern proposed by figure 3 which is a simulation completed using LES. The k-ε and RNGk-ε turbulence models show very similar patterns and values. The power output of row two is far less than any of the other rows. After this the power stays at around 70% of row 1 for the standard k-ε model and around 60% of row 1 for the RNGk-ε model. The spalartAllmarasDDES model also shows this pattern but with less of a power drop from row 1. Figure 17 shows why this happens. It is because the wake of the first row of turbines enters the second row perfectly. This supplies the second row of turbines with the most concentrated wake, after this the wakes are more spread and recover far more efficiently. This is present on the k-ε and DES models.

The LES results for these simulations can be compared with figures 1 and 2. Figure 1 shows the flow pattern off a turbine using LES and the velocity profile of the flow. The velocity profile of an upstream turbine can be seen in figure 21. The flow off the turbine looks slightly different within figure 1a when compared with the LES in figure 19 which shows much more rotating flows. Figure 1a looks far more similar to the downstream turbines of the DES simulations.

Figure 21: A graph to show the velocity profile upstream and downstream of the turbine

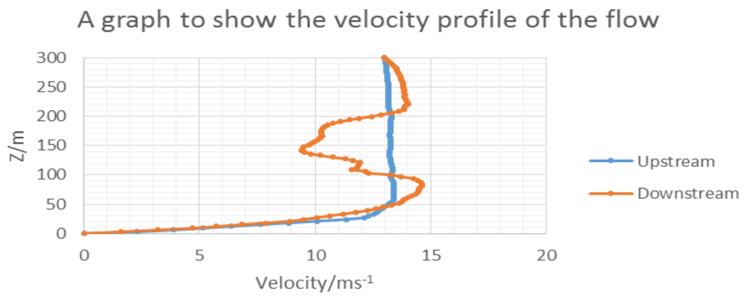


Figure 21 shows a lot of agreement with figure 1b as it shows that downstream from the turbine the velocity is a lot slower. The differences come around as the data within figure 1b takes into account the boundary layer effects, whereas these simulations do not. The comparison between the velocity profiles go a long way towards validating the LES simulations run for this project.

The simulations have been compared with external data and provide some quite different results, but this could be down to many factors including turbine layout and environmental effects. It is difficult to know how the simulations were set up for the external data. Without any real data from a real wind farm it is very difficult to validate these simulations.

The different turbulence model results can also be compared with the data found by Ben Withams [15]. Figure 15 shows the power distribution of the farm using different wake models. This can be compared with figure 20. Figure 20 shows that the k-ωSST turbulence model follows the power distribution of the wake models used in figure 15 extremely closely. There is very little different between them. This is not true for the other models however which show very different results. The rest of the turbulence models show some power recovery after the second row. This is something that is not present within figure 15.

The results from this section of the project can now be compared, evaluating each of the turbulence models. A chart has been created that can be used to compare the different turbulence models. Figure 22 shows the comparison between the turbulence models with respect to the average power output of the turbines.

Figure 22: A chart to show the average power of the turbines across the different turbulence models

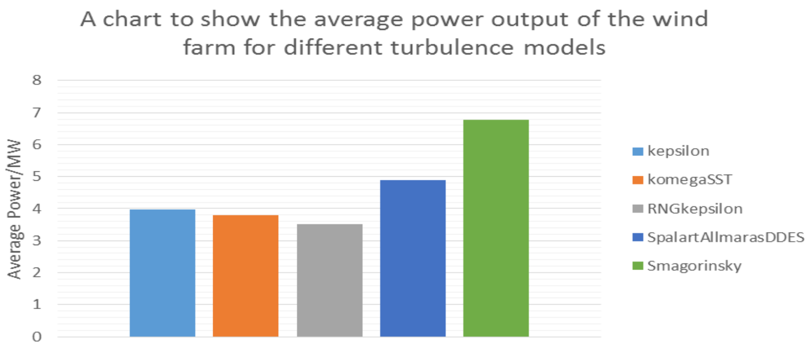
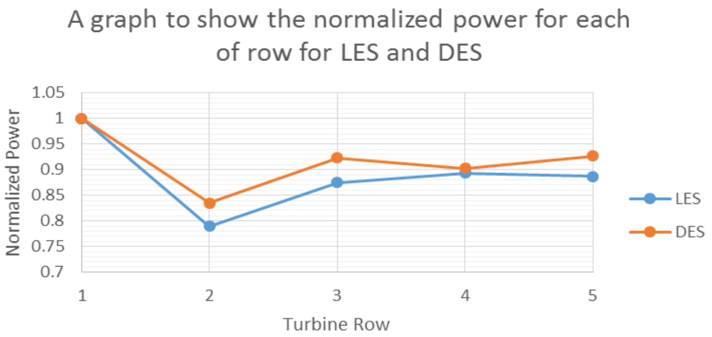


Figure 22 shows that the Smagorinsky (LES) model produces the most amount of power. This is very different to a statement made in the study conducted by M Tabib, A Rasheed and T Kvamsdal [6] who suggest that the RAS models produce around 10% more power than the LES. These simulations show that for this wind farm the LES actually produces between 41% and 48% more power than the RAS models and 28% more power than the DES simulation. The cause of this difference is most likely the layout of the turbines. It is possible that with a different layout the results would be much different. As with the LES simulations the wakes are distributed far wider and so if the turbines weren't directly behind each other the wakes could build up. Whereas the RAS model wakes are not as wide therefore if the turbines were not directly behind each other it is unlikely that they would affect the downstream turbines.

When it comes to which model is most suitable it is a matter of what the preference of the user is. Clearly figure 17 shows the LES model to have the most information on the complex flows and therefore is most likely to be the most accurate, however the LES simulation took around 10 times longer to run than the others. DES gives a lot more information on the flow than the RAS models without needing the extra time for the simulations. This gives the LES and DES advantages for different simulations. It is clear from the research conducted for this project that the RAS models are not accurate, however from the k-ωSST simulations it can be suggested that the normalized power of the farm is accurate when compared with simulations using LES. This suggests that the k-ωSST model is the most appropriate RAS model.

To properly analyse the suitability of the LES and DES models a finer mesh is needed. This is because these simulations will be more accurate with finer meshes and so unlike the RAS models the results will change considerably. Extra simulations were run to compare these two models and the velocity throughout the domain of the farm from these simulations can be seen in figure 19. These simulations immediately show to be very different from the previous ones (figure 17). The DES especially shows far more complex flows and it starts to gain far more similarities to the LES simulations. Again the LES proved to be very time consuming taking considerably more time to run.

Figure 23: A graph to show the normalized power of the turbine rows for LES and DES



Again a graph has been drawn to compare the normalized power of the turbine rows. Figure 23 shows that the lines follow each other very closely. The results for normalized power for DES match LES very well even though DES takes considerably far less time. However the normalized power does not tell the whole story as this is not raw power. The values of power are quite different from each other. The LES simulation produces an average turbine power of 5.9MW whereas the DES simulation calculates this value to be 4.57MW. This value is far closer than with the previous simulations as it is a difference of 23% compared with 28%. It is apparent from these simulations that DES provides a far more accurate representation of the flow compared with simulations run with RAS modelling. It does not add the extra computational expense that LES does. However LES is still the more accurate and true representation of the flow of a wind farm.

5. Discussion and conclusions

This individual project has been completed alongside a group project whereby the findings link with other group members and are part of a progression towards the overall aims of the group project. This project has studied the effects of changing environmental conditions on a wind farm's power output using Computational Fluid Dynamics. This has included changing the wind direction of the simulations, the yaw angle of the turbines, and evaluating a range of different turbulence models.

The main aims of this project were to use the actuator disk techniques within OpenFOAM to evaluate the effect of changing the wind direction on a wind farm's power output, evaluate the effect of changing the yaw angle of a wind turbine and to evaluate different turbulence models to find the most suitable. These aims are a part of the overall group aim which is to find areas at which the power output of wind farms is being over-estimated.

The simulations for changing the wind direction and yaw angle were performed using simpleFoam which is a steady-state OpenFOAM solver. The wind was altered from 0 to 30 degrees in 5 degree increments. The turbines were laid out in 5 straight rows and 4 straight columns to make a total of 20 turbines being simulated. The mesh used was an O-mesh which gave the possibility of changing the wind direction without having to generate new meshes. The main findings for this section of the report are listed below:

- The actuator disk solver is valid for different flow directions
- Simulating yaw angle is not possible using an actuator disk
- Positioning turbines directly behind one another has a significant impact on power output
- The power output is greatly improved if the turbines are not positioned directly behind one another (up to 20% greater power output at 20^{o} wind direction)

The second part of this project evaluates different turbulence models. Similar to the first part of the project the turbines are laid out in the same structure of rows and columns. However for these simulations the wind direction was unchanged. A version of pimpleFoam was used as the solver for these simulations as this transient solver was necessary for the evaluation of LES and DES. The mesh this time was not an O-mesh, it was a rectangular mesh that included areas of refinement where the wake and turbines would be present. The turbulence models included in the study were the standard k-ε, RNGk-ε, k-ωSST, smagorinsky (LES) and spalartAllmarasDDES models .The main findings for this section are listed as follows:

- LES and DES show more complex flows than the RAS simulations
- The RAS models show a far smaller power output than LES and DES
- This is contradictory of research completed in the literature review

- This contradiction could be due to the different wake dispersion characteristics
- The k-ωSST turbulence model is the most suitable RAS model
- LES is much more detailed than DES but is not worth the extra computational expense

The findings of the project have been significant in understanding where the discrepancies in turbine power output estimation lie. Just by changing the wind direction the power could be increased by as much as 20% and by changing the turbulence model this value could be up to 48%. However this project came across issues in validation and accuracy, these problems have been detailed as follows:

- The power equation used might not be accurate enough
- Difficult to validate the findings within this project as there is very little data to compare to
- Many of the results are different to expected, this could be down to simulation set-up or errors within the power calculation

These problems have been significant, however it is possible that some of the problems lie within the different set-up of simulations when compared with external data.

This project can be taken further, adjustments can be made to simulations to increase accuracy and validity and more in depth research can be completed to further evaluate a changing wind direction and other environmental factors. The further recommendations are listed as follows:

- Design a more accurate technique for calculating the power output of the turbines using more probes or redesigning the technique entirely
- Evaluate different wind directions further through the use of the k-ωSST turbulence model, LES and DES

By acting on these further recommendations more accurate, validated and significant findings can be produced.

The final two sections of this report will outline the project management techniques that were utilised, how this project linked with the group project and how the project contributed to the functioning of the group.

6. Project management techniques and risk assessment

Project management techniques have been utilised through the completion of the project. These techniques are essential to successfully completing a project as they ensure that the work is completed on time, any risks are mitigated and the group functions efficiently together. This section will outline each of the management techniques that were utilised throughout this project including an illustration of the Gantt chart and project risk assessment.

It is important to understand any health and safety guidelines through the completion of any project. However this project only involved the analysis of wind farms using computational techniques and so it was only necessary to consider the health and safety guidelines for office work. The same goes for sustainability, no materials were used consumed for this project and so sustainability issues were not incurred.

A logbook was kept for the duration of the project. This was used to take notes during meetings as well as key down important information. A logbook ensures that any important information is not lost or forgotten. Weekly group meetings were set-up and the responsibility of chair and secretary was rotated. This ensured that members of the group did not fall behind and were given help with any problems that they had.

6.1. Risk Assessment

Table 1: Project risk assessment

Risk	**Effect**	**Cause**	**L**	**S**	**I**	**Action**
Long simulation run time	Project overrunning	Unnecessarily complicated simulations	7	6	42	Make use of mesh refinement regions and cloud computing
No LiDAR data to compare with	Little data to compare the simulations	Not receiving data from outside source	9	3	27	Work does not rely on this data through the generation of a generic turbine
Loss of data through corruption	Project overrunning	Corrupted files with no backup	4	10	40	Use an external hard-drive to back up data

Table 1 above shows the risks associated with the project, the columns L and S are likelihood and severity respectively, these two columns are giving a value out of 10, 10 being the most likely/severe. The "I" column is importance which is found by multiplying L and S. From the table it can be seen that long simulation run times is the highest risk. This can lead to the project overrunning and not all of the simulations being completed in time. The next most important risk is loss of data which is a big risk in a project that is relying on computational results whereby all data is stored computationally. However this risk is quite unlikely and can be mitigated easily by backing up all data. The final risk which is not having any LiDAR data to compare the simulations with is the least important risk. This project does not rely so heavily on having that data as simulations can still be run comparing different aspects of wind farms with a generic layout.

As seen from the risk assessment the most important risk for this project is long simulation run times. This means that the time management is extremely important to mitigate any risk of overrunning. One way of ensuring good time management is through the use of a Gantt chart. The Gantt chart is a way of planning all of the aims of the project and giving them a time frame so that it is possible to keep track of how the project is progressing. The Gantt chart is shown below at the end of this report in figure 24, it is a continuation of the one found in I1 with slight changes where the project has evolved.

7. Contribution to group functioning

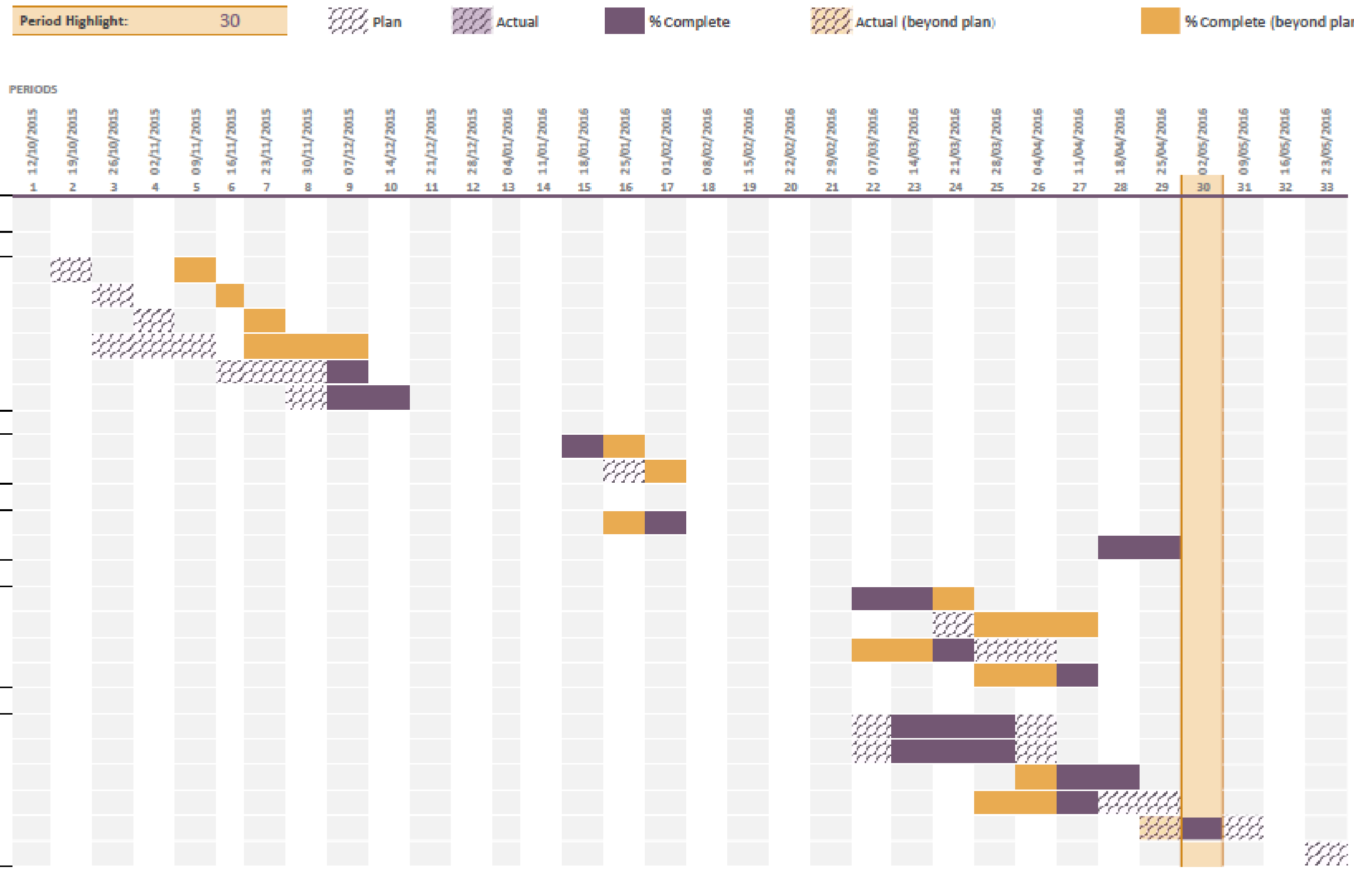
The group met weekly to discuss project matters, these meetings were run by a chair and the minutes taken by a secretary. The roles of chair and secretary were rotated on a weekly basis. These meetings were useful for discussing any work that other members needed help completing and any data that can be used to compare.

This project has strived towards achieving the goals of the group project. The aims of the group were to evaluate current techniques for the power prediction of wind farms and to develop improved techniques. This project has helped to evaluate the suitability of using an actuator disk for modelling a wind farm; it has also given recommendations on suitable turbulence models.

This project has been compared to other group members' work to investigate any differences. Although the results cannot be validated fully the comparisons made are still significant and conclusions can be drawn from them.

Figure 24: Gantt Chart used throughout the project

Gantt Chart



ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Individual Objectives					
Term 1 - Initial Model					
Complete Research	2	1	5	1	100%
Write Literature Review	3	1	6	1	100%
Evaluate Computational Techniques	4	1	7	1	100%
Create Initial Farm Model	3	3	7	3	100%
Complete Analysis on Initial Model	6	4	9	1	100%
Write I1 Report	8	3	9	2	100%
Term 2 - Completion of Farm Model					
Improve Farm Model	15	1	15	2	100%
Complete Farm Model	16	1	17	1	100%
Term 2 - Validation of Model					
Research Data to Compare Model Against	17	1	16	2	100%
Complete Comparison and Analysis	28	2	28	2	100%
Term 2 - Testing of Model					
Run Model Over a Selection of Wind Directions	22	2	22	3	100%
Plot Data and Complete Analysis	24	1	25	3	100%
Run Different Turbulence Models	24	3	22	3	100%
Plot Data and Complete Analysis	27	1	25	3	100%
Term 2/3 - Report Preperation and Completion					
I2 Report Preperation	22	5	23	3	100%
G2 Report Preperation	22	5	23	3	100%
Complete Section of G2 Report	27	2	26	3	100%
Complete I2 Report	27	3	25	3	100%
Design and Complete Poster	30	2	30		25%
Poster Presentation	33	1			0%

References

1. van der Laan M, Sørensen N, Réthoré P, Mann J, Kelly M, Troldborg N. The k - ε - f P model applied to double wind turbine wakes using different actuator disk force methods.*Wind Energ*. 2014;18(12):2223-2240. doi:10.1002/we.1816.

2. Svenning, E. (2010). Implementation of an actuator disk in OpenFOAM

3. Sanderse B, Pijl S, Koren B. Review of computational fluid dynamics for wind turbine wake aerodynamics.*Wind Energ*. 2011;14(7):799-819. doi:10.1002/we.458.

4. Emrah Kulunk (2011). Aerodynamics of Wind Turbines, Fundamental and Advanced Topics in Wind Power, Dr.Rupp Carriveau (Ed.), ISBN: 978-953-307-508-2, InTech, Available from:http://www.intechopen.com/books/fundamental-and-advanced-topics-in-wind-power/aerodynamics-of-wind-turbines

5. Mirocha J, Rajewski D, Marjanovic N et al. Investigating wind turbine impacts on near-wake flow using profiling lidar data and large-eddy simulations with an actuator disk model. *J Renewable Sustainable Energy*. 2015;7(4):043143. doi:10.1063/1.4928873.

6. Tabib M, Rasheed A, Kvamsdal T. LES and RANS simulation of onshore Bessaker wind farm: analysing terrain and wake effects on wind farm performance. *J Phys: Conf Ser*. 2015;625:012032. doi:10.1088/1742-6596/625/1/012032.

7. Eriksson O, Lindvall J, Breton S, Ivanell S. Wake downstream of the Lillgrund wind farm - A Comparison between LES using the actuator disc method and a Wind farm Parametrization in WRF. *J Phys: Conf Ser*. 2015;625:012028. doi:10.1088/1742-6596/625/1/012028.

8. Kragh K, Hansen M. Potential of power gain with improved yaw alignment. *Wind Energ*. 2014;18(6):979-989. doi:10.1002/we.1739.

9. Wu Y, Porté-Agel F. Modeling turbine wakes and power losses within a wind farm using LES: An application to the Horns Rev offshore wind farm. *Renewable Energy*. 2015;75:945-955. doi:10.1016/j.renene.2014.06.019.

10. Sturge D, Sobotta D, Howell R, While A, Lou J. A hybrid actuator disc – Full rotor CFD methodology for modelling the effects of wind turbine wake interactions on performance. *Renewable Energy*. 2015;80:525-537. doi:10.1016/j.renene.2015.02.053.

11. Gebraad P, Teeuwisse F, van Wingerden J et al. Wind plant power optimization through yaw control using a parametric model for wake effects-a CFD simulation study. *Wind Energ*. 2014;19(1):95-114. doi:10.1002/we.1822.

12. Castellani F, Astolfi D, Burlando M, Terzi L. Numerical modelling for wind farm operational assessment in complex terrain. *Journal of Wind Engineering and Industrial Aerodynamics*. 2015;147:320-329. doi:10.1016/j.jweia.2015.07.016.

13. Turbulence free-stream boundary conditions -- CFD-Wiki, the free CFD reference. Cfd-onlinecom. 2016. Available at: http://www.cfd-online.com/Wiki/Turbulence_free-stream_boundary_conditions. Accessed March 30, 2016.

14. benn:org » Rotating coordinates around a centre. Bennorg. 2016. Available at: http://benn.org/2007/01/06/rotating-coordinates-around-a-centre/. Accessed March 30, 2016.

15. Withams B. Investigating and validating current wake models for use in creating a Mathematical Model to predict power output and optimise the layout of Offshore Wind Farm Arrays 2016