Final report

1. Project details

Project title	WAKEBENCH3
File no.	64019-0573
Name of the funding scheme	EUDP
Project managing company / institution	DTU Wind Energy
CVR number (central business register)	30 06 09 46
Project partners	
Submission date	05 April 2022

2. Summary

Summary in English:

This project supports the participation of DTU Wind Energy in the IEA Task 31: WAKEBENCH phase 3: International Wind Farm Flow Modelling and Evaluation Framework. The overall objective of the project is to improve the numerical models, which are used in connection with simulations of wind farm flows, as well as to establish guidelines for how to use these models. Furthermore, it is to develop a framework for verification and validation (V&V) and uncertainty quantification (UQ). In practice, these objectives are achieved by benchmarking model results against high quality experimental data. DTU has participated in several benchmark cases and thereby pushed the model capabilities towards handling increasingly complex flow cases including interaction of atmospheric flow with complex terrain and vegetation and modelling of wakes at different atmospheric stabilities. Some of the benchmark cases are ongoing but many of the results from the comparisons are also already published in peer reviewed articles and/or has been presented at different conferences. Besides participating in the benchmarking activities, DTU has also worked on preparing a new benchmark case based on data from the Westermost Rogh wind farm to be used for validating offshore wind farm models. Although these activities did lead to the definition of a new benchmark case within this project, the data from the wind farm was still qualified and stored in a database to allow easy access to the data. DTU is planning to use the database together with preliminary simulations to establish a new high quality benchmark case for a offshore wind farm of large wind turbines.

Opsummering på dansk:

Dette projekt støtter op om DTU Vindergis deltagelse i IEA-Task 31: WAKEBENCH fase 3: International Vindmølleparkmodellering og Evalueringsramme. Det overordnede formål med projektet er at forbedre de modeller, der bruges i forbindelse med simulering af vindmøllepark-flow samt at etablere guidelines for hvordan disse modeller skal bruges. Desuden har projektet som mål at udvikle et rammeværktøj for verificering og validering (V&V) og usikkerhedskvantificering (UQ). I praksis er projektmålene opnået ved at sammenligne modelresultater med højkvalitetsmålinger. DTU har deltaget i adskillige sammenligningsstudier og har dermed forbedret modellernes evne til at håndtere mere komplekse flowscenarier inklusiv interaktion mellem det atmosfæriske grænselag og komplekst terræn og/eller vegetation samt modellering af wakes under forskellig atmosfærisk stabilitet. Nogle af studierne er stadig i gang mens resultaterne fra andre allerede er publicerede i fagfællebedømte artikler og/eller er præsenteret ved diverse konferencer. Ud over deltagelse i sammenligningsstudierne, har DTU også arbejdet på at forberede en ny benchmark case baseret på data fra Westermost Rough vindmølleparken. En endelig benchmark case er endnu ikke blevet defineret, men DTU har formået at kvalificere data fra vindmølleparken og gemme det i en database og dermed gøre det let tilgængeligt. DTU planlægger at bruge databasen til at definere en ny højkvalitets benchmark case for en offshore vindmøllepark bestående af store vindmøller.

3. Project objectives

The objective of this project is via participation in the third phase of IEA-Task 31 WAKEBENCH, to improve the numerical models, which are used in connection with simulations of wind farm flows, as well as to establish guidelines for how to use these models. Furthermore, it is to develop a framework for verification and validation (V&V) and uncertainty quantification (UQ).

4. Project implementation

Due to the COVID-19 situation, the project did not evolve exactly as expected. The main impact of the COVID-19 outbreak was that all the planned meetings and workshops had to take place online. The online meeting turned out to be quite good substitutes for the in-person meetings when it comes to knowledge sharing and presentation of results but of course are not as good for discussions, planning and networking. Another consequence of the COVID-19 situation was that the Wind Energy Conference 2020 was cancelled and therefore DTU could unfortunately not present the project results there as planned. However, the Torque, WESC and Wake conferences took place online and therefore the project results could still be disseminated to a broader audience at these conferences as originally planned.

Except for the above described setbacks, the project developed more or less according to planned and DTU realized most of the objectives of the project and milestones as outlined in the next section.

5. Project results

DTU has contributed with a significant amount of activities and publications during the project period and has thereby achieved most of the project objectives and milestones as listed below:

- In fulfilment of milestone M1 and deliverable D1, DTU has delivered results with two different models to the benchmark case ALEX17, which deals with the interaction of the atmospheric boundary layer with complex terrain during a diurnal cycle. The results has been published in a peer reviewed article (https://iopscience.iop.org/article/10.1088/1742-6596/1934/1/012002) in accordance to deliverable D5.
- DTU has contributed with simulation results using two different models to the SWiFT benchmark case, which deals with wake flow under different atmospheric stratification and thereby fulfil milestone M2 and deliverable D2. Besides the results of the benchmark case has been published in a peer reviewed journal article (http://dx.doi.org/10.1002/we.2543) and thereby DTU attain deliverable D6.
- In partial fulfilment of milestone M3, DTU has processed and qualified data from the Westermost Rough wind farm and made it available in a database (https://gitlab.windenergy.dtu.dk/fair-data/winddata-revamp/winddata-documentation/-/blob/master/NDAs/WMR.md).
- DTU has fulfilled milestone M4 and partially attained deliverable D5 by contributing to the industry driven benchmark case on IEC-61400-12-4 numerical site calibration in complex terrain. The work is ongoing and DTU is going to submit more simulation results in connection with this benchmark but a presentation of the initial comparison was given at a mini-symposium at the WESC conference and at the online annual meeting in May 2021 (https://www.youtube.com/watch?v=L_OTrQG6YvY).
- DTU has contributed with simulation results to the ongoing Hornamossen benchmark case, which deals with a diurnal cycle over a heterogeneous forested area in complex terrain. The initial results from the benchmark was presented at a mini-symposium at the WESC conference and at the online annual meeting in May 2021 (https://www.youtube.com/watch?v=L_OTrQG6YvY)
- DTU has in fulfilment of deliverable D7 together with the other IEA-Task 31 members contributed to the Wind Energy Model Evaluation Protocol (WEMEP) including open-source model evaluation scripts as actionable best practice guidelines
- DTU has published a journal article about the global trends in the performance of large wind farms, which is based on high-fidelity simulations conducted as part of previous benchmark cases defined in the IEA-Task 31 WAKEBENCH (https://wes.copernicus.org/articles/5/1689/2020/wes-5-1689-2020.pdf)
- DTU has developed a complexified version of the aero-elastic solver Flex5, which can be used together with the flow solver EllipSys3D to perform wake simulations with uncertainty quantification as well as for optimization

From the above listing, it is clear that DTU achieved most of the goals of the project. However, milestone M5 and deliverable D4, in which DTU was supposed to perform simulations and deliver results for a second benchmark case for wake models were unfortunately not obtained. At project start, it was expected that a second benchmark from the SWiFT facility with a focus on the wake of a turbine operating in yaw would be released by other members of the IEA-Task 31. However, this case has not been released yet and therefore DTU instead engaged in an additional benchmark on external wind conditions (the numerical site calibration case). According to the original plan (deliverable D8), DTU was also supposed to contribute to a joint white paper about wind farm flow modelling. However, DTU and the other members of the IEA-Task 31 were not able to finalize this paper within the project period but it is still the aim to finalize it in the future. At the end of the project period, a discussion was initiated about using such a paper to reframe the next phase of IEA-Task 31 (phase IV) towards more industry adaption.

DTU has participated in the following meetings and conferences where the work related to the WAKEBENCH project has been disseminated:

- IEA Task 31 meeting, June 17, 2020 (took place online)
- Torque conference, September 28 – October 2, 2020 (took place online)
- IEA Task 31 annual meeting, May 12, 2021 (took place online)
- WESC conference, May 25-28, 2021 (took place online)

- Wake conference, June 15-17, 2021 (took place online)

As described in section 4, the COVID-19 situation blocked for all in-person meetings and therefore all meetings had to take place online. Fortunately, most of the conferences and events managed to carry through online and therefore the project results could be disseminated to stakeholders from both the Danish and international wind energy industry and research institutes. An exception was the Wind Energy Conference 2020, which as mentioned above unfortunately was cancelled.

In the following, some of the main technological results from DTU's contributions are presented. For more details please consult the references and the project website https://thewindvaneblog.com/ in which the different benchmark cases are described.

Figure 1 and 2 show representative results from the SWiFT benchmark case in which 13 different models were used to simulate the wake of a turbine at different atmospheric stratifications and the results were compared to experimental data obtained by a lidar installed at the nacelle of the turbine. DTU contributed with both LES predictions (LES-EllipSys) and two different RANS models (RANS-EllipSys-ABL,RANS-EllipSys-MOST).

Figure 1 compares the numerical and measured wake predictions in the case of neutral stratification. The figure reveals a fairly large spread among the model predictions, which in part is explained by differences in the inflow, which turned out to be hard to reproduce. Nevertheless, the models predict quite well the recovery of the wake.

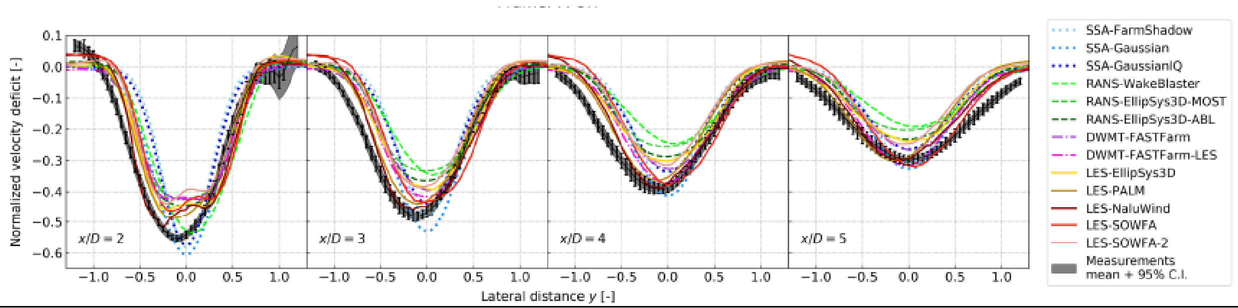

Figure 1: Comparison of measured and simulated wake deficit at neutral conditions. Results from [2].

To give a quantitative insight into the agreement between model predictions and measurements, Figure 2 shows the normalized difference norm, divided into the following model categories listed in ascending order of fidelity: Steady-state analytical (SSA), Reynols Averaged Navier-Stokes (RANS), Dynamic Wake Meandering Type (DWMT) and Large Eddy Simulations (LES). In neutral conditions, it is seen that the models with the highest level of fidelity as expected agrees better with the measurements than the lower fidelity models. For the stable and unstable cases, the lower fidelity RANS models on the other hand turned out to be more accurate. This was surprising but can be explained by the fact that these models more easily allow prescribing non-canonical inflow conditions and because their lower computational costs allow repeating simulations when necessary.

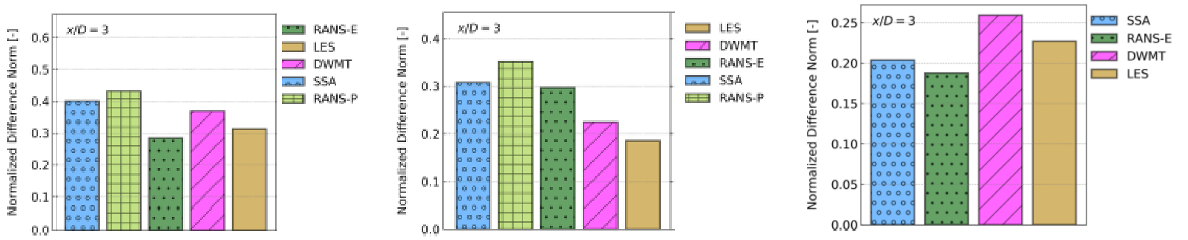

Figure 2: Normalized difference norm between simulated and measured wake profiles at 3D. Left) Stable, Middle) Neutral; Right) Unstable. Results from [2].

Figure 3 shows the average power production of the turbines in the Westermost Rough offshore wind farm, which is located about 8 km east of the Holderness coast in England. The data is extracted from the database which has been established by DTU. A challenge in extracting power performance data from the wind farm was that the undisturbed inflow conditions has not been measured and therefore had to be derived from the power and pitch settings of the front row of turbines. Figure 3 indicates that the derived equivalent wind speed is reasonable with a clear increase in power with wind speed below rated and a fairly constant (close to rated) power production at and above rated wind speed. Besides, Figure 3 clearly shows drops in the average power production when the wind direction is aligned with the wind turbine rows (150 and 330 degrees).

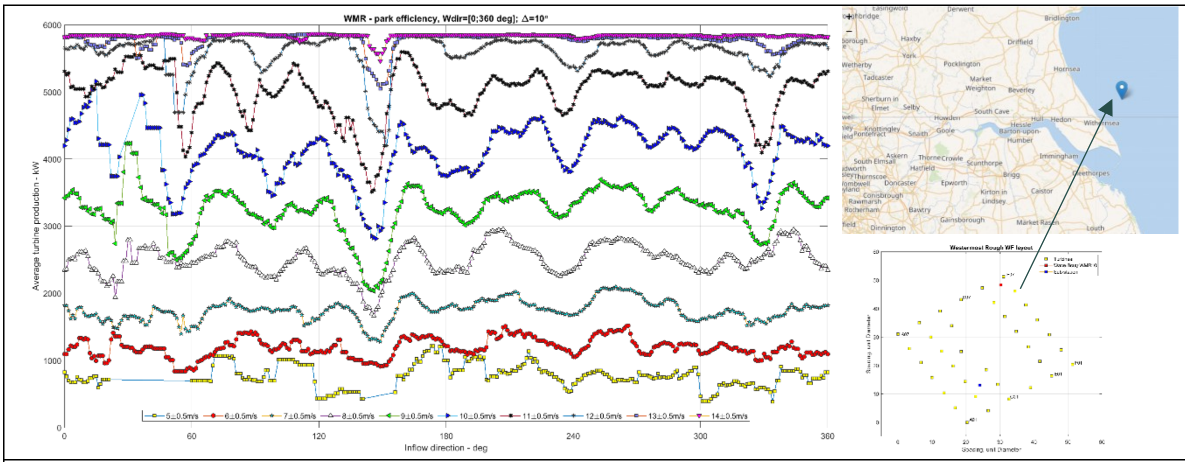

Figure 3: Average turbine production as a function of wind direction. Data from [5]

Figure 4-5 show representative plots from the ALEX17 benchmark case in which DTU participated with two different models both based on the Navier-Stokes solver EllipSys3D). This test case deals with diurnal cycles over complex terrain and involves coupling of meso and micro-meteorological models, where the tendencies from the meso-scale models are used to drive the micro-scale models. Figure 4 shows an elevation map of the considered very complex site with indication of the positions where meteorological masts were installed to measure the wind conditions. Figure 5 shows the bin averaged vertical wind speed profiles at stable conditions. As seen the coupled models does a good job in correction the meso-scale input model bias (purple line) towards achieving better agreement with the measurements. Overall, the study showed that by using only meso-scale modeling, the wind speed was overestimated by 32% but that by coupling with micro-scale models, this bias could be reduced to below 5% - a significant improvement. The comparison in the stable case showed better agreement than the corresponding comparisons in the neutral and unstable cases. This was a surprise because stable cases, due to the smaller turbulence scales and lower boundary layer heights, normally are the most difficult cases to simulate – at least for flat terrain. However, in complex terrain the flow scales are also highly governed by the terrain, which could explain why the model perform relatively well in stable conditions for the ALEX17 case. The study also highlighted that it may be problematic to use periodic boundary conditions because this approach may recirculate topographic waves. In the site calibration benchmark case, DTU saw the same issue and is currently working on mitigating this issue by using bigger simulation domains.

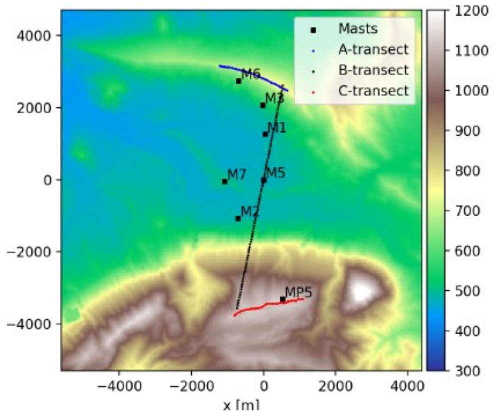

Figure 4: Evaluation map from the ALEX17 site with indication of mast positions. From [1].

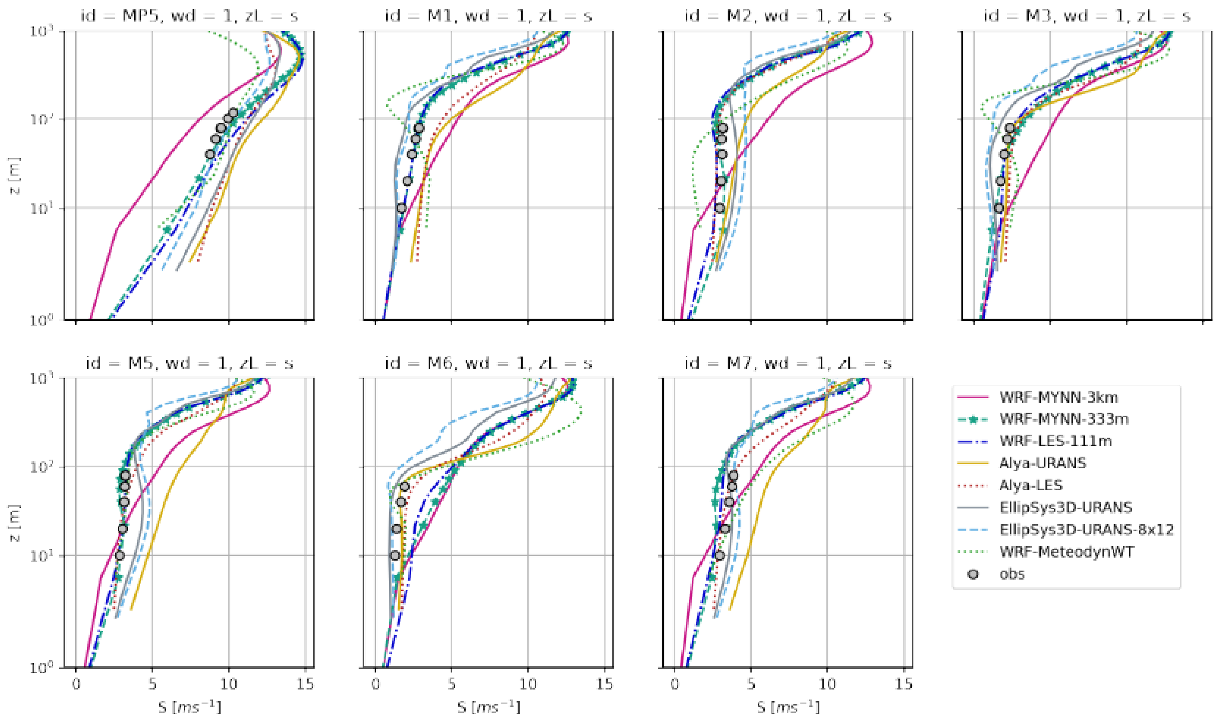

Figure 5: Vertical profiles of wind speed at each mast for stable conditions. From [1].

6. Utilisation of project results

The present project is contributing to an improved understanding and increased confidence in the models which are used in connection with wind farm flow models and as such the outcomes of the project is already used today. In addition, the benchmark exercises helps both researchers and representatives from the industry in pointing out the weak and strong parts of the used models. The focus of the project on industry involvement is also reflected in two industry driven benchmark cases out of which DTU participated in one, namely the IEC-61400-12-4 numerical site calibration. Besides, the project has supported the improvement and validation of EllipSys, PyEllipSys and PyWake which are licensed to industry and other institutes. For example it is a major advancement that EllipSys can now do meso-micro-scale coupling in complex terrain. Furthermore, the WAKEBENCH activities has contributed to the validation of a rather new atmospheric boundary layer model for RANS where the inflow is defined by analytic atmospheric surface layer profiles based on Monin–Obukhov Similarity Theory (MOST), and a modified k−ε turbulence model which is in balance with MOST.

7. Project conclusion and perspective

By supporting the third phase of the international collaboration IEA-Task 31 WAKEBENCH, this project have contributed to improving and validating many models which are used in connection with wind farm flow modelling and resource assessment. For example one of the benchmark cases revealed that a coupled meso-micro-scale model can improve the agreement with the measured wind resource over complex terrain with nearly 30% in comparison to using only a meso-scale model. Besides, the benchmarking activities have pointed out strengths and weaknesses in the models and provided new insight into how to plan validation exercises. During the project period, DTU's coupled meso-micro-scale model has been developed to also allow handling complex terrain and the new model has been validated as part of the benchmarking exercises.

DTU has processed a huge amount of data from the large Westermost Rough offshore wind farm, made data qualification and stored it in a database to allow others to easily access the data. Although DTU did not manage to define a final benchmark case based on the Westermost Rough wind farm data, the new database is still a major advancement for searching and defining new validation cases for the future.

Finally the international collaboration in the IEA-Task 31 has led to an updated version of the model evaluation platform including open-source evaluation scripts and best practice procedures.

The development and validation of models is a continuous process and therefore the activities started in this project will continue in the future. For this reason DTU and the other members of the IEA-Task 31 is already planning for a next phase of IEA-Task 31 with expected start in 2022. The aim of this phase is to build industry wide consensus on the development and adaption of a model evaluation framework for engineering wind farm flow models. The recipe is the same as in the previous phases, i.e. using benchmark cases for model validation and development but there will be a higher focus on improving the types of models which are typically used by industry.

8. Appendices

Publications

[1] J. Sanz Rodrigo, P. Santos, R. Chávez Arroyo, M. Avila, D. Cavar, O. Lehmkuhl, H. Owen, R. Li and E. Tromeur The ALEX17 diurnal cycle in complex terrain. In Journal of Physics: Conference Series, Vol. 1934, 2021, (The ALEX17 diurnal cycles in complex terrain benchmark - IOPscience)

[2] P. Doubrawa et al. Multimodel validation of single wakes in neutral and stratified atmospheric conditions. J. Wind Energy, **23**, 2020 (Multimodel validation of single wakes in neutral and stratified atmospheric conditions (wiley.com))

[3] S.J. Andersen et al. Global trends in the performance of large wind farms based on high-fidelity simulations, Wind Energy Science, 5, 1689-1703, 2020.

[4] Wind Energy Model Evaluation Protocol (WEMEP)

Database

[5] Westermost Rough database

Relevant webpages

[6] Project homepage: https://thewindvaneblog.com/