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REVIEW

Wind farm control part II: Model requirements to design and test wind farm flow control

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Abstract

Wind farm flow control (WFFC) is an emerging technology involving coordinated operation of wind turbines within a wind farm to achieve collective goals. To design and evaluate controllers, wind farm flow models are used that capture the key aerodynamics of the system whilst remaining computationally efficient for iterative controller design. This review article reveals considerable heterogeneity in the potential wind farm flow models to study WFFC. Lack of consensus is problematic as differences in results from separate studies are attributable to both controller and model effects, making it hard to draw comparative conclusions. Hence, an expert elicitation is completed surveying WFFC practitioners. Two key contributions are presented. First, a guide to available software for WFFC, which, combined with results from an expert elicitation on flow model requirements, facilitates selection of suitable software for investigating WFFC problems. Secondly, critical future research areas are identified. Research into high fidelity wind direction models (particularly transient effects) and wake meandering models for fatigue load investigations are identified as critical to the field. A lack of consensus regarding the importance of atmospheric boundary layer effects, wake induced turbulence, and lateral wind correlation identifies the requirement of sensitivity studies in these areas.

1 | INTRODUCTION

There has been increasing interest in wind farm flow control (WFFC) over the past decade, as wind farm operators look for novel ways to increase energy yield, decrease operations and maintenance (O&M) costs and reduce the levelised cost of energy (LCOE) of wind power. The term WFFC was recently suggested [1], differentiating the farm-wide aerodynamic turbine interactions from electrical aspects such as the compliance to grid codes and the provision of power system services. More specifically, WFFC is defined as actions taken at a wind farm level that alter the operational state of the wind farm considering flow dynamics. When developing and testing WFFC strategies, suitable farm-scale wind models are key to provide sufficiently accurate and computationally efficient simulations.

As the possibilities of WFFC become more apparent, suitable simulation models are required to test new WFFC strategies prior to implementation in the field. These models should consider wind farms as a whole rather than as collection of individual wind turbines. Flow interaction between turbines implies modelling a larger scale in both space and time and introducing various complex processes like wakes and their interactions, interaction with the atmospheric boundary layer, farm-scale spatiotemporal evolution of the ambient wind and cross-couplings through turbine and farm control. Depending on the application, a need for complex multiscale stochastic modelling of complex flow physics arises, conflicting with a need for simplicity for computational efficiency, multidisciplinary understanding and closed-form modelling for control design and optimisation. This trade-off between complexity and simplicity is key when developing and choosing flow models for development and testing of WFFC.

Abbreviations: CFD, computational fluid dynamics; LES, large eddy simulation; WFFC, wind farm flow control.

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There have been several reviews on wind flow models in recent years, however, none have focused specifically on wind farm flow models for use in wind farm flow control in particular. Porte-Agel et al. [2] use results from recent experimental, computational, and theoretical research to summarise the advances in atmospheric boundary layer flow. The paper is wide in scope and thorough in depth, but does not focus on control. In a similar vein, Stevens et al. [3] also discuss the modelling of wind flow in a wind farm context but have a focus on the fundamental physics and modelling rather than the applicability of the flow modelling methods to the wind farm control case. Work by Göçmen et al. [4] describes a number of DTU's wake models (Jensen, Larsen, dynamic wake meandering, Fuga) and the flow solver Ellipsys3D. The applicability of these models of varying fidelity to wind energy in general is discussed but the effects of modelling fidelity on controller performance/design are not specifically explored. Other reviews in the topic area primarily consider large eddy simulation (LES) methods [5–8] which are typically too computationally demanding for controller development and testing.

Three prior reviews of wind farm control models have been conducted in the past decade [9–11]. Of these, the first is limited in scope through only considering a turbine case with induction control. In the second reference, an in-depth discussion of the flow modelling paradigms is avoided, and the effect of different modelling paradigms on controller design is not discussed. The third reference is closest to the topic of the work presented here but focuses on power maximisation. Another review [12] introduces wind flow models of different fidelity without discussing their applicability for WFFC much further. Instead, model-free methods (and particularly reinforcement learning) are motivated given the challenges of model-based control such as model predictive control.

The objectives of this work are:

- To identify and categorise the flow model properties required for WFFC development and testing, and hence to classify existing simulation software packages based on the wind flow models that they use[1], with a focus on suitability for common wind farm flow control.
- To find out, via an expert elicitation, what flow model properties are considered necessary for common control objectives and methods, and to identify areas of strong agreement or disagreement within the field.
- Hence, to provide guidance on the selection of appropriate software for WFFC investigations and guidance on critical areas of future research regarding wind flow models for WFFC.

In Section 2, the three categories of wind farm flow model, based on computational cost, are introduced and different classes of wind farm flow model are then defined for use in the expert elicitation. In Section 3, the expert elicitation is described and the results are presented, representing the current view amongst WFFC experts in academia and industry on the required properties of wind models for particular WFFC objectives and methods. Section 4 then discusses the results of the expert elicitation, the commonly used and currently available software packages are also discussed with respect to their implemented model types and flow properties, their intended use, and their required computational power to run the software. The discussion serves as a useful resource for researchers to identify appropriate software based on the requirements of their WFFC approach and the software's built-in wind model(s). An example of selecting suitable software for an investigation is provided. The results from the expert elicitation are also coupled with the review of simulation software and models to identify critical gaps in the current research landscape for WFFC wind models that require future research. In Section 5, the conclusions of the work are summarised.

[1] Note that throughout this paper, the term 'model' is used to describe the particular algorithm that models a property of the wind flow and the term 'simulation software' is used to describe a program that implements the model allowing users to run WFFC simulations.

2 | WIND FARM FLOW MODELS IN THE LITERATURE

In this section, models are purposefully grouped according to their computational cost, which is, although strongly correlated, not equivalent to modelling fidelity. The mapping between the two is the subject of model classification for use in the expert elicitation, discussed in Section 2.5. As such, the list here does not claim to be exhaustive, but does provide examples of all the main types of model in common use. Many of the models have been adopted by particular software packages that have received regular updates over the years. The papers listed here are those that best describe the fundamentals of the models, rather than the most recent paper on the topic. It is a brief overview and not intended as an in-depth critique of the models themselves as other recent reviews in the literature fulfil this role [10, 11].

2.1 | High computational cost models

Aerodynamic flow models featuring computational costs that prevent practical use for structural and control design are discussed here. They numerically approximate the three dimensional (3D) unsteady Navier–Stokes equations (known as computational fluid dynamics - CFD), which describe the wind flow in a wind farm [8]. The degree of fidelity in these models depends on two major factors: (1) the extent to which the full flow spectrum is resolved using the computational grid and (2) the extent to which the solid turbine geometry (wind turbine elements in this context) is accurately represented in the model.

Based on the first criteria, the high-cost models can be categorised into direct numerical simulation (DNS), large eddy simulation (LES) and Reynolds averaged Navier Stokes (RANS) models. The DNS type resolves the whole flow spectrum close down to the Kolmogorov scales, the LES type resolves part of the spectrum resolved by the computational grid and models the sub-grid scales, and the RANS type models the time averaged effects of all the scales. DNS is not applied to the wind

TABLE 1 Commonly cited articles on wind farm LES models, with associated turbine geometry models and software packages.

Article(s)	Turbine model(s)	Associated software package
Sørensen et al., 1995 [13]; Heinz et al. [14], 2016	AD; AL; GR	Ellipsys3D
Albertson, 1996 [15]	AD; AL	LESGO
Porté-Agel et al., 2000 [16]; Stoll et al., 2006[17]	AD	
Raasch et al., 2001 [18]	AD; AL	PALM
Moeng et al., 2007 [19]	AD	WRF-LES
Meyers et al., 2010 [20]; Calaf et al., 2010 [21]	AD	SP-Wind
Churchfield et al., 2012 [22]	AL	SOWFA
Martinez-Tossas et al., 2012 [23]; Santoni et al., 2015 [24]	AD; AL	UTD-WF
Xie et al., 2015 [25]	AL	WiTTS

flow around turbines due to the high computational demand [5].

Based on the second criteria, the high-cost models can be categorised into full geometry resolving (GR) models, actuator line (AL) models and actuator disk (AD) models. These broad groups of models (LES, RANS and GR, AL, AD) have been combined to simulate the wind flow around turbines with varying levels of approximation. They are primarily used for analysis of underlying physics and calibration and validation of lower-cost models.

An overview of frequently cited publications on LES models is presented in Table 1, see Porté-Agel et al., 2020 [2] for a thorough list. An overview of RANS models may be found in Sanderse et al., 2011 [8].

2.2 | Medium computational cost models

The medium-cost flow models are developed as a compromise between accuracy and computational costs. Typically, these models simplify the original Navier–Stokes equations further using dimensional reduction (from 3D to 2D), linearisation, flow superposition and/or empirical modelling of subprocesses. Calibration from higher-cost models and measurements is used to compensate for the introduced uncertainty. These models can be divided into three families: the dynamic wake meandering (DWM) model and its variants, simplified CFD approaches, and potential flow solvers. A selection of commonly cited publications describing medium-fidelity models grouped by family is given in Table 2.

The DWM model, often referred to as a medium-fidelity solution, is widely used and is becoming standard for inclusion of wake effects for structural design purposes. It relies on the superposition principle, adding disturbances from wakes to the original ambient undisturbed flow. The undisturbed flow

TABLE 2 Commonly cited articles on medium-cost models, with the DWM family in the upper part, the simplified RANS family in the middle part and potential flow solvers in the lower part. The notes about the model give a short description about modelling approach and associated software package(s).

Article(s)	Notes
Ainslie, 1985 [27], Ainslie, 1988 [28]	Thin shear layer approximation and eddy viscosity modelling
Larsen, 1988, [29], Larsen et al., 2007 [30]	DWM model - Thin shear layer approximation, eddy viscocity modelling and vorticity formulation for added wake turbulence
Jonkman et al., 2017 [31]	Modification of DWM model in FAST.Farm
Crespo et al., 1996 [32]	Base model of UPMARK/UPWAKE/WAKEFARM/FARMFLOW - Steady-state parabolized Navier–Stokes equations in perturbation form in 3D and $\kappa - \varepsilon$ turbulence model
Ott et al., 2011 [33], Ott et al., 2014 [34]	Base model of FUGA - Linearised 3D RANS
Soleimanzadeh et al., 2014 [35]	Control-oriented linearised 2D Navier–Stokes equations without turbulence model
Rott et al., 2017 [36]	Control-oriented 2D semi-Lagrangian advection scheme
Boersma et al., 2016 [37]; Boersma et al., 2018 [38]	Base model of WFSim - 2D Navier–Stokes equations and continuity equation with finite volume method
Annoni et al., 2015 [39]	Control-oriented linearisation and reduction of higher fidelity models
Branlard et al., 2020 [40]	Includes 6 different potential flow methods from previous works

is typically generated beforehand by a wind precursor, which should be considered a separate tool with its own degree of fidelity. Differences lie in flow representation (LES or spectral) and included scales (mesoscale effects on the one hand, and turbine-scale turbulence on the other hand).

Compared to high-cost models, simplifications improve computational efficiency tremendously, making medium-cost models more control-oriented. For instance, adding time dependency in RANS (moving from RANS to Unsteady (U) RANS) becomes affordable [26]. Nevertheless, the number of states is still large making their use in wind farm control design challenging. As large assumptions are required to simplify the governing equations of underlying physics (Navier–Stokes), accuracy is known to be limited on particularly complex processes like wake superpositions and interactions with the atmospheric boundary layer. In this respect, the simplified RANS approach may offer better fidelity than DWM, by not relying on the superposition principle, to the cost of reduced use cases.

Potential flow solvers are of a distinct nature. Being inviscid, they are admittedly not appropriate for wake modelling, but are used to simulate blockage effects in a more computationally efficient way than high-cost models.

2.3 | Engineering wake models and surrogate models

Engineering wake models are on the low computational cost end of wind farm simulation models. They focus on simplicity and computational efficiency for wake modelling, describing the complex wake characteristics with a small number of parameters. These parametric wake models often estimate the steady-state situation for a given wind speed and direction assuming the same wind inflow characteristics for the entire farm. Recently, some engineering wake models have been augmented with dynamic advection (propagation) of the wake through the wind farm under coarse assumptions (partially uniform wind field, Taylor's frozen turbulence assumption). A selection of commonly cited articles describing engineering wake models is given in Table 3.

Despite being relatively simple, engineering models can estimate the wind speed deficit in the far wake region [63–67]. However, it was also reported that they may overestimate the deficit [68–70]. A comparison with measured data of some of the older models is given, e.g. by [71]. Engineering models may be coupled with other models like wind precursors to improve ambient wind modelling or potential flow solvers to include blockage effects. This results in hybrids with mixed fidelity and cost levels.

Another alternative for use in real-time operation and control is surrogate models, consisting of data-driven models trained on high-fidelity and medium-fidelity simulation data. Reduced order modelling (ROM) and machine learning are example approaches, with a myriad of variants. Common to all of them, is a hybrid computational cost with a huge offline cost to generate the training database and a negligible online cost, making the method eligible for real-time control. Though promising, the complexity associated with these methods has prevented them from being included in software packages available for broader use. For this reason, this choice has been excluded from this study.

Compared with medium-cost models, engineering and surrogate models rely more/only on empirical calibration and less/not on governing equations. They are therefore more application-specific, and are dependent on calibration/training data and methods with corresponding uncertainty.

2.4 | Classification for use in expert elicitation

The previous subsections introduced the three main categories of farm flow models illustrating the vast number of models available in the literature. In this section, a set of model classifications are defined to characterise the link between model type, flow properties and control objectives in a systematic manner. The classification of models into different types is essential to allow the expert elicitation to be easily digested by participants and to provide clear outcomes.

To ensure that the model classifications were easily understood by participants, a process known as 'think aloud' was

TABLE 3 Commonly cited articles about engineering wake models. The models above the dashed line are steady-state, those below include dynamic wake advection.

Article(s)	Notes
Jensen, 1983 [41]; Katic et al., 1987 [42]	Base of Jensen model - top-head wake deficit profile, extended to capture the interaction of multiple wakes
Ishihara et al., 2004 [43]	Considers added turbulence intensity
Frandsen et al., 2006 [44]	Base of Frandsen model - infinite wind-farm boundary-layer (IWFBL) model
Madjidian et al., 2011 [45]	Control-oriented - mean and variance of velocity of downwind turbines determined based on information from their closest neighbour
Stevens et al., 2015 [46]	Base of the coupled wake boundary layer (CWBL) model - coupling of the "top-down" Frandsen model and the "bottom-up" Jensen model
Bastankah et al., 2014 [47]; Bastankah et al., 2016 [48]	Mass and momentum conservation assuming a Gaussian distribution in the wake
Keane et al., 2016 [49]	Near wake model assuming a double-Gaussian velocity deficit
Thøgersen et al., 2017 [50]	Statistical meandering wake model including a statistical random component to the Jensen–Park model
Sun et al., 2018 [51]	3D model based on wind distribution dependent on downstream distance, hub axis distance and height over ground, assuming a Gaussian-distributed velocity deficit profile
Ge et al., 2019 [52]	Two-dimensional wake model based on Gaussian profile and mass conservation and accounting for the pressure recovery region
Kabir et al., 2020 [53]	Wake velocity and turbulence intensity model derived using genetic programming
Shen et al., 2023 [54]	Gaussian wake velocity model for non-yawed and yawed wind turbines
Farrell et al., 2020 [55]	Base model of FLORIS based on Bastankah et al., 2016
Grunnet et al. 2010 [56]	Base model of SimWindFarm/Aeolus toolbox - models the dynamics of wake centre, deficit and expansion
Gebraad et al., 2014 [57]	Based model of flow redirection and induction dynamics (FLORIDyn)
Annoni et al., 2016 [58]	Dynamic park model (DFP) - Jensen model extended with turbine and wake transport dynamics
Shapiro et al., 2017 [59, 60]	One-dimensional time varying wake model, extending the Jensen–Park model
Kazda et al. 2018 [61]	Base model of dynamic flow predictor - linear dynamic flow model predicting wind speed and turbine power
Bay et al., 2018 [62]	Wake deflection expressed by linearised model using small angle approximation and Taylor's frozen turbulence hypothesis

used to refine the initial definitions set by the authors to those presented here. The 'think aloud' method involves participants thinking out loud i.e. 'nonreactive verbalisation of thinking' [72], whilst undertaking a task, in this case the completion of the expert elicitation. The feedback from 'think aloud' participants is used to refine the definitions for the model classes and control strategies and approaches prior to the elicitation being conducted with larger numbers of participants.

2.5 | Model classification

First, flow properties are divided into the following categories,[2]

2.5.1 | Undisturbed flow

Ambient wind, i.e. the wind field as if no farm was present. It can be broken down further into:

Rotor-averaged effects
Which are commonly termed the rotor equivalent wind speed/direction or the effective wind speed/direction. These effects may in turn be divided into two subcategories:

Rotor-averaged, spatial variations across the wind farm of undisturbed mean wind speed and mean wind direction as function of atmospheric and surface conditions.

Rotor-averaged, spatio-temporal turbulent fluctuations, correlation between turbines and transients of mean wind speed and direction.

Local blade effects
Which depend on the local position within the swept area of the rotor. They can be further divided into spatial (shear, veer) and spatio-temporal (turbulence) effects.

2.5.2 | Disturbed flow

Effect of the wind farm on the flow, which may be broken down into:

Wake effects
Wake effects are alterations to the flow downstream of turbines caused by the pressure drop behind upstream turbines as they extract energy from the wind. As wakes are transported downstream by the wind, they may hit downstream turbines and/or superimpose with other wakes. Wake effects may be further split into 'wake pattern' referring to purely spatial variations and 'wake dynamics' adding time variability (similar to spatial and spatio-temporal effects for undisturbed flow).

Atmospheric boundary layer (ABL) effects
The alteration of the flow due to the wind farm as a whole and its interactions with the atmosphere, beyond wake effects. Rather than focusing on the pressure drop behind turbines, the focus is on the pressure surge in front of turbines, propagating in all directions causing blockage effects/farm induction and a change in atmospheric boundary layer thickness, interacting with higher layers of the ambient flow (flow stratification, atmospheric gravity waves).

Note that, unlike ABL effects which form a category in their own right, this list describes flow properties and not processes. Processes (like wake superposition, farm-scale wind evolution, turbulent mixing etc.) typically affect multiple properties, e.g. both pattern and dynamics of both velocity deficit and wake-induced turbulence.

At this point, it is important to distinguish models from codes/simulation software packages implementing models, although their developments are closely linked. Table 4 shows a suggestion for model classification. Instead of putting each model into a global fidelity class as in Tables 1–3, model types characterising modelling capabilities are first devised, wrapping models from Section 2. They are then mapped against the above-introduced flow properties. The classifications in Table 4 are used in Section 4.1 to help match software using the models discussed with WFFC applications.

Notations for model types are explained in the following:

- DWM: Variants of the dynamic wake meandering model using the superposition principle (total flow = undisturbed + disturbed). They come in two versions: T for turbine level, that include wake flow in pre-generated wind field prior to running single-turbine simulations; and F for farm level, that solves for wake flow at runtime while running all turbines in parallel. They are generally ranked as mid-fidelity models (found in Table 2), but may also partly use low-fidelity models from Table 3.
- WP: Wind precursor used to pre-generate wind fields for mid-fidelity simulations (associated with DWM above). For DWM-T tools, WP-T includes wake (disturbed) flow, while for DWM-F tools, WP-F only includes ambient (undisturbed) wind. The ambient wind part comes in two versions: ABL for LES-based ambient-wind precursor solving the undisturbed atmospheric boundary layer, and ST for synthetic turbulence-based precursor based on spectral representation of turbulence and empirical atmospheric boundary layer models. They cover the entire fidelity range.
- RANS and LES: CFD models solving Navier–Stokes equations that come in two versions: AD (actuator disc) and AL (actuator line). URANS is unsteady RANS, introducing time variability (RANS is originally quasi-steady). They are typically ranked as mid- to high-fidelity models (found in Tables 1 and 2).
- ENG: Engineering analytical/empirical models, that could be steady state (SS) or include some dynamic aspects (DYN). They roughly correspond to low-fidelity models in Table 3. Engineering models are developed with a specific application in mind. Therefore, ENG shows up in multiple boxes in Table 4, but this typically refers to distinct models.

[2] Note that these properties are broken down further with a more detailed description in Appendix A, when linking to control objectives in the elicitation survey.

TABLE 4 Classification of models against farm flow properties.

		Not modelled	Low fidelity	Mid fidelity	High fidelity
Undisturbed flow	Spatial	ENG	WP-ST	RANS-AD	RANS-AL
			URANS		LES, WP-ABL
	Spatio-temporal	ENG,		WP-ST	LES
		(U)RANS			WP-ABL
	Local blade effects	ENG, LES-AD	WP-ST	RANS-AL	LES-AL
	(spatial)	RANS-AD, URANS			WP-ABL
	Local blade effects	ENG, LES-AD		WP-ST	LES-AL
	(spatio-temporal)	(U)RANS			WP-ABL
Disturbed flow	Wake pattern	DWM-T	ENG, DWM-F	RANS	LES
		WP-F	URANS, WP-T		
	Wake dynamics	ENG-SS, RANS	ENG-DYN	DWM-F,	LES
		DWM-T, WP-F	WP-T	URANS	
	ABL effects	ENG, DWM	POT	RANS	LES
		WP, URANS			

Abbreviations: ABL, atmospheric boundary layer; AD, actuator disk; AL, actuator line; DWM, dynamic wake meandering; DYN, dynamic; ENG, engineering; F, farm level; LES, large eddy simulation; RANS, Reynolds-averaged Navier–Stokes; SS, steady state; ST, synthetic turbulence; T, turbine level; URANS, unsteady RANS; WP, wind precursor; POT, potential flow solver.

3 | EXPERT ELICITATION

An expert elicitation is conducted to investigate the required properties of wind models for different purposes in WFFC research. The elicitation takes the form of a survey, completed by leading researchers and industry figures working within WFFC. The elicitation uses the typical objectives and methods for achieving these objectives as described in Section 3.1. Full definitions of all the categories of the survey are given in Appendix A.

The ranking system used in the elicitation is first described, alongside a discussion behind the chosen system. Then, the demographics of the participants and the results from the elicitation are presented. Further discussion of the results can be found in Section 4.

3.1 | Control methods and objectives

The majority of research in WFFC concerns two distinct control methods, which are wake steering and induction control. When testing these methods, researchers are typically interested in one (or more) of three objectives or measures of performance, the power output/energy capture at low frequencies, the variation in power output at higher frequencies, and/or the fatigue loads on the wind turbines in the farm. Hence, the expert elicitation uses six combinations of objective and method. Whilst a greater variety of methods and objectives could be considered, it was found via the 'think aloud' sessions, that grouping the methods and objectives into the chosen categories was the best balance between detail and timeliness for participants.

TABLE 5 Ranking system used for the expert elicitation.

Rank	Definition
1	Not required/not adequate
2	Beneficial to have
3	Required (low fidelity/resolution)
4	Required (high fidelity/resolution)

3.2 | Ranking system

Respondents were asked to rank model inputs in terms of their importance. Each question asked respondents to assign a 'rank' from 1 to 4 in terms of the model input's importance towards the desired objective. Table 5 shows the definitions associated with the ranks in the system.

The system was chosen as it effectively allowed respondents to separate the inputs into required or not required (a binary measure), and then further demarcate within those subcategories. A degree of consensus could then be determined from the choices. In theory, the rank of an input purely relates to the model aim being considered and independent of the other inputs in the same category, however this is hard to judge in practice. An example of four response fields that appear in the elicitation is shown in Figure 1.

Finally, the ranking system does not represent a continuous scale, therefore statistics such as mean and variance are effectively meaningless. Some consideration was taken in choosing the summary statistics to present, especially as they relate to degree of consensus. The summary statistics are discussed in detail in Section 3.4.

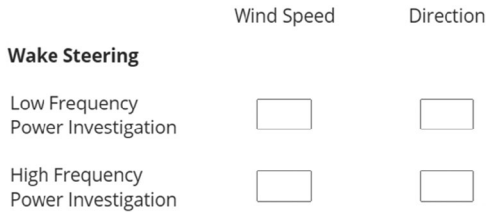

FIGURE 1 Example of the expert elicitation response field.

Note that participants were also encouraged to leave comments, which could take any form, to communicate any nuance or difficulty they may have had with their scoring.

3.3 | Participants

The participants were invited through several different channels, but mostly in connection with the IEA Wind Task 44 on wind farm flow control. Since this IEA Task includes individuals from both industry and academia, the aim was to reach a pool of participants that would reflect different backgrounds and interests. However, out of 22 participants, 20 were from either an academia or research centre background and 2 were from industry (the percentages are shown in Figure 2a). Participants were also asked to choose the topics they were most interested in from a list. The majority of participants chose wind farm engineering models, followed by wake steering and structural loads which each represented around half of the participants. The full details of the selected areas of interests are shown in Figure 2b.

3.4 | Condensed results for discussion

The full elicitation results are presented in Appendix B. See Figure B1 in Appendix B for ambient wind properties results, Figure B2 in Appendix B for disturbed flow properties results, and Figure B3 in Appendix B for simulation properties results. In addition, some useful visualisations displaying compact results from each category are presented in Figure 3. The most frequent response represents the majority view therefore the modal value is used as the primary summary statistic. However, the mode does not always represent a majority consensus, therefore it is important to measure the degree of consensus on the modal value.

The unalikeability coefficient [73] is a mechanism for quantifying the degree of consensus around a modal value; it is somewhat analogous to the variance but for categorical data. Let x_i represent the rank given by the ith participant out of n participants for an arbitrary response field, then the unalikeability coefficient u for the response field is

$$u = \frac{\sum_{i \neq j} c(x_i, x_j)}{n^2 - n} \tag{1}$$

where

$$c(x_i, x_j) = \begin{cases} 1, & \text{if } x_i \neq x_j, \\ 0, & \text{otherwise.} \end{cases}$$

Explicitly, the coefficient is a value between 0 and 1 where 0 represents complete consensus amongst participants and 1 represents an even split amongst all choices. A value less than 0.5 represents majority consensus on the modal value, whereas a value greater than 0.5 represents no majority consensus. Two coefficients are calculated per response field; the coefficient for the binary categorisation (required or not required) as well as the coefficient calculated across all four categories. The larger the binary coefficient, the lighter the colour of the corresponding entry in Figure 3. Additionally, the larger the 4-category coefficient, the greater the size of the corresponding containers in Figure 3.

As an example, Figure 3 shows how there is consensus around wind speed and wind direction as very important towards investigating most aspect of the two control approaches. The depth of the orange/red colour demonstrates a low unalikeability score in the binary required/not required metric. There is also strong consensus that these two factors are required at high resolution, choice 4, when investigating fatigue loading associated with wake steering. This is demonstrated by the smaller size of the two containers associated with these responses. Conversely, ABL effects are identified as only beneficial to have for each investigation, signified by the blue colour and the choice 2. Consensus is particularly strong around this for low frequency power investigation with induction control.

The results from the elicitation survey are used for two purposes. Firstly, guidance is provided for researchers starting new WFFC investigations about which models match well with their proposed purpose. Secondly, potential gaps in the literature are identified that can serve as directions for future research for targeted improvements in wind field modelling for WFFC. These aspects are discussed in Sections 4.1 and 4.2, respectively.

4 | DISCUSSION

This section discusses the results of the expert elicitation introduced in Section 3. Firstly, Section 4.1 identifies the available software packages suitable for wind farm simulation, classifies them in terms of the flow modelling methodology and aims to guide researchers in appropriate model selection. Following this, Section 4.2 discusses the implications of the elicitation results in terms of future WFFC research, identifying high priority areas for model development, and areas in which more fundamental research is required to bring consensus on the necessary model fidelity.

4.1 | Simulation software for wind farm flow control

A list of available (i.e. released or planned to be released, public or commercial, excluding in-house use only) simulation software packages has been identified. A selection is presented in Table 6. It is not meant to be definitive: for instance, there are many more available engineering quasi-steady software packages developed for farm design and layout optimisation. Many

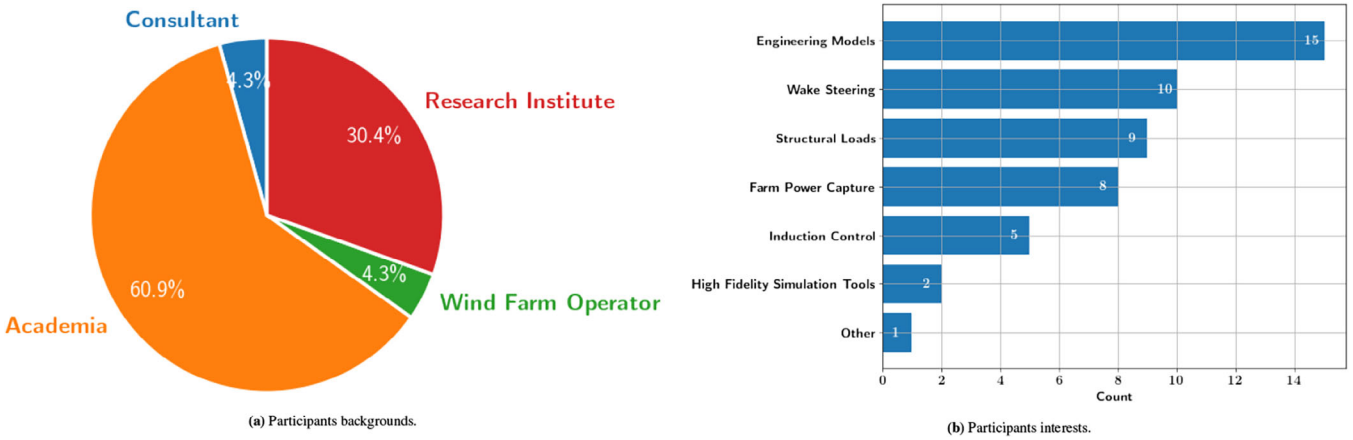

FIGURE 2 Expert elicitation participants backgrounds and interests.

TABLE 6 Classified available simulation software packages suitable for WFFC investigations.

Code	Developer	Class	Primary objective
Bladed [74]	DNV	DWM-T	Turbine-level structural design
DIWA	SINTEF[a]	WP-T	Turbine-level structural design, AEP estimation and grid integration
Ellipsys 3D [75]	DTU	LES-AD	Validation and calibration of lower-fidelity models
FAST.Farm [76]	NREL	DWM-F	Farm-level structural design
FLORIDyn [77]	TU Delft	ENG-DYN	WFFC
FLORIS [78]	NREL	ENG-SS	AEP estimation, layout optimisation and steady-state WFFC
Fuga [79]	DTU/WAsP	RANS-AD	AEP estimation and layout optimisation
HAWC2 [80]	DTU	DWM-T	Turbine-level structural design
HAWC2Farm [81]	DTU	DWM-F	Farm-level structural design
LongSim [82]	DNV	DWM-F	WFFC
PALM [83]	U. Hannover	LES-AD/AL	Multiscale simulations (link to mesoscale)
PyWake [84]	DTU	ENG-SS	AEP estimation, layout optimisation and steady-state WFFC
SOWFA [85]	NREL	LES-AL	Validation and calibration of lower-fidelity models
StrathFarm	U. Strathclyde[a]	DWM-F	WFFC and grid integration
WFSim [86]	TU Delft	URANS	WFFC
WRF [87]	NCAR	LES-AD	Multiscale simulations (link to mesoscale)

aTool planned for release in which at least one of the authors is involved, included for completeness
Abbreviations: ABL, atmospheric boundary layer; AD, actuator disk; AL, actuator line; DWM, dynamic wake meandering; DYN, dynamic; ENG, engineering; F, farm level; LES, large eddy simulation; RANS, Reynolds-averaged Navier–Stokes; SS, steady state; ST, synthetic turbulence; T, turbine level; URANS, unsteady RANS; WP, wind precursor.

of these software packages directly correspond to one of the models in Tables 1–3, linking model and software development.

Each software package in the table is attributed a class, according to the definitions introduced in Section 2.5. This mapping to model capabilities presented in Table 4, and in turn linking to control objectives through the elicitation survey results in Section 3, facilitates readers to assess the suitability of the various software packages for WFFC purposes.

Although the class of the software package provides information about the potential degree of modelling fidelity, the implementation approach and business model may significantly affect development priorities and in turn actual capabilities. While providing such level of detail is out of the scope of this paper, the primary objective of each software package is given in addition to its class, for guidance purposes. For instance, it is reasonable to assume that a software package developed with wind farm flow control in mind will prioritise computational efficiency; aiming for validation and calibration will prioritise accuracy in development choices with little consideration for computational cost; and a focus on structural design will lead to a trade-off between the two.

As introduced in Section 2.2, DWM-F models are to be used in conjunction with a farm-level wind precursor (WP-F). Precursors can also be used as standalone or as input to engineering models. A list is provided in Table 7.

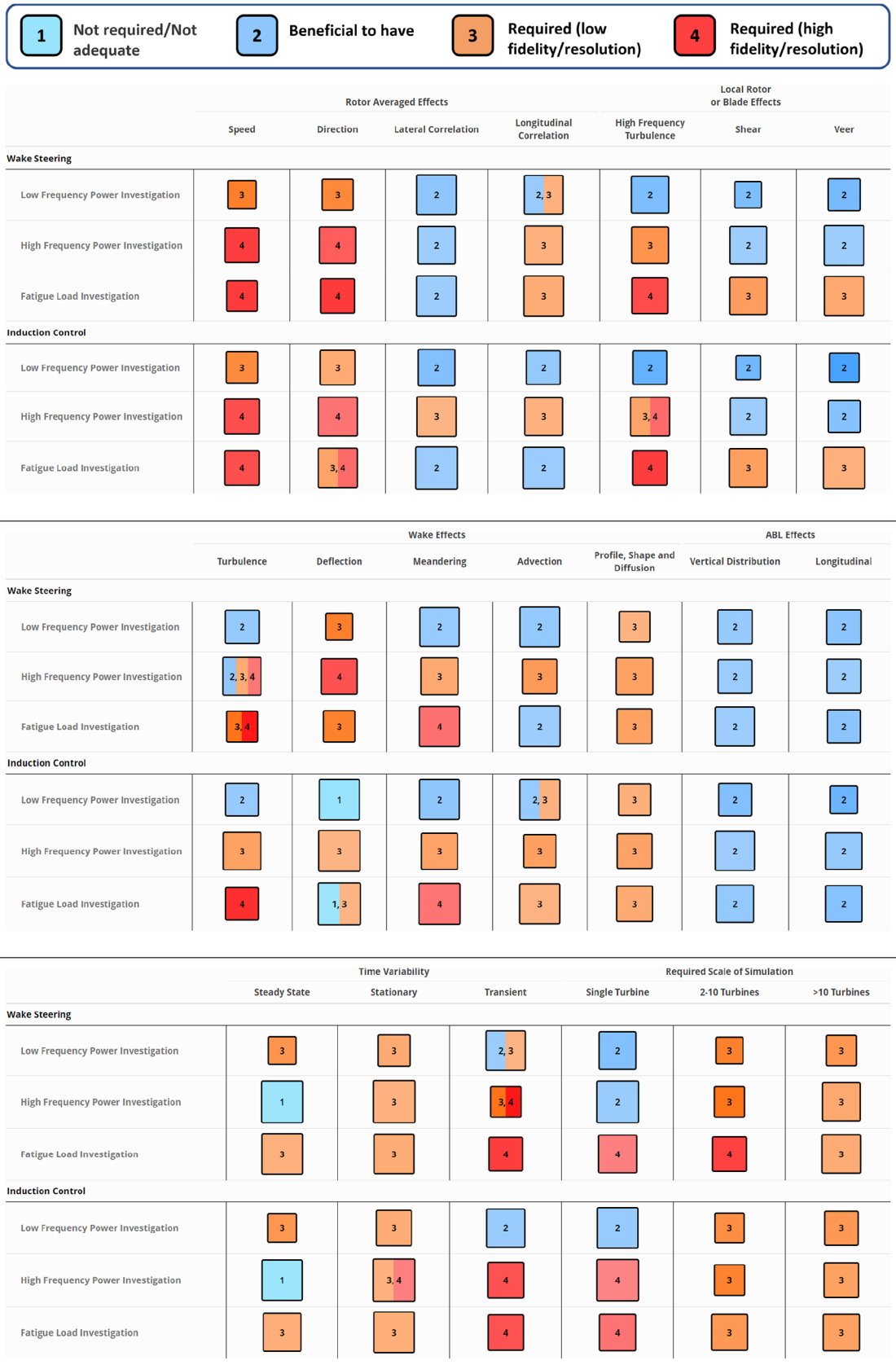

FIGURE 3 Condensed results from the expert elicitation. The numbers and colours reflect the mode, the colour depth is correlated with the binary unalikeability coefficient, and the area is correlated with the 4-category coefficient.

TABLE 7 Classified available wind precursors.

Code	Developer	Class	Primary objective
ABLSolver [85]	NREL	WP-F, LES	Terrain effects
FLAggTurb [88]	SINTEF[a]	WP-F, ST	Grid integration and WFFC
Mann.rs [89]	DTU	WP-F, ST	Structural design
TurbSim [76]	NREL	WP-F, ST	Structural design
WRF [87]	NCAR	WP-F, LES	Multiscale simulations (link to mesoscale)

aTool planned for release in which at least one of the authors is involved, included for completeness
Abbreviations: LES, large eddy simulation; ST, synthetic turbulence.

The purpose of Tables 6 and 7 is to act as a guide for researchers either new to the topic of WFFC or who may be transitioning between different aspects of WFFC. Table 6 and 7 are not intended as a definitive proclamation of the 'correct' software to use for a particular purpose, however, with the large variety of software now available it should serve, alongside the other aspects of the paper, as a highly useful map of the WFFC software space.

Example: Pre-study on wake steering for damage mitigation
Requires a low-cost model appropriate for fatigue load investigation. From Figure 3, it can be seen that spatial variations in the rotor-averaged ambient field, local blade effects, wake pattern and wake dynamics are important, while ABL effects and spatio-temporal variations of the ambient field are optional. Time variability with multiple turbines is needed. Looking in Table 4, a DWM model appears as most appropriate. Suitable software in Tables 6 and 7 narrows selection to a smaller range of solutions, from which the user can choose depending on personal preference, e.g. one solution may be a full NREL package with a TurbSim and FAST.Farm (full NREL), whilst another could be a full DTU package with Mann.rs and HAWC2Farm.

4.2 | Implications of elicitation on future WFFC wind model research

The results of the elicitation afford the opportunity to identify gaps in the current state-of-the-art wind field modelling for WFFC. In general, if there is strong agreement that a given fidelity of model is required for a particular purpose, and such models exist within the literature, then, whilst additional research could always be of benefit, such an area of research would not be top priority. If strong agreement is coupled with a lack of suitable models then it is clear that research into new modelling methods has a high priority.

Conversely, if the elicitation showed very low agreement on a required level of fidelity then this implies that research is needed to identify the level of uncertainty regarding that aspect of modelling to bring clarity to the required level of fidelity necessary.

It is also useful to consider differences in the required model fidelity of different features not just in a general sense, but also for different control objectives or for different control methods. Some aspects become more or less important for different objectives and methods, highlighting how different models may be suitable for different investigations.

Using the above criteria, the following future research opportunities can be inferred.

4.2.1 | Wind direction modelling

It is clear from the ambient wind conditions results in Figure 3, that modelling of the wind direction is strongly rated as required. Additionally, for all investigations except low frequency power investigations, modelling of transient conditions is similarly rated (see Figure 3). Current modelling of the wind direction in the literature tends towards either using a constant direction for circa 10 min of simulation time, or uses data, which is not commonly available in higher resolutions than 10-min averages. Hence, there is a clear opportunity for researchers to develop improved wind direction models that facilitate WFFC research.

4.2.2 | Atmospheric boundary layer effects

The results for atmospheric boundary layer (ABL) effects shown in Figure 3 show ABL to be rated as "beneficial to have", however, there is a large spread on the responses. The spread may be due to the respondents having comparatively little experience in the area compared to others. Another explanation could be that ABL effects are important for some investigations but not for others. Finally, a third explanation could be that the importance of ABL effects for WFFC is not well known. No matter which if these three explanations holds, there is a clear need for future research that demonstrates the importance (or lack of importance) of ABL effects for WFFC.

It is noted that one respondent commented that 'There is a huge need to better understand how things behave in large wind farms (offshore trends see future wind farms with lots of turbines) and this is connected to the previous question on vertical and longitudinal evolution of the boundary layer properties'. The spread of the results is consistent with this assertion.

4.2.3 | Required scale of simulation

Results around the level of fidelity required for single-turbine simulations showed a fairly large range of responses (see Figure 3). Whilst there is a chance that this could be due to more research being required on the importance of the simulations, in this case it is perhaps more likely that the elicitation could have asked the question more clearly. One comment was 'Single-turbine simulations refer more to 'turbine control in a farm wind field' problems. For some people such problems would not fall under the auspices of WFFC and for others they would. Hence,

it is perhaps not wise to read too much into the numerical result for single turbine simulations.

4.2.4 | Wake meandering

Regarding wake meandering, the respondents see a clear increase in the required fidelity for different objectives, with fidelity level required for low frequency power investigations, high frequency power investigations and fatigue load investigations being 2, 3, and 4 respectively for both waked steering and induction control. Meandering of wakes tends to be modelled in lower fidelity for the majority of WFFC simulation software and so this could be an interesting topic for research for researchers interested in fatigue load investigation.

4.2.5 | Wake-induced turbulence

The desired fidelity of wake-induced turbulence modelling varies strongly between control objectives. For low frequency power investigation, there was a fairly good agreement that wake-induced turbulence is 'beneficial to have', whilst for fatigue load investigation it is 'required' (and for induction control it should be high fidelity). These results are useful in and of themselves, but it is also very interesting to see the lack of consensus on the required fidelity of modelling of wake-induced turbulence for high frequency power investigations. For wake steering, there is an even split between 'beneficial to have', 'Required (low fidelity)', and 'Required (high fidelity)', and there is similar spread for induction control. Future research to show the importance (or lack of importance) of wake induced turbulence can hence be inferred to be useful.

4.2.6 | Lateral correlation

Lateral correlation of the ambient wind was clearly viewed in all cases as not requiring high fidelity modelling. However, for all control objectives except low frequency power there was a near even split between those who rated the modelling of lateral correlation as 'beneficial to have' and those that rated it as 'required'. This implies some disagreement within the field, making this topic a fertile area for future research into the sensitivity of results to the lateral correlation model used.

5 | CONCLUSIONS

Wind farm flow control is a research area that is rapidly developing to include a broad range of control objectives and methods. Various software has been developed and/or adapted to facilitate design and testing of WFFC algorithms, using a variety of wind flow models at a range of fidelity levels.

The broad range of objectives for WFFC has necessitated the development of different software using different wind models, however, such variety in objectives, methods, models and software can be confusing. A review of the literature has facilitated classification of wind models into distinct types. Hence, a guide to the openly available software for WFFC is presented, with information on the fidelity of the models used in the software. This guide is useful for identifying the most appropriate software to use for a particular WFFC investigation.

The classification of wind models facilitated an expert elicitation to gather the collated opinions of experts in the field. The elicitation has identified critical areas for future research into new modelling methods. These are:

- High fidelity wind direction modelling for fatigue load analyses and high frequency power investigations—particularly transient effects.
- High fidelity wake meandering models for fatigue load investigations.

The expert elicitation also reveals a level of disagreement about the importance of aspects of wind modelling for WFFC. This implies a high degree of uncertainty that in turn demands investigation of the sensitivity of results to higher fidelity models of:

- Atmospheric boundary layer effects for all WFFC investigations.
- Wake induced turbulence for high frequency power investigations and fatigue load investigations.
- Lateral correlation of the wind for high frequency power and fatigue load investigations.

Conclusions are strongly dependent on how flow physics have been broken down into features. Focusing on flow properties rather than processes facilitates linking to control objectives, but does not allow for direct identification of research needs on specific processes (among others; wake superpositions, effect of atmospheric stability, weather events etc.) which can be deduced from their respective effects on flow properties.

The results of the expert elicitation can also be used as a guide for researchers new to the field in selecting appropriate software for undertaking particular WFFC studies.

AUTHOR CONTRIBUTIONS

All authors have made an important contribution to the creation of this paper. **Adam Stock**: Conceptualization; methodology; investigation; writing–original draft preparation; writing—review and editing; supervision; project administration. **Scott Dallas**: Methodology; formal analysis; writing–original draft preparation; writing—review and editing. **Valentin Chabaud**: Conceptualisation; methodology; formal analysis; writing–original draft preparation; writing—review and editing. **Konstanze Kölle**: Conceptualisation; methodology; writing–original draft preparation; project administration. **Laurence Morgan**: Methodology; formal analysis; writing–original draft preparation; writing—review and editing. **John Olav Tande**: Writing–original draft preparation; project administration; funding acquisition. **Olimpo Anaya-Lara**: Writing–original draft preparation; project administration. All

authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data available in article supplementary material.

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APPENDIX A: DEFINITION OF TERMS USED IN EXPERT ELICITATION

Accompanying the expert elicitation survey was a document defining the terms used in the elicitation. The definitions are presented here for reference.

The wind models are considered based on several sub-components within the sub-categories of ambient wind properties and disturbed flow properties introduced in Section 2.5. The sub-components are defined in Sections A.2 and A.3. The properties of suitable simulations are also defined in Section A.4. Finally, in Section A.1, the typical WFFC aims and methods for achieving said aims are defined.

A.1 | Classification of control objectives and methods

Wind farm flow control (WFFC) is a method of altering the performance of a wind farm through adjustments to the flow of wind through the wind farm. It presents an alternative to the common practice of operating wind turbines in a wind farm in a so called 'greedy' manner, whereby they maximise their own power capture and limit their own mechanical loading with no regard for other turbines in the farm.

Control objectives

Whilst there are many different potential objectives of WFFC, they can be broken down into three broad categories. These are,

1. High frequency power control
2. Low frequency power control
3. Fatigue load reduction

High frequency power control is defined here as control of the power with the objective of meeting some requirement that could change at a timescale of the order of sub-seconds to seconds. An example of a more precise control objective that falls within this category is frequency response (e.g. droop control or synthetic inertia). The second category is low frequency power control, in which the time scale of interest is of the order of minutes to hours. An example of this type of control is curtailment to meet a 10-min average power output or wake steering to maximise energy capture. Of course, many applications could be argued to fall under both high frequency and low frequency power control; for example a curtailment controller to meet a 10-min average would typically not be considered successful if the power varied wildly over the 10 min on a second by second basis. However, for such examples, the primary goal is considered in the definition of the frequency. The final potential objective for WFFC is fatigue load reduction, in which the WFFC aims to reduce the fatigue loads on the turbines compared to a baseline case. This third objective is typically coupled with a power control objective, for example, providing droop control whilst reducing fatigue loads.

Control methods

To achieve the control objectives detailed in Section A.1.1, there are two broad categories that encompass the main methods used:

Wake steering: redirects the wake by intended misalignment between turbine rotor and wind direction. This is used to steer the wake away from the centre of downwind turbines. Most common is wake steering by yaw misalignment, i.e. adjusting the yaw angle of turbine nacelles, which redirects the wake in the horizontal plane, e.g. [92]. Changing the tilt angle of the nacelle is another option which redirects the wake in the vertical direction [93].

Induction control: Intentionally curtails the power production of wind turbines. The curtailment reduces the energy captured from the wind and decreases the wind speed deficit behind the curtailed turbines [94]. This reduced power production by some turbines can still lead to an increased power output of the whole wind farm. For axial induction control, turbine nacelles are aligned with the wind direction. The controlled variables are the axial induction factors which are implemented at the turbines by changing the generator torque and blade pitch angle. Some work (e.g. [95]) has also considered a form of induction control for wake mixing, often referred to as the helix method, in which the turbine pitch actuators are operated in a manner that encourages the free-stream to mix with the wake to speed up wake recovery.

Note that there are other methods for wind farm control, such as moving floating wind turbines to avoid wakes using a system of pulleys [96], however, such alternative methods are rare and the vast majority of research in WFFC can be split into the two broad categories of wake steering and induction control.

A.2 | Wind model components - ambient wind

Rotor averaged effects

Wind speed. The wind speed in this context is the rotor-averaged wind speed experienced by each wind turbine in the wind farm. The wind speed model could be as basic as a mean wind speed that does not change for the duration of the simulation or could be a highly complex Naviar–Stokes representation of the flow. All wind models will have some wind speed model as it is the most fundamental part of any wind flow model.

Wind direction. The wind direction is the direction that the wind is travelling in, either local to turbine within the wind farm or across the wind farm as a whole. The direction of the wind is most basically modelled as steady state, i.e. no change in direction for the duration of a simulation. mid-fidelity models may include variation in the wind direction through application of engineering models that approximate the behaviour, whilst high fidelity models use either physical models or data based models (or even direct use of data) to represent the change in wind direction.

Lateral correlation. The lateral correlation is the statistical similarity of the wind orthogonal to the mean wind direction. Common methods for modelling the lateral correlation include very simple models (such as assuming either no correlation or identical signals), use of numerical simulation methods, meso scale modelling of the wind, or the use of real data. The real data may be used directly or as an input to machine learning methods.

Longitudinal correlation. The longitudinal correlation of the wind is the statistical similarity of the wind parallel to the mean wind direction. Turbulent wind flows evolve over time, however, often the 'frozen wake hypothesis' is used whereby the turbulent characteristics of the wind flow do not evolve but move in the mean wind direction at the mean wind speed. More high fidelity models include full atmospheric modelling.

Transients. Transients include large gusts, lulls, wind direction changes and other large transient flow structures due to weather events. These features are not statistically stationary. Transients may not be modelled at all, they could be modelled through simple 'engineering models' such as the gust and direction change models in the IEC standards. At higher fidelities, mesoscale models of wind farms include physical parameterizations to model the outer flow phenomena by including radiative transfer, surface layer models, land use models, physics parameterisation, boundary layer parameterisations, and more. These physical modelling methods can be useful as a basis for modelling transient events.

Relating to the classes introduced in Section 2.5, wind speed and direction belong to spatial properties while correlation and transients belong to spatio-temporal properties.

Local blade/rotor effects

High frequency turbulence. Whilst the rotor averaged wind speed varies with a bandwidth of around 1 rad/s, higher frequency stochastic turbulence is also present, which is rotationally sampled by the turbine blades as they sweep the rotor. This high frequency turbulence typically has little effect on the energy capture, however, the high frequency power may be affected, and the mechanical loads on the turbine are also sensitive to these higher frequency disturbances.

Wind shear. In addition to the high frequency stochastic turbulence, there are deterministic features that are sampled by the blades as they rotate. Wind shear is the variation of the wind with the height above the ground. Simple models of the wind shear, including exponential and logarithmic models are options given in the IEC standards, however, across a wind farm and over time, the wind shear may vary. Further, other effects, such as tower shadow may also be accounted for in the turbine level modelling.

Wind veer. Wind veer is the variation of the wind direction across the turbine rotor. Wind veer may have significant effects on energy capture and loads for turbines, but there could also be implications for the wake in wind farm control simulations.

A.3 | Wind model components - disturbed flow effects

Wake effects

Profile. The magnitude and spatial distribution of the wake-induced velocity deficit caused by the pressure drop. The velocity deficit diminishes as the wake recovers through turbulent mixing with the ambient flow. Depending on the wake's trajectory and recovery, available power on downstream turbines will be reduced.

Wake-induced turbulence. Increased turbulence in wakes arising from vortex shedding at upstream turbines' blade tips as well as added vorticity induced by turbulent mixing in the wake recovery process. Depending on the wake's trajectory and recovery, structural loads will increase on downstream turbines.

Deflection. The persistent lateral (or vertical) movement of wakes (with a non-zero mean direction) originating from yaw (or tilt) misalignment, changing the wake's downstream trajectory.

Meandering. The oscillatory lateral movement of wakes (with a zero mean direction), originating from low-frequency turbulent oscillations of cross-wind (lateral and vertical) velocity components. This results in spatially and temporally varying wake impact on downstream turbines situated close to the wake's mean trajectory, with a particular effect on structural loads.

Advection. The transport of the wake with the longitudinal wind speed, causing changes from upstream turbines to be felt by downstream turbine after a time delay.

Relating to the classes introduced in Section 2.5, profile and deflection belong to wake pattern while advection, meandering and added turbulence belong to wake dynamics.

Atmospheric boundary layer effects

Vertical distribution (profile). Alterations of the wind speed or direction in the vertical plane on the wind farm in a global sense due to blockage effects or global interaction with the atmospheric boundary layer.

Longitudinal (along wind evolution). Going further than the above-described average effect, the focus here is on the evolution of the wind profile in the along wind direction due to gradual influence from the wind farm through the cumulative effects of each turbine row, or interaction with atmospheric longitudinal variations such as gravity waves.

A.4 | Simulation properties

Simulation properties refer to assumptions about time variability and number of turbines made when developing and/or using models to reduce complexity.

In mid-fidelity codes, the simulation is typically two-stage with a pre-generation of the wind field prior to the dynamic simulation of the farm/turbine. Information about the stage that simulation properties typically refer to is given in the following.

Time variability

Time variability is how the simulated wind field changes over time. In steady state models, changes in the flow are computed quasi-statically over time (i.e. independently on each other), the mean value is of interest at each step. This is the typical approach for engineering (low-fidelity) wake models and RANS models. Dynamic models on the other hand encompass time-varying changes in for instance turbine response, controls and wake, but may treat flow fluctuations in a stationary or transient way, explained in the following. In mid-fidelity simulations, this refers typically to the first of the two stages where choices about time variability are made.

Stationary. The statistical properties of the process do not vary through the simulation (the statistical properties are of interest). This category includes time variability of Gaussian processes associated with linear and frequency-domain models, obtained for instance by using a spectral representation of turbulence. This is the typical mid-fidelity approach based on synthetic turbulence used in mid-fidelity simulations.

Transient. The statistical properties of the process do vary through the simulation (the continuous/instantaneous/time domain values are of interest). This is the typical high-fidelity approach in LES models. In mid-fidelity simulations, this is the approach when high-fidelity LES simulations are used for the first stage (resulting in a hybrid-fidelity approach).

Required scale of simulation

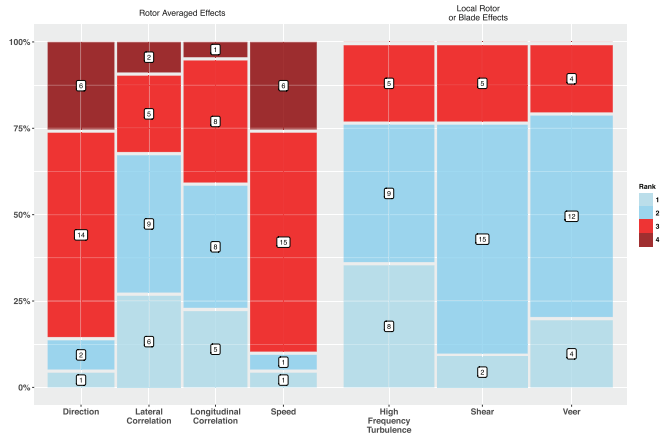
The required scale of simulation is the number of turbines that must be represented in a single simulation to give an accurate assessment of the control method. This may range from single turbine to cluster (part of a farm, typically 2–9 turbines) to farm (10+ turbines).

In mid-fidelity codes, the scale of simulation refers to the dynamic second stage, which may be one single turbine while the effect of other turbines is incorporated through the first stage (then not in a fully dynamic manner).

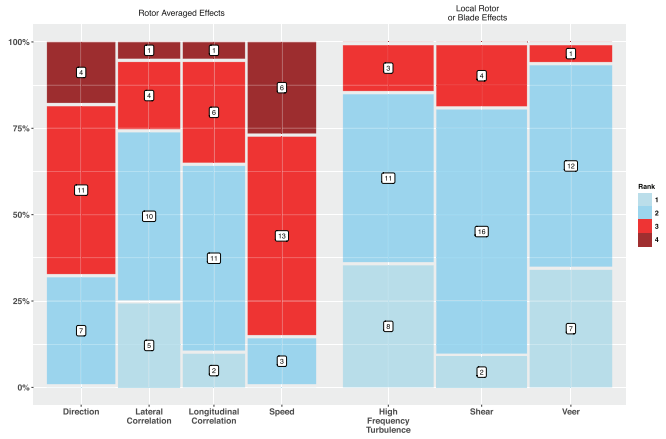
While the difference between single- and multiple-turbine simulations relates to clearly distinct modelling approaches and code architectures, the difference between cluster and farm scales is typically more related to computational complexity and cost.

APPENDIX B: FULL RESULTS OF ELICITATION

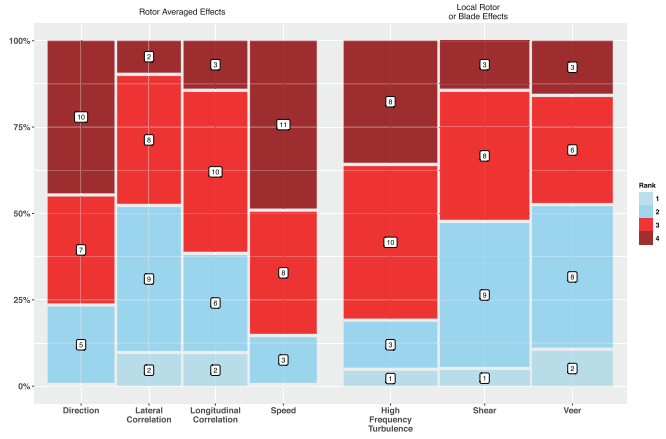
In this appendix the full results of the expert elicitation survey are presented for reference. See Figure B1 for ambient wind properties results, Figure B2 for disturbed flow properties results, and Figure B3 for simulation properties results.



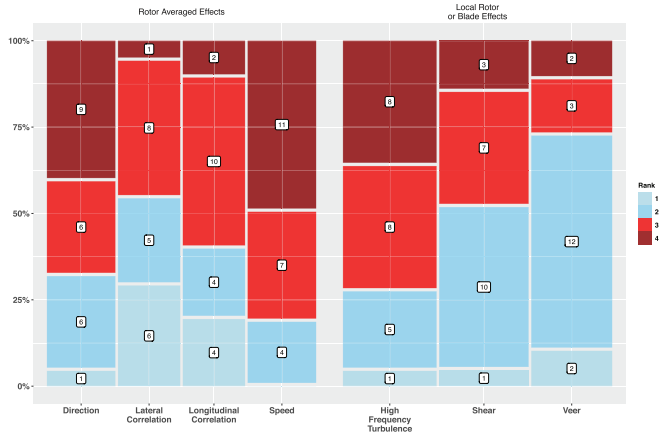
(a) Low frequency power investigation with wake steering control.



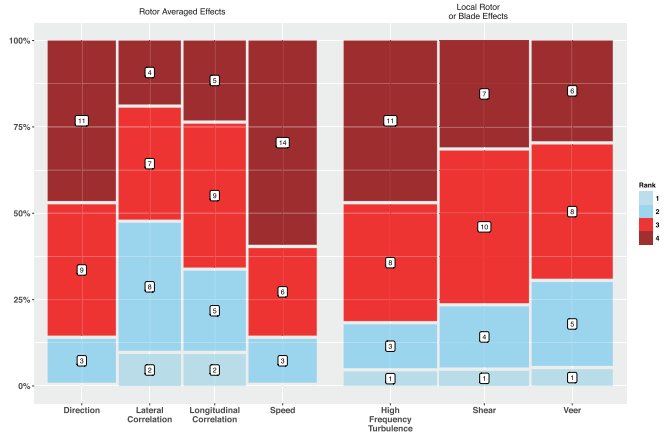
(b) Low frequency power investigation with induction control.



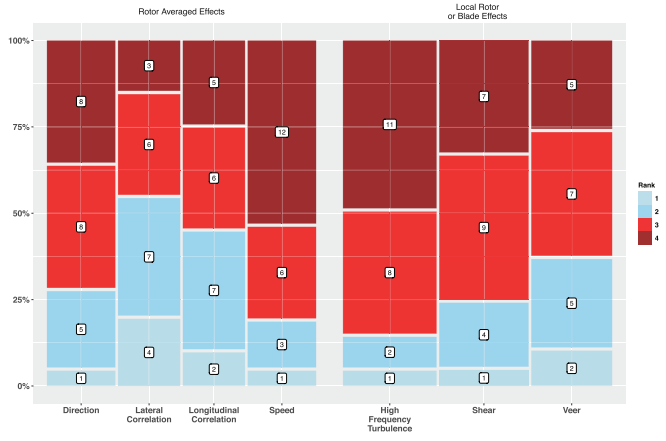
(c) High frequency power investigation with wake steering control.



(d) High frequency power investigation with induction control.

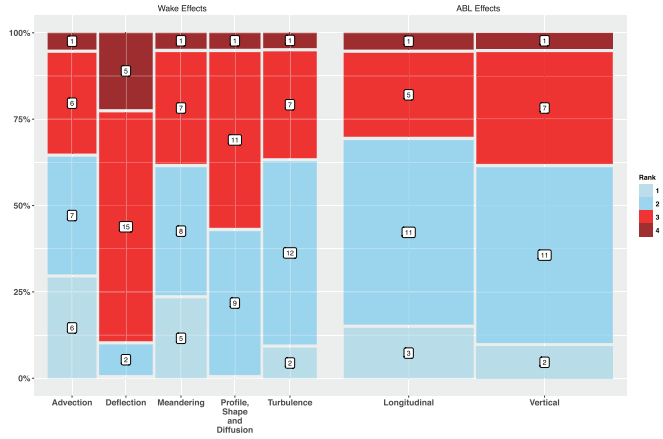


(e) Fatigue load investigation with wake steering control.

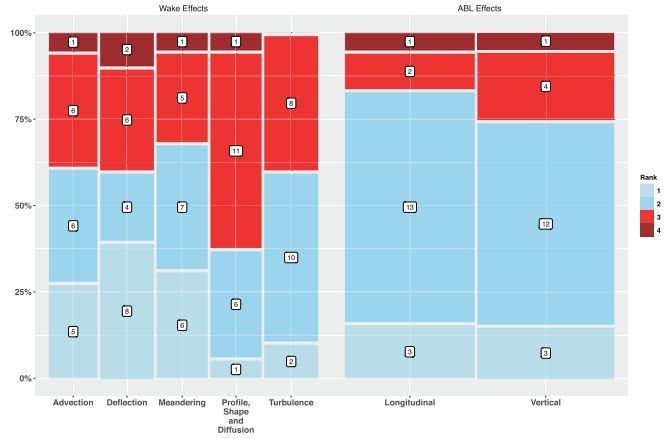


(f) Fatigue load investigation with induction control.

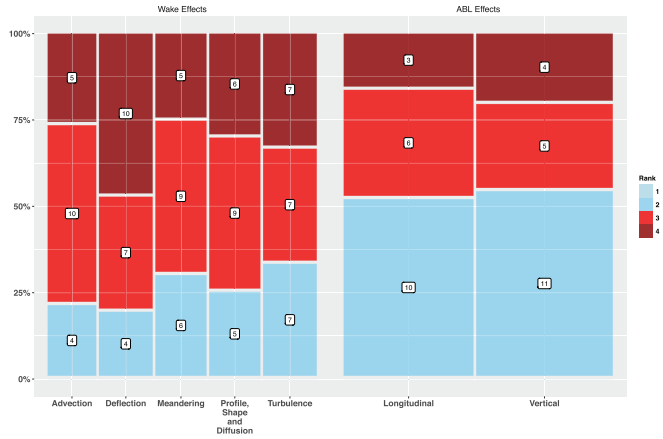
FIGURE B1 Ambient wind properties, importance of model inputs for different simulation objectives. Ranking system: 1 - not required/not adequate; 2 - beneficial to have; 3 - required (low fidelity/resolution); 4 - required (high fidelity/resolution).



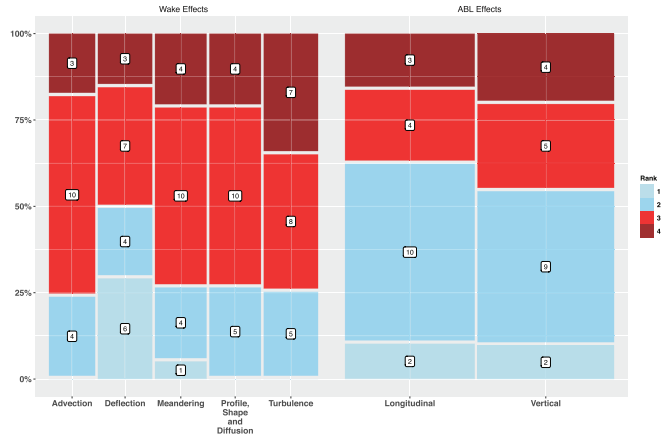
(a) Low frequency power investigation with wake steering control.



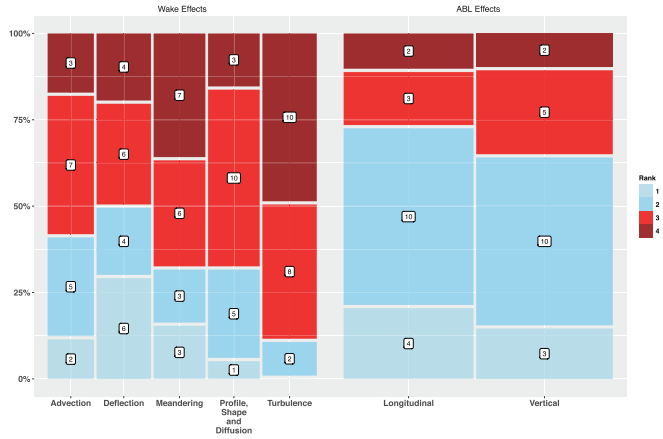
(b) Low frequency power investigation with induction control.



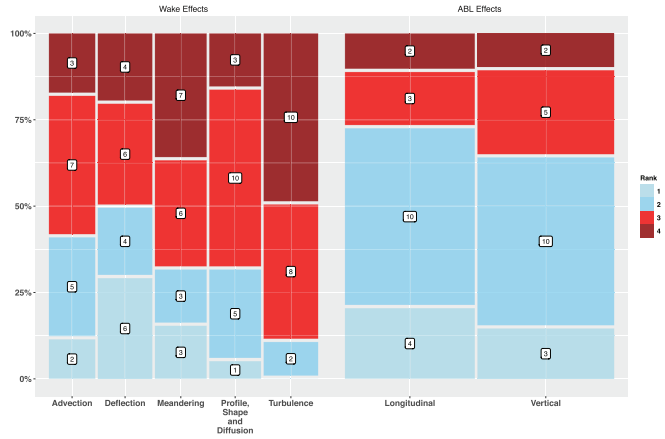
(c) High frequency power investigation with wake steering control.



(d) High frequency power investigation with induction control.

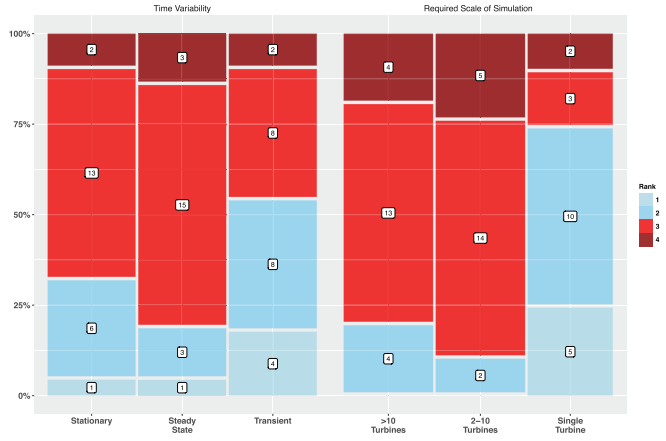


(e) Fatigue load investigation with wake steering control.

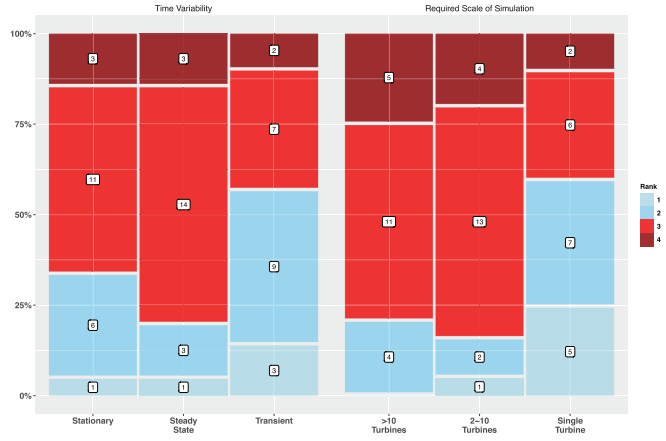


(f) Fatigue load investigation with induction control.

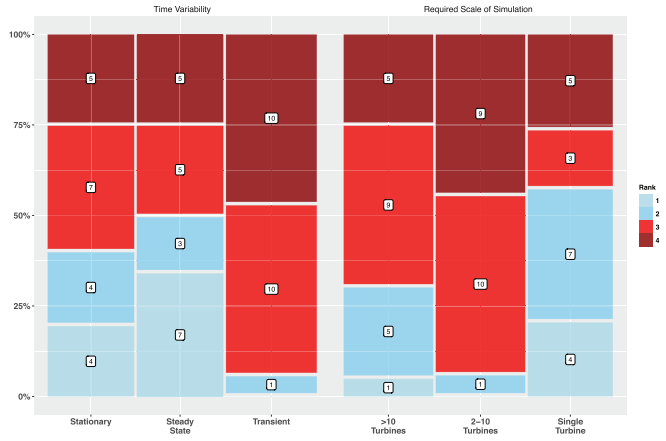
FIGURE B2 Disturbed flow properties, importance of model inputs for different simulation objectives. Ranking system: 1 - not required/not adequate; 2 - beneficial to have; 3 - required (low fidelity/resolution); 4 - required (high fidelity/resolution).



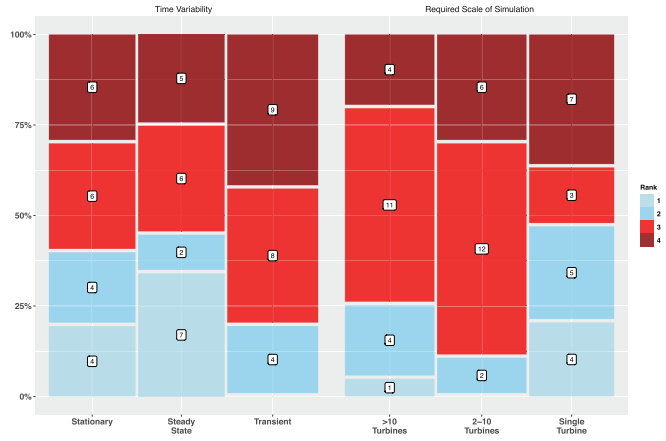
(a) Low frequency power investigation with wake steering control.



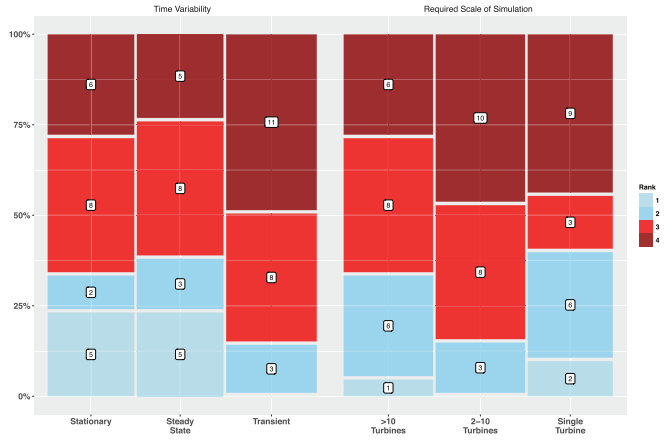
(b) Low frequency power investigation with induction control.



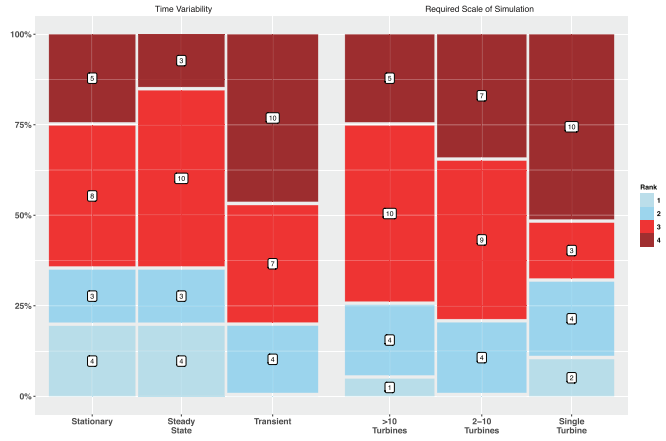
(c) High frequency power investigation with wake steering control.



(d) High frequency power investigation with induction control.



(e) Fatigue load investigation with wake steering control.



(f) Fatigue load investigation with induction control.

FIGURE B3 Simulation properties, importance of model inputs for different simulation objectives. Ranking system: 1 - not required/not adequate; 2 - beneficial to have; 3 - required (low fidelity/resolution); 4 - required (high fidelity/resolution).