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System Modeling Frameworks for Wind Turbines and Plants: Review and Requirements Specifications

iea wind

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Executive Summary

System modeling frameworks for wind turbines and wind power plants are used by research groups and industry to design wind energy systems that take into account key trade-offs across performance, cost, and reliability at both the turbine and plant levels. The frameworks are exercised using a variety of multidisciplinary design, analysis, and optimization methods. To improve interoperability and foster collaboration, this report proposes a classification system for the frameworks along the dimensions of model fidelity and scope. The classification system is first motivated by a review of the state of the art in the development of software frameworks for integrated wind turbine and plant simulation. Within each major wind turbine and power plant subsystem, a matrix is developed for the disciplines used and the fidelity levels with which each discipline can be modeled. The existing frameworks are then classified according to the matrix. Next, an ontology is proposed that allows for standardizing how data are transferred between the most common discipline-fidelity combinations used in the frameworks. A common representation of data creates the ability to (1) share system descriptions and analysis results, supporting more transparent benchmarks and comparison, and (2) integrate models into workflows within and across organizations for improving the efficiency and performance of wind turbine and power plant design processes. Ultimately, this integration leads to better overall wind energy system designs with high performance and low costs.

Acknowledgments

This work is the result of six years of effort from the team that forms the International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Task 37 on Wind Energy Systems Engineering and Integrated Research, Design, and Development. All task participants are gratefully acknowledged.

List of Acronyms

AEP annual energy production

BEM blade element momentum

CFD computational fluid dynamics

CPACS Common Parametric Aircraft Configuration Schema

DOE U.S. Department of Energy

IEA Wind International Energy Agency Wind Technology Collaboration Programme

JSON JavaScript Object Notation is a lightweight data-interchange format

MDAO multidisciplinary design, analysis, and optimization

MDO multidisciplinary design optimization

NetCDF Network Common Data Form

NREL National Renewable Energy Laboratory

SCADA supervisory control and data acquisition

SDO system design optimization

YAML human-friendly data serialization language for all programming languages

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivating Multidisciplinary Analysis and Optimization

Over the last few decades, wind energy has evolved into a large international industry involving major players in the manufacturing, construction, and utility sectors. Coinciding with industry growth, significant technological innovation has resulted in larger turbines and wind plants with lower associated costs of energy. However, the increasing importance of wind energy's role within the electricity sector imposes more requirements on the technology in terms of performance, reliability, and cost (Veers et al. 2019). To address these changing expectations, the industry has focused on achieving a variety of goals, including reducing installed capital costs for the turbine and plant, decreasing the downstream costs for operation and maintenance, increasing energy production, and minimizing negative external environmental impacts such as noise emission or habitat disruption. In many cases, these goals involve trade-offs. For example, up-front investment in a robust component design may avoid large downstream costs for component repair and replacement. In another case, the design of a machine with a higher tip speed can reduce required torque and loads through the drivetrain but also leads to more aeroacoustic noise that adversely impacts surrounding communities.

Trade-offs and techno-economic conflicts such as these exist throughout the entire system (Dykes et al. 2011; Ning, Dykes, and Quick 2019). Wind turbine and wind power plants involve complex physics from many disciplines that must be analyzed together to inform wind turbine and power plant design, operation, and control. Wind energy systems are linked via a set of physics crossing a huge range of geospatial and temporal scales (Veers et al. 2019):

- The atmosphere and plant flow physics: Large-scale weather phenomena flow down and into the plant where the flow field is also influenced by local topography and other terrain features. In addition, upstream turbines modify the flow locally, with a velocity deficit and added turbulence behind each rotor, to create "wakes" that propagate downstream, interacting with each other and other structures in the flow that builds in complexity with each successive row of turbines in the plant.
- Plant and turbine loads and control: Each turbine interacts with the flow dynamically and adapts its behavior based on its own individual performance criteria (increasing energy production, reducing loads, or providing frequency/voltage control support to the electric grid). Additionally, there are plant-level control signals that increasingly treat the fleet of wind turbines in a plant as an integrated system for optimizing overall energy production and costs.
- Electric system dynamics: Increasingly, the larger electric system dynamics can not be treated as exogenous, and the coupled modeling of the dynamics of the wind turbine electrical system and larger grid system must be addressed to thoroughly assess the ability of wind power plants to provide critical services to the grid.

Given the complexity and coupling, understanding and improving the design and dynamics of a wind power plant requires system-level models with increasing levels of scope and fidelity. But this is a challenging task and there are open research topics in all areas of wind power plant design and operation. For instance, how does pitching the blades in one set of turbines affect the atmospheric boundary layer flow at a group of downstream turbines, where the convection time at the nominal hub-height wind speed may be a half-hour or more? How should the power dispatch function respond to rapidly varying flow conditions across the plant with, for example, the passage of weather fronts or thunderstorms? How should the converters at each turbine—and at substations for plants with high-voltage direct-current transmission—be operated to best support power-system stability? How should the level of fatigue degradation of each turbine be monitored, and how should the turbines be operated, in order to most economically distribute the degradation among the turbines in the plant? What influence does turbine placement have on energy production, effective turbulence intensity, fatigue degradation, maintenance requirements, and system costs?

Finding answers to those and many more system-level questions is a multidisciplinary effort, requiring the coordination of diverse research groups and analytical capabilities. A community of wind energy researchers and practitioners has developed over the last decade that leverages formal multidisciplinary design, analysis, and optimization (MDAO) approaches to tackle system-level questions. MDAO is a class of methods that has been applied to a range of design and analysis problems for complex technical systems such as aircraft, aerospace technologies, vehicles,

ships, and more (Martins and Ning 2022). The key elements of MDAO can be broken down into the problem formulation and workflow. The problem formulation identifies the major important elements of an analysis or design optimization, including variables, parameters, outputs, and quantities of interest (for analysis) or constraints and objective(s) (for optimization). Closely tied to the problem formulation is the workflow architecture, which governs how models pass information to one another within the overall analysis and/or optimization. From the most simple perspective, a workflow could be a linear sequence of analysis passing information from one discipline to the next. At another extreme, the MDAO workflow could include several nested analyses or optimizations with various levels of couplings between them. For more detail on MDAO in general, refer to Martins and Ning (2022), or for wind energy applications specifically, refer to Ning, Dykes, and Quick (2019) and references therein.

1.2 The Need and Value of an Ontology

To support MDAO of any system with various levels of scope and model fidelity, standard representations of the information passing from one discipline to another, and from one fidelity level to another within a given discipline, are required. Such standard representations ensure the accuracy of integrated system modeling as well as enable collaboration across an increasingly diverse set of stakeholders. Therefore, the International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Task 37 on Wind Energy Systems Engineering and Integrated Research, Design, and Development has developed an *ontology* to help standardize the representation of information that flows across MDAO workflows applied to wind turbine and plant design, operation, and control.

In computer and information science fields, an ontology involves the formal naming and definition of concepts and data within categories and having specific properties and relations. There are a number of efforts, as will be discussed, within the wind energy community to establish taxonomies, particularly for wind energy data. In contrast to an ontology, a taxonomy provides classification of information (even with hierarchies), but does not necessarily involve the additional step of specifying properties and relations. The specific emphasis of IEA Wind Task 37 on MDAO, which necessarily involves the transfer and translation of information across many disciplines (i.e., with an emphasis on the flow of information), led to the decision to develop an ontology rather than a taxonomy.

This wind energy MDAO ontology has two primary objectives such that through its adoption, researchers and practitioners will have the ability to:

- Share system descriptions and analysis results for supporting more transparent benchmarking and comparison
- Integrate models together into streamlined workflows within and across organizations for improving the efficiency and performance of wind turbine and power plant design processes.

The value in terms of reducing the burden of information exchange can be seen as happening at two levels. For example, if you have a number of stakeholders performing similar analysis who need to share a common system model (say, of a particular aircraft or wind turbine design) and easily compare analysis results, the approach reduces the effort to translate the model among all the different models used by each stakeholder, because only a single translator is needed for each model. Conversely, if a number of different models are chained together in an MDAO workflow, and the desire is to swap a particular model or set of models for another (for instance, different aerodynamics analysis tools), having a standard interface of that module with the rest of the tool chain simplifies the need for having a custom modeling workflow for every different MDAO workflow permutation.

Also related to the ontology development are activities to establish taxonomies for wind energy applications. There have been several efforts over the years to provide taxonomies that break down information at the wind plant and turbine level for applications related to sharing data, classifying system uncertainties and costs, and organizing information about system reliability. A major effort to establish a wind energy taxonomy was part of a larger effort to systematically analyze wind turbine failure and reliability data. In 2008, Sandia National Laboratories in the United States established a wind plant reliability database to characterize current wind power plant reliability performance and identify patterns and trends to inform research and industry action to improve plant reliability and lower maintenance costs (Hill et al. 2009). A wind turbine and power plant taxonomy was developed to help classify the supervisory control and data acquisition (SCADA) event codes for further analysis. This taxonomy was component-based and categorized the turbine into finer and finer physical elements (i.e., drivetrain, then low-speed-shaft subsystem, then main bearing component). This taxonomy was later used as one of the sources of information for the development of a much more detailed system cost breakdown structure for offshore and land-based wind turbines and power

plants in the United States (Mone et al. 2017) and subsequent yearly review reports on the cost of wind energy. In this case, a much more detailed breakdown of plant costs was provided both for the balance of systems costs as well as for operational expenditures. A similar taxonomy for distributed wind energy applications was also developed at the National Renewable Energy Laboratory (NREL) in 2017 (Forsyth et al. 2017).

A commonality across all the taxonomy activities is that they are focused more on the classification of data according to hierarchy rather than information exchange in a modeling paradigm, let alone an MDAO paradigm. An example of a data format standard targeting the modeling community is the Network Common Data Form (NetCDF) used within atmospheric science and meteorological modeling to aid in easier exchange of very large sets of data as produced by the models within that community (Rew and Davis 1990). Specifically, NetCDF is a set of software libraries and self-describing, machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data. Compared to the current effort, NetCDF is much more generic and applicable to a large range of scientific modeling applications involving models that create very large sets of data, such as, for example, high-fidelity fluid dynamic and structural models.

The current effort of a wind energy MDAO ontology differs from the previously described taxonomy activities in a few important ways—it is focused on the exchange of specific types of information used to describe wind turbine and power plant physics and other models, and on the easier development of MDAO workflows that couple models across components and subsystems potentially involving multiple disciplines and fidelities. However, this effort is synergistic with the previously described efforts and may in the future become part of a broader harmonization effort for both modeling and data applications in wind energy.

Through the more efficient exchange of model information and increasingly integrated analysis and optimization efforts, the wind research and wind industry community will ultimately design, build, and operate wind power plants with the best possible performance and lowest possible costs. The specifics of how the ontology serves these objectives will be discussed in this report along with a detailed discussion of the underlying principles for its development and an overview of its implementation for both wind turbine and plant MDAO. This report is organized in sequence in terms of the process used by IEA Wind Task 37 to develop the ontology:

1. State-of-the-art MDAO activities for wind energy are reviewed and a catalogue of MDAO tools for both wind turbine and plant applications is developed to provide insight into the range of applications, models, and methods used in practice.

2. A classification of MDAO workflows is developed that is decomposed first into turbine- and plant-level applications, then subsystems within each, and then the disciplines used to model each subsystem and the variations in levels of fidelity by which they are represented. The most commonly used discipline-fidelity combination for each subsystem are identified and discussed.

3. The commonly used discipline-fidelity combinations are used to construct a first version of a turbine and a plant ontology that can be employed by researchers and practitioners to share system design descriptions, analysis results, and even support more streamlined integration of models into MDAO workflows. The ontology uses a standard called JSON schema (where JSON stands for JavaScript Object Notation), which, as will be described, is an international standard for ontology structure that is supported by a set of tools for enforcing ontology implementation. High-level visualizations of the turbine and plant ontology are provided together with links to the online documentation: https://github.com/IEAWindTask37/windIO.

2 MDAO for Wind Turbines and Power Plants

MDAO, or also commonly referred to as multidisciplinary design optimization (MDO), originated in aerospace engineering and was applied to aircraft design as early as the 1970s with coupled aerostructural optimization but has only recently found broad use for wind turbine and power plant applications. MDAO generally involves coupling across a large number of disciplines that may encompass different types of physics (e.g., aerodynamics, structural analysis, controls) as well as cost or other nontechnical aspects of the system. These other models could be component cost models capturing materials and manufacturing or even models related to social acceptance, such as visual perception of wind turbine flicker or human tolerance of noise. The acknowledgement that these design decisions affect key couplings that in turn affect the system-level performance and cost of both individual wind turbines and full wind power plants has spurred the development of active MDAO research in wind energy over the last decade. The following discussion highlights these research efforts for wind turbines and plants.

2.1 Wind Turbine MDAO

Design of wind turbines using optimization dates back to the mid-1990s, when Selig and Coverstone-Carroll (1996) presented an aerodynamic design methodology combining a genetic algorithm with inverse design. Fuglsang and Madsen (1999) presented one of the first works on the multidisciplinary design of a wind turbine, in which an aeroelastic model of the wind turbine blade was used to optimize the cost of energy. Several other works followed, among them Bottasso, Campagnolo, and Croce (2012), who combined a multibody aeroelastic model with a detailed cross-sectional structural model to maximize annual energy production (AEP) and minimize mass, and also investigated design features such as bend-twist coupling. Even more recently, MDAO for wind turbine work has been extended to consider the overall design of the wind turbine, including the preliminary design and sizing of tower and drivetrain components (Bortolotti et al. 2021) as well as offshore and floating substructures (Barter, Robertson, and Musial 2020).

The workflow in Figure 1 shows the major subsystems involved in the design optimization of a wind turbine and their interactions.

Earlier works tended to use lower-fidelity models of the wind turbine rotor physics in order to keep the optimization tractable while still capturing couplings across the major subsystems and their key disciplines. However, in recent years, there have been several efforts to increase the fidelity of the models used in the optimization using advances in related fields either independently or in concert. These efforts take advantage of one or more of the following innovations:

- Leveraging increased computational power of high-performance computing and advances in computational sciences
- Applying advanced MDAO methods for more efficient optimization and lower computational cost
- Adaptation of models for optimization applications through the development of analytic, exact, or adjoint-based gradients and other model improvements.

For more detail on historical developments, recent progress, and advanced research in wind turbine MDAO, refer to Ning, Dykes, and Quick (2019).

2.2 Wind Plant MDAO

Wind power plant analysis and design is a very broad multidisciplinary field, as the design of the wind turbines, the choice of their location within the power plant, the balance of systems design, and the plantwide control strategy have complex interactions that significantly impact the plant economics and financial viability. The major modeling elements required for wind power plant design include:

- Energy production, including the flow models, models for turbine power production, and models of turbine wakes that affect the flow on downstream turbines.

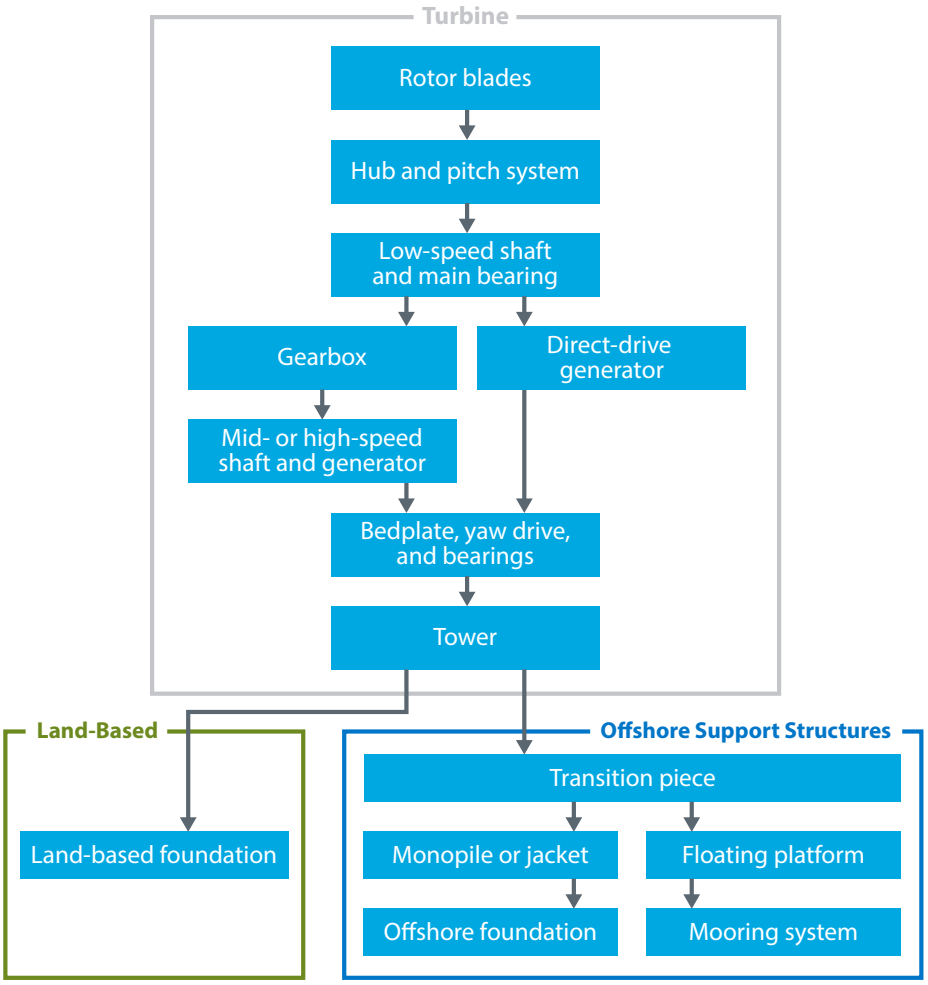

Figure 1. Major elements of a wind turbine system, including the rotor, nacelle, and drivetrain components, and the support structure. The arrows indicate the primary load paths of the turbine that create system coupling for structural design.

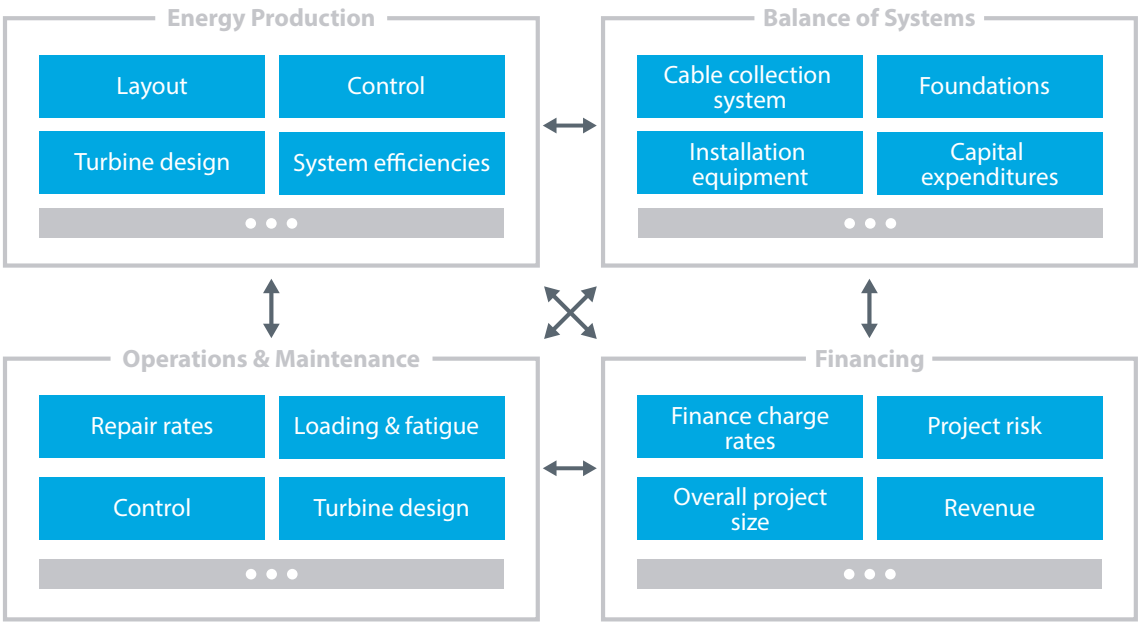

Figure 2. Wind power plant profitability/cost of energy: major subelements in the analysis and design of wind power plants

- Balance of systems costs, including overall project management and development, foundation design, plant infrastructure design including the electrical collection system and potentially substation, other plant infrastructure elements (roads on land, etc.), and turbine and foundation assembly and installation. More detailed design models for any of these plant subsystems are also commonplace.
- Operation and maintenance, including the reliability and availability of turbine and other plant components and associated costs over the plant lifetime through decommissioning.
- Financing of the plant to include the capital and operations expenses listed in the previous bullets, as well as financial parameters related to the project structure, taxes, incentives, insurance, and more.

Each of the areas described can be broken down into a number of additional subsystems and/or processes. The diagram in Figure 2 shows the major wind power plant elements that include both physical and cost analysis. Due to the system couplings, there are decisions in each subsystem that affect other aspects of the plant performance and cost. For example, the placement of the wind turbine influences the plant AEP but also affects the design of the cable collection system, which in turn affects not only the balance of systems costs but also the electric system losses. These coupled relationships are often exposed as circular dependencies in a design process that must be addressed with iteration.

The field of wind power plant MDAO is so broad that researchers typically only focus on a subset of the problem, such as wind plant AEP predictions, wind plant control, or wind plant layout optimization. Furthermore, as researchers typically have educational backgrounds in a single discipline, there is a tendency to focus modeling efforts on that discipline while relying on low-fidelity models in other disciplines or even disregarding them. For instance, studies that approach wind power plant analysis from a "mechanical" perspective—for example, trading off energy production with mechanical loads on the turbine structures—tend to ignore the electrical grid; studies that approach wind power plant analysis from the wider grid integration perspective tend to employ aggregated turbine models, in which many turbines are lumped into one equivalent unit. Similarly, studies on the atmospheric dynamics of wind plants tend to ignore or greatly simplify the mechanical and electrical models.

An imbalance in model fidelity can be an appropriate modeling choice to address a specific research question, but full MDAO methods seek a balanced level of fidelity throughout the system. Historically, MDAO of wind power plants centered around flow models focused on plant AEP, given the interests of the original developers. Over time, these models evolved to become frameworks that included design optimization capability of several subsystems such

Table 1. Catalogue of Research Wind Turbine MDAO Tool Sets Listed in Alphabetical Order

#	Name	Organization	Research/Commercial
1	ATOM	ORE Catapult, UK Uni Bristol, UK	Research, closed source
2	BladeOASIS	CENER, ES	Research, closed source
3	Cp-Max	TU Munich, DE Politecnico di Milano, IT	Research, closed source
4	FOCUS6	Knowledge Centre WMC, NL	Commercial
5	HAWTOpt2	DTU Wind Energy, DK	Research, partially open source
6	LMS Samtech Samcef Wind Turbines	LMS Samtech (Siemens), DE	Commercial
7	OneWind Modelica Library	Fraunhofer IWES, DE	Research, partially open source
8	QBlade	TU Berlin, DE	Research, fully open source
9	Turbine.Architect	DNVGL, UK	Commercial
10	WISDEM® and WEIS	NREL, USA	Research, fully open source

as the electrical collection system, turbine foundations, road layout network, and even plant control strategies that affect energy production and loads. Once MDAO modeling capabilities for wind were able to account for critical cost elements such as electric cables and roads, industry confidence and use of formal optimization approaches to wind power plant design increased—for example, by using commercial software packages such as WindFarmer from Det Norske Veritas (DNV) or OpenWind from UL. However, the models for the various plant subsystems still tend to be of lower fidelity compared to the energy production models, which range from low to middle fidelity. Just as with wind turbine MDAO, the community is moving toward the use of higher-fidelity models and advanced MDAO techniques (refer to Ning, Dykes, and Quick (2019) for a more detailed review).

2.3 Catalogue of Wind Energy MDAO Tool Sets

The recognition of the potential for MDAO to improve wind turbine and power plant operation, design, and control has led to the development of a number of software tool sets both in the research and industry communities. IEA Wind Task 37 has developed a catalogue of these tool sets to help inform the needs of ontology development by identifying commonalities and differences between the existing modeling frameworks. In building the catalogue, the Task found that there are many traditional tools for modeling wind turbine components and overall system dynamics along with separate tools for modeling wind plant performance, cost, and subsystem design. The surveys of tools shown in the tables below focus on those that go beyond the system boundaries of component-focused models to look at wind turbines and plants in more integrated ways.

2.3.1 Wind Turbine MDAO Tool Sets

A list of MDAO-capable tool sets developed by research institutes and consulting firms is found in Table 1. The tool sets have different focus areas and follow different approaches for the design optimization. Some, such as ATOM, BladeOASIS, Cp-Max, HAWTOPT2, and QBlade, have a stronger (or even only) focus on the rotor design, often adopting mid- or high-fidelity simulation models for that component. Other tool sets, such as LMS Samtech, OneWind, Turbine.Architect, and WISDEM, have a broader focus and typically adopt lower fidelity models that have the advantage of being computationally lighter.

In terms of simulation models, all frameworks listed in Table 1 adopt blade element momentum (BEM) theory to estimate rotor loads and performance, whereas different frameworks adopt different fidelity levels to design the rotor structure. Here, the tools BladeOASIS and WISDEM® (WISDEM stands for Wind-Plant Integrated System Design & Engineering Model) have so far adopted modal beam formulations coupled to Euler cross-sectional analysis models while Cp-Max, HAWTOpt2, and Turbine.Architect, have opted for multibody models with fully coupled cross-sectional solvers. For the controller, a wider variety of approaches have been adopted, ranging from simple power/speed regulation to full supervisory controllers, some with load alleviation capabilities (e.g., Turbine.Architect). Only a portion of the tool sets have the capability to design the nacelle system—of them, WISDEM includes the most detail. Nevertheless, more tool sets address the challenge of an integrated design of the tower (Cp-Max, FOCUS6, OneWind, Turbine.Architect, WISDEM), in which the simulation approach can mimic that of the rotor blades. For a land foundation, no framework has yet gone beyond equivalent stiffness properties. Finally, the

Table 2. Catalogue of Research Wind Power Plant MDAO Tool Sets Listed in Alphabetical Order.

#	Name	Organization	Research/Commercial
1	FLORIS	NREL, USA	Research, fully open source
2	Openwind	UL - AWS Truepower	Commercial, partially open source
3	PyWake	DTU Wind Energy, DK	Research, fully open source
4	TopFarm	DTU Wind Energy, DK	Research, partially open source
5	WAsP	DTU Wind Energy, DK	Commercial
6	WindFarmDesigns Park Optimizer	WindFarmDesigns	Commercial
7	Windfarmer	DNV GL, UK	Commercial
8	Window	TU Delft, NL	Research, fully open source
9	WindPRO	EMD, DK	Commercial
10	WindSE	NREL, USA	Research, fully open source
11	WindSim	WindSim AS, NO	Commercial

cost analysis typically combines bottom-up cost models for some components, notably full bill of materials and manufacturing models for the blades (Cp-Max, WISDEM), with semiempirical cost models, often derived from the ones originally implemented in the NREL Cost and Scaling Model (Fingersh, Hand, and Laxson 2005) and now available via WISDEM.

All tool sets offer a high degree of automation, with some also offering a modular approach (HAWTOpt2, OneWind, Turbine.Architect, WISDEM). A few tool sets adopt dedicated MDAO libraries, such as OpenMDAO (HAWTOpt2, WISDEM) (Gray et al. 2019) and Modelica (OneWind) (Fritzson et al. 2020). Multifidelity approaches are also used, especially in Cp-Max and Turbine.Architect, offering the possibility to switch between static and dynamic loads estimation as well as between beam and 3D finite-element analysis for the blades. All tools are implemented to support parallel computing, at varying degrees. Python is the most common programming language, which is, however, often only a wrapper around submodels programmed in a variety of languages (mostly C#, C++, and Fortran). Finally, most tool sets are at least partially closed source and have either commercial or limited public availability. WISDEM is the notable exception, in that it is fully open source under the Apache v2 license. Major turbine manufacturers also have their own conceptual design tools, which typically remain in-house. Examples are Predator and GRC Tool from General Electric, RotorOpt 2.0 from LM Windpower, and SBOpt from Siemens-Gamesa. Those tools are far less publicly described, but their capabilities are known to be fairly advanced.

2.3.2 Wind Power Plant MDAO Tool Sets

MDAO capabilities were developed earlier for wind power plants than for wind turbines. Numerous academic frameworks for wind plant optimization have been created to support the significant body of research on the topic developed over multiple decades (refer to Ning, Dykes, and Quick (2019) for more detail). There have also been several commercial tool sets that have been developed over the past decade and are now commonly used in industry for real-world applications. However, formal MDAO for wind power plant applications is arguably less mature than for wind turbines due to several factors, including:

- Large scope of design problem, including energy production, turbine loading, foundation design, electrical collection subsystem, plant infrastructure, and more
- Large uncertainties in both the physical and cost models associated with the different system elements.

As a result, there are fewer comprehensive and self-sustaining frameworks for wind power plant MDAO. Table 2 provides a high-level overview of these frameworks.

The commercial tools include Openwind, Park Optimizer, WAsp, Windfarmer, WindPRO, and WindSim. The oldest is WindFarmer from DNV, but most of the tools have undergone significant development with respect to their optimization capabilities in the last several years. The commercial tool sets largely grew from resource and energy assessment for prescribed turbine layouts and account for various levels of fidelity in the modeling of the wind resource and turbine wakes. Over time, the tool sets have evolved to enable optimization of the layout first for energy production and subsequently for key project costs, thereby giving on overall cost of energy. As of early 2019, Openwind is the most sophisticated commercial tool set from an MDAO perspective, as it combines models for energy

as well as balance of systems costs for electrical infrastructure and roads, with suboptimization of these other plant features, into a full wind power plant cost of energy evaluation.

The remaining tools—FLORIS, PyWake, TopFarm, Window, and WindSE—have been developed within the research community and have been applied largely to research applications. FLORIS is a controls-focused wind power plant simulation software implemented in Python that is used to design wind power plant controllers, especially for wake steering, and perform system-level optimizations, including layout and coupled layout/wake steering (Fleming et al. 2016; Gebraad et al. 2017; NREL 2022). PyWake is a wind power plant simulation tool with optimization features that can calculate wind power plant flow fields, power production, and annual energy production of wind power plants using models of different fidelities (Pedersen et al. 2019). TopFarm was the earliest of the tools to be developed and integrated for the first time the ability to design a wind power plant while taking into account, to a degree, the impact of the site design on the wind turbine loads and reliability (Réthoré et al. 2014). It has recently seen renewed application to wind power plant design accounting for loads but also other considerations including plant infrastructure and wind plant controls (Réthoré et al. 2014). WindSE is a Python package initially developed to perform wind power plant simulations and optimization; the scope has recently been expanded to run integrated plant and turbine design optimization studies (Allen et al. 2022). Window is an MDAO framework from Delft University of Technology (TU Delft) developed for offshore wind power plant design that accounts for energy production as well as major infrastructure costs of electric collection system design (including substation placement) and support structure sizing and cost (Moreno and Zaaijer 2018). However, it has not been developed since its initial release.

3 Classification of Wind Energy MDAO Workflows by Subsystems, Discipline, and Fidelity

The catalogues listed in Tables 1 and 2 identify a diverse set of model frameworks and approaches to wind energy applications. Developing an ontology that simultaneously addresses all applications and model types is nearly limitless in scope and would require constant updating. At the same time, there are core commonalities across the different research and commercial efforts that enable us to incrementally build out an ontology that meets minimum requirements for interoperability.

To achieve this goal, the IEA Wind Task 37 participants surveyed related efforts in other industries and developed an approach to provide the basic functionalities that would benefit a broad cross section of the community. A related effort for aeronautical applications is the Common Parametric Aircraft Configuration Schema (CPACS) (Alder et al. 2020). Per its website, CPACS is "a driver for multi-disciplinary and multi-fidelity design in distributed environments. CPACS describes the characteristics of aircraft, rotorcraft, engines, climate impact, fleets and mission in a structured, hierarchical manner." Early efforts involving CPACS identified the need for providing information exchange in MDAO applications to aircraft design not just across disciplines, but also across different discipline levels. For instance, in Rizzi et al. (2012), a matrix is presented and discussed that breaks down airplane design first into disciplines and then, for each discipline, different models representing that discipline at low, medium, and high levels. The examples include disciplines such as aerodynamics, structures, and noise, with low-, medium-, and high-fidelity model types identified for each. For instance, for aerodynamics the low-fidelity model includes empirical methods or vortex lattice methods, the mid-fidelity model considers Euler equations, and the high-fidelity model includes Reynolds-averaged Navier-Stokes methods. An interesting insight is that each of these different aerodynamic models involves a different level of model abstraction away from the "real" aerodynamics of the system and thus different sets of information. More broadly, a critical element of information flow in MDAO is understanding that both the discipline and the specific fidelity level (and model implementation) used within that discipline determine the information needed for that particular analysis.

The insight of the influence of fidelity on how system information is represented led to the development of a series of discipline-fidelity matrices to explore potential MDAO workflows for wind turbine and power plants. This also highlighted the most-used combinations of discipline and fidelity in current research and industry practice. The approach and findings are explained in greater detail by Perez-Moreno et al. (2018). Through working sessions organized by the Task, a three-dimensional view of the MDAO landscape emerged with scope (disciplines), fidelity, and workflow architecture, as shown in Figure 3. An MDAO setup may involve multiple models of the same discipline at different fidelity levels, models across disciplines of the same fidelity, or a mixture thereof. In addition, the workflow architecture may involve various levels of complexity, from a simple sequential analysis to a set of nested analyses, to multilevel analyses with coupled variables. Figure 3 depicts a hypothetical wind turbine MDAO application in which three disciplines describe the scope along the x-axis (blades, hub, tower), the workflow with two alternative MDAO architectures along the y-axis, and the model fidelity along the z-axis with three distinct levels.

Figure 3 underscores that the number of permutations of potential MDAO applications to wind energy is limitless. It is thus important to focus on the minimum level of required information exchange to foster interoperability, rather than trying to address all potential scenarios at the same time. Additionally, it is recognized that both wind turbines and power plants are systems of systems, such that it is beneficial to first decompose both wind turbines and wind power plants into subsystems, for which multiple discipline-fidelity matrices are then developed. This was the development philosophy used by the Task 37 team.

A helpful paradigm for this next step is the differentiation between MDO—focused on disciplines—and system design optimization (SDO), which addresses the integration of multiple components, subsystems, or systems together into an optimization (Sartori 2019). In MDAO, both MDO and SDO are included. For the purposes of the development of wind energy discipline-fidelity matrices, the Task 37 team first decomposed the metasystem (the wind turbine or wind power plant) into subsystems and then developed one or more discipline-fidelity matrices for each subsystem.

In the next two subsections, the discipline-fidelity matrices for wind turbines and plants are presented for all the major subsystems of interest. The most common combinations of discipline and fidelity used by the wind energy

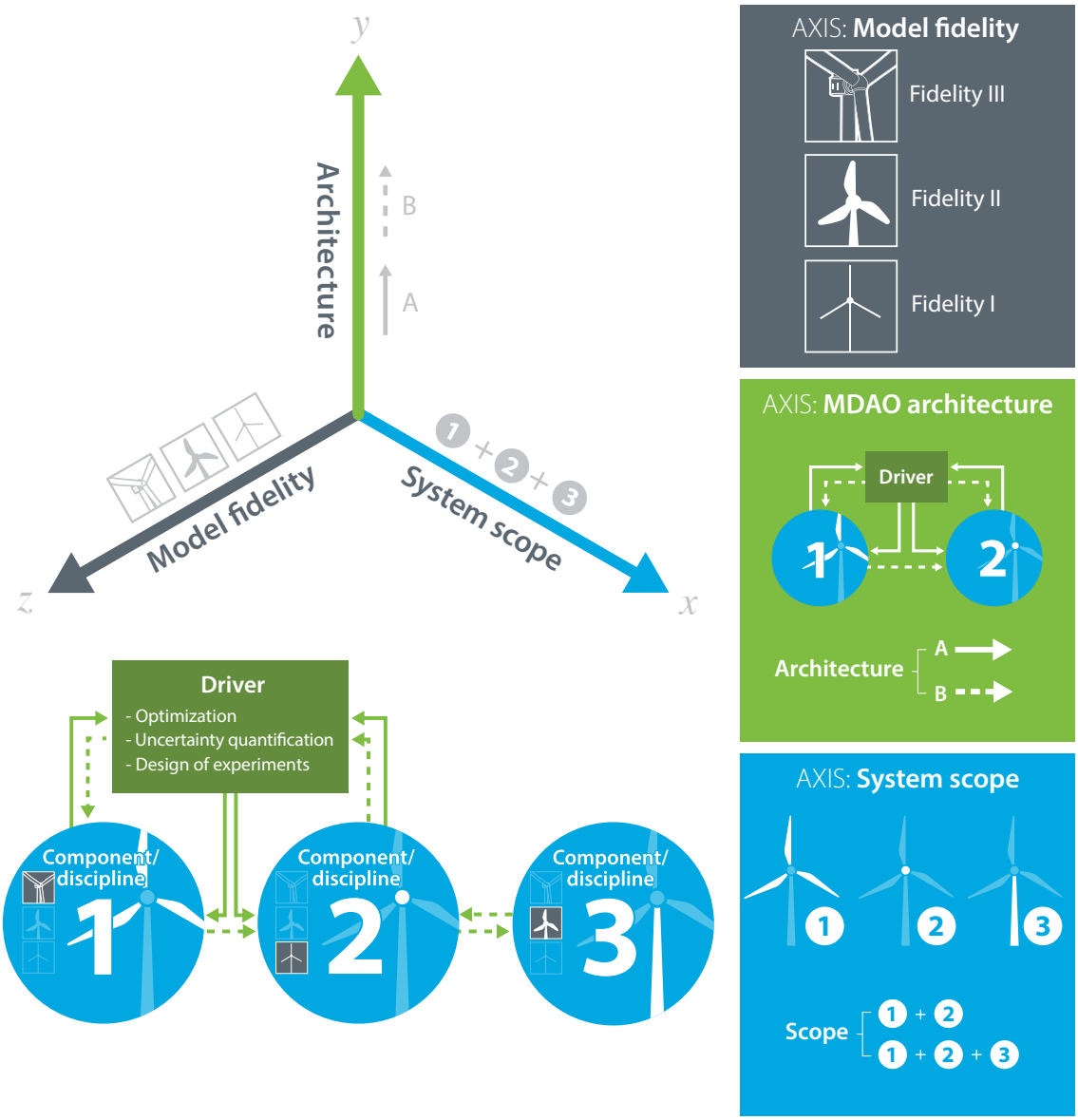

Figure 3. Dimensions of MDAO that include the system scope (disciplines), model fidelity, and workflow architecture, inspired by illustrations from Perez-Moreno et al. (2018)

		Hi-fi time-resolved turbulent CFD	3D solid				
Time-resolved LES CFD		Blade-resolved CFD	3D shell			Time-resolved LES	
Vortex methods	LES	Actuator line CFD	Super-element		Supervisory controllers		
DWM	RANS CFD	Actuator disc CFD	Elemental non-linearity (GEBT)	Generalized 6x6	Safety protection functions		Full BOM and end-to-end virtual factory
Engineering unsteady 3D (Veers/Mann)	Inviscid Euler methods	Vortex methods	Multibody (linear/nonlinear)	Timoshenko	Load mitigation	Time- and frequency-based models	Full BOM and manufacturing process flow
Unsteady uniform	Panel methods	BEM	Modal	Euler	Power/speed regulation	Frequency-based models	Empirical design-based
Steady inflow	Look-up table	Look-up table Cp/Ct/Cq	Rigid	Analytical solid	Prescribed operation	Semiempirical	Empirical parametric
Inflow aero	**Airfoil aero**	**Rotor aero**	**Structures**	**Cross-sections**	**Controls**	**Aeroacoustics**	**Cost**

Modeling Fidelity

System Scope: Disciplines Included

Figure 4. Discipline-fidelity matrix for the wind turbine rotor. The blue cells represent the most common combinations for the task participants (3D = three-dimensional; DWM = dynamic wake meandering; LES = large-eddy simulation; CFD = computational fluid dynamics; RANS = Reynolds-averaged Navier-Stokes; Hi-fi = high fidelity; BEM = blade element momentum; Cp/Ct/Cq = power, thrust, and torque coefficients; GEBT = geometrically exact beam theory; BOM = bill of materials)

MDAO community are highlighted in blue in Figures 4–9 and discussed, as they will serve the basis for the development of the ontology itself.

3.1 Discipline-Fidelity Matrices for Wind Turbines by Subsystem

The first component of a wind turbine addressed in this collaborative study is the rotor, for which the discipline-fidelity matrix is shown in Figure 4.

The disciplines involved with a MDAO process of a wind turbine rotor are found in bold on the x-axis in Figure 4; they are inflow aerodynamics, airfoil aerodynamics, rotor aerodynamics, structures, cross-sectional analysis, controls, aeroacoustics, and cost analysis. The modeling fidelity grows along the y-axis. The task participants found that the most common approach to model the inflow is through an unsteady uniform wind model (such as the one implemented in TurbSim (Kelley and Jonkman 2005)), whereas the aerodynamics of airfoils is commonly modeled with panel methods, such as the one implemented in XFOIL (Drela 1989). For rotor aerodynamics, BEM is certainly the standard. For the elastic response, although lower-fidelity models are sometimes used, a multibody solver and a Timoschenko cross-sectional analysis are most common. For controls, participants returned a variety of answers, but basic power/speed regulation is the most common fidelity chosen within MDAO studies. Finally, aeroacoustics is often not modeled or modeled via semiempirical methods, such as the Brooks, Pope, and Marcolini (1989) model, and cost analysis also typically relies on semiempirical relationships.

A similar table is populated for the nacelle mechanical components (bearings, actuators, drivetrain system, shafts, etc.) in Figure 5. Here, the MDAO wind community is moving slowly compared to rotor design, and the nacelle components are typically modeled across all disciplines (loads, thermal, contact, stress, acoustics, vibration, and cost) with empirical, semiempirical, or simple analytical models. The drivetrain component experts use more sophisticated approaches in their commercial or research projects, which suggests that the wind turbine MDAO community has not sufficiently engaged them.

Figure 6 identifies four disciplines for the generator: structural, electromagnetic, thermal, and cost. The MDAO community has also been disconnected from the generator domain experts, as no clear indications can be provided

FEA						
Lumped-parameter					FEA	
Analytical	FEA	Computational (Green-function)	FEA	Boundary element	Lumped-parameter	Full BOM and manufacturing process flow
Empirical	Analytical	Analytical	Analytical	Analytical	Analytical	Empirical design-based
Rigid	Empirical	Empirical	Empirical	Empirical	Empirical	Empirical parametric
Loads	**Thermal**	**Contact**	**Stress**	**Acoustics**	**Vibration**	**Cost**

Modeling Fidelity

System Scope: Disciplines Included

Figure 5. Discipline-fidelity matrix for the nacelle mechanical components, such as drivetrain gears, bearings, and shafts (FEA = finite-element analysis)

about the most common modeling fidelity. Indeed, there are few publicly available studies that address wind turbine generator MDAO.

The final discipline-fidelity matrix is shown in Figure 7 for the wind turbine tower. Here, there are more similarities to the rotor design matrix, with disciplines for structures, cross-sectional analysis, aerodynamic and hydrodynamic loads, soil mechanics, rotor-nacelle representation, and cost analysis. The fidelity levels vary greatly among participants, with the most common approaches highlighted in blue. The elastic response of the tower is the discipline with the highest fidelity and is similar to the one used for the blades, whereas the cross-sectional analysis and the aeroelastic load analysis are generally of lower fidelity than in the models used for the blades. Cost analysis is also often lower fidelity.

3.2 Discipline-Fidelity Matrices for Wind Power Plants by Subsystem

The major elements that make up MDAO workflows for the design optimization of wind power plants are energy production, balance of systems (or plant) costs, operational expenditures, and financing. Within each of these areas there can be further decomposition of the system into various components. Depending on the tool set and application of interest, there can be a wide range of fidelity levels used to represent different subsystems and their respective disciplines. The following set of discipline-fidelity matrices illustrate this spectrum; the highlighted cells demonstrate that wind plant optimization often uses relatively low-fidelity discipline models. Some categories have two cells highlighted because both fidelity levels are used within the same framework, depending on the desired analysis and fidelity.

3.2.1 Plant Energy Production

The first subsystem presented is energy production (Figure 8), which has been the most active area for wind plant optimization to date. The major elements include a model for the wind resource itself followed by the power and thrust turbine response to that flow, and then wake models that adapt the local conditions at a given turbine position. Next, the power across the turbines is aggregated for each wind speed and direction of interest, and then an expected energy production is calculated that may or may not account for other losses in the plant. Typical workflows currently used in practice tend to have fidelity levels consistent across the full workflow, as will be discussed in the following examples.

Multi-body (linear/nonlinear/ rigid/flexible)			
Modal	Full finite-element 3D Maxwell's		
Full finite-element 3D	Finite-element 2D Maxwell's	Full finite-element 3D heat transfer	Full BOM and manufacturing process flow
Analytical parametric	Analytical Maxwell's	Analytical-lumped parameter thermal equivalent network	Empirical design-based
Empirical	Empirical	Empirical	Empirical parametric
Structures	**Electromagnetic design**	**Thermal design**	**Cost**

Modeling Fidelity

System Scope: Disciplines Included

Figure 6. Discipline-fidelity matrix for the generator

3D shell					
Super-element		LES			
Elemental nonlinearity (GEBT)	Generalized 6x6	URANS		Coupled dynamic structural response	
Multibody (linear/nonlinear)	Timoshenko	RANS	Nonlinear constitutive model	Coupled static structural response	
Modal	Euler	Simulated turbulent inflow	Linear constitutive model	Super-element	Full BOM and manufacturing process flow
Rigid	Analytical solid	Analytic profiles	Engineering stiffness model	Fixed moments of inertia and forces	Empirical design-based
Empirical	Empirical	Empirical	Rigid	Empirical	Empirical parametric
Structures	**Cross-section**	**Aero/hydro loads**	**Soil**	**Rotor nacelle assembly**	**Cost**

Modeling Fidelity

System Scope: Disciplines Included

Figure 7. Discipline-fidelity matrix for the tower (URANS = unresolved grid RANS)

	Hi-fi time-resolved turbulence-modeled CFD		CFD LES			
LES CFD	Blade-resolved CFD		CFD RANS (2D and 3D) (unsteady)			
CFD RANS (2D and 3D) (unsteady)	Actuator line CFD		CFD RANS (2D and 3D) (steady-state)			
CFD RANS (2D and 3D) (steady-state)	Actuator disc CFD	Dynamic closed loop	DWM/linearized CFD			
Semiempirical turbulent inflow	Vortex methods	Closed loop	Vortex methods			
Nonuniform resource distribution	BEM	Open loop	Steady/field PDE (Ainslie)		Time series	Semiempirical explicit electric array cable
Uniform resource distribution	Look-up table thrust and power curves	Prescribed operation/look-up table	Steady/analytical/ semiempirical	Analytical/empirical	Convolution	Empirical
Resource/inflow	**Rotor (aero and control)**	**Wind farm control**	**Wakes/plant flow**	**Power conversion**	**Energy aggregation**	**Loss model/ non-wakes**

Modeling Fidelity

System Scope: Disciplines Included

Figure 8. Discipline-fidelity matrix for plant annual energy production

Low-fidelity workflows

Classic wind power plant optimization for energy production includes steady-state, low-fidelity models across all disciplines. For the resource, this may include either a single wind rose (wind speed vs. direction frequency distribution) or a wind resource grid that provides a wind speed frequency or wind rose at several points throughout the wind plant. The latter is often generated in a preprocessing step by a modeling framework tailored specifically to wind resource assessment (for example WaSP, WindSim, or others). Increasingly, the capability to do both the resource assessment and plant optimization are integrated into a single code base that shares common models (for example, OpenWind, WindFarmer, WindPro, or others). Next, a set of models are run that include the turbine responses to the flow and the creation and aggregation of wake effects. Linearized flow and wake models are used to model the full wind plant power production and flow response for each input wind speed-direction combination of interest. The turbine itself is typically modeled as a look-up table for power production and thrust in response to the inflow at the rotor. However, more advanced models of the turbine—including blade element momentum theory—could be used to capture additional effects, including asymmetry of flow across the rotor plane due to wind shear, for example. Energy aggregation is then performed by a convolution of the probability distribution for the input conditions (i.e., the wind rose) with the full plant power output for each of those input conditions. The final energy production estimate is scaled by other losses, including electrical, plant availability, icing and soiling losses, and more. This steady-state, low-fidelity workflow can usually be executed in a short computational time, which makes it well-suited for use inside an optimization loop that may change the turbine positions, number, operational states, and more.

Mid- to high-fidelity workflows

The need to address more complex environments and nonlinear flow phenomena affected by terrain, atmospheric stability, and control strategies challenges the assumptions made in each step of the low-fidelity workflow. In a middle-fidelity or high-fidelity workflow, the key difference is that the models typically, though not always, include unsteady dynamics where time-domain simulations are used. This makes their use within an optimization difficult, if not intractable. However, one of the advantages of these higher-fidelity models is the ability to model more advanced control strategies (open-loop and/or closed-loop strategies), which have many of the same modeling needs as the plant optimization field. From a wind resource and plant flow perspective, statistical models of the turbulence may be used or various forms of computational fluid dynamics (CFD) models are used directly. The flow models inherently capture the physics of the turbine response and wake propagation through the plant. In these cases, the turbines are often modeled as actuator discs, or potentially actuator lines in more advanced models. These flow models output

Unsteady 3D FEA					
3D shell					
Super-element		LES			
Elemental nonlinearity (GEBT)	Generalized 6x6	URANS			
Multibody (linear/nonlinear)	Timoshenko	RANS	Nonlinear constitutive model	Coupled dynamic structural response	
Modal	Euler	Simulated turbulent inflow	Linear constitutive model	Coupled static structural response	Full BOM and manufacturing process flow
Rigid	Analytical solid	Analytic profiles	Engineering stiffness model	Fixed moments of inertia and forces	Empirical design-based
Empirical	Empirical	Empirical	Rigid	Empirical	Empirical parametric
Structures	**Cross-section**	**Aero/hydro loads**	**Soil mechanics**	**Production/erection/ impact loads**	**Cost (excludes installation)**

Modeling Fidelity

System Scope: Disciplines Included

Figure 9. Discipline-fidelity matrix for balance-of-systems foundation

average plant power yield directly, where energy aggregation and losses are calculated as before, or they output the dynamic power production signal over time. In the latter case, losses can then also be modeled over time, including turbine availability, curtailment, and electrical losses, which depend on the power produced at each turbine node in the collection system network. As the field matures, research is often pushing the boundary on one or more of these advanced modeling approaches. A good example from a flow perspective is the use of Reynolds-averaged Navier-Stokes CFD models with turbine actuator discs to look at flow in complex terrain (Allen, King, and Barter 2020) or under different atmospheric stability conditions (Adcock and King 2018). From an electrical perspective, the losses of the plant can be affected by turbine power production and cable layout, as shown in Fleming et al. (2016).

3.2.2 Plant Balance of Systems

The next major component of plant modeling includes all of the up-front balance of systems cost elements. This includes the turbine foundations (land-based) or support structures (offshore), electrical collection system, export cables, substation (if applicable), and various infrastructure elements, such as roads for land-based plants, staging, assembly, cranes and/or vessels, turbine installation costs, and other balance of systems elements. Here, the turbine foundation aspects within the plant balance of systems is tackled. For offshore conditions, the design and fabrication of the support structure is a major capital cost expenditure that varies significantly by sea depth. Both land-based foundations and offshore substructures, while commonly categorized as balance of plant items, should really be considered as part of the turbine optimization (Stehly and Duffy 2022). It is no surprise then that the foundation discipline-fidelity matrix, shown in Figure 9, mirrors that for the turbine tower. This particular instance focuses on offshore support structure design, which may include traditional monopile foundations or jacket foundations. Floating foundation design, which includes additional components such as mooring lines, has not yet converged on a discipline-fidelity matrix, although an ontology has been drafted to support project-specific goals.

4 Implementation of Wind Energy MDAO Ontology

As discussed, common interfaces in modeling frameworks can enable accurate comparisons between different analytical modeling tools as well as enable more seamless collaboration among a variety of stakeholders. In the former case, the ability to define standardized input/output and interfaces among software packages allows more accurate comparison of analysis results among the very broad set of software tools used by the industry for system analysis. In the latter case, barriers to information exchange across and even within organizations can be addressed by the use of standardized frameworks, where interfaces between historical silos are well-delineated to encourage coupled system analysis across those boundaries. The Task 37 wind energy MDAO ontology seeks to address both of these needs through a recommended standard for representing wind turbine and power plant information for MDAO applications with the most commonly used disciplines and fidelities. Note that both the turbine and plant ontologies are dynamic and always evolving. Users and other interested practitioners are encouraged to reference the latest documentation available online at https://github.com/IEAWindTask37/windIO.

4.1 Requirements

This work builds upon the discipline-fidelity matrices reported in Figures 4–9. To arrive at a common ontology that would be the most useful for the widest audience, the most important goals are identified as being unambiguous and accurate across multiple components, disciplines, and fidelity levels. In addition, ontologies should be flexible enough to allow the definition of nonstandard and unanticipated future designs and technologies. Finally, ontologies should be implemented in the most user-friendly way, in which it is easy for users to grasp and describe existing designs, or create new ones, without tedious effort. To reach this goal, we decided to develop the wind turbine and wind power plant ontologies within a YAML data format (`.yaml` file extension). YAML is a human- and machine-readable data-serialization language that satisfies all six goals listed earlier. Technically, YAML is a superset of JSON that improves readability. In addition to the advantages of user-friendliness and flexibility to accommodate multiple disciplines and fidelity levels for each component, YAML is pleasantly human-readable and supports comments and descriptions. Both JSON and YAML offer the advantage of supporting a schema, which is a vocabulary that allows rules or annotations that can validate JSON and YAML documents and provide clear human- and machine-readable documentation. A schema is especially useful to automate testing and ensure quality of data coming from external sources. In the context of collaborations among institutes and companies, a schema is a powerful tool that can greatly simplify the exchange of files and data sets.

The schema developed for wind turbines and wind power plants comprises a tree-structure in which the top level is an object characterized by a set of properties, some of which can be required and others optional. The properties of the top-level object are objects or lists of objects themselves, so the tree develops branches. The leaves of the tree, which terminate the branching, consist of a string, a number (integer or float), an array of numbers, or a Boolean. For numbers and arrays of numbers, minimum and maximum allowable values can be optionally defined, together with the unit of measure and a default value. The latter is adopted when the actual input YAML files omit the entry. For arrays, the schema can also specify whether the numbers can repeat, such as in a nondimensional grid. At all levels along the tree, the field description can be included, which can guide the user and self-document the inputs. In the following sections, the ontologies of wind turbines and wind plants are presented in terms of YAML formats and corresponding schema.

4.2 Turbine

The wind turbine ontology, which is implemented in YAML and supported by a schema, comprises 10 top-level elements:

1. `name`: the unique identifier of the wind turbine model
2. `assembly`: an object reporting the macro parameters of the wind turbine assembly
3. `components`: a nested object of the components composing the wind turbine assembly
4. `airfoils`: a list of airfoils, each being an object that can be referenced at the blade component level
5. `materials`: a list of materials, each being an object that can be referenced at the component level

6. `actuators`: an object reporting the data describing the actuators available in the wind turbine
7. `control`: an object reporting the data describing the wind turbine control
8. `environment`: an object reporting the data describing the environment where the wind turbine operates
9. `bos`: an object reporting the inputs to estimate balance of station costs
10. `costs`: an object reporting the main inputs for a levelized cost of energy analysis.

The 10 elements and further branches of the tree are shown in Figure 10, which was generated with an online visualizer of JSON-compliant schemas[1] and an online converter from YAML to JSON.[2] Of particular interest are the elements underneath the `components` property—the nested objects describing the key components of the turbine with an approach focused on aeroelastic modeling:

- `blade`
- `hub`
- `nacelle`
- `tower`
- `monopile`
- `foundation`
- `floating platform`
- `mooring`.

Some of the fields have multiple subfields. For example, the field `blade` has four subfields:

1. `outer_shape_bem`: object containing the data for blade BEM-based aerodynamics
2. `internal_structure_2d_fem`: object containing the data describing the blade internal structure for a 2D analysis
3. `elastic_properties_mb`: object containing the elastic equivalent properties of multiple beam models for the blade
4. `lofted_shape`: object containing the 3D points describing the outer lofted shape of the blade for blade-resolved CFD analysis.

The keys of `outer_shape_bem` are each objects of two keys only, namely `grid` and `values`. These represent the distributed properties along the span of the blade, such as chord, twist, relative thickness, and nondimensional chordwise positioning of the pitch axis. Two exceptions are represented by the reference axis, which has three subfields representing the xyz-coordinates, and airfoil positioning, which is made of two arrays, a grid of spanwise position numbers and labels of airfoil name strings. The airfoils themselves are defined at the top level of the ontology. Each airfoil is characterized by a unique name, 2D xy-coordinates, a relative thickness value, the aerodynamic center, and the performance polars, which itself is a list of objects. Within `polars`, sets of lift, drag, and moment coefficients along a grid of angles of attack are defined for a given Reynolds number and other airfoil configuration information, which can easily accommodate clean, rough, and blended airfoil polars.

The object `internal_structure_2d_fem` follows a more complex architecture that is better elaborated in the online documentation. From a broad perspective, it includes all data to model the internal structure of the blade. An arbitrary number of structural components, such as shear webs, spar caps, reinforcements, and so on, are defined along each 2D profile and along the blade span. Multiple definitions are supported by the ontology. Finally, the object `elastic_properties_mb` includes the data to construct the equivalent elastic beam model of a wind turbine blade. Here, because fairly deep differences exist among different beam models, the choice is to define the generic 6x6 stiffness and inertia matrices for a specific three-dimensional reference axis as default, while alternative beam models, such as the Timoschenko beam, can be optionally defined.

The hub and nacelle components mimic the blade component, in that they adopt simpler `outer_shape_bem` and `elastic_properties_mb` fields, but do not have the field `internal_structure_2d_fem`. The main

[1] https://navneethg.github.io/jsonschemaviewer/
[2] https://www.convertjson.com/yaml-to-json.htm

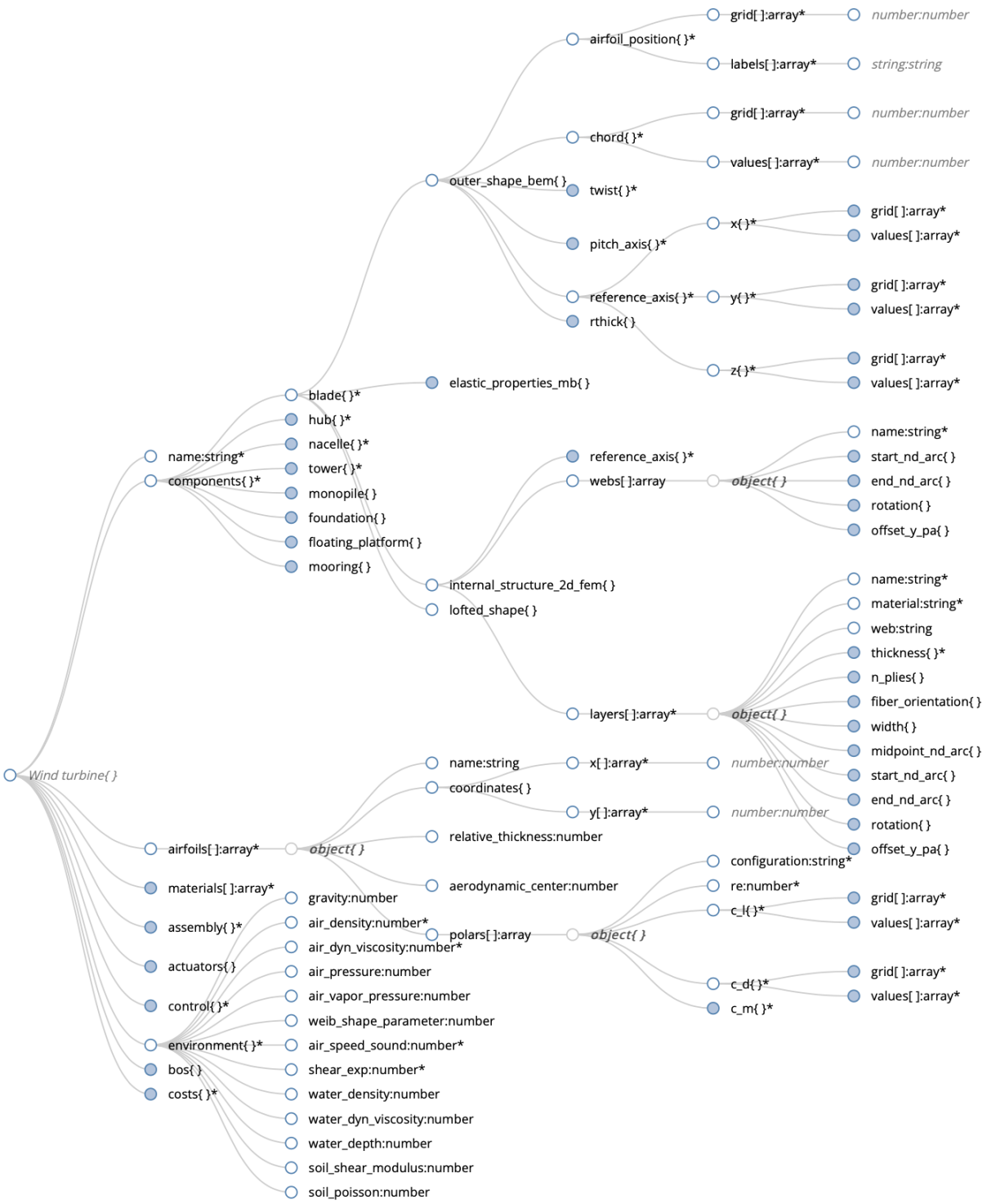

Figure 10. Overview of the turbine ontology

reason behind this difference can be found in the lower fidelity used to model, design, and optimize the hub and nacelle of wind turbines within automated systems engineering approaches, as shown in Figure 5. In contrast, the `tower` component follows the `blade` template more closerly and has the field `internal_structure_2d_fem`.

Another notable top-level object, `materials`, is made of a list of objects. The materials, which can either be isotropic or orthotropic, are defined as sets of properties, such as density, Young's moduli, shear moduli, and ultimate and fatigue strength values. Similar to the airfoils, the materials are referenced by name elsewhere in the ontology that describe the internal structure of a component.

Lastly, the entries `assembly`, `actuators`, `control`, `environment`, balance of station (`bos`), and `costs`, are simpler objects that describe the overall wind turbine configuration, such as whether the rotor is upwind or downwind and the number of blades; the control parameters, such as nameplate power, maximum rotor speed, and rated tip speed ratio; the environmental parameters, such as air density and dynamic viscosity; and finally the inputs to a standard cost analysis, such as the fixed charge rate and the operational expenditures.

4.3 Plant

The plant-level ontology is broken into five top-level elements, as shown in Figure 11:

1. `Namestring`: the name of the plant
2. `Site definition`: physical definition of the plant boundaries, terrain, and wind resource
3. `Wind farm`: description of the turbines in the plant and their layout
4. `Attributes`: computed values of energy production and wake models to be used
5. `Optimisation`: formulation of plant layout and design optimization problem.

The schema is designed to provide a structure that enables repeatable sharing of both wind energy system definitions (more definite attributes/characteristics) and of analysis results and optimization techniques used on the wind energy system.

The site definition includes physical information such as the boundary of a wind energy area, any important exclusionary areas or objects where turbines cannot be placed, the bathymetry for offshore locations, and the elevation/topology for land-based locations. The site definition also includes the wind energy resource, which supports many different definition types, including uniform/nonuniform resources, Weibull distributions, and direct measurements, among others. For more details, refer to Figure 11. The wind power plant focuses on turbine-specific information, including turbine performance data and turbine locations within the wind energy system. For each of these entries, there are required values defined by the schema that a user should provide; however, in the case of custom information, additional fields can be added within the dictionary structure as needed.

The attributes portion of the schema includes calculated values such as net AEP, gross AEP, and wake array efficiency. The attribute schema is flexible to allow for the addition of specific user-defined analyses as needed. Similarly, the optimization schema provides some basic structure for required information such as the optimization method, the design variables, initial values, and any constraints enforced; however, users can include additional information as needed for their specific optimization cases.

The online plant ontology documentation (https://github.com/IEAWindTask37/windIO) includes several examples covering the different definition types, complete with publicly available turbine definitions, and wind energy system properties.

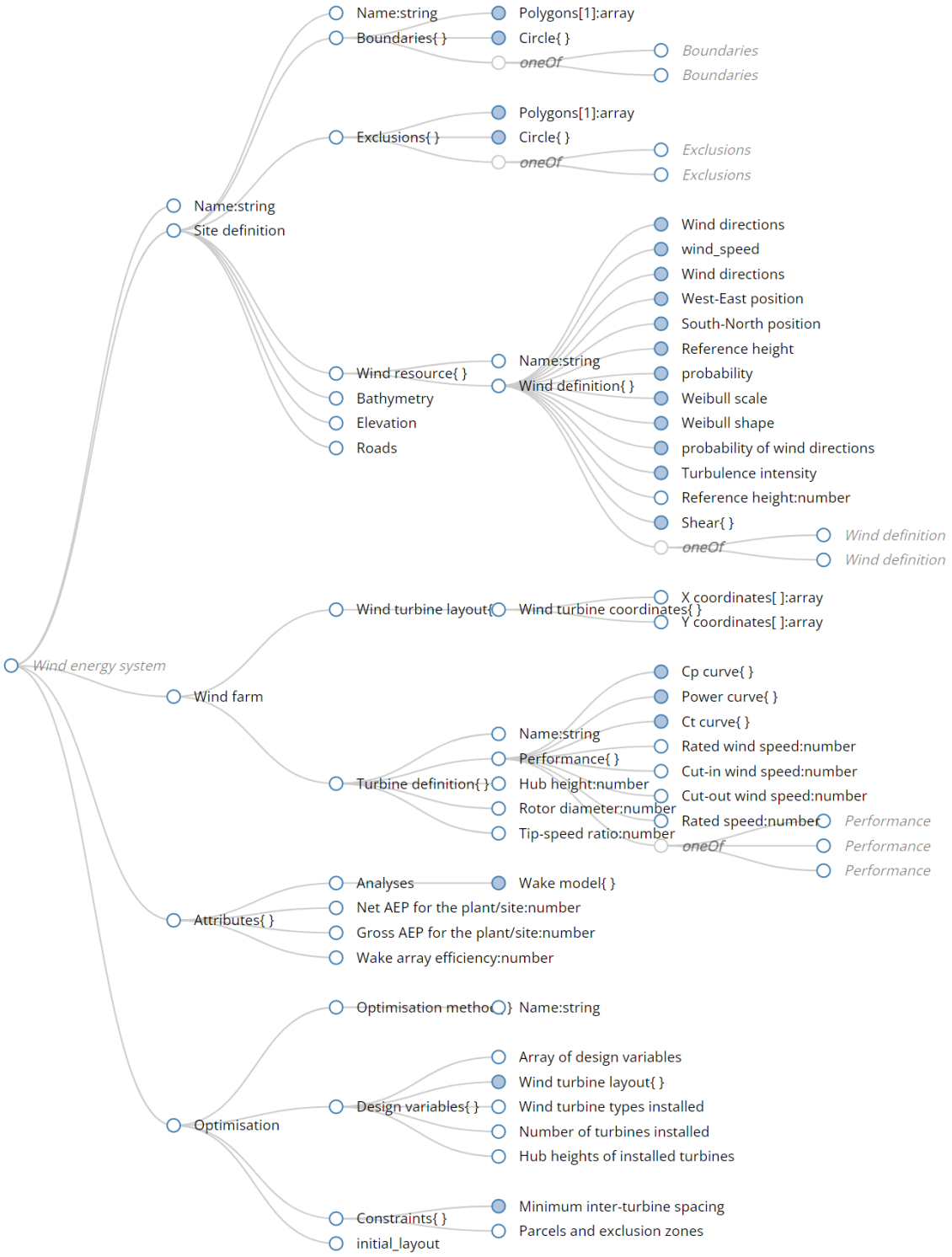

Figure 11. Overview of the plant ontology

5 Conclusions

This technical report describes the process developed with IEA Wind Task 37 on Wind Energy Systems Engineering and Integrated Research, Design, and Development to define a common representation, or ontology, for wind turbines and wind power plants. The ultimate goal is to create the ability to (1) share system descriptions and analysis results or supporting more transparent benchmarking and comparison and (2) integrate models together into workflows within and across organizations for improving the efficiency and performance of wind turbine and power plant design processes, ultimately leading to better overall wind energy system designs with high performance and low costs.

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