Roadmap to the multidisciplinary design analysis and optimisation of wind energy systems

You may also be interested in:

Optimal design analysis for thermal performance of high power 2.5D package
Liu Xiaoyang, Ma He, Yu Daquan et al.

The design and characterization of a piezo-driven ultra-precision stepping positioner
Peng Gao, Hong Tan and Zhejun Yuan

Design, analysis and testing of a piezoelectric flex transducer for harvesting bio-kinetic energy
A Daniels, M Zhu and A Tiwari

Computational design analysis for deployment of cardiovascular stents
Sriram Tammareddi, Guangyong Sun and Qing Li

Array of piezoelectric energy harvesting by the equivalent impedance approach
I C Lien and Y C Shu

Designing analysis of the polarization beam splitter in two communication bands based on a
gold-filled dual-core photonic crystal fiber
Fan Zhen-Kai, Li Shu-Guang, Fan Yu-Qiu et al.

A design analysis of a GaInP/GaInAs/GaAs-based 980 nmAl-free pump laser using self-consistent
numerical simulation
Muhammad Nawaz and Komet Permthammasin

A six-degree-of-freedom micro-manipulator
Peng Gao and Shan-Min Swei

Analysis of photonic band gap shifting by single-exposure holographic design
X L Yang, L Z Cai, Y R Wang et al.

Roadmap to the multidisciplinary design analysis and optimisation of wind energy systems

S Sanchez Perez-Moreno[1], M B Zaaijer[1], C L Bottasso[2], K Dykes[3], K O Merz[4], P-E Réthoré[5] and F Zahle[5]

[1] TU Delft, Kluyverweg 1, 2629HS Delft, the Netherlands
[2] TUM, Boltzmannstraße 15, 85748, Garching bei München, Germany
[3] NREL, 1617 Cole Blvd., Golden CO, United States of America
[4] SINTEF Energy Research, P.O. Box 4760 Sluppen, NO-7465 Trondheim, Norway
[5] DTU Wind Energy, Risø Campus, Frederiksborgvej 399, 4000 Roskilde, Denmark

E-mail: `s.sanchezperezmoreno@tudelft.nl`

Abstract. A research agenda is described to further encourage the application of Multidisciplinary Design Analysis and Optimisation (MDAO) methodologies to wind energy systems. As a group of researchers closely collaborating within the International Energy Agency (IEA) Wind Task 37 for Wind Energy Systems Engineering: Integrated Research, Design and Development, we have identified challenges that will be encountered by users building an MDAO framework. This roadmap comprises 17 research questions and activities recognised to belong to three research directions: model fidelity, system scope and workflow architecture. It is foreseen that sensible answers to all these questions will enable to more easily apply MDAO in the wind energy domain. Beyond the agenda, this work also promotes the use of systems engineering to design, analyse and optimise wind turbines and wind farms, to complement existing compartmentalised research and design paradigms.

1. Introduction

Wind farms are amongst the most complex systems deployed worldwide, based on their uncertainty, heterogeneity and complexity [1]. Often, many technical and social disciplines may simultaneously describe the performance of a complex system. The complete model of a wind farm includes the behaviour of the atmosphere and water body (for the offshore case), the flow inside the wind farm, the complex terrain, the energy production and loads, turbine and plant control, balance of plant construction and assembly including foundation structures, the operation and maintenance strategies, the electrical grid infrastructure and operation, as well as environmental and societal impacts [2]. Isolating the wind turbines themselves, we find yet another complex system, where disciplines such as aerodynamics, structures and materials engineering, control, cost modelling and electromagnetism interact significantly [3].

A system may be seen as a set of interconnected components whose individual behaviour and interactions determine the overall performance of the set. In view of this definition, limited understanding can be gained when the subject of study is a sub-set of components of a given system.

Systems engineering is a well established branch of engineering that tackles the design of a system as a whole, considering the contributions of every component and the advantages

or disadvantages of their mutual interactions for the system's operation [4]. The application of systems engineering relies on a number of methods, of which the discussion presented in this paper is restricted to one: Multidisciplinary Design Analysis and Optimisation, commonly shortened to MDAO.

Wind plants qualify, therefore, as prime beneficiaries of systems engineering methods, and their design and analysis necessitate the use of MDAO. The industry's current wind turbine and farm design practices mainly involve sequential or parallel optimisation processes for each component or discipline, with limited communication between monodisciplinary teams [5]. However, the typical focus of the wind energy community's research and development programmes on isolated components or single disciplines is gradually being complemented with a rather new approach, where the methodology applied at the system level is the priority. The integration of knowledge from all disciplinary teams is desired in order to shed light on the complexity of the system and inherent trade-offs and thus improving the optimality of the resulting designs.

Researchers, designers, project developers or policymakers would like to be able to simulate the entire wind farm or wind turbine for a myriad of *use cases*. *Use case* is the term given in this context to the particular application of an MDAO framework to a wind energy domain problem. Examples of use cases include the optimisation of levelised cost of energy (LCOE) with respect to wind farm layout; optimisation of annual energy production (AEP) with respect to turbine rotor diameter; uncertainty quantification of wind turbine fatigue loads; assessment of the impact of new generator technologies on the performance of a wind plant; and analysis of an offshore support structure design.

The importance of the present work is twofold. First, this paper serves to clarify the value of designing, analysing and optimising wind energy systems with a holistic and integrated approach. Second, there is a need to develop a research programme that advances the application of such an approach through the identification of open research questions surrounding MDAO techniques applied to wind energy. By drawing the roadmap to achieve an integrated computational framework to execute system level analyses and optimisation, the hurdles will be known before they are reached and will more easily be overcome.

Furthermore, the agenda presented herein is a reflection of the goals for Multidisciplinary Design, Analysis and Optimisation of the International Energy Agency (IEA) Wind Task 37 for Wind Energy Systems Engineering: Integrated Research, Design and Development [2]. This group is comprised of researchers from academia, industry and national institutes.

This paper is organised as follows. To give the reader the context in which our research agenda is meaningful, related research agendas, MDAO and its application to wind energy are revisited in section 2. The core of this work, the research questions and discussion thereof, is given in section 3. Finally, in section 4 we conclude with a brief summary of the work and further considerations.

2. Background
2.1. What is MDAO?
Multidisciplinary Design Analysis and Optimisation is a technique that deals with the interactions between different components and disciplines of a system. An example of an interaction between components in a wind turbine is the mutual effect of the rotor, gearbox and generator on their torque and rotational speed. An example from a full wind plant perspective is the design of the electrical cabling layout for the plant and the analysis of energy production of the plant including wake losses. The exploration of interactions is achieved by integrating numerical models of different disciplines together into a holistic analysis toolset. This technique allows the exploration not only of the behaviour of every component and individual discipline, but also of their reciprocal actions [6]. MDAO was originally developed in the aerospace industry,

due to the strong influences between diverse disciplines that impact the performance of aircraft—particularly structures and aerodynamics [1]. Later, MDAO went on to be applied successfully in the automotive, naval and civil engineering industries, amongst others [6].

The principle of the MDAO technique is to couple a set of computational models that represent different components and disciplines to simulate the entire system. With this technique valuable analyses that assist the decision making process during the design of the system can be performed. The IEA Wind Task 37 has identified three important dimensions of an MDAO simulation set-up or problem: fidelity of the models used, size and scope of the simulation, and MDAO architecture [2]. These three characteristics are fundamental to any MDAO framework.

Model fidelity (Fig. 1): for any given discipline, different model fidelity levels can be used (e.g. from a simple beam model to a full Finite Element Model).
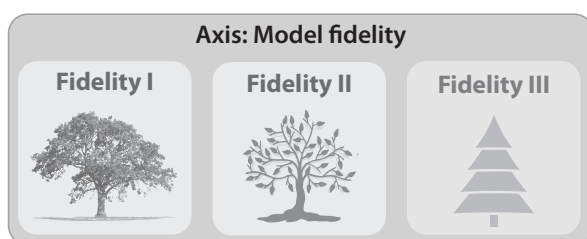

Figure 1. MDAO axis model fidelity: level of sophistication of the integrated models.

System scope (Fig. 2): size and type of disciplines involved; an MDAO framework exists as soon as two disciplines (or more) are coupled (e.g. aerodynamics and structures). Given an application, only a set of component or discipline models are relevant.
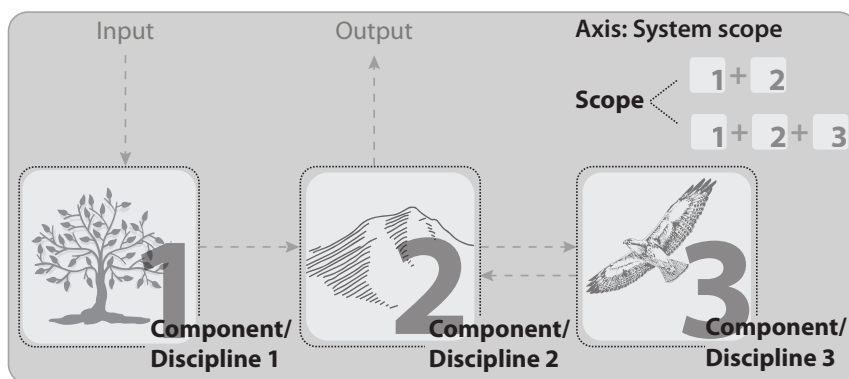

Figure 2. MDAO axis system scope: disciplines that are relevant for a particular application.

MDAO architecture (Fig. 3): the path of the dataflow between driver and models (e.g. whether to update the entire system at every iteration of an optimisation or have the optimiser determine which disciplines should be updated).

The scope, fidelity of the models, and architecture come together to form the overall MDAO workflow. Put another way, a workflow is defined as a set of integrated models and the driving numerical method (*driver*) that may operate on individual disciplines or the overall system simulation. A few examples of drivers that may be used in an MDAO framework are design of experiments (DOE), sensitivity analyses, uncertainty quantification or optimisation algorithms.
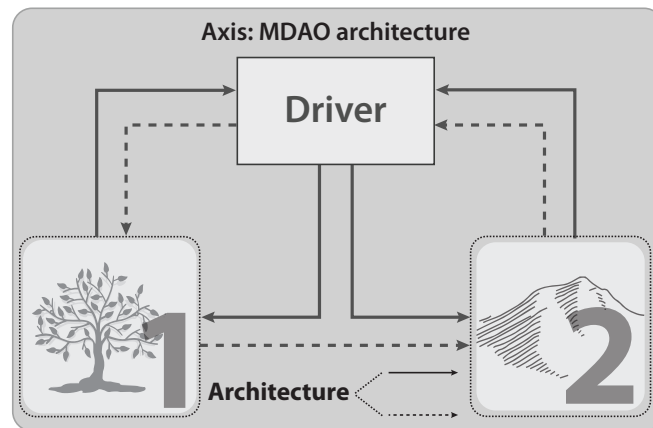
Figure 3. MDAO axis architecture: the path of data transferred between drivers and discipline analyses.

2.2. MDAO applied to wind energy systems

For a background on prior work in wind energy system MDAO, we refer the reader to the two following papers.

An extensive review of MDAO applied to wind turbines was done by Caboni in his work on multidisciplinary robust optimisation [7].

Additionally, the seminal paper by Dykes et al. explores works in MDAO applied to both wind turbines and wind farms, and sets the foundations of what would later become the software WISDEM (Wind-Plant Integrated System Design and Engineering Model) [1]. Dykes et al. found that most research was being done on singular components or disciplines, and thus concluded that there were huge opportunities to research and develop MDAO for wind energy. Similar observations and conclusions were made by Zaaijer [8].

A few research publications on MDAO for wind energy systems have arisen more recently, which confirm the need for further research programmes. Some examples include the work by Ashuri et al., where an offshore wind turbine is optimised using multiple disciplines [9]; the rotor nacelle assembly for offshore wind farms comprehensive design tool by Zaaijer [10]; a multilevel wind turbine design approach that makes use of metamodels by Maki et al. [11]; and the work by Fleming et al., demonstrating that coupling two disciplines (in this case controls and wake modeling) decreases the cost of energy more than optimising each discipline sequentially [12]. A comprehensive wind turbine design methodology and tool is presented in [13], which successfully couples detailed and high fidelity aerodynamic, structural and control models with nested optimisation algorithms. All these papers report a system level performance improvement through the use of multidisciplinary design analysis and optimisation. This suggestion is further supported by one conclusion drawn from a review of approaches to wind farm design [14]: "New holistic models are required to improve the wind farm performance modeling and its optimization. ... optimization frameworks must encompass all the design variables during the micro-siting process, since current existing approaches have limited the number of design variables and their degrees of freedom."

2.3. Related research agendas

Setting the agenda for future research in wind energy and MDAO in particular has been the focus of a number of papers. Two of these are given as examples of successful research agendas that currently lay the groundwork for discussion and research programmes alike.

Agte et al. [15] presented directions for general research on MDO (the focus of MDO is on optimisation, and shall be referred to here as MDAO). They identified the limitations of MDAO and were able to recommend work on model validation, MDAO architecture development, uncertainty propagation for design, development of surrogate models, inclusion of manufacturing in MDAO, and to rely more on computers for describing optimisation search spaces and problem formulations, and thus explore unimaginable designs.

The second research agenda states the long-term challenges of wind energy and was the result of a collaborative effort led by van Kuik et al [5]. This group of researchers posed research questions in a wide range of topics, one of which deals with design methods. The need to develop holistic design tools is explicitly addressed in the form of a research challenge: "To develop holistic automated and comprehensive design methods for wind turbines and wind power plants for exploring the available design space and identify optimal trade-offs."

Both of these research agendas influence research programmes and indirectly justify the present work. Other papers where the needs and challenges are described in the field of MDAO are [16], [17] and [18]. The latter identifies five MDAO research directions: Modeling and the Design Space; Metrics, Objectives, and Requirements; Coupling in Complex Engineered Systems, Dealing with Uncertainty, and People and Workflow.

Multidisciplinary Design Analysis and Optimisation for wind energy systems is still in its infancy. It is possible, nonetheless, to sketch the desired state of knowledge and practice that academia and industry strive to achieve. During the process to reach the desired state many challenges will be encountered, and these are broken down into research questions.

The research agenda proposed in this work focuses exclusively on the computational aspects of MDAO. Despite the paramount influence that other *human* aspects (e.g. design teams communication and collaboration, education and the gap between academia and the industry) have on the overall success of MDAO, challenges in that regard are thoroughly reviewed in [15].

2.4. Towards an agenda for MDAO for wind energy
As discussed in section 2.1, the successful instantiation of an MDAO framework is invariably described by three aspects. By means of an abstract depiction of a complete MDAO process shown in Fig. 4, we demonstrate how the overall complexity of MDAO can be affected by moving along the axes of all dimensions: system scope, model fidelity and architecture [2].

First, the scope of the models or disciplines that need to be included will scale the complexity (depicted in Fig. 4 with square boxes numbered 1, 2 and 3). For example, the turbine rotor could be designed using only aerodynamic analysis, or including structural analysis, or to more detail using control algorithms, the drivetrain and electrical performance, and even the tower. Similarly, the fidelity of the models (depicted in Fig. 4 with the levels of detail of a tree) increase complexity. Particular use cases will require simpler or more sophisticated models and varying levels of fidelity for each discipline. For example, in an integrated turbine MDAO analysis, one may use a very simple controller and simple sizing models for the drivetrain and tower while using very detailed models of the rotor aerodynamics and structure. This allows the user to capture important system-level trade-offs in the rotor design process without the large computational requirements that would be necessary if each discipline was modeled with the highest level of fidelity. Thirdly, the architecture of the workflow (depicted in Fig. 4 with solid and dashed arrows) can have increased complexity. The outcome and performance of the MDAO framework will also depend on which drivers are chosen and how models and drivers are coupled together. It is worth mentioning that a low-level workflow may be nested inside another higher-level workflow.

The three dimensions for MDAO research (condensed in Fig. 5) are regarded to be compatible with the research directions suggested by Agte et al. [15]. They mention a "horizontal growth for more capability ... using existing theory and tools, and a vertical growth attacking qualitatively
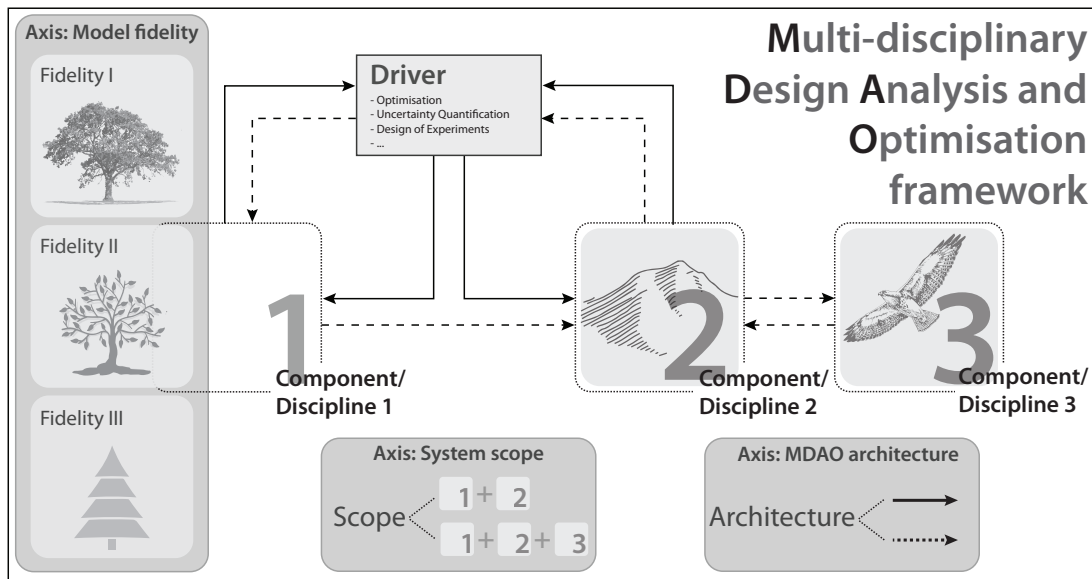
Figure 4. Abstraction of an MDAO framework. Three disciplines describe the domain, one driver describes the iteration procedure, two MDAO architectures are shown, two system scopes and three model fidelities for discipline/component 1.
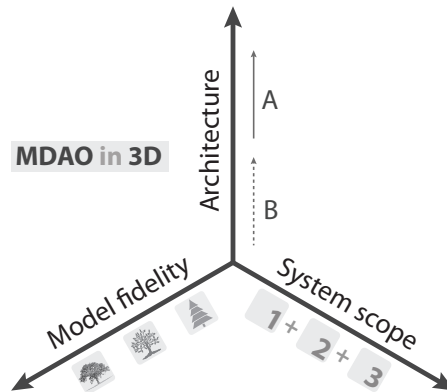

Figure 5. Diagram of the three dimensional nature of an MDAO framework [2].

new problems with innovative solutions". Using existing models and architectures in new ways (horizontal growth) is contrasted with the development of new architectures, drivers and methods to select the system scope and model fidelity (vertical growth).

Similarly, the four research directions that address computational MDAO suggested by Simpson and Martins [18], can also be related to Fig. 5. Broadening the system scope and model fidelity also widens the exploration of the design space; the development of metrics and objectives for MDAO formulations and the design of coupling interfaces lie in the architecture dimension; and uncertainty quantification is intimately related to model fidelity and drivers that define the workflow. Most of the current research on the implementation of MDAO lies on the architecture axis and to a lesser extent on the model fidelity and system scope axes.

Specifically, the architecture of the workflow has been the subject of much scrutiny, due to its capacity to improve the speed of an optimisation problem by decoupling the disciplines

and letting the driver be in charge of the coupling instead. Several architectures have been developed, each with its own strengths and weaknesses. Typical strengths are the reduced time of the optimisation process and the ability to yield feasible results at every iteration. Common weaknesses are the reduced convergence ability, longer execution times and feasible designs being obtained only when optimisation convergence is achieved.

The reader is referred to a number of publications that describe and compare different architectures using common variables and reference problems from different engineering fields [6], [19], [20], [21], [22], [23], [24].

In addition, the aspect of model fidelity has been under development more recently. Publications have arisen that discuss the possibilities of creating multifidelity frameworks by combining the outputs of sophisticated physics and simple engineering models [25], [26]; the exploration of surrogate modelling and model reduction techniques [27], and sensitivity analyses of MDAO frameworks with varying model fidelity [28].

3. Research agenda

3.1. Preliminaries

In this section we list the research questions that could lay the groundwork for future research programmes. Although scientists from other industries will recognise some of the challenges of MDAO, we aim to provide particular examples for wind energy systems where deemed appropriate.

The roadmap drawn is the result of the collective experience of the authors with MDAO applied to wind energy systems, and it has been constructed by reflecting whether the eventual answers to the research questions will help overcome current and foreseen obstacles. The authors participate in the International Energy Agency (IEA) Wind Task 37 Wind Energy Systems Engineering: Integrated Research, Design and Development [2]. This collaborative effort is an international initiative that captures the state of the art of MDAO applied to wind farms and wind turbines. The task is specifically focused on evaluating MDAO for wind energy applications across the three identified dimensions. Thus, this paper is meant to align with the efforts of the task.

Since this roadmap was converged to by open discussion and personal experiences, it does not intend to reflect a complete and final set of the research lying ahead. It does aim, however, to persuade the community to further discussion and involvement.

This research agenda is hierarchised from fundamental research questions to practical issues as follows:

- (**Use case**) - Use case formulation in the wind energy domain.
- (**Theory**) - Theoretical MDAO research.
- (**Implementation**) - Practical implementation of MDAO.

Moreover, desirable research activities that could ease the realisation of MDAO frameworks are included.

Key is to note that answers to these research questions will vary per use case.

3.2. Agenda

The roadmap to the Multidisciplinary Design Analysis and Optimisation of wind energy systems is depicted in Fig. 6 and is developed below. All research questions or activities show the sought level of knowledge and the research dimensions their answer will cover.
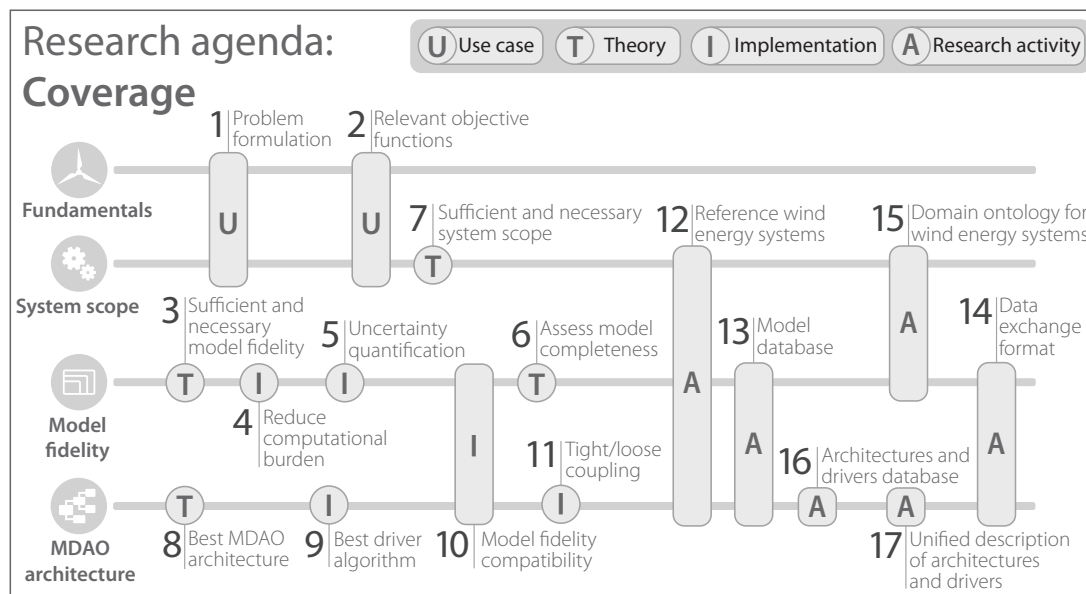
Figure 6. Diagram of the roadmap to the MDAO of wind energy systems. Each question shows the sought level of knowledge (use case, MDAO theory, MDAO implementation or MDAO research activity) and the research dimensions its answer will cover (fundamentals, system scope, model fidelity or MDAO architecture).

3.2.1. Fundamentals

1 (Use case) What is the problem formulation that best reflects the interest of a wind energy stakeholder?

The starting point for MDAO is a correct problem description. There is no benefit in running analyses or iterative processes on an ill-formulated problem. A well-formulated problem has a sensible objective function and constraints, and only then will its solution have real value. In short, different stakeholders have different interests, and these must be reflected through a clear common use of mathematical expressions and language for the eventual use of logical reasoners [29].

IEA Wind Task 37 addresses this issue by benchmarking different problem formulations [2].

2 (Use case) What are the relevant and adequate technical and economic[1] objective functions?

Several objective functions have been proposed to evaluate the overall performance of wind turbines or wind farms. Some examples of system level indicators commonly used are the cost of energy, annual energy production, levelised production costs, financial balance, net present value, amongst others [14]. However, MDAO users need objective functions that reflect the current needs of the wind energy industry, and which consider all technical and economic aspects. Developing and exploring common objective functions will enable the comparison of different MDAO frameworks.

---

[1] Wind energy has ceased to be a purely technical field. The ever increasing participation of communities and environmental stakeholders from the early design phases to the decommissioning of wind turbines and plants, is acknowledged to translate into holistic system performance indicators. However, decisions in these regards have to be made by designers and developers, which at present cannot be substituted by an MDAO workflow.

3.2.2. Model fidelity dimension

3 (Theory) What is the sufficient and necessary fidelity for all models involved?

This research line is an essential component of MDAO theory. The community strives to achieve the most realistic simulations in the least possible time, but these are conflicting objectives. Too sophisticated models at the negligible disciplines implies computational power will have been wasted. Too simple models in the crucial disciplines will produce unreliable data. For example, the impact of the soil-structure interaction on the optimisation of an offshore wind turbine rotor is minimal, and could thus be neglected. On the contrary, the layout of the wind plant impacts the performance of the rotor, and so a more sophisticated wake model would provide more insight.

This research involves finding the trade-offs of particular characteristics of the models, such as accuracy, precision, resolution and speed: effectively (re)defining the term *fidelity*. A key objective is to define the necessary and sufficient fidelity for each model for a given wind energy use case.

The IEA Wind Task 37 is particularly concerned with evaluating the impact of model fidelity on MDAO results [2].

4 (Implementation) How to reduce the computational burden of sophisticated models in iterative processes?

Highly sophisticated models are currently not well suited for optimisation, uncertainty quantification or design space exploration. This research question can be interpreted in two ways. First, metamodels, approximation or surrogate models are built to substitute expensive models using a number of methods, including response surfaces, artificial neural networks and kriging [27]. The exploration of multifidelity approaches also has value, where sophisticated models are executed a few times to improve the results obtained with simpler models. The goal is to accurately capture the behaviour of the original model at the lowest computational cost. Research directions on surrogate modelling are explored in [27] and [30], and compared in [31]. Multifidelity techniques are extensively reviewed in [26].

The second interpretation is to advance mathematical algorithms that solve model equations to reduce prohibitive execution times. This research aims to keep the physics unaltered. Computational fluid dynamics (CFD) is one technique that could be of great worth to MDAO, though its solution algorithms must be improved.

5 (Implementation) How to quantify the uncertainty of system level parameters?

Robust design is the name that captures the set of activities that lead to the specification of a system that is insensitive to variations in external conditions. Most models available have yet to provide their model uncertainty and a confidence interval of their output. Work can certainly be done across all wind energy disciplines to further promote MDAO for robust design and consequently avoid over-engineering [5]. An example of the robust design of a wind turbine is described in [7].

6 (Theory) Assess model completeness and identify weaknesses.

An MDAO framework cannot be said to be complete if its constituent models are not complete either. The modelling of certain disciplines that govern wind energy conversion are known to be deficient from the physical standpoint [5] (e.g. blade icing, manufacture, life cycle economics, logistics, transport, supply chain management, grid response). We stress that the present document poses a roadmap to MDAO, and as such, the assessment of the physics and processes modelled will impact its implementation by acknowledging the boundaries of the simulation.

3.2.3. System scope dimension

7 (Theory) Which disciplines/components have a strong interaction with the subject of study?

Analogous to research question 3 where the physics in a model is assessed, there is also a need to include the sufficient and necessary disciplines and components in an MDAO framework. This is done by identifying which disciplines and components have to be present and which can be neglected without compromise. Sensitivity analyses and dependency graphs may help understand the interactions. A broad opportunity for research arises in the joint wind farm and turbine design [5].

IEA Wind Task 37 explores what disciplines should be integrated in a series of case studies [2].

3.2.4. Architecture dimension

8 (Theory) What is an MDAO architecture that converges to useful results with acceptable use of resources?

Similar recommendations for research appear recurrently in papers addressing general MDAO architectures [6]. Architectures are meant to improve optimisation processes, and as such, this research suggestion appeals to MDAO practitioners regardless of their field of application. An architecture is formally presented as a non-linear programming formulation of the problem at hand.

One of the goals of the IEA Wind Task 37 is to benchmark MDAO activities. In particular, MDAO architectures will be compared by defining common case studies and by having participants apply their own workflows and set of models [2].

9 (Implementation) What methods or algorithms for an iterative process are the most adequate?

Particular applications of MDAO may benefit from using adequate algorithms. Meta-heuristic and gradient based optimisers, for instance, are known to be better suited to specific problems. Furthermore, discrete optimisation algorithms need to be considered for discrete variables e.g. number of blades, type of generator, foundation sub-structure, etc. It would also be valuable to investigate the potential effects between the algorithms and the architecture.

IEA Wind Task 37 will also benchmark the performance of a diverse range of drivers using common case studies [2].

10 (Implementation) How can the sophisticated output of one model be adapted as input for another simpler model, and vice versa, in a reliable way?

In the case that a model outputs more or less variables than admitted by another model as input, a real challenge arises. One possibility for solving this issue is foreseen: an attempt to model the conversion of one set of variables into another by describing physical processes.

11 (Implementation) Is the coupling of outputs and inputs of existing tools sufficient, or is a tighter coupling required?

Tight coupling refers to an iterative convergence between two solvers at every step, whereas in a loose coupling the solvers are run sequentially once. A fluid—structure interaction (FSI) simulation is an example in which tight and loose couplings yield different results. FSI is relevant for the study of floating wind turbines [32].

3.2.5. Research activities

12 Define reference wind turbines and wind plants.
In order to better benchmark and compare the results of MDAO activities, it makes sense to use a reference specification of the system. Reference turbines and wind farms are meant to represent the current practice of the industry, and they need thus to be updated to include the latest technologies and procedures. Running MDAO frameworks with varying model fidelities, system scopes and architectures on the same reference systems will enable their comparison.

The IEA Wind Task 37 has among its objectives the definition of a series of wind energy reference systems for both land-based and offshore applications [2].

13 Create an information portal of available models.
A catalogue of the models available, including metadata, is helpful to easily interchange modules in an MDAO framework. A logical reasoner could also access this database to eventually automate model selection.

The IEA Wind Task 37 is currently surveying and cataloguing different MDAO frameworks and models currently used for wind energy problems [2].

14 Create standard model input/output file formats.
By standardising exchange data formats, researchers could more easily share and compare models, as well as reduce the burden of wrapping models into an MDAO framework.

This activity is currently under development by the IEA Wind Task 37 [2].

15 Create a code agnostic domain ontology for wind energy systems.
MDAO users will benefit from a community-driven effort to fully describe the specification and state variables of wind energy systems. This benefit becomes patent when building the base of an MDAO framework for wind turbines or wind plants. An ontology will allow to more easily integrate models and translate models among different levels of fidelity in the system.

In this regard, the IEA Wind Task 37 is currently developing one such common ontology for wind energy systems [2].

16 Create a local database of architectures and available drivers.
A catalogue of architectures and drivers increases the efficiency of an MDAO process, by allowing for easier implementation of several methods. A logical reasoner could also use this database to automatically change the MDAO workflow [29].

17 Create standard descriptions of architectures and drivers.
The advantages of using a unified description of architectures and drivers are that their comparison would be less time consuming and improve reproducibility between organisations. Although many unified descriptions of MDAO architectures exist as reviewed above, this is a continuous process, as more approaches are constantly being developed.

4. Conclusion
We provide a comprehensive research agenda to support evaluation of MDAO applied to wind energy, to enable improved reliability of such approaches, encourage the deployment of this technique and increase its accessibility.

Most of the research questions identified can be grouped into three dimensions. These are easy to identify by asking three simple questions: Which model fidelity should be used? Which

disciplines or components should be integrated? How should the models and drivers be organized into a workflow?

When investigating the first direction, it is easy to come across other issues that deal with the practical implementation of varying fidelities and costly models. The second research direction looks into the sufficient and necessary scope of the system to reliably solve the problem at hand. Last, the third direction aims at providing a systematic approach to know how the ingredients of an MDAO framework should be integrated. A few research activities are also provided which are not essential nor comprehensive, but definitely desired to reduce the burden of the user. Examples of suggested research activities include the specification of reference wind energy systems that represent the industry's current state; the creation of data exchange formats based on a code agnostic domain ontology for more efficient model integration and collaboration; and the development and support of model and driver databases. A next step for the IEA Wind Task 37 is to prioritise these research topics.

The long sought decrease in cost of energy (and improvement of environmental and societal impact measures) shall be accomplished when researchers and developers make the transition from mono-disciplinary research to system level activities. This paper should attract interest to the field of MDAO by arguing the value of integrated, holistic approaches and by laying the roadmap of scientific challenges lying ahead.

As stated before, this document reflects the agenda of the IEA Wind Task 37 for wind energy systems engineering. It aims to trigger research programmes in academia and industry that will help advance what we, as a community, understand about Multidisciplinary Design Analysis and Optimisation and its application to wind energy systems.

Acknowledgements

References

[1] Dykes K, Meadows R, Felker F, Graf P, Hand M, Lunacek M, Michalakes J, Moriarty P, Musial W and Veers P 2011 *Applications of systems engineering to the research, design, and development of wind energy systems* (National Renewable Energy Laboratory)
[2] Dykes K, Rethore P, Zahle F and Merz K 2015 IEA Wind Task 37 Final Proposal. Wind Energy Systems Engineering: Integrated RD&D. Tech. rep. International Energy Agency
[3] Bottasso C L, Campagnolo F and Croce A 2012 *Multibody System Dynamics* **27** 21–53
[4] 2007 Systems engineering handbook Tech. rep. National Aeronautics and Space Administration
[5] van Kuik G A M, Peinke J, Nijssen R, Lekou D, Mann J, Sørensen J N, Ferreira C, vanWingerden J W, Schlipf D, Gebraad P *et al.* 2016 *Wind Energy Science* **1** 1–39 URL http://www.wind-energ-sci.net/1/1/2016/
[6] Martins J R and Lambe A B 2013 *AIAA journal* **51** 2049–2075
[7] Caboni M 2016 *Probabilistic design optimization of horizontal axis wind turbine rotors* Ph.D. thesis University of Glasgow
[8] Zaaijer M 2009 *Wind Energy* **12** 411–430
[9] Ashuri T, Zaaijer M B, Martins J R, van Bussel G J and van Kuik G A 2014 *Renewable Energy* **68** 893–905
[10] Zaaijer M B 2013 *Great expectations for offshore wind turbines: Emulation of wind farm design to anticipate their value for customers* Ph.D. thesis Delft University of Technology
[11] Maki K, Sbragio R and Vlahopoulos N 2012 *Renewable Energy* **43** 101–110
[12] Fleming P A, Ning A, Gebraad P M and Dykes K 2015 *Wind Energy*
[13] Bortolotti P, Bottasso C L and Croce A 2016 *Wind Energy Science* **1** 71–88 URL http://www.wind-energ-sci.net/1/71/2016/
[14] Herbert-Acero J F, Probst O, Réthoré P E, Larsen G C and Castillo-Villar K K 2014 *Energies* **7** 6930–7016
[15] Agte J, De Weck O, Sobieszczanski-Sobieski J, Arendsen P, Morris A and Spieck M 2010 *Structural and Multidisciplinary Optimization* **40** 17–33
[16] Giesing J P and Barthelemy J F M 1998 *AIAA White Paper*
[17] Sobieszczanski-Sobieski J and Haftka R T 1997 *Structural optimization* **14** 1–23
[18] Simpson T W and Martins J R 2011 *Journal of Mechanical Design* **133** 101002

[19] Balesdent M, Bérend N, Dépincé P and Chriette A 2012 *Structural and Multidisciplinary Optimization* **45** 619–642

[20] Balling R J and Sobieszczanski-Sobieski J 1996 *AIAA journal* **34** 6–17

[21] Cramer E J, Dennis Jr J, Frank P D, Lewis R M and Shubin G R 1994 *SIAM Journal on Optimization* **4** 754–776

[22] de Weck O, Agte J, Sobieski J, Arendsen P, Morris A and Spieck M 2007 *Proceedings of the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA* vol 1905

[23] Alexandrov N M and Lewis R M 2002 *AIAA journal* **40** 301–309

[24] Alexandrov N M and Kodiyalam S 1998 *AIAA paper* **4884** 1998

[25] Réthoré P E, Fuglsang P, Larsen G C, Buhl T, Larsen T J and Madsen H A 2014 *Wind Energy* **17** 1797–1816

[26] Peherstorfer B, Willcox K and Gunzburger M 2016 Survey of multifidelity methods in uncertainty propagation, inference, and optimization Tech. rep. Aerospace Computational Design Lab, Department of Aeronautics & Astronautics, MIT

[27] Simpson T W, Booker A J, Ghosh D, Giunta A A, Koch P N and Yang R J 2004 *Structural and multidisciplinary optimization* **27** 302–313

[28] Dykes K, Ning A, King R, Graf P, Scott G and Veers P 2014 *32nd ASME Wind Energy Symposium, National Harbor, Maryland*

[29] Hoogreef M F and La Rocca G 2015 *16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Dallas, Texas, 22-26 June 2015; AIAA 2015-2945* (American Institute of Aeronautics and Astronautics (AIAA))

[30] Simpson T W, Toropov V, Balabanov V and Viana F A 2008 *12th AIAA/ISSMO multidisciplinary analysis and optimization conference* vol 5 pp 10–12

[31] Simpson T W, Korte J J, Mauery T M and Mistree F 1998 Comparison of response surface and kriging models for multidisciplinary design optimization Tech. rep. National Aeronautics and Space Administration

[32] Hsu M C and Bazilevs Y 2012 *Computational Mechanics* **50** 821–833