PAPER • **OPEN ACCESS**

Multidisciplinary design analysis and optimisation of a reference offshore wind plant

To cite this article: S Sanchez Perez-Moreno *et al* 2018 *J. Phys.: Conf. Ser.* **1037** 042004

IOP Conf. Series: Journal of Physics: Conf. Series **1037** (2018) 042004 doi:10.1088/1742-6596/1037/4/042004

Multidisciplinary design analysis and optimisation of a reference offshore wind plant

S Sanchez Perez-Moreno[1], **K Dykes**[2], **K O Merz**[3] **and M B Zaaijer**[1]
[1] TU Delft, Kluyverweg 1, 2629HS Delft, the Netherlands
[2] NREL, 15013 Denver West Parkway, Golden CO, United States of America
[3] SINTEF Energy Research Stiftelsen, P.O. Box 4760 Sluppen, NO-7465 Trondheim, Norway

E-mail: s.sanchezperezmoreno@tudelft.nl

Abstract
Motivated by the need to develop reference wind energy systems for optimisation and technology assessment studies, the International Energy Agency Wind Task 37 on Wind Energy Systems Engineering is developing a reference offshore wind power plant at the Dutch offshore wind energy areas Borssele III and IV. This paper presents a comparison between two approaches for developing the preliminary design of an offshore wind plant turbine layout, electrical collection system, and support structures. The first is a sequential approach, where components of the wind farm are optimised sequentially, each with its own objective function, thus neglecting potential interactions between them. The second approach uses Multidisciplinary Design Analysis and Optimisation (MDAO), where all components are jointly optimised with the overall system levelised cost of energy (LCOE) as a global objective function. Studying the cases of regular and irregular layouts, the integrated approach always shows a greater improvement in the LCOE of the final design compared to the design resulting from the traditional sequential approach. The most significant trade-off exploited by the MDAO approach used in this study is between losses in energy production due to turbine wake effects and the costs of electrical cable infrastructure.

1. Introduction

Offshore wind farms are complex systems composed of many components that are governed by multiple phenomena and disciplines that interact with one another [1]. Compounding this complexity is the large number of industry stakeholders involved—each responsible for different components of the system. Because of the partitioned nature of the industry, overall projects are to a large degree developed sequentially. Due to the lack of consideration about how some design decisions affect other aspects of the plant, this sequential approach often leads to suboptimal designs and higher costs of energy.

One common example of a missed opportunity for reducing the levelised cost of energy (LCOE) is the optimisation of the layout of a wind plant without robust consideration of its impact on balance-of-system costs—including the electrical collection system or the cost of the support structure with varying water depths, among others.

1.1. Multidisciplinary Design Analysis and Optimisation

One technique that helps the designer exploit the interactions between components and disciplines while automating the design process of a system is Multidisciplinary Design Analysis

IOP Conf. Series: Journal of Physics: Conf. Series **1037** (2018) 042004 doi:10.1088/1742-6596/1037/4/042004

Table 1. Key parameters of the reference wind plant.

Parameter	Value	Unit
Rated capacity	740	MW
Number of turbines	74	-
Infield collection voltage	66	kV
Number of substations	1	-

and Optimisation (MDAO).

MDAO consists of coupling tools that analyse specific subcomponents with the goal of simulating the performance and cost of the whole system. It also includes an optimisation algorithm that drives the design variables to optimise the entire system [2].

To demonstrate the power of MDAO for solving trade-offs between competing disciplines, this work includes a thorough study in section 5 that shows the potential improvements that each discipline can contribute to the overall performance of the system. With this information, it is possible to explain how MDAO is able to sacrifice the performance of some subcomponents for the benefit of others, which combined yield a better system performance.

The purpose of this paper is to illustrate the superiority of the overall wind plant design and performance when optimised using MDAO over a traditional sequential optimisation, in which each component is optimised with its own objective function. Our primary interest is therefore in the relative comparison between sequential and MDAO optimisations.

In addition, the goal at this stage is not to provide a fully realistic estimate of LCOE, nor a final layout for the Borssele site: this study uses low-fidelity models that do not capture many aspects of the detailed physical design of plant components, and the accuracy of cost functions is limited.

1.2. Reference wind plants

The International Energy Agency (IEA) Wind Task 37 - Wind Energy Systems Engineering: Integrated RD&D is currently tasked with the development of a reference offshore wind plant (RWP) that will enable the benchmark of MDAO workflows and comparison of resulting optimised designs with a baseline design that is publically available [3]. The reference offshore wind plant will occupy the Borssele wind energy areas III and IV off the coast of the Netherlands. These sites are merged into a single connected and non-convex space. This site was chosen due to the relatively comprehensive set of publicly available data for the site as well as its location and water depths (ranging from roughly 20 to 40 m) [4]. Similar to the planned projects at Borssele, the reference plant will comprise 74 wind turbines. Each will have a 10 MW rating— corresponding to the new 10 MW reference turbine also developed within the IEA Wind Task 37 [5].

Figure 1 depicts the windrose and Fig. 2 shows the probability distribution of the bathymetry of the reference site.

Tables 1 and 2 contain some of the key parameters of the site and the turbine selected for this study, respectively.

The authors are aware of two reference offshore wind plants: one published by NORCOWE [6], and another developed within the NOWITECH project [7, 8]. The NORCOWE RWP did not consider bathymetry for wind turbine placement, and thus, the support structure has a predefined geometry. The NOWITECH RWP did not consider the effect of the layout on the costs of the electrical collection system [9].

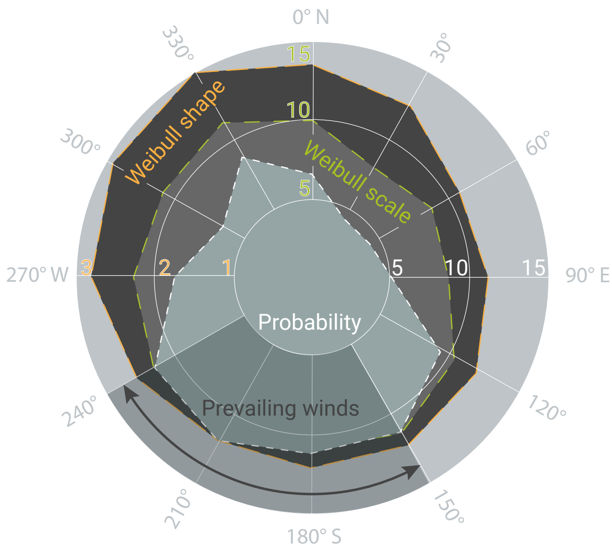

Figure 1. Windrose at the reference site Borssele III and IV.

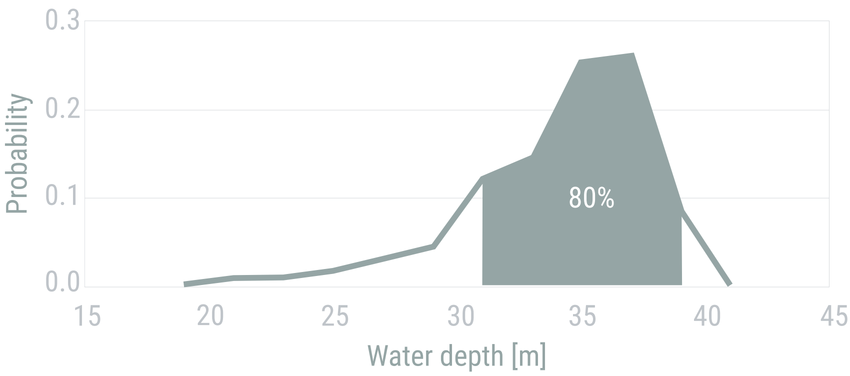

Figure 2. Probability distribution of water depth at the reference site Borssele III and IV.

Table 2. Key parameters of the IEA reference wind turbine.

Parameter	Value	Unit
Rated power	10	MW
Rated wind speed	11.4	ms^{-1}
Rotor diameter	190	m
Hub height	119	m

In contrast to prior RWPs, the goal of the IEA Wind Task 37 offshore RWP is to enable the multidisciplinary design of offshore wind farms by means of specifying the design of all subsystems and their components.

One way to achieve a sound and consistent design is to simultaneously optimise the layout with respect to annual energy production, the cost of the electrical collection system, and the cost of the support structures. This is achieved by using the LCOE as the objective function.

Table 3. Models and sizing tools used in the sequential and MDAO approaches.

Module	Model
Wake speed	Jensen wake model [10]
Wake turbulence	Danish Recommendation [11]
Infield cable topology	Esau-Williams heuristic algorithm [12, 13]
Support structure design	TeamPlay [14]
Balance of station cost model	TeamPlay [14]
Support structure optimisation	Brent's root finding algorithm [15]

Furthermore, since this is a preliminary design stage, the workflow uses low-fidelity tools and couples them together for a full wind plant design.

Once the layout of the reference plant has been fixed, the electrical collection and transmission system, operations and maintenance strategy, and support structures will be designed with greater detail and using higher-fidelity tools. This paper presents the development of the layout design while subsequent work will address the detailed design of the various wind plant subsystems.

1.3. Outline

This paper is organised as follows. Section 2 introduces the analysis tools and optimisation algorithms included in the workflows of the sequential and MDAO design approaches. Section 3 describes the baseline layout designs used to compare the performance of the design workflows. Section 4 shows the optimal regular and irregular layouts found with both design approaches and a breakdown of their costs and energy production. Section 5 discusses how MDAO is able to solve the trade-off between competing disciplines. Lastly, section 6 aggregates the key conclusions of this research and future work.

2. MDAO and a traditional design approach

This section describes the workflows used for a sequential optimisation of plant subcomponents and MDAO. The analysis and sizing tools used in both approaches are the same and are listed in Table 3. All of these are implementations of low-fidelity engineering models, justified for making early-stage design decisions. These models are explained further below.

The Jensen wake model assumes a linear expansion of the wake and is commonly used for wake studies. The Danish Recommendation is a simple model that calculates the added turbulence in the wake based on the mean wind speed and the spacing between turbines. The total electrical cable length is minimised with the Esau-Williams heuristic, which finds a branched topology. TeamPlay is a wind farm integrated optimisation tool, and its support structure design module and balance-of-station cost model are used in this work. The support structure design module uses a root-finding algorithm to yield the geometry of the monopile, transition piece, tower, and scour protection that withstand ultimate loads, and it applies a safety factor to account for fatigue loads. The ultimate states considered are defined in the standards [16, 17, 18] and the load cases evaluated are operation at rated wind speed and maximum wave in one-year extreme state, and parked with maximum gust in 50-year average wind speed and wave in 50-year extreme sea state [14]. The cost module is a parametric empirical model that accounts for procurement, installation, operations, maintenance, and decommissioning of diverse components.

Both design approaches use a Particle Swarm Optimisation (PSO) algorithm [19, 20] to drive

Table 4. Design variables per component.

Component	Design variables (number)	Bounds	Unit
Layout (irregular)	Transformed coordinates (148)	$[0,1] \times [0,1]$	[-]
Layout (regular)	Spacing 1 (1)	$[2D_{rotor}, \infty)$	[m]
	Spacing 2 (1)	$[2D_{rotor}, \infty)$	[m]
	Odd-row shift (1)	$[0, \infty)$	[m]
	Orientation (1)	[0, 180]	[deg]
Electrical collection	List of cable links (74)		
Support structures	Monopile diameter (1)	$(0, \infty)$	[m]
	Monopile penetration depth (1)	$[0, \infty)$	[m]
	Tower wall thicknesses (50)	$(0, 0.5D_{tower}]$	[m]
	Transition piece (TP) wall thickness (1)	$(0, 0.5D_{TP}]$	[m]
	Scour protection d_{50} (1)	$(0, H]$	[m]

only the wind farm layout. PSO is a gradient-free method for solving optimisation problems that mimics a swarm of particles exploring the design space, where each particle broadcasts information to the rest of the swarm about the best solution found at every iteration. Each particle is attracted at every time step to its own best-known solution and to the swarm's best-known solution. Since PSO makes no assumptions about the underlying function, it is particularly fit for approximating the global minimum of multimodal functions.

PSO is used to optimise the layout for two reasons. The first is that the design variables of the layout are so interrelated through wake effects and cable costs, which makes the wind farm layout optimisation problem contain multiple local minima. For example, if the coordinates of all but one wind turbines are fixed, a minimum LCOE can be found by moving the remaining turbine. However, if another wind turbine is allowed to move freely, then the minimum will be given by a different layout. A gradient-based optimiser would rapidly get stuck in a local minimum [21, 22]. Multi-start approaches may be used to address problems with many local minima, but if the design space is very flat with a large number of local minima, the computational time for a gradient-based approach using multi-start can be cumbersome. The second reason is that PSO has the capability of sampling the entire design space and then converging to the best solution found. Alternatives such as genetic algorithms provide solutions that are as good as the initial guess and a limited random search induced by mutations. Furthermore, genetic algorithms take longer to converge due to the slow nature of evolution, while PSO includes a social component that drives the candidate solutions to converge faster [23]. The PSO algorithm implemented runs with 24 particles in the swarm, 200 time steps or number of iterations, and equal particle inertia, cognitive, and social weights. Layout feasibility is enforced at every iteration.

The design variables and constraints used in both approaches are summarised in Tables 4 and 5, respectively.

The mapping [24] of the irregular polygon described by the boundaries of the Borssele III and IV sites to the unit square enables the PSO swarm to search in the transformed space $[0, 1]\times[0,1]$. This method simplifies the process of enforcing lower and upper bounds to the turbines' x and y coordinates, and it enforces feasible layouts at every step of the optimisation. The number of turbines is fixed, and thus, strong penalties are imposed on the objective function in the regular layout case when the number of turbines is less than 74. The regular and irregular layouts are constrained to maintain a minimum separation of two rotor diameters (D_{rotor}) to avoid collisions and unrealistic loads and wake losses. Concerning the electrical collection system, the topology

Table 5. Constraints per component.

Component	Constraints (number)
Layout (irregular)	$distance(T_i, Tj) \leq 2D \; \forall \; i \neq j$ (2701)
Electrical collection	No cable crossings
Support structures	Combined stress on monopile $\leq$ Critical stress Overturning moment of monopile $\leq$ Soil lateral bearing capacity Shear stress on scour protection $\leq$ Critical stress

is expressed as a list of edges that connect nodes. In this study, the location and number of substations are fixed. Cables are not allowed to cross each other as they are trenched into the seabed [13]. The design variables of the support structure and scour protection are bounded by physical constraints such as the diameters of the tower (D_{tower}) and the transition piece (D_{TP}), and water depth (H). Other geometrical parameters are found using knowledge-based rules. The support structure is optimised with constraints on the maximum stresses on the monopile and tower and lateral load on the soil under extreme loads. An important consideration missing in this design approach is the fatigue of the monopile driven by wave loading [14].

2.1. Sequential optimisation workflow

The term "traditional design" implies a sequential optimisation of different components, as is currently the standard practice in the industry.

Figure 3 shows the extended design structure matrix (XDSM) [2] of a traditional sequential design workflow. In this workflow, modules have their own optimiser, which disregards the overall performance of the system.

The first step is to optimise the wind farm layout with respect to annual energy production (AEP). This phase takes as inputs the Weibull distribution of the wind speed for 12 wind direction sectors, and it does a steady wake effects estimation to calculate local wind speeds. The main trade-off present in the pure AEP optimisation is the gross energy production of trying to place all turbines in the windiest section of the plant boundary against the losses incurred from wind turbine wakes interacting with downstream wind turbines. The second step is to optimise the support structures (monopiles) for every wind turbine, where the input is the local water depth and turbulence intensity. This turbulence is a function of the ambient and added turbulence intensities from the wake of the nearest wind turbine [11]. The third step is the optimisation of the infield collection system, where the design variable is the topology of the cables. This process minimises cable cost with a hybrid heuristic that combines branched and radial topologies [13]. Once each of the three subsystems is optimised, then LCOE is calculated. This sequence is followed once, with no feedback to previous design steps. However, in practice, often there is a feedback process with a few iterations of a traditional or sequential design process until the final design is reached. The cumbersome nature of repeating the sequential process many times is another reason why MDAO approaches can be advantageous.

2.2. MDAO workflow

Figure 4 shows the XDSM of the MDAO workflow (modified from [25]), in which the system's overall performance is the objective function of the top-level optimiser.

The MDAO approach consists of optimising the layout, electrical collection system and support structures simultaneously, driven by the single layout optimiser. The disciplines still

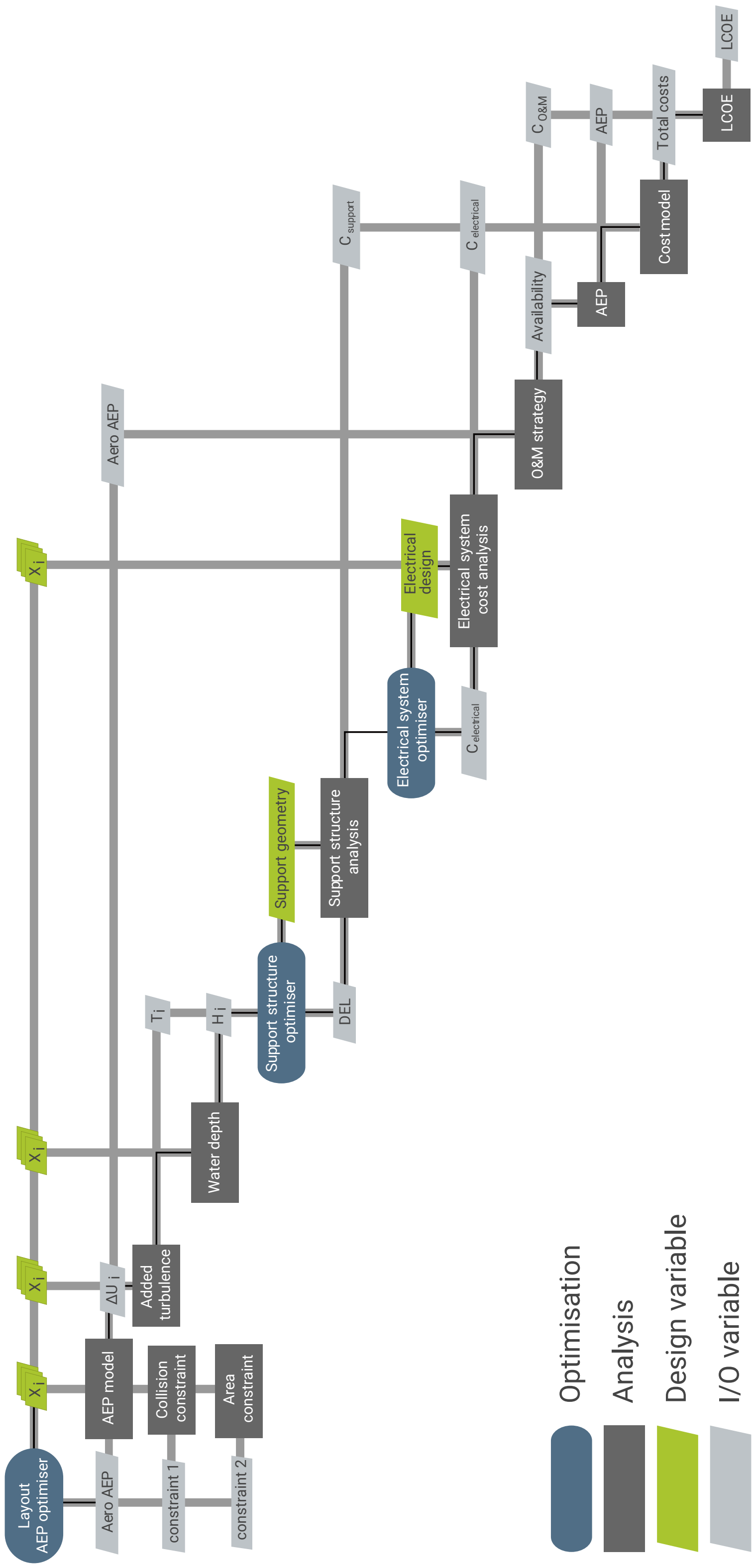

Figure 3. XDSM of a sequential optimisation approach.

IOP Conf. Series: Journal of Physics: Conf. Series **1037** (2018) 042004 doi:10.1088/1742-6596/1037/4/042004

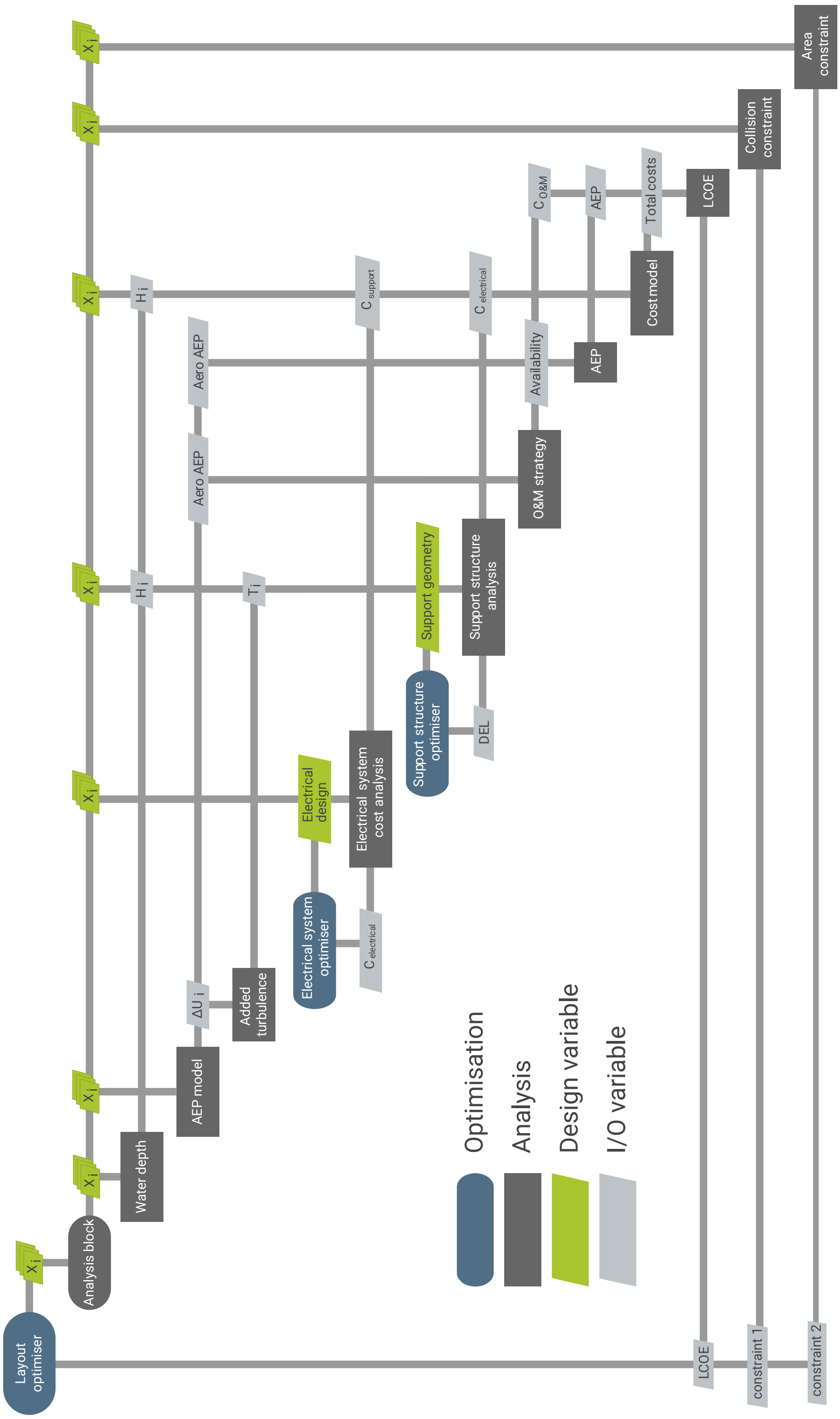

Figure 4. XDSM of the MDAO workflow.

IOP Conf. Series: Journal of Physics: Conf. Series **1037** (2018) 042004 doi:10.1088/1742-6596/1037/4/042004

appear sequentially in the analysis block, but they are all called as a group in each iteration of the optimisation. There is a top-level PSO algorithm driving the layout of the wind farm, with LCOE as the objective function to be minimised. This way, it takes into account the impact of design changes to the layout on all subsystems simultaneously.

3. Baseline design

This work considers two baseline designs, one with a regular layout and one with an irregular layout. The layout of the regular baseline wind plant design was obtained according to standard spacing rules used currently by industry to reduce wake losses: 9D downstream and 7D crosswind spacings [26]. The entire grid is aligned so that the downstream spacing was parallel to the prevailing wind direction (210°). The layout of the irregular baseline wind plant design is the result of a greedy algorithm that sequentially places every turbine as far as possible from all the previous turbines. This choice also aims at reducing wake losses. For a fair comparison with the optimised layouts, the topology of the electrical collection system and the support structures were optimised for the baseline layouts. Figure 5 shows the layout and infield cables of the baseline designs.

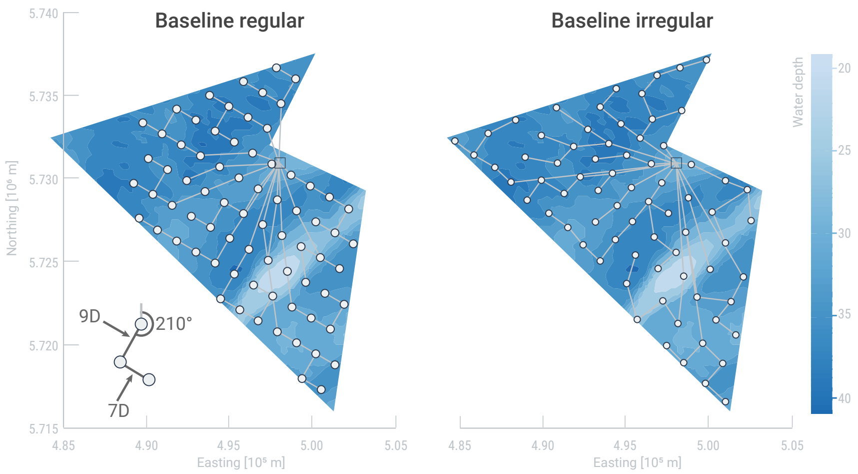

Figure 5. Baseline designs for a regular and irregular wind plant layout designs.

4. Results

This section shows the comparison of the LCOE of the baseline design with the designs produced by a sequential approach and MDAO. The results and discussion for regular and irregular layouts are separated. In addition, the AEP and costs of the electrical collection system and support structures are also shown for all designs.

The layouts shown below were the best found across five optimisation runs with different initial populations for each design approach, analysing in total 24,000 designs for every design approach.

4.1. Regular layout

The best regular layouts and cable topologies found by the two design approaches appear in Fig. 6.

The layout found with the sequential design is such that the AEP is maximised, or in other words, the wake losses are minimised. The resulting grid has 10.5D and 7.22 spacings, of which the former is aligned with winds coming approximately from the South at 188°. This direction

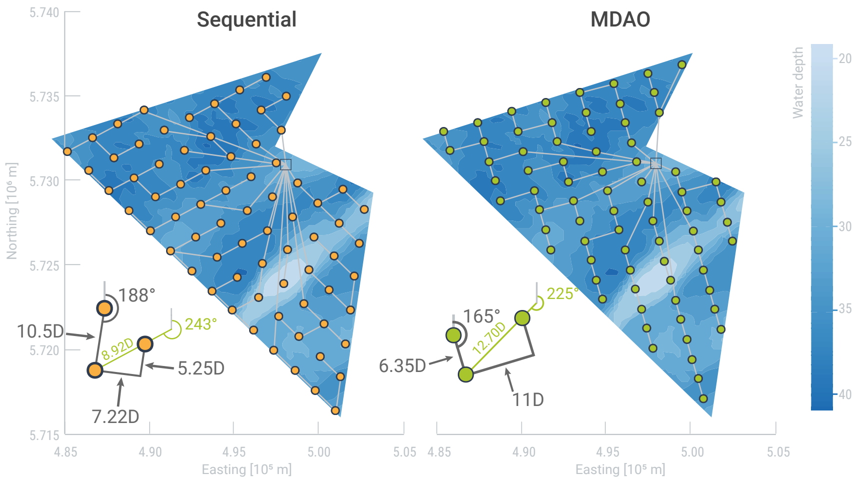

Figure 6. Resulting layout and infield cable topology of the regular-layout wind plant using MDAO and a sequential approach.

falls within the range of the more frequent wind direction for the site as can be observed in Fig. 1. The off-axis alignment of turbines in the 243° direction has a spacing of 8.92D, similar to the baseline design, but falls in the edge of the prevailing winds. It is of particular interest to note that odd rows are staggered with a shift of exactly half a spacing (5.25D), so that the resulting layout forms a hexagonal pattern that maximises the distances between turbines.

In the design resulting from the MDAO approach, an off-axis row of turbines appears parallel to the 225° direction, which is within the most frequent wind directions. This row has a relatively large spacing of 12.7D. The odd-rows offset is nearly zero, and thus, the grid is practically arranged in a quadrangular structure.

With regards to the performance of these layouts, Fig. 7 presents the LCOE, AEP, and costs of the electrical collection system and support structures. All quantities are normalised with respect to the baseline values.

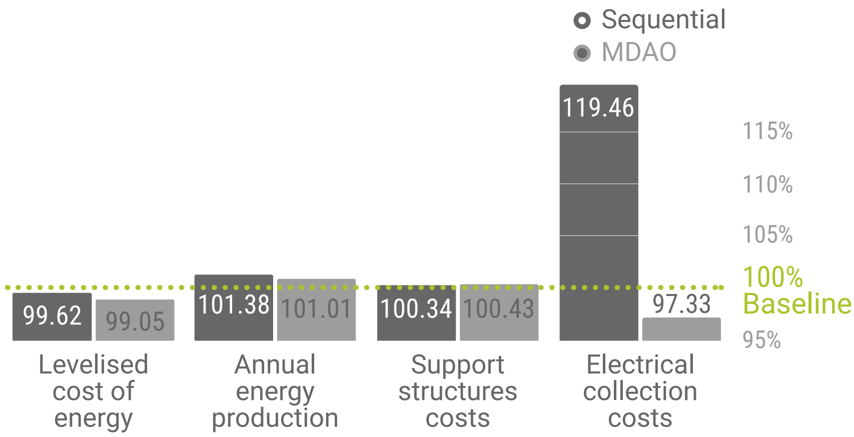

Figure 7. LCOE, AEP, electrical costs, and support structure costs of the optimal regular layouts found with the sequential and MDAO approaches.

Since regular layouts impose very strong constraints on the positions of the wind turbines, the difference in the LCOE of the three layouts is small. However, the MDAO approach yields a design with a lower LCOE than the result of optimising the wind farm sequentially, confirming the expectation that integrated optimisation provides better solutions. The reason for the lower overall LCOE achieved by the MDAO approach is the ability of the optimiser to exploit the trade-off between energy production losses from wake effects and electrical cable costs. The optimal design by MDAO places the turbines closer together to decrease collection cable costs although it increases wake losses that lead to a lower AEP. Additionally, cramming wind turbines in the shallowest region of the site—the southern tip—would lead to small inter-turbine spacings that lead to high wake-effect losses. Also, due to the irregular bathymetry of the site, the cost of support structures is almost the same in all three cases.

4.2. Irregular layout

Figure 8 shows the irregular optimal layouts and collection cable topologies found with the sequential and MDAO approaches.

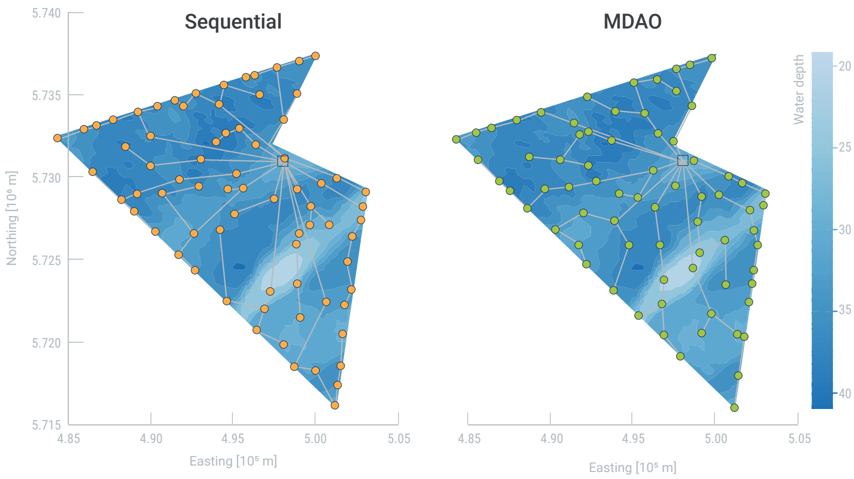

Figure 8. Resulting layout and infield cable topology of the irregular-layout wind plant using MDAO and a sequential approach.

Without the constraint of the regular layout, both designs put roughly half of the turbines on the boundaries of the site. This is a hint that wake effects are a strong driver in their positioning.

The performance of the optimal designs obtained with both approaches are summarised in Fig. 9.

Again, the LCOE of the design found with MDAO is lower than that of the design found by a sequential optimisation. Similar to the case with regular layouts, the MDAO approach sacrifices energy conversion in favour of reducing the infield collection cables and support structures costs, with respect to the sequential design method. The Esau-Williams heuristic minimises total cable cost for a given layout, with three cable ratings (and their respective cost) to choose from. In irregular layouts, the spacings between turbines is very flexible, so a more significant trade-off between capital costs of the support structures and electrical systems versus wake losses can be solved.

With regards to the smaller reduction in support structures costs using MDAO, three effects are thought to be responsible for the apparent low sensitivity of LCOE to water depth. First, the MDAO workflow does not account for important factors that affect real monopile design and costs, such as the effect of increased wave loading at deeper waters on the fatigue of the monopiles [27]. In addition, monopile diameters grow very large at deeper waters and may require specialised vessels for installation which result in a step-change in balance-of-system

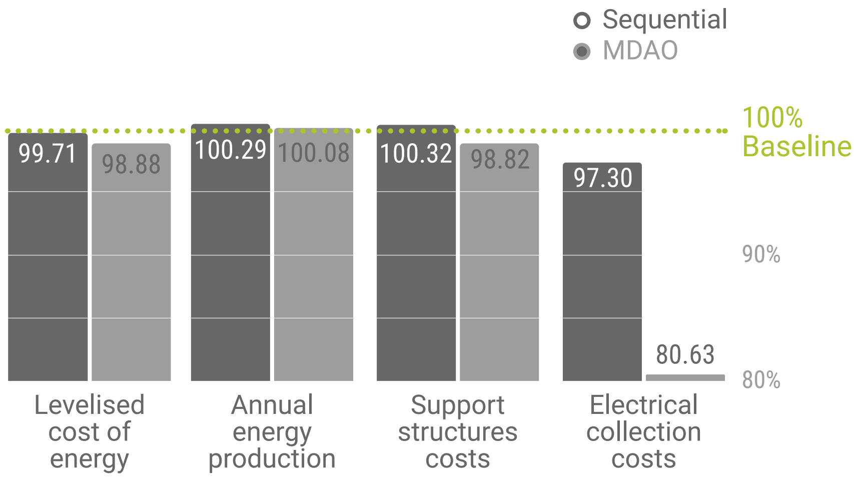

Figure 9. LCOE, AEP, electrical costs, and support structure costs of the optimal irregular layouts found with the sequential and MDAO approaches.

costs [28]. Thus, both the materials and the transportation and logistics costs associated with the current model may not be accurate enough to adequately model trade-offs for support-structure design with the rest of the system costs and energy production. Lastly, 80% of the Borssele site has a water depth between 31 and 39 m (see Fig. 2), a small difference when translated into LCOE with the implemented cost model.

Likewise, the electrical infrastructure sizing module is constrained to yield a branched cable topology. While branched topologies are known to help mitigate power loss from cable outings [13], the module does not consider cable redundancy or the need of specialised vessels for installing cables with different ratings.

5. Discussion

To help explain why MDAO is able to solve the trade-offs between competing disciplines, two additional optimisation exercises were done: finding the irregular layouts that minimise only support structures costs and electrical infrastructure costs, while keeping the 2D spacing constraint. Together with the sequential approach described above that only maximises AEP, the best values found of the three objective functions were then substituted one by one into the analysis of the LCOE of the baseline design, keeping all other values the same, and the new LCOE was recorded. The new LCOE values of the baseline design inform what is the potential improvement that each discipline can contribute to the LCOE. Figure 10 shows the normalised potential of every discipline to reduce the LCOE of the baseline design.

Since the baseline irregular layout was made with a greedy algorithm that maximises spacing and has a high AEP and high electrical cable costs, AEP has the least potential to contribute to the reduction of the LCOE of the baseline, while the electrical infrastructure has the greatest LCOE reduction potential. Support structures costs also have a low LCOE reduction potential because of the high wake-effects losses due to turbines clustering at shallow regions.

Furthermore, by substituting the values of AEP, electrical collection cost, and support structures cost found with the MDAO and sequential approaches one by one into the LCOE analysis of the baseline design, the first-order contribution of each discipline to LCOE reduction is found. Figure 11 shows the LCOE reduction of each discipline with respect to the baseline design values and normalised. In the MDAO approach, the electrical infrastructure costs contribute the most to the reduction of LCOE, consistent with the fact that it is the discipline with the most potential to contribute. Likewise, AEP contributes the least as the baseline design

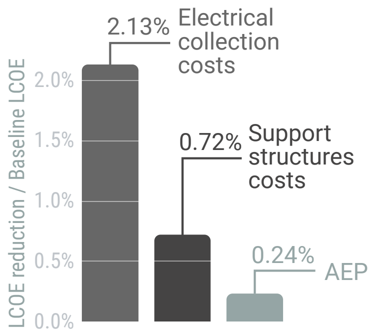

Figure 10. Potential contributions to LCOE improvement of the baseline design. LCOE improvement values are normalised with respect to values of the baseline design.

already has a high AEP. All three disciplines combined achieve an LCOE reduction of 1.11% of the LCOE of the baseline design. In contrast to MDAO, the sequential approach only considers AEP, and that is its only direct contribution to LCOE. The marginal contribution of electrical collection costs to LCOE reduction is not explained by the virtues of the sequential approach, but by the large spacings of the baseline design.

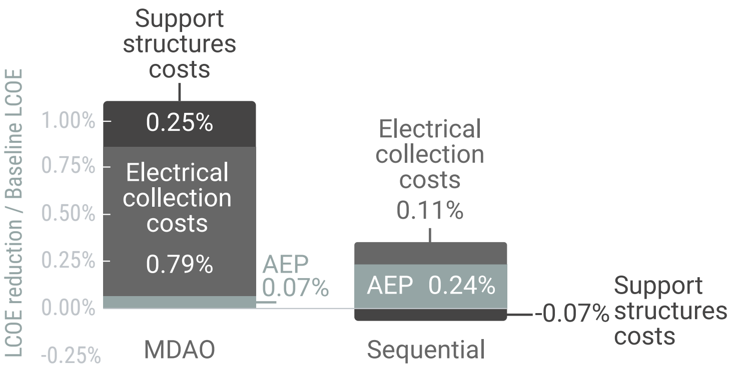

Figure 11. Contributions to LCOE improvement of the baseline design of the MDAO and sequential design approaches. LCOE improvement values are normalised with respect to the baseline design.

While these contributions to LCOE reduction depend on the baseline design, MDAO always solves the trade-offs to reduce the LCOE of any baseline design.

6. Conclusions

The hypothesis throughout this work is that MDAO enables wind farm designers to take advantage of couplings between components that are not exploited when optimising them using a sequential design approach—a more traditional approach.

By optimising regular and irregular layouts with both approaches, this paper shows that system performance—the LCOE—is best served when the design simultaneously takes into account energy production and system costs and balances the trade-offs in how each affects LCOE.

Specifically, MDAO achieves lower LCOE than in sequential optimisation by sacrificing the conversion of energy and decreasing the costs of the infield collection cables and the support structures. MDAO achieves this reduction mostly by reducing the electrical cables length, followed by a lesser contribution from the reduction of support structures costs.

It is noteworthy that the order of magnitude of the improvement in LCOE found with MDAO comes from a subtle redistribution of costs and benefits. The MDAO workflow optimises only a subset of the design variables that affect LCOE of an offshore wind plant. Moreover, while MDAO promises better results compared to a sequential approach, this work does not imply that MDAO shall always greatly improve LCOE.

Despite limitations in the model accuracy used for the study, in general, a trade-off between electrical system costs, support structure costs, and wake effects, were solved using MDAO.

Furthermore, this work reports the early stage of the design process of the IEA Wind Task 37 reference offshore wind farm. This work will continue with the detailed design of the electrical infrastructure, foundations, and the installation, operation, and maintenance strategies.

Acknowledgements

This work was partly financed by the Mexican National Council for Science and Technology.

The Alliance for Sustainable Energy, LLC (Alliance) is the manager and operator of the National Renewable Energy Laboratory (NREL). NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. This work was authored by the Alliance and supported by the U. S. Department of Energy under Contract No. DE-AC36-08GO28308. Funding was provided by the U.S. Department of Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the U.S. Department of Energy or the U.S. government. The U.S. government retains, and the publisher, by accepting the article for publication, acknowledges that the U.S. government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. government purposes.

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] Martins J R and Lambe A B 2013 *AIAA Journal* **51** 2049–2075
[3] 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
[4] Netherlands Enterprise Agency 2014 *Borssele Wind Farm Zone Project & Site Description*
[5] Bortolotti P, Dykes K, Merz K and Zahle F IEA Wind Task 37 on Systems Engineering in Wind Energy - WP2 - Reference Wind Turbines
[6] Bak T, Graham A, Sapronova A, Chen Z, Knudsen T, Sørensen J D, Florian M, Hou P and Asgarpour M 2015 *Annual Report Norcowe 2014* pp 38–40
[7] Merz K O 2014 Turbine placement in the NOWITECH reference wind farm Tech. Rep. Memo AN 14.12.09 SINTEF Energy Research
[8] Kirkeby H 2014 NOWITECH reference wind farm electrical design Tech. rep. SINTEF Energy Research
[9] Anaya-Lara O, Tande J O, Uhlen K and Merz K 2018 *Offshore Wind Energy Technology* (Wiley-Blackwell)
[10] Katic I, Højstrup J and Jensen N 1986 *European Wind Energy Association Conference and Exhibition* pp 407–410
[11] Danish Energy Agency 1992 *Recommendation for the fulfillment of the requirements found in the technical criteria*
[12] Esau L R and Williams K C 1966 *IBM Systems Journal* **5** 142–147
[13] Katsouris G 2015 *Infield Cable Topology Optimization of Offshore Wind Farms* Master's thesis TU Delft University of Technology
[14] 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
[15] Brent R P 2013 *Algorithms for minimization without derivatives* (Courier Corporation)
[16] Germanischer Lloyd 2005 *Rules and Guidelines, IV–Industrial Services, Part 2–Guideline for the Certification of Offshore Wind Turbines*

[17] Det Norske Veritas 2004 *Design of Offshore Wind Turbine Structure: Offshore Standard DNV-OS-J101*
[18] International Electrotechnical Commission 2009 *IEC 61400-3, Wind TurbinesPart 3: Design Requirements for Offshore Wind Turbines*
[19] Kennedy J 2010 *Encyclopedia of Machine Learning* ed Sammut C and Webb G (Springer US) pp 760–766 ISBN 978-0-387-30768-8
[20] Eberhart R C and Kennedy J 1995 *Proceedings of the Sixth International Symposium on Micro Machine and Human Science* vol 1 (New York, NY) pp 39–43
[21] Maringer D 2005 *Portfolio Management with Heuristic Optimization* 38–76
[22] Kramer O, Ciaurri D E and Koziel S 2011 *Derivative-Free Optimization* (Berlin, Heidelberg: Springer Berlin Heidelberg) pp 61–83 ISBN 978-3-642-20859-1
[23] Hassan R, Cohanim B, De Weck O and Venter G 2005 *46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference*
[24] Heckbert P S 1989 *Fundamentals of Texture Mapping and Image Warping* Master's thesis Department of Electrical Engineering and Computer Science, University of California, Berkeley
[25] Sanchez Perez Moreno S and Zaaijer M B 2018 *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* p 0654
[26] Samorani M 2013 *Handbook of Wind Power Systems* (Springer) pp 21–38
[27] Kallehave D, Byrne B W, Thilsted C L and Mikkelsen K K 2015 *Phil. Trans. R. Soc. A* **373** 20140100
[28] Damiani R, Dykes K and Scott G 2016 *Journal of Physics: Conference Series* vol 753 (IOP Publishing) p 092003