Chapter

A Research Framework for the Multidisciplinary Design and Optimization of Wind Turbines

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Abstract

The design of very large wind turbines is a complex task which requires the development of dedicated tools and techniques. In this chapter, we present a system-level design procedure based on the combination of multi-body numerical models of the turbine and a multilevel optimization scheme. The overall design aims at the minimization of the cost of energy (COE) through the optimization of all the characteristics of the turbine, and the procedure automatically manages all the simulations required to compute relevant loads and displacements. This unique setup allows the designer to conduct trade-off studies in a highly realistic virtual environment and is an ideal test bench for advanced research studies in which it is important to assess the economic impact of specific design choices. Examples of such studies include the impact of stall-induced vibrations on fatigue, the development of active/passive control laws for large rotors, and the complete definition of 10–20 MW reference turbines.

Keywords: wind energy, design, optimization, MDO, system design

1. Introduction

Wind energy has known a rapid transformation in recent years, and the increasing use of wind power as a strategic asset has supported a continuous growth in the size of wind turbines. This is mainly due to the fact that larger turbines allow a higher energy production and a faster recovery of the investment [1]; however, progressive upscaling requires technological developments in order to successfully manage the analysis and design of very large rotors. In fact, modern wind turbines exhibit an intrinsic multidisciplinary behavior which makes it difficult to disentangle the effects of different design aspects. Complexity arises from a variety of phenomena: for example, an increasing length of the beam-like elements implies a high flexibility of the rotor blades and the tower, which originates high displacements and deformations when the turbine is loaded. This produces a highly nonlinear and continuous interaction between the aerodynamic field and the underlying structure, so that the dynamic behavior of the turbine is typically fully coupled. When the turbine is deployed offshore, the motion of waves, currents, and tides contributes to further complicate the inflow conditions and the response of the system. In addition, the extreme flexibility of the turbine components means that the eigenfrequencies of the turbine are relatively low, which increases the risk of dangerous superposition among different turbine modes or between the natural frequencies of the turbine and the *per-revolution* ones introduced by the rotating motion. The consequences of unresolved resonances can be perceived through the dynamic response of the system, which could cause a sharp increase of the fatigue damage along the turbine, but also increased vibration problems and instabilities. In this scenario, unstable behaviors can also be triggered by purely aeroelastic effects, like flutter- or stall-induced vibrations [2, 3].

To address these issues, a novel approach is needed to successfully conduct the design of next-generation wind turbines. In fact, most current design strategies rely on a sequential process where different aspects of the project (i.e., aerodynamic design, structural verification, control tuning) are conducted separately according to discipline-specific procedures and methodologies. As the complexity of the phenomena increases, however, it's easy to see how such an approach is prone to some limitations: in a coupled system where each part of the design has a cascade effect on all other components it would be hard, if at all possible, to separate the scope into a number of subproblems which are then treated individually. A modern approach, on the contrary, must forcibly be based on the integration of different expertises and procedures coming from different disciplines into a unified perspective at system level.

In recent years, there has been a great effort from the wind energy community to develop such a multidisciplinary vision, and this required to renegotiate the assumptions of most design applications and, in particular, a redefinition of what are the fundamental design drivers. While classic approaches usually optimized the turbine to produce the maximum energy production, it is now widely accepted that modern turbine design should aim at the minimization of the cost of energy (COE) [4–7]. This is often achieved by defining the COE as the merit function of a dedicated multidisciplinary design optimization (MDO) algorithm. The advantage of targeting the COE in lieu of individual figures like the annual energy production (AEP) or the blade mass is that the computation of the cost of energy is directly affected by technical, managerial, and economical characteristics of the project which are condensed into a unified parameter. This way, it is much easier to properly evaluate the impact of certain design choices on the overall performance of the system. The effective implementation of an MDO procedure, however, is not a trivial task as multiple choices and solutions are possible, and typically, every design framework supports a different philosophy.

A first, fundamental aspect to discuss is the computation of the cost of energy: at present, most MDO algorithms available in the literature rely on the COE as the objective function to drive their optimization process. However, the way this figure is calculated can dramatically influence the optimization and potentially drive the optimization in completely different directions.

Another important aspect to leverage on concerns the physics of the turbine: the numerical modeling of wind turbines has improved significantly, and different models of increasing complexity are available. While the choice of low- or high-fidelity models certainly has some impact, it is absolutely necessary that the models are able to capture the multidisciplinary aspects of the wind turbine behavior. Usually, higher-fidelity models intrinsically support a better physical description, but this comes at the expenses of the computational time.

A third fundamental choice is the domain of optimization in terms of how many design variables are included into the multidisciplinary optimization algorithm. To support a system-level design, in fact, different unknowns coming from different disciplines should be collected together. These parameters ideally account for the blade shape, the internal structure of the blades and tower, and the general features of the rotor and, potentially, of the wind farm. Usually, combining a satisfactory

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number of variables to a sufficient quality of the physical modeling is hard and often compromises have to be made. The nature of such compromises and the direction they favor typically characterize a certain approach to the MDO design.

1.1 State of the art in the multidisciplinary design of wind turbines

Numerical optimization methods have been successfully applied to specific wind turbine design tasks, in particular the shape optimization of the rotor and the structural sizing of blades and tower. Recently, several authors have proposed different approaches toward the implementation of multidisciplinary design algorithms. These contributions have been quite heterogeneous and show wide differences in the methods, the level of modeling, and the definition of the design variables. In the following, we provide a brief survey of the most prominent contributions in the field of MDO design of wind turbines.

In this context, a broad family of MDO applications has its focal point on the design of the rotor, and a great deal of contributions is available in the literature. For example, Kenway and Martins [8] were among the first to conduct a truly coupled aero-structural design, in which variables related to chord, twist, airfoils, and structure were optimized to minimize the COE at a certain wind site. Later, Xudong et al. [9] introduced an aeroelastic model of the wind turbine and optimized the aerodynamic shape of the rotor under limits on the axial thrust and the shaft torque. In this work, the structure was indirectly optimized through the thickness of the blade. More recently, Pourrajabian et al. [10] applied a genetic algorithm to design a small-scale wind turbine rotor. Here the design variables account for chord and twist as well as the shell thickness, while the design objectives include the starting time and the power output. Bottasso et al. [11] developed a procedure in which the chord and twist of the blade are optimized together with the thickness of all the structural components. Here, the procedure is based on a multistage process in which the rotor shape is firstly optimized and the resulting solution is then fed to a structural optimization problem. A peculiarity of this application is that the structural optimization is based on a broad set of fully resolved design load cases (DLC). The problem of defining an accurate yet computationally affordable load basis has been investigated in detail by several authors. For example, Sessarego and Shen [12] proposed an optimization method based on surrogate modeling which include a very large set of load cases. In this case, the chord, twist, and thickness of a 5 MW rotor are successfully optimized, together with the spar caps and the shear webs, for a set of hundreds of load cases. An alternative methodology has been proposed by Pavese et al. [13] and is based on the substitution of computationally expensive turbulent cases with custom-made shear zones and equivalent deterministic loads. This way, the authors were able to embed the load computation directly within the workflow of the MDO algorithm and to re-optimize a 10 MW rotor with the reduced load basis. Several authors have applied genetic algorithms to the design of rotors: Zhu et al. [14], for example, combined the blade element momentum (BEM) theory to a three-dimensional finite elements method (FEM) to conduct the aero-structural optimization of a 1.5 MW rotor blade. Aerodynamic design variables in this work include the rotor speed and the chord distribution, while structural ones account for the thickness and the width of the spar caps and the positioning of the shear webs. The optimization is then managed by a non-dominated sorting genetic algorithm. A similar study in which BEM and finite elements are combined has been conducted by Dal Monte et al. [15] although the focus here is on small-scale rotors.

Very recently, Yang et al. [16] proposed a similar methodology to redesign a 2.1 MW rotor. A particular aspect of this work is that airfoil shapes are described by means of Taylor series and directly designed as part of the optimization problem. The possibility of designing the airfoils together with other aero-structural variables is a prominent topic and will be extensively discussed in this work. A recent application of rotor-based MDOs concerns the study of solutions for very large rotors and, possibly, load-mitigating techniques to support lightweight ones. In this light, for example, Richards et al. [17] proposed an integrated aeroelastic design of a 100 m blade. The study considers the impact of bond-line damage, a common failure mode for long blades, on the design and explores how an MDO-based design can reduce its influence on the integrity of the wind turbines. Pavese et al. [18], instead, employed an MDO approach to optimize the sweep of the blade achieving an important load alleviation on a 10 MW rotor.

More recently, several researchers extended the concept of multidisciplinary design to the whole wind turbine, introducing the idea that accurate modeling of physics, coupled to suitable optimization schemes, could pave the way for a system-engineering approach to the design of modern wind turbines. An early realization of this perspective was proposed by Fuglsang et al. [19], who first combined aeroelastic simulations to an optimization cycle based on the COE. Here, the design variables are some macro-parameters of the wind turbine like rotor shape and diameter, tower height, and rotor speed, whose impact on the COE is computed through a dedicated model. Later on, Maki et al. [20] discussed an MDO based on a multilevel design architecture. In this framework, an external optimization is employed to minimize the cost of energy. At this level, design variables include rated power, rotor diameter, rotor speed, and other turbine parameters. This loop is interfaced with two sublevels, which conduct discipline-based optimizations. The first allows to maximize the AEP of the rotor, while the second minimizes the loads produced by the blades.

Another formulation at system-level has been presented by Ashuri et al. [21, 22]. Here, a preliminary round of design can be made by optimizing blade length, tower height, and the rotor speed for minimum COE. Then the optimal configuration is fed to a second optimization problem which manages aero-structural design variables from the rotor and the tower. The design unknowns, which are simultaneously designed together, account for the chord, the twist, the blade structure, and the tower. The simulation environment is built around the solver FAST, which allows to take full DLCs into considerations during the design.

Significant research on MDO algorithms has been done at NREL, where Dykes et al. [23] developed an integrated tool for the analysis and design of a wind energy project from component level to the entire wind plant. The algorithm is based on the OpenMDAO software by Gray et al. [24] which manages the optimization problems and links the different models required for the various simulations, supporting increasing levels of detail depending on the needs. The engine of the algorithm is the internal cost models which recursively computes the COE by taking information from the various modules. A similar project, also based on OpenMDAO, has been recently developed by Zahle et al. [25]. The structure of the information flow basically allows to conduct a full aero-structural optimization of large wind turbines, and the simulation environment is widely based on internally developed software. The tool includes some particular specialisms, like the possibility to design the airfoils during the optimization and a frequency-based fatigue model which reduces the computational time.

1.2 Overview of this research

In this chapter, we present a detailed approach to MDO optimization of a wind turbine, which is the result of more than a decade of research and development in the field.

The fundamental idea put forward is to create a design framework which combines a detailed multi-body modeling of the wind turbine and a specifically engineered optimization structure, which relies on the combination of different design layers. Within this architecture, the complex multidisciplinary design problem is conducted by various modules which individually perform the optimization of specific aspects of the system including the aerodynamic design, prebend optimization, tower and structural design, and the automatic synthesis of the control laws. An additional outer loop manages the overall optimization of the wind turbine, thus ensuring that the design modules work harmoniously toward the minimization of the cost of energy.

This approach is a novelty in wind energy, since previous research was based either on monolithic approaches or on multilevel design but, usually, with only low-fidelity models or a limited load spectra. One of the essential advantages of this construction is the possibility to maintain a possibly large number of DLCs directly within the design, so that optimal solutions automatically comply with international certification standards. Another important feature of this modular scheme is that it makes possible to introduce new modules and procedures without the need to redesign the whole software. Due to its intrinsic generality and flexibility, this approach provides an ideal platform to conduct cost-oriented design studies.

2. Multilevel MDO optimization of wind turbines

As discussed, a modern approach to wind turbine design should implement an MDO approach and identify a certain balance between conflicting requirements of scope, number of design variables, modeling accuracy, and computational time. The development of our design tool Cp-Max was initiated by Bottasso et al. [26] and continuously expanded through subsequent research activities by Gualdoni [27], Bortolotti et al. [28], and recently by Sartori [29]. The main feature of the integrated MDO approach here proposed is the nested/multilevel architecture shown in **Figure 1**. The idea is to interface two different layers of design, one dedicated to the preliminary optimization of the turbine and the other based on as a series of individual design modules which perform detailed design of specific wind turbine subcomponents. The main advantage of such construction is that it allows to combine the level of detail of highly physical simulations with a high number of design variables typical of aero-structural design problems. Another important feature is that different design variables, which form a highly heterogeneous set, are not treated all at the same level, like it happens in monolithic approaches. Vice versa, the variables are divided among the different design modules, so that quantities affecting a certain merit function could be grouped together and provide a better sensitivity to the optimization scheme. A fundamental assumption behind this architecture is that the external loop *and* all the modules work together in the same direction, that is, the target of each design step must be coordinated to the others, in order to avoid a scenario where the design within a module evolves independently from that at the global/macro level. This is summarized in **Figure 1** where different modules act on different contributions of the merit function, whereas the outermost layer acts on the minimization of the COE as a whole. During the optimization, all the required simulations are automatically managed and performed by our multibody simulation tool Cp-Lambda (see Bottasso and Croce [30] for details).

2.1 Macro design loop

The macro design loop (MDL) is the outer layer of Cp-Max, and it drives the global optimization of the wind turbine, as well as the data flow between the various

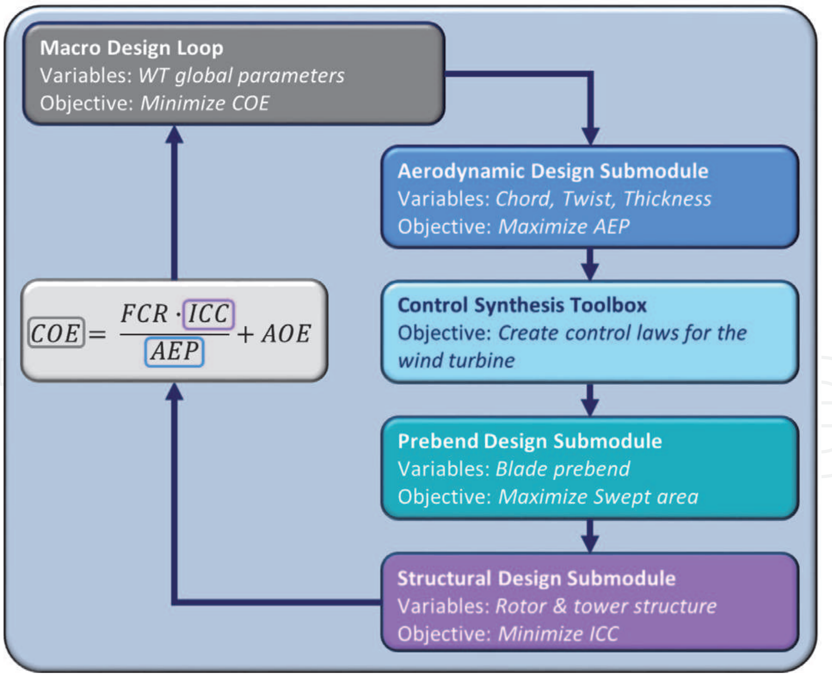

Figure 1.
Architecture of the MDO algorithm implemented in Cp-Max.

submodules. For a certain target of power rating and wind class, the main task of the MDL is to conduct a preliminary design in which few important (macro) parameters of the turbine are optimized in order to minimize the cost of energy according to the well-known scaling model from Fingersh et al. [31]. However, given the multilevel nature of Cp-Max, for each perturbation of those parameters, one or more submodules at the inner level perform the detailed design of the desired aspects of the wind turbine. This can be formalized by the following optimization problem:

$$\left(\boldsymbol{p}_a^*, \boldsymbol{p}_b^*, \boldsymbol{p}_s^*, \boldsymbol{p}_g^*, \boldsymbol{r}_\epsilon^*, COE^*\right) = \min_{\boldsymbol{p}_g}\left(COE\left(\boldsymbol{p}_a, \boldsymbol{p}_b, \boldsymbol{p}_s, \boldsymbol{p}_g\right)\right) \tag{1}$$

$$\boldsymbol{p}_g = \left[R, h_{Hub}, \theta_\pi, \gamma_b, \sigma_c^g, \tau_c^g, \sigma_t^g, \tau_t^g\right] \tag{2}$$

$$s.t.: \boldsymbol{g}_g\left(\boldsymbol{p}_a, \boldsymbol{p}_b, \boldsymbol{p}_s, \boldsymbol{p}_g\right) \le \boldsymbol{0} \tag{3}$$

Eq. (1) shows that the MDL takes as input all the design variables subdivided into different sub-arrays: $\boldsymbol{p}_a$ identifies aerodynamic design variables, $\boldsymbol{p}_b$ is the set of prebend design variables, $\boldsymbol{p}_s$ are the structural ones, and $\boldsymbol{p}_g$ identifies the macro design variables. The latter are directly optimized by the MDL, while the other families are progressively optimized by the various submodules. The set of the control laws $\boldsymbol{r}_\epsilon^*$ is also produced as part of the optimal solution. It must be noticed that in this notation, a star superscript identifies optimal quantities. The array of the macro design variables includes a set of global features of the wind turbine. As shown in Eq. (2), these include the rotor radius R, the nominal hub height h_{Hub}, the rotor tilt angle θ_π, the blades collective coning angle γ_b, and four additional shape parameters $\sigma_c^g, \tau_c^g, \sigma_t^g, \tau_t^g$.

The role of these parameters is to provide a channel to connect the MDL with the individual design submodules and in particular to the aerodynamic design. These parameters are computed for the rotor blade starting from the spanwise distribution of chord and thickness as follows:

$$\sigma_c^g = \frac{3A_b}{A_\pi} = \frac{3\int_0^R c(r)dr}{\pi R^2} \quad (4)$$

$$\tau_c^g = \frac{\int_0^R rc(r)dr}{A_b} \quad (5)$$

$$\sigma_t^g = \frac{1}{100}\int_0^1 t(\eta)d\eta \quad (6)$$

$$\tau_t^g = \frac{\int_0^1 \eta t(\eta)d\eta}{\int_0^1 t(\eta)d\eta} \quad (7)$$

where A_b is the blade solid area, A_π is the ideal rotor area, $c = c(r)$ is the blade chord distribution as a function of the local radius r, and $t = t(\eta)$ is the distribution of blade percent thickness as a function of the nondimensional length coordinate η. The detailed design of the blade shape, in terms of chord, twist, and percent thickness is not managed at the MDL level: in fact, this would require a certain number of dedicated design variables which should be added to the array $\boldsymbol{p}_g$, with consequences on the computational time. Instead, the blade shape is actually designed by the aerodynamic submodule, which performs a detailed sizing for the maximum AEP. The module performs a genuinely aerodynamic design, which means that, if the problem is not properly constrained, the evolution of the aerodynamic design is completely independent from the underlying structure, which is sized at a later stage. Within an economic perspective, the risks of such an approach are clear: it might happen that the aerodynamic design evolves toward a highly efficient blade with low solidity and reduced sectional thickness. This would require to design a heavier structure and, ultimately, would achieve a higher cost of energy. To avoid such kind of bad positioning of the MDL optimization, the four shape parameters are used to constrain the aerodynamic design within certain limits. Those limits, in turn, are directly managed by the MDL on behalf of the aerodynamic design module. Eq. (3) includes all the nonlinear inequality constraints acting on the MDL optimization problem. Although a full global design is typically unconstrained, it is possible in Cp-Max to introduce constraints on the maximum individual loads so that it is possible, for example, to find the optimal design for a certain load spectrum.

2.2 Aerodynamic design submodule

The aerodynamic design submodule (ADS) performs the optimization of chord, twist, and thickness of the blades in order to maximize the AEP of the rotor. During this stage, the internal structure of the blades is frozen, so that it is possible to avoid the computation of the dynamic loads and deflections required to redesign the structure. However, this strategy is reasonable only when the blade shape is not changed significantly during the aerodynamic design. Otherwise, if the blade planform or its thickness is broadly modified during the optimization, this would typically require a complete redesign of the structure which might potentially overshadow the advantages of an improved energy capture. Then, it is vital to ensure that the external MDL loop has enough authority on the individual design modules to avoid that the outcomes of a single design step march against the global strategy of minimizing the COE. In the ADS, this is done by applying the four shape parameters defined as part of the MDL design variables as nonlinear constraints of the aerodynamic optimization problem. As a consequence, the aerodynamic submodule conducts a constrained maximization of the AEP for given target values of those parameters. This automatically assures that the variations are not too sharp during the design. Following the notation introduced by Eqs. (1)–(3), the workflow of the ADS can be summarized in the following optimization problem:

$$\left(\boldsymbol{p}_a^*, AEP^*\right) = \max_{\boldsymbol{p}_a} \left(AEP\left(\boldsymbol{p}_a, \boldsymbol{p}_b, \boldsymbol{p}_s, \boldsymbol{p}_g\right)\right) \quad (8)$$

$$\boldsymbol{p}_a = \left[\boldsymbol{p}_{a_c}\, \boldsymbol{p}_{a_\theta}\, \boldsymbol{p}_{a_t}\right] \quad (9)$$

$$s.t. : v_{tip} \leq v_{tip_{max}} \quad (10)$$

$$\boldsymbol{g}_a\left(\boldsymbol{p}_a, \boldsymbol{p}_g\right) \leq \boldsymbol{0} \quad (11)$$

Eq. (8) suggests that the ADS provides the optimization of the aerodynamic variables; however, given that all the required simulation are based on a complete multi-body model of the rotor, it is possible to account for cross-disciplinary effects like the deformation of the blades at this step. This explains why all design variables and not only those directly pertaining to the ADS enter the module. Eq. (9) shows the composition of the aerodynamic design variables: in particular, the array $\boldsymbol{p}_a$ encompasses parameters related to the chord ($\boldsymbol{p}_{a_c}$), twist ($\boldsymbol{p}_{a_\theta}$), and nondimensional thickness ($\mathbf{p}_{\mathbf{a}_\mathbf{t}}$) of the blade. To limit the number of degrees of freedom, all these distributions are controlled by specific parameterizations based on additive or multiplicative gains (see Gualdoni [27] for details).

At the beginning of each evaluation, the aerodynamic model of Cp-Lambda is updated with the actualized values of the design variables $\mathbf{p}_\mathbf{a}$. Once the model is correctly updated, $C_p - TSR - \beta$ curves are computed as a three-dimensional surface for varying values of the collective pitch angle β and tip-speed ratio TSR. From the envelope of the $C_p - TSR - \beta$ curves, it is possible to compute the ideal regulation trajectory for the wind turbine, under the assumption that the control strategy is based on the tracking of the optimal power C_p^* when the turbine works in the partial-power region. A constant power strategy is instead considered for the full-power range. It should be noticed that, according to Eq. (10), the automatic buildup of the power curve must ensure at any time that the maximum tip speed is lower than a certain bound, in order to constraint the acoustic emissions of the rotor. Once the theoretical power curve is known, it is weighted by the site-specific Weibull distribution to assess the AEP. Eq. (11) includes a list of nonlinear inequality constraints acting on the aerodynamic design problems. As mentioned, four constraints are always enforced by the MDL through the four shape parameters of Eqs. (4)–(7). The possible additional constraints include maximum values for chord and twist as well as maximum gradient of the chord, twist, and thickness distributions.

2.3 Control synthesis tool

Looking at the many DLCs accounted for in the design of a novel wind turbine, it can be noticed that the control system plays a relevant part in many of them. For this reason, a realistic control system is an unmissable complement to the aeroelastic simulation tool in the ideal flowchart of an MDO procedure.

Based on the multilayer paradigm proposed by Bottasso et al. [32], considering horizontal axis wind turbines, the functions of a controller can be arranged into decoupled layers, each targeting a control objective by means of a suitable control law, designed independently from the others.

The innermost layer implements a trimming control, tasked with piloting the turbine so as to produce the design power output corresponding to the current wind. The outcome of this layer is typically a set point for collective pitch and generator torque. The measurements needed for this part are most basically the rotational speed of the rotor (or electrical generator) and the wind itself. The latter is usually measured for supervisory tasks, i.e., in order to feed a gain scheduler, accounting for the different behavior of the turbine in partial-power, transition, and full-power regions.

The actual trimming law design can be chosen based on several considerations. Of course, the simplest PI laws make for a generally easier-to-design alternative, thanks to the lower number of control gains (see [33, 34]). Control laws of this type are not model-dependent and do not need any detailed knowledge of the features of the machine. This in turn increases robustness with respect to potential deficiencies in the reduced model used for control design.

As possible drawbacks, tuning procedures are usually heuristics without an assured performance, and some form of manual tweaking is needed to increase performance to the desired level. Furthermore, unless semi-automatable numerical algorithms for gain synthesis are deployed which would make a possible adoption of these laws for more complex tasks [34], in order to reduce the effort necessary for control tuning, these controllers are typically purely single-input single-output. This limitation can be dealt with in a smart way by analyzing the operative spectrum of the turbine. Trimming can be obtained in the partial-power and transition regions by governing torque only through a PI law based on rotational speed, setting pitch at a predefined set-point function of the wind speed. In the full-power region, torque is kept at a preassigned value, whereas pitch is changed according to a PI law, again based on a measurement of the rotational speed [33]. Another control scheme operates with a PI loop closed on the rotational speed all over the operational spectrum for pitch, and torque assigned using a pre-determined schedule with respect to the wind speed [34].

Alternatively, more sophisticated model-based trimming control laws can be adopted. These are based on a reduced model, assembled from state equations for all the dynamics which are required for an accurate description of the interaction between machine states and controls (see [11]). Typically, for trimming purposes it is necessary to include state equations for torque balance, as well as for pitch and torque actuator dynamics. Clearly, if the number of state variables is greater than 1 and controls are simultaneously collective pitch and generator torque, the ensuing law is implicitly multiple-input multiple-output. Very reliable methods for the computation of optimal gains can be deployed to automatically compute the gain matrix for this type of control problems, with some guarantees on control performance obtained a priori under design conditions.

Model-based trimming laws are lighter to manage than model-independent laws, do not make distinction between regions in the operating envelope, and are suitable for extensions, obtained by considering individually the pitch input of each blade and including states corresponding to deformable systems on board, like the tower, shaft, and blades (in so doing, incorporating in the trimming layer also functions typical to the outer control layers). Of course, model-based control is more exposed to robustness issues in case of inaccuracies in the reduced model. Furthermore, in order to supply the control laws with all necessary measurement signals, observers for deformative states may be needed (see [35], Chapter 5).

It has been shown in [36] how to simply extend the basic feedback capabilities of a model-based trimming control law to take advantage of simple LiDAR measurements, providing a reading of the average wind speed measured in a volume ahead of the turbine. This is exploited to better cope with fast changes in the average speed of the stream, thus helping reducing machine downtime and ultimate loads.

In any case, due to the change in the behavior of the turbine over the operative regions, it is often necessary to include a form of model or gain scheduling in trimming control laws, in turn requiring the adoption of wind measurements or more stable and accurate wind observers (see [37–39]).

Concerning outer layers, the frequency band of pitch actuators can be employed to target the lower per-revolution frequencies showing up in the spectra of load signals from the blades, tower, and shaft. Works by Bossanyi [33] propose an approach based on Coleman's transformation, developed to target higher harmonics in the works of Cacciola [40–42], whereas Bottasso et al. [32] describe a model-based approach for deterministic loads and a model-free approach for residual noise components, typically due to high-frequency turbulence. Synthesizing the gains of this control layer, whatever the selected approach, can be done according to heuristics or optimal numerical procedures [43].

As stated at the beginning of this section, in the flow of an MDO problem, a trimming controller is needed for all load cases where the machine is not parked, and load-targeting layers may be included usually to the aim of making the machine lighter.

During an iteration, when the aerodynamics and structure of the model have been assigned, all elements needed to synthesize a control law are available. The analysis of $C_P - TSR - \beta$ curves, considered together with required rated power and limitations on the blade peripheral speed for complying with noise constraints, produce an optimal regulation trajectory [11]. This is readily translated into set points for the rotational speed, input collective pitch, and electrical torque for increasing values of the wind between cut-in and cut-out speed.

For model-independent trimmers, these equilibrium points are the only needed information. Gains usually designed a priori, and typically scheduled with respect to the wind speed, can be applied online to trim the machine to the desired set point. Empirical methods for slightly changing these gains, in view of modifications in the model brought in by the evolution of the turbine design solution over the optimization, may be accounted for. A redesign of the PI gains iteration by iteration, by means of dedicated optimal numerical procedures, is usually not possible in the realm of an optimization, unless based on dynamic simulations carried out on a reduced model, thus imposing a lower computational effort than when run on the high-fidelity aeroelastic code.

In this sense, model-dependent trimmers offer a good level of simplification. Once the regulation trajectory has been obtained, it is possible to readily synthesize a reduced model, linearized around selected operative conditions along the trajectory. Gains are then synthesized for every considered equilibrium condition. When going online, previously computed gains are simply scheduled with respect to the wind following a linear interpolation scheme.

As said, it is possible to include more states in the reduced model than those related to dynamic rotational equilibrium. Most typically, a decoupled equation for the tower fore-aft dynamics, obtained from the truncation to the first mode of a modal representation of the tower top displacement, can be included with good results on tower base loads and basically no effect on trimming performance. In the workflow of the MDO, once a high-fidelity model has been prepared, a model reduction can be carried out, obtaining the coefficients to feed the corresponding equation of the reduced model. Considering Cp-Lambda, it can be reported that a modal reduction tool can be found in the code, suitable for the task.

Both in case deformative states are accounted for or not, the presence of a reduced model allows to consider more accurately the evolution of the optimal turbine design, iteration by iteration.

2.4 Prebend design submodule

In those designs where the maximum tip displacement is an active constraint, the prebend design submodule (PDS) is used for optimizing the prebend, i.e., the native out-of-plane deflection of the blade. During the optimization loop, the PDS tries to design the prebend so that, when the rotor undergoes normal loading, the resulting swept area is maximized. It must be noticed that this criterion can be translated into the requirement of minimizing the parameter A_δ as defined by Eq. (12):

$$A_\delta = \int_0^1 \delta_y(\eta) d\eta \tag{12}$$

where $\delta_y(\eta)$ is the spanwise distance between the deformed blade and the ideal rotor plane. This way, the parameter A_δ corresponds to the gray-shaded area in **Figure 2**.

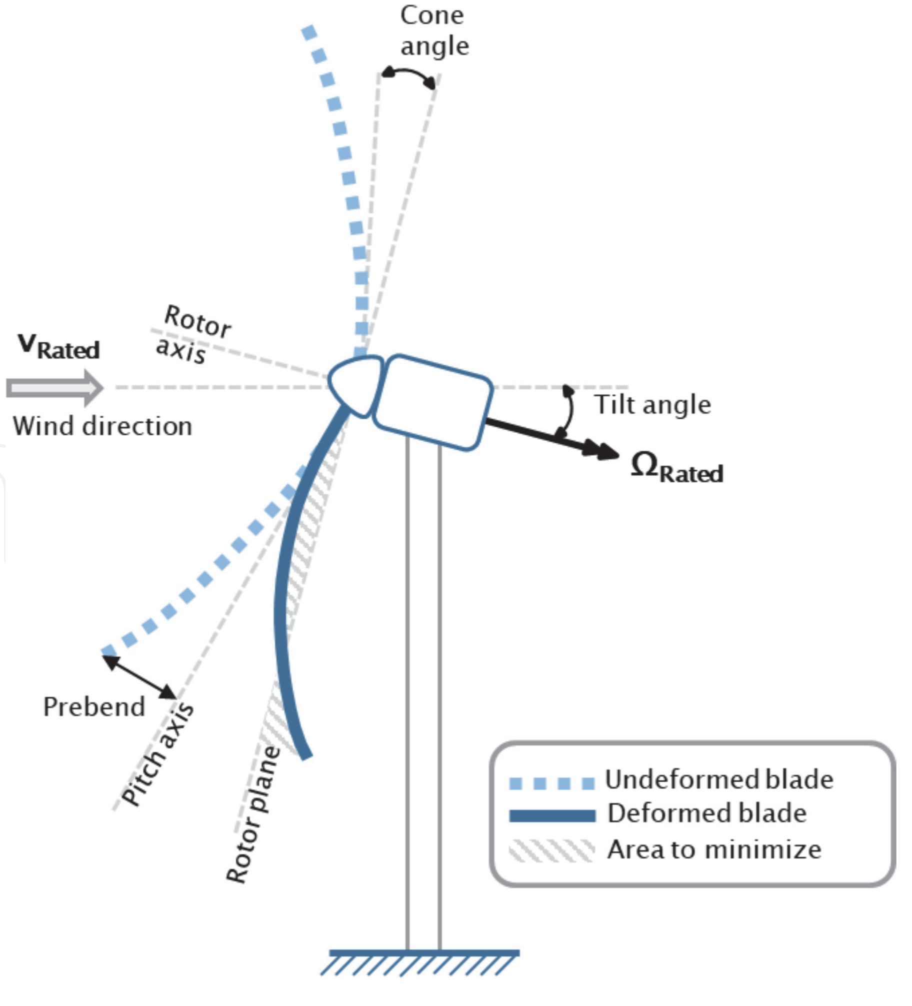

Figure 2.
Representation of the prebend design process.

With this in mind, the formalization of the prebend optimization subproblem can be stated according to Eqs. (13) and (14):

$$\left(\boldsymbol{p}_b^*, A_\delta^*\right) = \min_{\boldsymbol{p}_b} \left(A_\delta\left(\boldsymbol{p}_a^*, \boldsymbol{p}_b, \boldsymbol{p}_s, \boldsymbol{p}_g, \boldsymbol{r}_\epsilon^*\right)\right) \tag{13}$$

$$s.t.: \boldsymbol{g}_b\left(\boldsymbol{p}_b, \boldsymbol{p}_g\right) \le \boldsymbol{0} \tag{14}$$

It must be noticed that, according to Eq. (14), the parameter A_δ is influenced not only by the shape of the prebend itself (defined by the parameters $\boldsymbol{p}_b$) but also by variables coming from the aerodynamic, structural, and global design. In particular, the PDS assumes that an aerodynamic design loop has been performed ahead, so that the optimal values of the aerodynamic design variables enter the module. Similarly, the PDS requires the knowledge of the regulation trajectory of the machine, computed at a previous step. With all this data available, the deflection of the blade is computed from simple static simulations in operating conditions, in order to design the prebend for a representative condition of the system without the need of time-consuming dynamic simulations. Eq. (15) lists a series of nonlinear constraints which are specific for the prebend design problem. These typically account for common manufacturing limitations such as maximum prebend at tip, maximum steepness of the prebend distribution, or application-specific requirements.

2.5 Structural design submodule

The structural design submodule (SDS) allows to perform the structural optimization of blades and tower with the aim of minimizing the initial capital costs (ICC) associated to the turbine manufacturing. This can be summarized in the optimization subproblem of Eqs. (15)–(17):

$$\left(\boldsymbol{p}_s^*, ICC^*\right) = \min_{\boldsymbol{p}_s} \left(ICC\left(\boldsymbol{p}_a^*, \boldsymbol{p}_b^*, \boldsymbol{p}_s, \boldsymbol{p}_g, \boldsymbol{r}_\epsilon^*\right)\right) \tag{15}$$

$$\boldsymbol{p}_s = \left[\boldsymbol{t}_b^{Fabrics}, \boldsymbol{t}_b^{Core}, \boldsymbol{t}_t, \boldsymbol{\rho}_t\right] \tag{16}$$

$$s.t.: \boldsymbol{g}_s\left(\boldsymbol{p}_a^*, \boldsymbol{p}_b^*, \boldsymbol{p}_s, \boldsymbol{p}_g, \boldsymbol{r}_\epsilon^*\right) \le \boldsymbol{0} \tag{17}$$

According to Eq. (16), the computation of the ICC depends on the entire wind turbine model, so that all families of design variables enter the module. Since the SDS is the last submodule within the workflow of Cp-Max, it is assumed that the aerodynamic variables, as well as those related to prebend have been previously optimized. Eq. (17) shows the composition of the structural design variables: here, $\boldsymbol{t}_b^{Fabrics}$ is the thickness of all the blade structural elements, while $\boldsymbol{t}_b^{Core}$ accounts for the thickness of fillers (typically balsa or foam). The terms $\boldsymbol{t}_t$ and $\boldsymbol{\rho}_t$ account, respectively, for the internal thickness and radius of the tower segments. Starting from the internal layout and from the mechanical properties of the different materials, the SDS performs a sectional analysis based on the anisotropic beam theory proposed by Giavotto et al. [44]. This allows to compute, for each section, the fully populated mass and stiffness matrix. Those properties are then supplied to Cp-Lambda in order to update the structural properties of the blades and tower. Then, the ultimate loads and displacements are computed from an arbitrarily large set of design load cases (DLC) according to the international standards [45, 46], which typically include both deterministic and turbulent simulations. Once the envelope of ultimate and fatigue loads is known, a set of nonlinear constraints is enforced according to Eq. (18) in order to achieve a fully feasible structural solution. Classic constraints include resonance avoidance and frequency placement as well as ultimate stress/strain verification, a full fatigue analysis, a check on the maximum blade displacement, and a preliminary buckling analysis. The entire procedure is then repeated until the ICC is minimized. During optimization, it is also possible to perform detailed 3D FEM analyses in order to further refine the structural solution. The procedure is reported by Bottasso et al. [26].

2.6 Stability submodule

Stability analysis tools are of general utility for analyzing the causes of excessive vibration or for quantifying the effects of controllers on the closed-loop turbine behavior. Within the multidisciplinary design process of wind turbines, the stability analysis represents an important step to verify the proximity of flutter limits and drive the design onto regions in which all modes of interest are characterized by suitable damping levels.

The stability check can be performed on the entire turbine or on part of it, such as single blade. Within the design process, it is treated as a submodule external to the optimization loop. Hence, it is employed to verify the stability margins after the whole design or at the end of any MDL iteration.

Although stability is a well-known and studied problem for linear time invariant systems (LTI), some issue arises over the application of standard analysis methods to the case of wind turbines. In fact, as it often happens for rotating systems, wind turbines exhibit a behavior which is better comprehended within the theory of linear time periodic systems (LTP). This can be simply demonstrated by the fact that many physical phenomena entail wind turbine models characterized by periodic coefficients. Among all, one may mention the periodic stiffening induced by gravity, which compresses and extends the blades according to their position (upward or downward), or the asymmetry of the wind which entails periodically variable aerodynamic forces [47].

Periodic models can be rigorously studied through the Floquet theory [48], which shows that the stability of the system is uniquely defined by the characteristic multipliers, which are the eigenvalues of the so-called monodromy matrix (i.e., the transition matrix computed over one period). If the norm of each characteristic multiplier is lower than 1, then the system is asymptotically stable [49]. Since the computation of the monodromy matrix requires one integration of the equation of motion over a period for each state of the system, the application of the pure Floquet analysis to large and very large systems with thousands of degrees of freedom, as those characterizing modern high-fidelity multi-body models, is so much computationally expensive to result basically unaffordable even for current technology.

For this reason, many simplified methodologies, with much lower computational cost, often developed in the context of multi-body modeling of helicopters and wind turbines, have been proposed in literature with the aim of coping with Floquet analysis for very large systems. Among all, one can mention techniques which approximate the monodromy matrix with cascading Runge–Kutta solutions [50] or Chebyshev expansions [51] or algorithms which extract only the lowest characteristic multipliers from an incomplete transition matrix (noted as partial Floquet analysis [52]) or using Arnoldi's method (noted as implicit Floquet analysis [53]).

Dealing with wind turbine system stability, two other methods were recently proposed, one based on Coleman's transformation [54] and the other on a system identification procedure.

In the first method, Coleman's transformation is applied to a linearized state-space model of the turbine [3, 55, 56]. Such transformation has the effect of dramatically reducing the periodicity in the system matrices. The remaining periodic terms in the transformed system are then removed leading to an invariant system, which can be studied by a standard stability tool for LTI systems. Clearly, such an analysis is computationally affordable but presents two specific issues. Firstly, it cannot be applied to two-bladed wind turbines, as Coleman's transformation exists only for rotors with three or more blades. Secondarily, this approach is model-dependent, in the sense that any change of the topology of the turbine or any improvement in the nonlinear mathematical model has to be followed by an update of the linearization tool and of the implementation of Coleman's transformation itself. Due to the complexity of modern high-fidelity multi-body software tools, all these modifications may entail a significant effort.

Because of these issues and with the scope of having a MDO applicable to turbine models with any complexity, the approach based on system identification [47, 57, 58] has been chosen for the stability submodule. According to this approach, a simplified discrete periodic model of the periodic auto-regressive moving-average model with exogenous input (PARMAX) family is identified from input–output time histories of some suitable variables of interest. Then, the Floquet theory is applied to the reduced-order identified model, which accounts for only few states, i.e., those needed to capture the relevant behavior of the system. Such an approach, being based on input–output time histories, is independent from the simulator and from the model, in principle applicable to real turbines. Furthermore, since the Floquet analysis is performed on a system with few degrees of freedom, the entire approach results fully compliant with the periodic nature of the problem and affordable from a computational point of view.

From a practical standpoint, one has to generate input–output time histories from specific simulations where the modes of interest are mainly involved. Typically, one may introduce in the simulations some impulsive forces on the tower top and on the blade tip in order to excite the low-damped tower, whirling, and blade modes. Then the PARMAX model can be fitted on the measure of tower base and blade root bending moments, recorded after the end of the perturbation, where the aforementioned modes are well visible. With such an analysis, one may typically capture the most significant and low-damped modes of the wind turbine, which are the tower fore-aft and side-side modes, the forward and backward in-plane whirling, and the blade edgewise modes.

The damping ratios of those modes are then used within the MDO process to verify the stability margins and assess the possible proximity of the flutter boundaries. Using this approach, in [59] it was possible to prove that after a redesign of a blade including bend-twist-coupling, tower fore-aft and blade edgewise modes are characterized by a lower but still safe level of damping.

3. Applications

As discussed in the previous sections, the development of the design tool Cp-Max started in 2007, thanks to several funded industrial projects first in Italy and then also abroad. Over the years, up to four different blades have been designed and manufactured based on computations performed with this tool. Besides these industrial projects, other research activities have been carried out leading to the implementation of the Cp-Max code, as discussed in the previous sections. In the next paragraphs, we present some results aiming to highlight some features of the tool.

3.1 Design of a 20 MW wind turbine

Within the European FP7 project INNWIND.EU [60], significant efforts have been dedicated to the development of technological solutions able to reduce the COE. Among these, the synergy between active and passive load alleviation systems represents certainly an interesting solution for the design of lightweight rotors. These solutions have demonstrated how to smartly increase the size and power of future wind turbines. For this reason, a conceptual design of a 20 MW wind turbine has represented an important step, and the design tool Cp-Max has been demonstrated to have all the features needed to obtain a good preliminary design without upscaling laws.

From a historical perspective, as Sartori shows in details [61], the rotor design started from a reference wind turbine obtained from the INNWIND.EU 10 MW. At first, classical scaling laws have been applied to upscale the reference 10 MW turbine to 20 MW. Afterward, Cp-Max has been employed to produce a realistic structure for the upscaled model. These two steps provided a baseline model (in the following referred to as "baseline 20 MW"), which was optimized afterward. In order to deeply understand the effect of each submodule presented in Section 2, we adopted a parametric approach where we performed three design steps: (I) a prebend analysis, (II) a bend-twist coupling analysis, and (III) a solidity analysis. At the end of each step, the optimal configuration was taken as the starting point of the following one. It must be stressed that a full structural redesign of each solution under investigation has been conducted, so that all the configurations analyzed satisfy the same design constraints and hence may be fairly compared.

First, the prebend submodule of Section 2.4,was used to define the prebend distribution. In a sensitivity analysis, the main parameter was the tip value of prebend distribution, which was assumed equal to 2 and 4 m. The final spanwise distribution computed by the Cp-Max submodule is shown in **Figure 3**. The latter solution has been selected for the following step due to its (slightly) better capability of reducing the COE, as can be noticed in **Figure 4**. This COE reduction is due to the mass drop caused by the higher blade-to-tower distance, which allows the blade itself to be more flexible.

The second step was the introduction of a passive load alleviation system in the blade. This has been achieved with a coupling between the bending and the torsion deformation of the blade, the so-called bend-twist coupling (BTC), as previously presented in [62] for a smaller blade. This coupling is here obtained by moving the fiber direction of the unidirectional material in the spar caps away from the pitch axis.

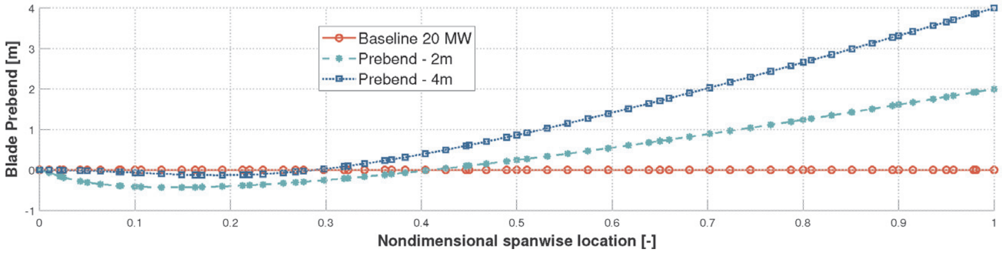

Figure 3.
Spanwise optimal prebend distribution.

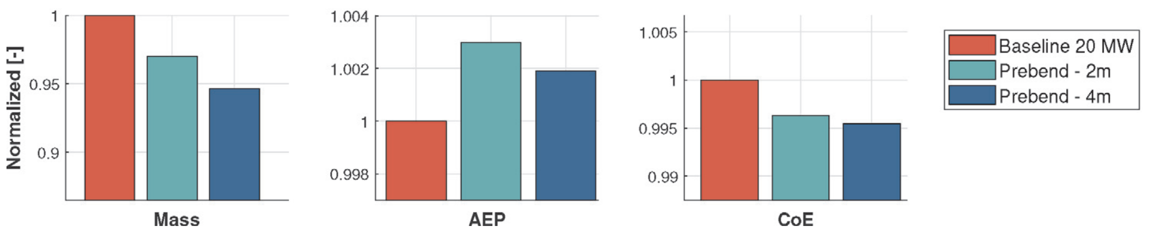

Figure 4.
Nondimensional mass, AEP, and COE of the optimized prebended blades.

Again, a sensitivity analysis has been conducted to deeply understand the effects of the BTC angle, assumed as the parameter of the analysis, on the wind turbine loads and on global parameters as well, i.e., the blade mass, the AEP, and the COE. The values considered here, selected from previous analyses performed on other blades, are 4, 6, and 8°. The effects of the BTC are mainly felt on the fatigue loads of wind turbine subcomponents (as shown in [61]) and on the actuator duty cycle, so that without any further action (i.e., stretching of the blade, redesign of the tower/ hub systems, etc.), the COE is almost unchanged, as one can see in **Figure 5**. However, the same figure shows that the blade mass may start to rise when over-increasing the fiber angle. This is because the higher the fiber angle, the higher the spar cap thickness needed to restore the flapwise stiffness, which is constrained in the design process by the maximum blade deflection and by the blade frequency placement with respect to the rotor speed. Finally, the AEP picture shows that the BTC tends to reduce the power output of the rotor. This is due to the increased torsional deformation of the blade which, during the normal operation of the wind turbine, changes the optimal local angle of attack. This effect may be bypassed by a fine tuning of the control law as shown in Section 2.3.

The last step involves an analysis of the effect of solidity, starting from the optimal 6° BTC blade, which represents the best compromise between the load and mass reductions. This solidity analysis required the aerodynamic submodule (2.2) to define the external geometry, together with the structural submodule (2.5) to size the internal geometry for each chord distribution. The solidity has been reduced to 98, 96, and 94%, and the effects on the fatigue loads of these reductions are shown in **Figure 6**, whereas the effects on the global parameters are featured in **Figure 7**.

As one can see, the reduction in the blade solidity generates lower fatigue loads in the nonrotating subsystems of the wind turbine (i.e., nacelle and tower), while it increases the loads at the root of the blades. This is because the reduction of the chord, and hence in the blade thickness, must be compensated by an increase of the spar cap thickness to restore the flapwise stiffness, for fixed airfoils characteristics. This increase in the total blade mass (see **Figure 7**) in turn increases blade loads. The overall effects on the AEP and COE are, on the other side, negligible. Therefore, the 96% solution is here assumed as the best compromise considering all performance indicators.

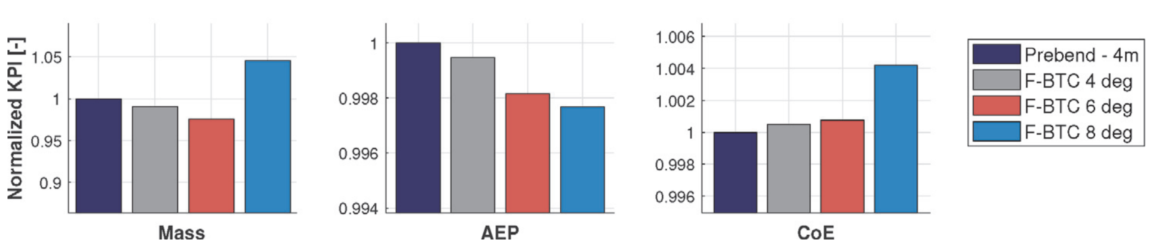

Figure 5.
Nondimensional mass, AEP, and COE of the optimized bend-twist coupled blades.

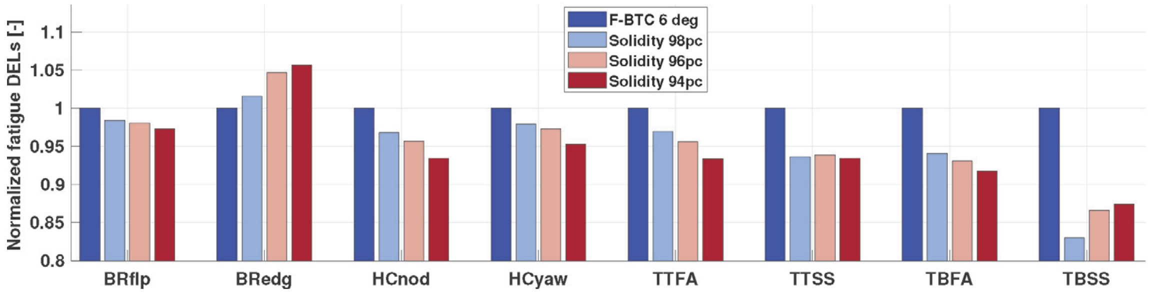

Figure 6.
Nondimensional fatigue loads (DELs) comparison. BR = blade root, TB = tower base, TT = tower top, and HC=hub center.

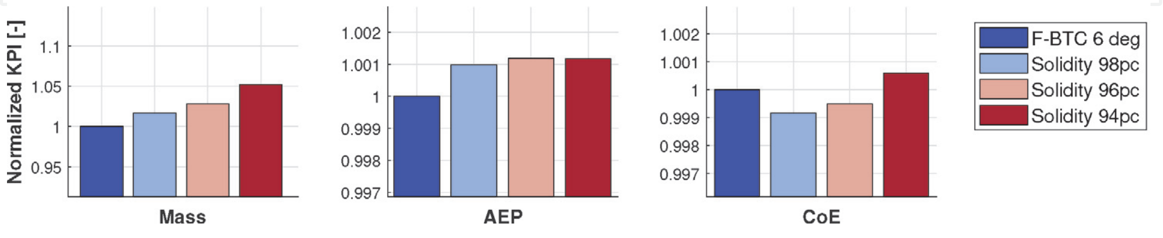

Figure 7.
Mass, AEP, and COE of the optimized blades.

	Units	Baseline	Optimal	Change
		20 MW	20 MW	
Total blade mass	[ton]	113.5	107.8	−5.05%
AEP	[GWh]	91.6	91.7	+0.12%
COE	[EUR/MWh]	84.9	84.6	−0.42%
Blade root flap DEL	[MNm]	83.8	75.6	−9.79%
Hub nodding DEL	[MNm]	53.6	46.7	−12.83%
Tower base FA DEL	[MNm]	278.5	271.6	−2.48%
Tower base SS DEL	[MNm]	204.4	164.9	−19.2%

Table 1.
Performance comparison between the baseline and the optimal 20 MW rotors.

Finally, an overall comparison between the baseline rotor and the optimized one, equipped with a 6° BTC, a 4-m-tip prebend, and a reduced 98% solidity, is shown in **Table 1**. The comparison highlights only a slight decrease in the COE (of about 0.42%), but it is important to stress here that this reduction is also coupled with lower tower and hub loads. This trend suggests the chance to redesign these subcomponents and/or to design a longer blade able to transmit to the fixed subsystems of the turbine the same baseline loads. Both of these solutions, or a combination of them, may hence further decrease the COE.

3.2 Wind turbine under wind farm control

In recent years, many efforts have been placed in research activities related to the development of wind farm controllers. The idea behind this topic is to look for optimal wind farm operations in order to maximize the power output of the farm which, in turn, is strictly connected to the minimization of the wake interfaces between the machines. In the analyses related to the development of these wind farm control algorithms, much attention has been devoted to the verification of the AEP and the fatigue loads, but little has been done about the analysis of the impact of these controllers on the load envelope of the single machine and therefore on its design. In fact, the wind farm controller techniques may alter the normal functionality of the single wind turbine and hence change the critical design conditions. This may cause design loads and blade deflections to exceed the design constraints.

In this paragraph we present, as a further example of a possible use of the multidisciplinary design tool Cp-Max, the redesign of the 10 MW INNWIND.EU wind turbine, in case it is subjected to a wind farm control technique, named active wake mixing (AWM). This is a control scenario where the blades are pitched to create a dynamic rotor thrust, with the effect of sucking undisturbed air into the wake, so as to reenergize it. In this research, the AWM is obtained by periodically changing the collective pitch angle [63] as

$$\beta_{\mathrm{AWM}} = A_{\mathrm{AWM}} \sin\left(2\pi f_{\mathrm{AWM}} t\right), \tag{18}$$

where β_{AWM} is the pitch setting imposed by wind farm control, which is superimposed to the pitch of the trimmer, A_{AWM} is the related amplitude, and f_{AWM} is the frequency. Typically, rather than in terms of frequency f, the effect of AWM is viewed in terms of the dimensionless Strouhal number S_t, defined as

$$S_t = \frac{f_{\mathrm{AWM}} D}{U_\infty}, \tag{19}$$

being U_∞ the undisturbed wind velocity and D the rotor diameter. Parametric aeroelastic analyses conducted on this wind turbine showed that the maximum loads on the blade, and hence the maximum deflection, may exceed the design values especially for higher amplitude of pitch actuation A_{AWM} and Strouhal numbers. This means that the rotor may need to be redesigned when the wind farm controller is applied to the farm. The design problem here requires to include in the control system synthesis of Section 2.3 the AWM activity in order to include in all DLCs the effect of the wind farm controllers. Energizing the wake is useful only at low wind speed, because in the above-rated region, the wake still maintains enough energy to allow the downstream wind turbine to operate at full power. For this reason, the AWM in this research is switched off in all the simulations where the mean hub wind speed is higher than 15 m/s. Clearly, the wind farm control is not included in the DLCs where the wind turbine is parked. Nevertheless, the latter simulations must be included in the design process since they may turn out to be design-driving loads. When this happens, i.e., when the design-driving loads arise from not-controlled cases, the wind farm controllers do not affect the wind turbine rotor. The two parameters of the AWM, after a sensitivity analysis, have been defined as $A_{\mathrm{AWM}} = 2°$ and $S_t = 0.5$, which corresponds to a good compromise between the need to energize the wake and to avoid excessive loads on the upwind turbine. To better understand the effects of the wind farm controller on the rotor design, we first redesign the INNWIND.EU 10 MW wind turbine without any farm controllers. In so doing, we are sure the new 10 MW baseline will be the result of a design process considering the same trimmer (2.3), the same DLCs, the same aeroelastic model, and the same design approach and constraints. Starting from this new 10 MW baseline, we restart the Cp-Max design loop including in the process also the DLCs with the AWM controller. It is important to stress here that also the simulations without the farm controller must be considered, since they may generate higher loads and, in general, the AWM may be switched off for selected wind

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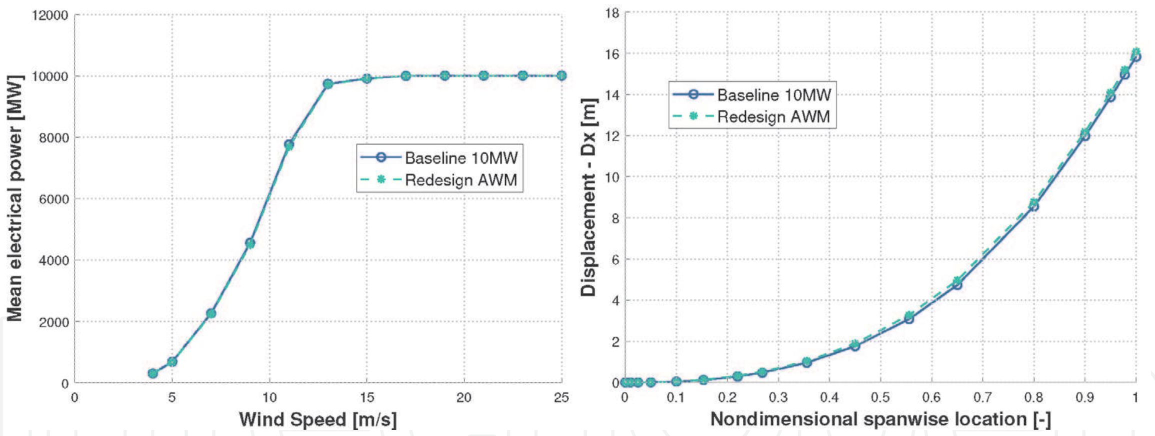

Figure 8.
Power curves (left) and maximum blade deflections (right) for the baseline model and the optimized one.

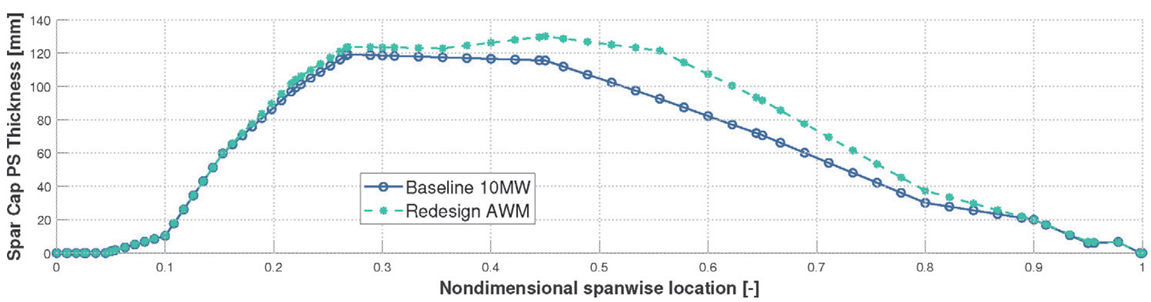

Figure 9.
Spanwise pressure-side spar cap thickness distributions.

directions. In **Figure 8**, the power curves' comparison between the baseline wind turbine and the optimized one is displayed. As one can see, in the partial-power region, despite the AWM actuation, which causes the blade to move out of its optimal pitch value, the power curve remains close to the baseline. **Figure 8** shows the maximum blade deflections to be very close to each other. This result comes directly from the optimization process, where the blade tip deflection is for this rotor an active constraint. However, these maximum deflections are obtained with a different blade stiffness. Due to the higher loads under the wind farm controllers, Cp-Max has to increase the spar cap thicknesses in the structural submodule (2.5) as

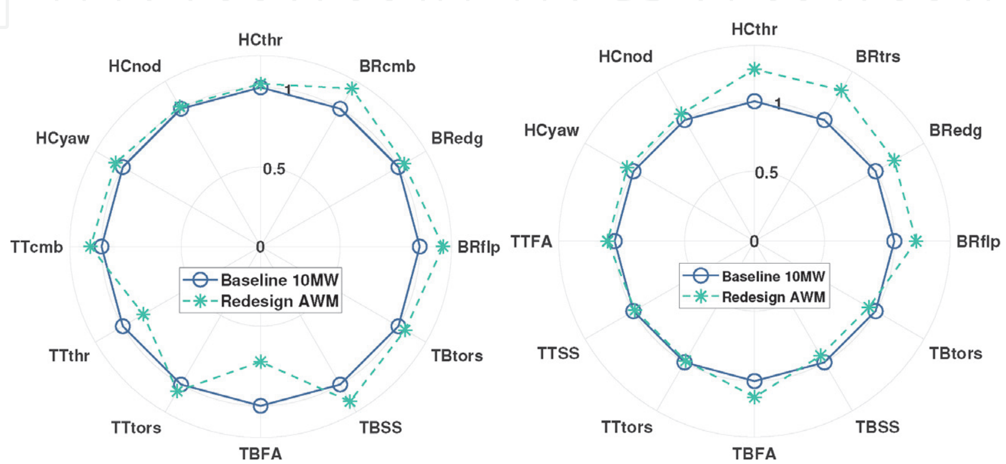

Figure 10.
Fatigue DEL (left) and ultimate loads (right) comparison of the redesign AWM against the baseline (the latter normalized to one). BR = blade root, TB = tower base, TT = tower top and HC = hub center.

	Baseline	AWM-redesigned	Variation
Blade mass	40,643 kg	45,436 kg	+11.8%
AEP	45.86 GWh	45.63 GWh	−0.5%
COE	89.42 EUR/MWh	90.22 EUR/MWh	+0.89%

Table 2.
Baseline rotor vs. AWM-redesigned rotor.

shown in **Figure 9**. Finally, **Figure 10** shows the comparison between the normalized loads on the baseline and optimized rotor. In this figure, on the left plot, one can see the fatigue loads (DELs) and on the right the maximum ones. BR refers to blade root, TB to tower base, TT to tower top, and HC to hub center. The main conclusion from this picture is that the loads to which the single wind turbine is subjected when operating under AWM control may increase, and this generates a heavier structure as shown in **Table 2**.

4. Conclusions

In this chapter, we proposed the use of a multidisciplinary design optimization framework to design next-generation wind turbines. We showed how such algorithms require to compromise between different aspects pertaining to the optimization, such as scope, number of variables, merit functions, and modeling fidelity. In this context, we presented a multilevel algorithm which is able to perform the complete design of a wind turbine, through the interface of several optimization modules.

Based on the results presented in this chapter and on an extensive practice on MDO, not shown here for the sake of brevity, the following conclusions can be drawn:

- A wind turbine design conducted in a multidisciplinary environment is necessary to fully capture all the couplings and interconnections existing in the nonlinear response of the turbine. In fact, a rotor which is optimal only from an aerodynamics standpoint may be far from optimal when it comes to the overall design (i.e., structure, control, cost of energy).

- The proposed modular architecture offers a sufficient flexibility to treat a wide number of design variables without sacrificing the accuracy of the physical description. This allows to derive driving loads and deflections directly from fully resolved design load cases, so that the optimal solution is automatically standard-compliant.

- The use of a model-based control eases the optimization procedure since the control parameters are automatically adjusted to the evolving model within the design process.

- As the entire proposed loop operates on a full multi-body model of the wind turbine, it is immediately possible to perform specific further analyses, thus improving the confidence of the solution. For example, the assessment of the stability of the system can be run to ensure that the optimal solution does not show resonance problems.

- The procedure hitherto exposed can be employed for a variety of applications, which include preliminary wind turbine or detailed component design, trade-off analyses, verification of the impact of selected control laws on cost of energy, and design of unconventional configurations.

Conflict of interest

The authors declare that there is no conflict of interest.

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