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Multi-objective optimisation of horizontal axis wind turbine structure and energy production using aerofoil and blade properties as design variables

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A B S T R A C T

The design of wind turbine blades is a true multi-objective engineering task. The aerodynamic effectiveness of the turbine needs to be balanced with the system loads introduced by the rotor. Moreover the problem is not dependent on a single geometric property, but besides other parameters on a combination of aerofoil family and various blade functions. The aim of this paper is therefore to present a tool which can help designers to get a deeper insight into the complexity of the design space and to find a blade design which is likely to have a low cost of energy. For the research we use a Computational Blade Optimisation and Load Deflation Tool (CoBOLDT) to investigate the three extreme point designs obtained from a multi-objective optimisation of turbine thrust, annual energy production as well as mass for a horizontal axis wind turbine blade. The optimisation algorithm utilised is based on Multi-Objective Tabu Search which constitutes the core of CoBOLDT. The methodology is capable to parametrise the spanning aerofoils with two-dimensional Free Form Deformation and blade functions with two tangentially connected cubic splines. After geometry generation we use a panel code to create aerofoil polars and a stationary Blade Element Momentum code to evaluate turbine performance. Finally, the obtained loads are fed into a structural layout module to estimate the mass and stiffness of the current blade by means of a fully stressed design. For the presented test case we chose post optimisation analysis with parallel coordinates to reveal geometrical features of the extreme point designs and to select a compromise design from the Pareto set. The research revealed that a blade with a feasible laminate layout can be obtained, that can increase the energy capture and lower steady state systems loads. The reduced aerofoil camber and an increased L/D-ratio could be identified as the main drivers. This statement could not be made with other tools of the research community before.

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1. Introduction

Regardless of the recent economic challenges, global wind turbine installation can record healthy growth figures year by year. Despite this encouraging development, competition between companies in the sector is intensified and the profit margins are shrinking. The development of new, more reliable and efficient turbines is one way to answer this competitive pressure. Therefore, tools like the Computational Blade Optimisation and Load Deflation Tool (CoBOLDT) can help to gain new insights into a highly constrained and complex design space represented by wind turbine rotor blade development.

For the presented research paper three objective functions are minimize, that are proportional to the cost of energy (CoE) of a wind turbine investment over its life time. This approach has been taken because the direct calculation of CoE is partly ambitious and many cost factors cannot be influenced by the turbine manufacturer but are depended on the site where the wind turbine is erected. To evaluate all cost factors Fingersh et al. [1] proposed a wind turbine scaling and cost model, in which statistical data of thousands of turbines is used to derive empirical formulations for the costs of the main wind turbine components. However, the physics behind a certain turbine design is not reflected. We are approaching the topic from a manufacturer perspective and focus on the reduction of wind turbine thrust and blade mass as proxy of turbine capital cost and the improvement of Annual Energy Production (AEP). For this purpose we concentrate on the geometrical blade properties, namely the shape of the aerofoils and the blade

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Nomenclature

AEP	annual energy production
AoA	angle of attack
BEM	blade element momentum
CFD	computational fluid dynamics
Cl	lift coefficient
CoBOLDT	Computational Blade Optimisation and Load Deflation Tool
CoE	cost of energy
DoF	degrees of freedom
EPD	extreme point design
FEM	finite element method
GA	genetic algorithm
GFRP	glass fibre reinforced plastics
HAWT	horizontal axis wind turbine
IEC	international electrotechnical commission
MOTS	Multi-Objective Tabu Search
2D-FFD	two-dimensional Free Form Deformation

functions, since they represent turbine parameters with high impact on the chosen objective functions.

The paper is subdivided into six sections. After this introduction and the methodology and research outline in chapter two, the construction and functional details of the optimisation package CoBOLDT are presented in chapter three. In chapter four a design case using the Nordex Rotor Blade NR41 [2] as initial design is shown and the optimisation setup is stated. A detailed post optimisation analysis of several points in the Pareto set will follow in chapter five which contains a parallel coordinates analysis to relate geometrical features to the considered performance metrics. This analysis is supposed to help the designer to concentrate on only those parameters that are important for the design problem. The conclusion in chapter six summarizes the findings and discusses possible future developments.

2. Methodology and research outline

In the field of wind turbine blade optimisation the choice of the optimisation technique is particularly challenging since traditional gradient-based algorithms are often unable to cope with numerical, mathematical or physical noise of the processed signals. In some cases the solution can be to evaluate and improve the gradient quality by curve approximation [3]. Another way to circumvent the problem of establishing suitable gradients can be the use of metaheuristic optimisation approaches. Especially Genetic Algorithms have been in the focus of many recently published articles [4–8]. A Paper from Benini and Toffolo [9] shows how a multi-objective GA can solve the trade-off between structural requirements in the root section versus the aerodynamic requirements at the middle and tip section of the blade. The design case uses a stall regulated wind turbine with chord and twist parametrised with Bezier curves and the tip speed and tip speed ratio as scalar parameters. The structural mass is estimated with an I-beam for which the skin thickness is calculated with glass fibre reinforced plastics (GFRP) and loads from a steady Blade Element Momentum (BEM) simulation. This structural model originally proposed by Fuglsang and Madsen [10] has also been used by other researchers in this field [11,12].

However in the current paper the core of the optimisation package CoBOLDT is based on the Multi-Objective Tabu Search (MOTS) as described by Jaeggi et al. [13]. It is a fast and efficient algorithm with a powerful local searching scheme which has been proven to successfully solve multi-dimensional aerodynamic optimisation problems [14–18]. Since MOTS was designed to solve large problems it is able to run in a parallel computing environment on a 64 bit Linux operating system. The memory management and the selection of new parameters is the task of the master code, whereas the evaluation of each design will be performed by a number of slaves. We prefer this type of optimisation over the mentioned examples of GAs as the small modification from one design to the other in MOTS is perfectly suited for parameters with high impact on the optimisation objectives.

In terms of the aerodynamic performance evaluation of the rotor three different methods with varying fidelity and associated computational cost are most common. The slowest option is Computational Fluid Dynamics (CFD) which is therefore mainly used to verify rotor performance after the optimisation [17] or to investigate wind turbine sub models like the blade tip [19]. Secondly potential flow theory methods like in Abedi et al. [20] can be used but are also quite slow and usually require knowledge of the wind turbine wake. The third and most prevalent method is the BEM method, which is very fast a reasonably accurate [3,17,17] and is employed for this research. The automated structural layout with a Bernoulli beam model has been chosen due to its fast computational speed opposed to the Finite Element Method (FEM) presented by Jureczko et al. [7] or Chen et al. [21]. The model takes advantage of the real laminate properties of the structure and can provide a more realistic mass and stiffness prediction opposed to the structural model of Benini and Toffolo [9] or Young and Wu [11]. The polar data needed for the BEM is created with Xfoil [22] like shown in other publications in the field [6,23].

The paper combines these theories and applies them in multidisciplinary, multi-objective optimisation to an industrial scale wind turbine to achieve the afore mentioned research objective. Opposed to other design system presented in the literature a simultaneous relative parameterisation of aerofoils and the blade functions allows to exploit the effects of both design areas without being limited to one of them. The structural model at the same time should guarantee the structural feasibility, which is considered another novelty. The design strategy can hence give a more holistic indication of what kind of aerofoils properties are needed at which span wise position and how important the actual blade functions are. However the tool cannot replace the designer as in the absence of a loads base turbine cost model the selection of a compromise design is to some extend always subjective.

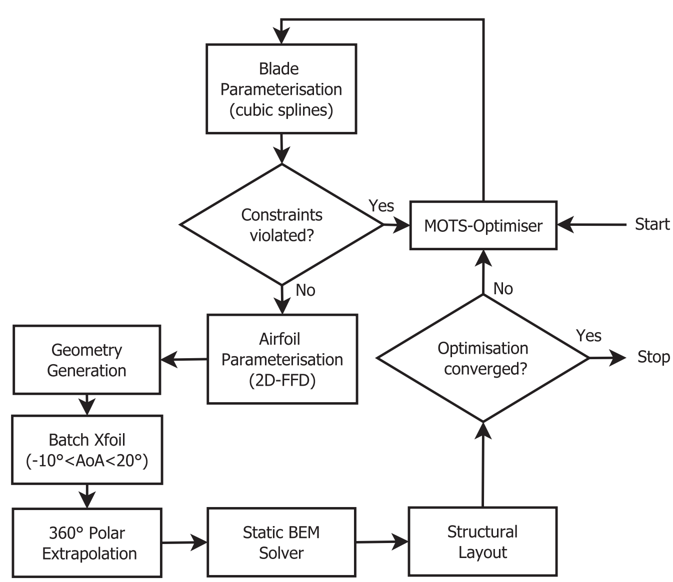

Fig. 1. Workflow of CoBOLDT.

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