Sensitivity analysis of a wind rotor blade utilizing a multi-disciplinary tool chain

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Summary

Due to the multi-disciplinary nature in the design of wind turbines, developers and manufacturers face several challenges. One of them is the exchange of model data between the different disciplines, e.g. aerodynamic or structural dynamics. To overcome the problems of data exchange between the disciplines the Common Parametric Aircraft Configuration Schema (CPACS) has been developed by the German Aerospace Center (DLR). Based on this data scheme a multi-disciplinary tool chain and the verification of their components are presented.
Due to some similarities in the design of aircraft wings and wind turbine blades, the tool DELiS has been extended to create structural finite element models of wind turbine blades. The tool has been validated to an industrial rotor and the DTU 10-MW reference rotor blade. The finite element models are dynamically reduced and exported as flexible bodies to the multi-body simulation tool Simpack. For aeroelastic analyses an aerodynamic model is coupled to the multi-body simulation tool. The aerodynamic models can be either a high-fidelity CFD-simulation or a low-fidelity model based blade element momentum theory. This paper illustrates guidelines for the development of a multi-disciplinary tool chain and its interfaces. Based on this framework, sensitivities of parameter changes as well as parameter optimization can be done utilizing a trained neuronal network. The methodology of this analysis with a low number of parameters will allow a sensitivity analysis for complete rotor blade designs in the future.

Introduction

Over the last decade the size of wind turbines has substantially increased. Currently this trend seems to continue in order to reach the ambitious goals which have been set for energy production from renewable sources, especially wind energy. Increasing hub heights and blade lengths will require major technological improvements.
The energy policy of the German federal government is to produce 30% of the gross power generation by wind energy by 2030. Based on this decision wind energy plays an important role in Germany's power generation concept. In order to meet the ambitious goals the overall size of each individual wind turbine will have to be increased. The envisaged 20MW turbine class can only be achieved if major technological improvements are made. Rising hub heights and blade lengths will require new integrated design concepts, new materials and manufacturing technologies. A key-element for the technological improvement is the availability of an integrated design tool which includes accurate prediction methods for all relevant design aspects [1].
The German Aerospace Center has a high level of experience in the field of aircraft research and a long tradition in developing solutions for the aircraft industry. Consequently, the aim is in creating an integrated design tool and the development of guidelines for multidisciplinary design of wind turbine rotors. This will be achieved by including accurate prediction methods for all relevant design aspects. To allow an evaluation of the analysed wind turbine blade a cost assessment is included in the simulation process chain as well as an acoustics analysis tool.

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In this paper, first the tool chain is presented. After that, the three simulation disciplines, namely structural mechanics, aeroelastic and aerodynamic, as well as the cost assessment are described. The separate disciplines have been verified with free available and industrial data.
The goal of the paper is to give an overview about the actual status of the fully coupled tool chain.

Tool chain

The rotor blade analysis follows a multilevel decomposition approach as depicted in Figure 1. As abstract database the Common Parametric Aircraft Configuration Schema (CPACS) [2] is used. In the process chain all tools interpret the CPACS database and create their specific models. The tool chain starts with the creation and sizing of the structural model utilizing critical loads. The critical loads are calculated separately based on the certification requirements. The resulting critical aerodynamic loads are passed to the structural sizing. An internal optimization process seeks for minimizing the structural weight while assuring structural integrity. The loads are then updated to consider the new stiffness and mass distribution. The sizing is finished if no changes in the structure and critical loads occur.
Once an adequate structural blade design has been found the blade deformation according to aerodynamic load scenarios are calculated. Load scenarios mean for example a performance analysis for a turbine at a specific place or under defined environmental conditions. To do so, a modal reduction of the structural model has to be performed including the rotation stiffness of the rotor blade. The resulting data is exported to the multi-body simulation tool SIMPACK. To be able to make a performance analysis the aeroelastic simulation has to analysis the behaviour of the complete wind turbine. This analysis considers the fluid-structure interaction which influences the performance of the turbine. Convergence in each time step is reached if the deformation between two subsequent fluid-structure interactions changes only slightly. Otherwise the next fluid-structure interaction cycle is started. The fluid-structure interaction process is embedded in the framework AutoOpti which changes the design vector in order to perform a sensitivity analysis as described in [1].

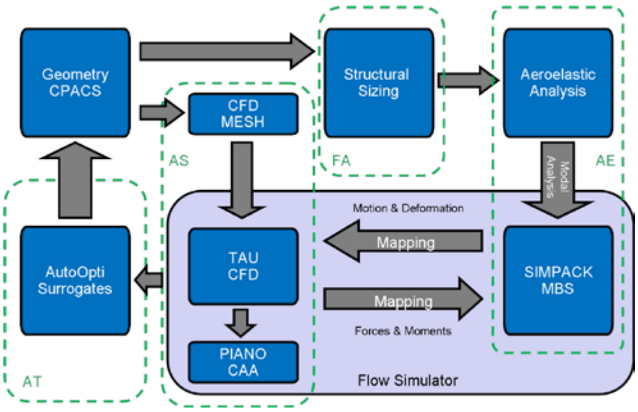
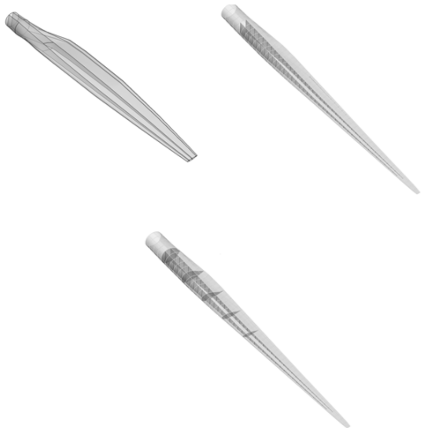


Figure 1 Tool chain

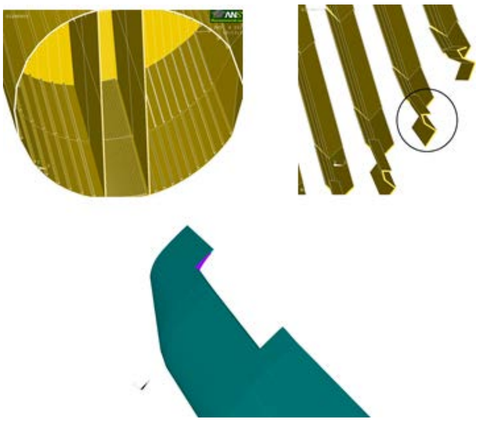
Structural sizing

Based on the CPACS, which is an abstract aircraft namespace, it is possible to create models with variable level of detail, e.g. wings simplified as beam models. With the support of several commercial finite element (FE) solvers many 3rd party applications can be utilized, such as sizing tools. The 3rd party tool Hypersizer is able to size a FE-based structure very efficient. An automated and efficient process based on Hypersizer has been developed originally for aerospace wing designs which are now adapted to wind blade designs. Based on the parametric model generation of DELiS along with the automated sizing the present process is well suited for multi-disciplinary frameworks [3]–[5].
Figure 2 illustrates the advantage of a flexible parametrized model generation process. All exemplarily created finite element models are based on the same common database. Wind blade rotors with different geometries, additional topology as ribs and stringers, as well as

beyond state of the art designs like flaps can be created. On the contrary to parametrization in computer aided design (CAD) tools topology changes as well as partial model creation with higher fidelity for detailed analysis of the local behaviour are easy to realize.



(a) global design changes (Numad rotor, three spar rotor, rotor with ribs)



(b) local design elements (stringer, stringer profiles, flaps)

Figure 2 Rotor designs

As briefly explained in the last section for an evaluation of the design an analysis and sizing process is needed. Figure 3 illustrates this process. The CPACS dataset is interpreted to create a Python object model in the software DELiS. It includes the loads provided by an external tool. The parameterization allows it to study various wind blade designs. Based on the Python object model, DELiS is able to create the input for a finite element (FE) tool. The resulting model is used to calculate displacements and stresses as response from given external loads. The evaluation of the stresses is done with the commercial software Hypersizer.
Hypersizer calculates the laminates and/or thicknesses for different regions and updates the FE model. The material and the concept of specific regions have to be predefined. The material definition includes metals, laminates, foams, etc. and the material specific allowables. The concepts define sandwich, stringer stiffened regions or unstiffened areas. Iteratively the process creates a sized structure, in the range of the predefined possible solutions and DELiS writes the thickness and material distribution back to the CPACS dataset.

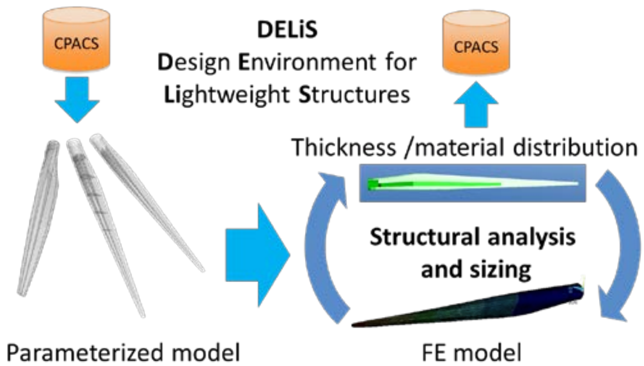


Figure 3 Structural analysis and sizing process

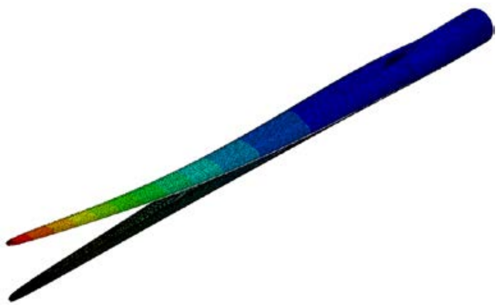
The process has been verified to a state of the art wind turbine from a manufacturer. The loads, material properties and allowables were given. Although the number of sizing regions was much lower compared to the reference rotor and the sizing process was stopped in a preliminary stage the difference in weight was lower than 10%.
If the whole sizing process is performed the interaction between aerodynamic loads and the structural response has to be considered. A sized structure leads to a change of mass and stiffness distribution of the wind turbine blade. A simplified aeroelastic simulation is performed to

create new critical loads based on the aero-structure interaction. Automatically an input for an aeroelastic simulation is created by a modal reduction of the wind rotor to obtain the correct load distribution. This process is done until a converged solution exists.
To proof the quality of the structural model creation and analysis process two results are shown. As geometrical model the original finite element model from the DTU [6] was taken and a constant thickness with isotropic material was applied. The material and thickness has been chosen constant to separate sizing errors from geometry and/or discretization errors. A load of F_x=F_y=F_z=1N has been applied at the tip of the blade p=[-89.839E-03, -5.381E-03, 89.166]. The results in Table 1 show a good agreement of the solutions.

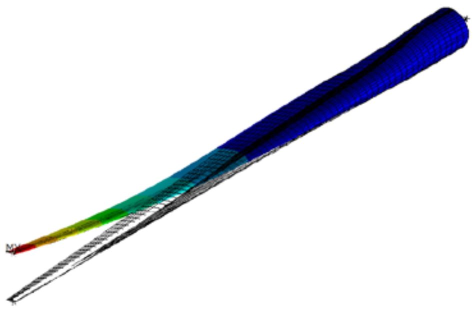
Table 1 Comparision of the tip deflection

Direction	**DTU**	**DELiS**	**Abs. Error [%]**
U1	1.28e-5	1.26e-5	1.5
U2	6.87e-5	6.80e-5	1.01
U3	-7.12e-7 / 6.2e-7	-7.18e7 / 5.94e-7	0.8 / 4.3

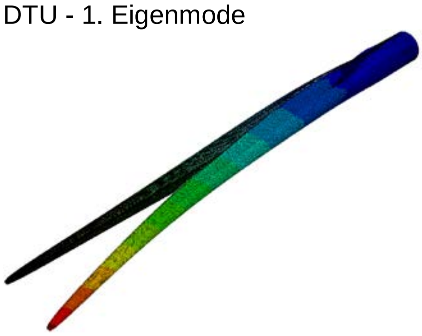
To proof the accuracy of the mass distribution of the model a modal analysis has been performed. The the eigenmodes (cf. Figure 4) as well as the eigenfrequency (cf. Table 2) are checked. There are in good agreement. Similar tests with an industrial rotor show the same result. In that case, the result of the sizing process was also in good agreement and the error was below 10%.



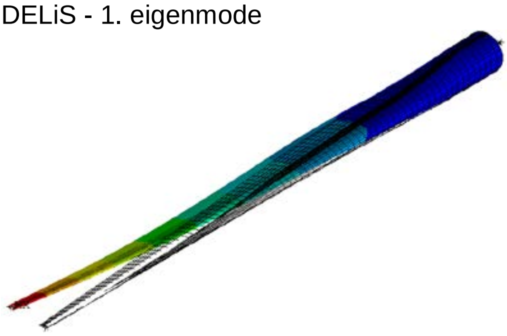
DTU - 1. Eigenmode



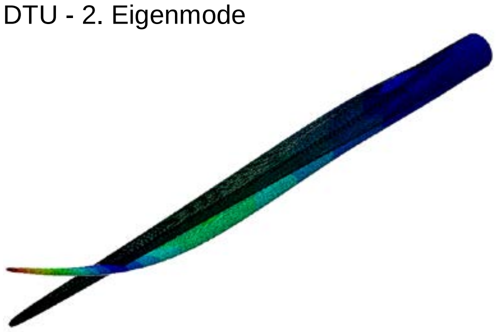
DELiS - 1. eigenmode



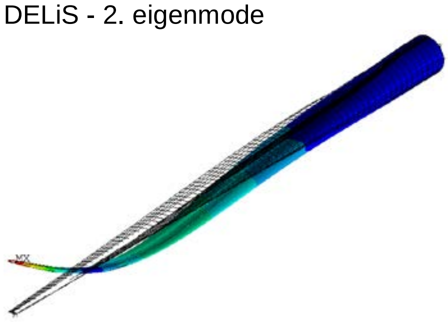
DTU - 2. Eigenmode



DELiS - 2. eigenmode



DTU - 3. Eigenmode



DELiS - 3. eigenmode

(a) DTU model

(b) DELiS model

Figure 4 Eigenforms 1-3

Table 2 Comparision of the eigenfrequencies

Eigenfrequency	DTU [Hz]	DELiS [Hz]
1	1.44	1.41
2	2.94	2.91
3	4.67	4.64

Aeroelastic simulation

In addition to rigid aerodynamic simulations of the full wind turbine, fluid-structure-coupled simulations of the isolated rotor under steady inflow conditions are performed. The fluid-structure-interaction process couples the commercial multibody solver SIMPACK with DLR's in-house CFD-solver TAU. The aeroelastic process is sketched in Figure 5. It provides a platform for high-fidelity load and deformation predictions for both steady and unsteady conditions, which can complement the BEM-based aeroelastic simulation tools. Rigid body motions are imposed through grid velocities and relative motions between overset grids, while flexible body deformations result in a deformation of the CFD-mesh. Blade surface loads are extracted from the CFD-solution and mapped onto the multibody discretization of the blades using radial basis function interpolation.

Since only the blade structure changes during tool chain iterations, a constant multibody model of the hub is outfitted with the current blade model. The blade model is imported into the multibody solver as a flexible body from the finite element model generated during the sizing process. An up to date CFD-mesh is generated by inserting the chimera blade meshes from the aerodynamic simulations into a cylindrical background grid.

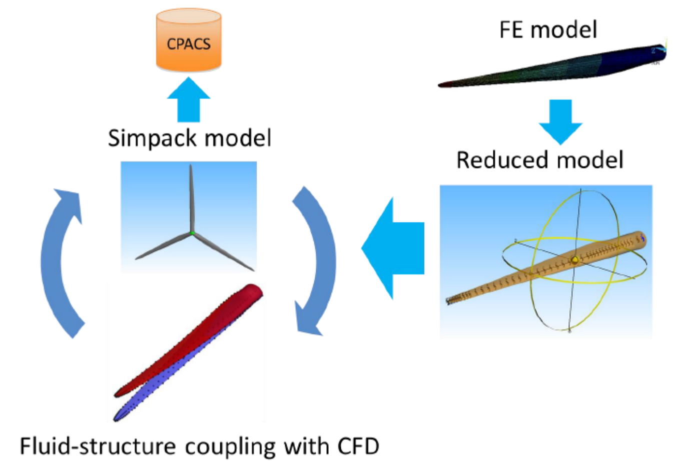


Figure 5 Aeroelastic simulation process

As described before in the structural design process critical loads has to be calculated to perform an accurate sizing. In addition to the CFD-based fluid-structure-interaction process a second low-fidelity process using BEM is integrated into the toolchain. It is used to generate design loads by simulating a subset of the IEC-61400 design load cases for each sizing iteration.

The resulting CFD-loads on the blades from the high-fidelity toolchain can then be used to validate the low-fidelity loads and to gain additional information about the flow state around the deformed rotor. The combined set of high- and low-fidelity loads on the rotor is returned to the sizing process. An example of an aeroelastic simulation is given in **Fehler! Verweisquelle konnte nicht gefunden werden.**. Here, results from a steady wake vortex structure of the Nrel 5MW are illustrated. In the left figure the comparision of the tip deflection and the rigid rotor is shown. Due to the increased rotor size this effect has to

be considerred accurately to approximate the fluid-structure interaction approbiate.

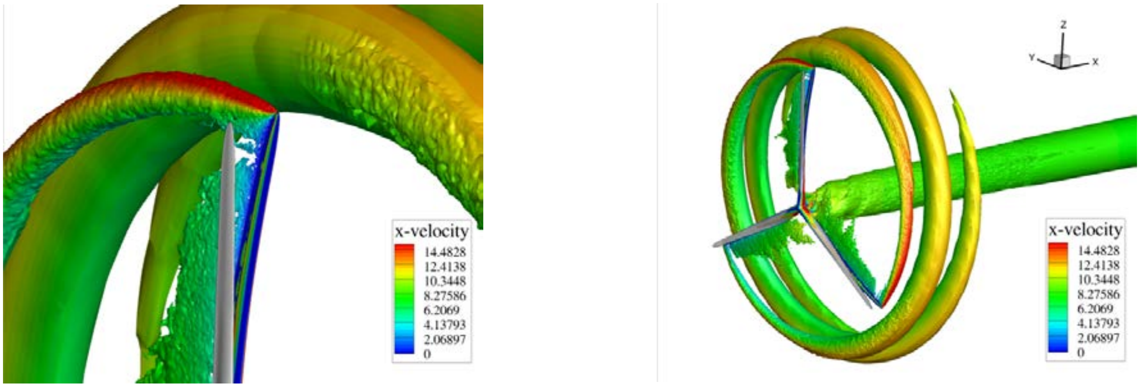


Figure 6: Steady wake vortex structure of the Nrel 5MW rated case shown as a λ_2=-0.02 isosurface with the rigid rotor structure shown in grey.

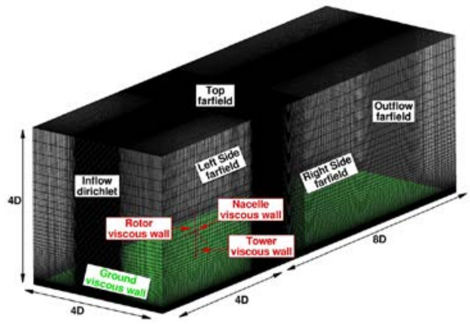
In Table 3 rotor thrust, torque and power of the flexible simulations are reported together with the corresponding rigid results and the NREL reference results provided by Jason Jonkman [7]. The deformations of the rotor lead to an increased thrust and power output of the rotor in the coupled CFD-simulations. Thrust increases by 10.6% whereas torque increases by 5.9%. The most likely cause is an increase of angle of attack at the blade tip through torsional deformation. Further investigations into the exact causes are under way. Detailed plots of flap, lag, and torsion deformations along the blade will be given. A similar overprediction occurs in comparison to the Nrel-5MW reference results provided by Jason Jonkman. The comparison yields a reasonable agreement between reference and flexible simulations.
The reference results are based on blade element momentum theory simulations using different inflow conditions than the CFD-simulation. Therefore the results cannot be compared directly and should be seen on the level of proof of concept.

Table 3 Flexible and rigid rotor results for the rated case compared to NREL reference values [7]**.**

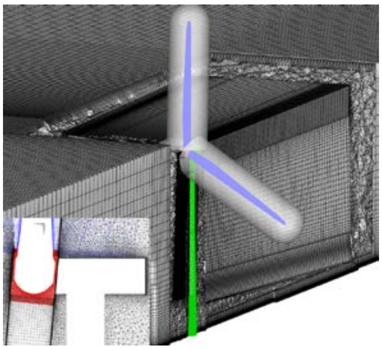
	Rigid	**Flexible**	**NREL**
Thrust [kN]	768	850	790
Torque [kNm]	4562	4831	4200
Power [MW]	5.78	6.12	5.32

Aerodynamic simulation

To perform a valid aerodynamic simulation a CAD geometry of the wind turbine has to be created. For the generation of the CAD geometry the relevant CPACS parameters are extracted from the CPACS database.



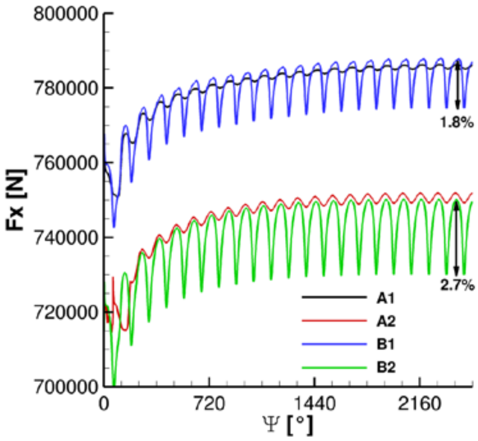
(a) Dimensions and boundary conditions for the simulation of the complete turbine

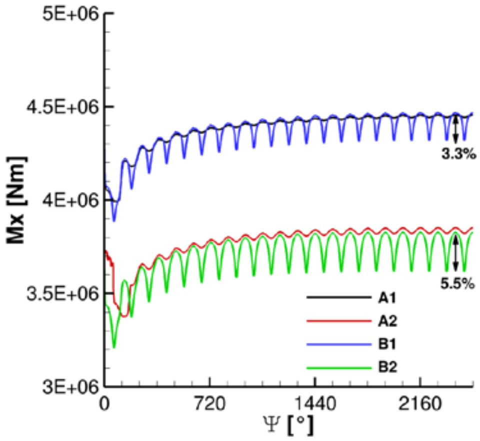


(b) Close-up of the discretization in the vicinity of the turbine and the overlapping region

Figure 7: Flow domain for the simulation of the NREL 5MW complete turbine

Subsequently the CAD model is updated and the blade mesh is generated. The aerodynamic simulation is conducted using the DLR TAU code using the k-w model. While for pure aerodynamic calculations the whole turbine, including the atmospheric boundary layer, can be simulated. Stationary simulations of only the rotor are carried out when coupled with the multibody code SIMPACK.
Figure 7 shows the discretization and boundary conditions of the flow domain for the simulation of the NREL 5MW turbine. Special attention has been paid to the resolution of the boundary layer within the blade meshes as well as to the resolution of the atmospheric boundary layer profile. Therefore, in each region the first wall distance has been chosen in order to reach a y^+ value below one. Structured mesh regions have been used for the blade meshes as well as in most parts of the background grid in order to ease the generation of overlapping regions and a better control of the grid resolution behind the turbine. Simulations are usually carried out for 12 rotor revolutions in order to reach a periodic simulation.
Figure 8 shows one result of the calculations made. The completely modelled turbine has been compared with a rotor without nacelle and tower. The results show, that the thrust and torque are greater compared to the full turbine. Furthermore, the effect of the tower is low. For further results and discussion see reference [8].





(a) Thrust ***(b) Torque***

Figure 8 Comparison of the thrust and torque of a rotor and a full turbine

Cost assessment

To conduct a holistic cost assessment it is most important to look at an actual production process with the consistency to manufacture composite components. Virtually designed production processes usually lack this consistency. So, as a start an industrial rotor blade manufacturing process was recorded to gather basic production process data. Holistic cost assessment means, that all relevant parameters of the manufacturing process of a rotor blade were recorded and measured accurately. Building services were excluded due to the limited access to related data. To fulfil this vast requirement of 100% documentation, two main paths have been used. On one hand the non-recurring costs (NRC) of all production process steps had to be evaluated, while on the other hand a detailed recording of the manufacturing itself had to be guaranteed to detect all kinds of recurring costs (RC). The NRC include both specific investment, such as the molds, as well as non-specific like the resin mixing equipment. To disconnect the recorded data from the manufacturer the mold, and alike, have been accounted to a fictional production scenario of 1000 rotor blades depreciated over 3 years. The investment of the resin mixing equipment and other facilities is broken down into an investment/day with depreciation over 5 years and allocated to the days of usage correspondingly.
Both, RC and NRC costs are assigned to certain process steps individually. This allows visualization of both cost driving process steps and cost driving cost types for subsequent process and cost optimization.

The cost model is linked to CPACS where the amount of materials is defined through the structural design which integrates the cost assessment into the multidisciplinary tool chain.
The assessed cost is sheer manufacturing cost excluding design and manufacturing engineering which could be added as a factor, of course. This assessment allows changing individual process steps, such as replacing manual procedures by automated processes, connected to corresponding investment in equipment. It enables decision makers to demonstrate the impact of implementing automation a new technologies.

Conclusion

The paper presented a multi-disciplinary tool chain for wind turbine blades. In addition to the fully coupled simulations the results can be evaluated by performing an aero-acoustic analysis. The overall process aims to determine sensitivities in arbitrary disciplines or against chosen parameters.
To obtain accurate results each tool has been verified with data from literature or industry. So far, the results of the disciplines are in good agreement. The actual work flow allows the simulation and the comparison structural designs such as stringers, ribs or flaps. Based on this structural design the aeroelastic simulation allows a performance analysis of the problem. Detailed CFD analysis can be used to get improved information of the fluid behaviour. In future work sensitivity analysis as well as rotor blade optimizations will be performed. The connection of a cost assessment tool to the design tool chain allows to evaluate the impact of changes in individual disciplines on manufacturing cost. This information can be used to design wind energy rotor blades cost-effectively. To enable a more general assessment of manufacturing in the future the production process database has to be enhanced with alternative technologies and processes.

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