Towards an Integrated Design Complex for Wind Turbines

Design of a 10 MW Reference Turbine

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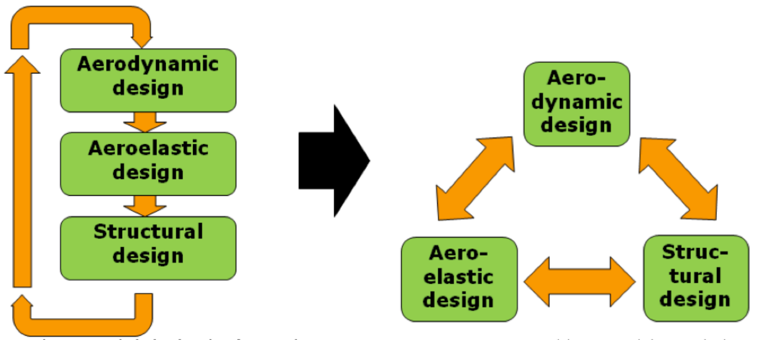
Outline

- Presentation of the recently developed DTU 10 MW Reference Wind Turbine.
  - The Light Rotor Project
  - What it is and what it isn’t!
  - Description of the design process

- A unified framework for design and analysis of wind energy systems.
  - The next steps towards a systematic integration of wind energy analysis tools into a single framework

The Light Rotor Project

- The Light Rotor project aims at creating the design basis for next-generation wind turbines of 10+ MW.
- Collaboration with Vestas Wind Systems
- The project seeks to create an integrated design process composed of:
  - Advanced airfoil design taking into account both aerodynamic and structural objectives/constraints,
  - Aero-servo-elastic blade optimization,
  - High fidelity 3D simulation tools such as CFD and FEM,
  - Structural topology optimization.



Upscaling of Wind Turbines

- One of the main challenges to the continuous up-scaling of wind turbines is to maintain **low weight** while achieving **high power efficiency** and the necessary **stiffness** of the blade.
- To meet the demands on structural stiffness, designs move towards higher relative thickness and increasingly flexible blades.
- This poses challenges to the aerodynamic design, since thick airfoils are generally less efficient than thin ones.
- The aeroelastic design likewise requires increasingly advanced tools to tailor the blade to the large deflections.
- New solutions, both aerodynamic, structural and aeroelastic are thus needed for the next generation of multi-MW turbines.

The DTU 10 MW Reference Wind Turbine

- The purpose with the design is:
  - To provide a publicly available representative design basis for next generation new optimized rotors.
  - To achieve a design made with traditional design methods in a sequential MDO process
  - Good aerodynamic performance and fairly low weight.
  - To provide a design with high enough detail for use for comprehensive comparison of both aero-elastic as well as high fidelity aerodynamic and structural tools,
- The purpose is not:
  - To design a rotor pushed to the limit with lowest weight possible,
  - Provide a design of a complete wind turbine – focus is on the rotor,
  - To provide a design ready to be manufactured; the manufacturing process is not considered.

  - DISCLAIMER: DTU will not be held responsible for failures or financial loss should someone choose to manufacture this turbine!

The Design Process

- DTU Wind Energy is responsible for developing a number of wind turbine analysis codes that are all used by industry in their design of wind turbines:
  - HAWC2 (multibody time domain aeroelastic code)
  - HAWCstab2 (Aero-servo-elastic modal analysis tool)
  - BECAS (Cross-sectional structural analysis tool)
  - HAWTOPT (Wind turbine optimization code)
  - EllipSys2D / 3D (RANS / DES / LES Navier-Stokes solvers)
- Other solvers used: Xfoil, ABAQUS
- In our normal research context we do not normally use these tools in a synthesized manner in a design process.
- The exercise for us was to apply our tools and specialist knowledge in a comprehensive design process of a 10 MW wind turbine rotor, something we have not done to this level of detail before.
- Identify areas in the design process suited for more integrated MDO architectures.

Design Team

- The design of the 10 MW RWT was a team effort with several participants:
  - Christian Bak (PM, design lead and aerodynamic design),
  - Robert Bitche (structural design),
  - Taeseong Kim (aeroelastic analysis),
  - Anders Yde (aeroelastic analysis),
  - Morten Hartvig Hansen (stability analysis and control),
  - Frederik Zahle (aerodynamic analysis).

- And many others who contributed to development of the tools that we used in the design process.

Design Summary

Table 6.1.: Gross Properties for the DTU 10MW RWT

Rating	10 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	178.2 m, 5.6 m
Hub Height	127.37 m
Cut-In, Rated, Cut-Out Wind Speed	4 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	7 rpm, 9.6 rpm
Rated Tip Speed	90 m/s
Overhang, Shaft Tilt, Precone	7.07 m, 5, 2.5
prebend	5m
Rotor Mass	224,000 kg
Nacelle Mass	393,800 kg
Tower Mass	494,572 kg

Workflow

Preliminary Design

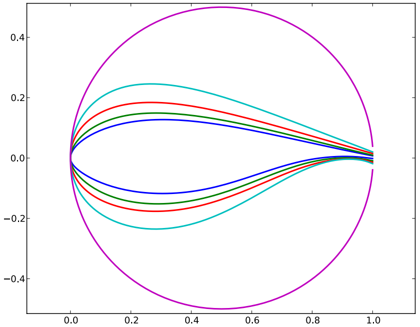
- Upscaling: roughly based on NREL 5MW RWT
- Airfoil choice & airfoil data (based on 2D CFD)
- Preliminary aerodynamic layout
- Estimate of structural properties
- Establish DVs, constraints, and objectives

Design cycle

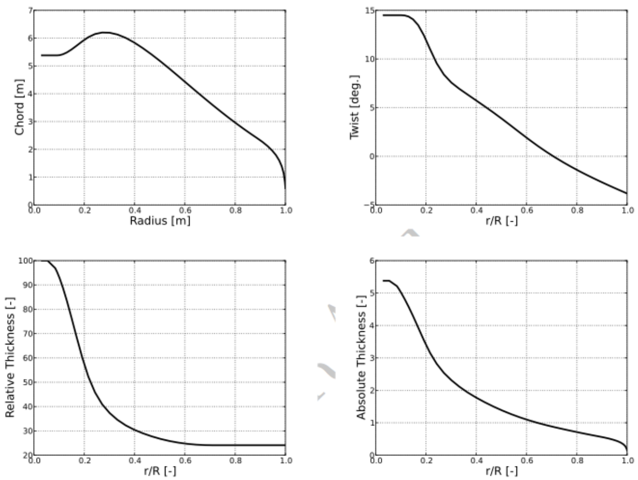
- Quasi-steady BEM aerodynamic optimization of C_P based on parameterized blade geometry
- 3D Geometry generation
- FEM structural design
- 3D CFD evaluation
- Stability analysis and controller tuning
- Aeroelastic IEC load basis evaluation
- Structural failure analysis

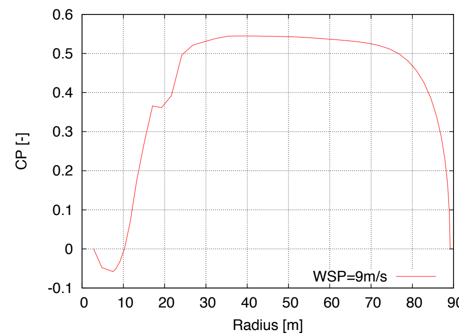
Aerodynamic Optimization

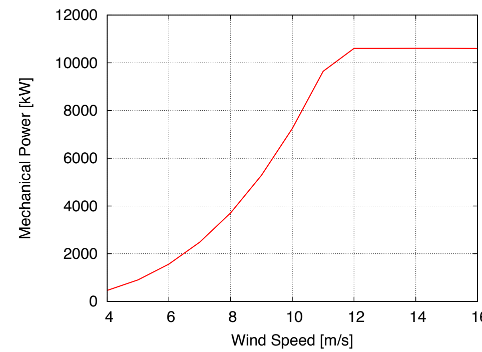
- Airfoil choice limited to open source airfoils.
- No public WT airfoils exist that are designed or tested for high Re (>10e6).
- Airfoil choice: FFA-W3 series.
- Optimization carried out using HAWTOPT
  - in-house quasi-steady BEM based rotor optimization code,
  - Gradient-based optimizer (SLP),
- Objective: power coefficient
- Three TSRs – 7, 7.5, 8.06.
- Design variables:
  - Chord (14 cps), twist (13 cps), relative thickness (13 cps) – all Bezier
- Constraints:
  - rotor radius fixed at 89.166 m - direct upscale of the NREL-5MW-RWT,
  - minimum relative thickness = 24.1% - challenge aerodynamics
  - max thrust at rated – constrain loads in normal operation
  - Mean thrust at standstill – implicit constraint on maximum chord
  - Additional geometric constraints on design variables

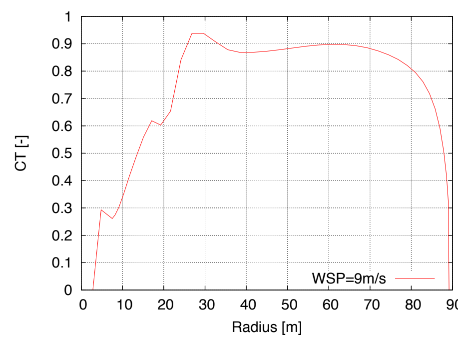


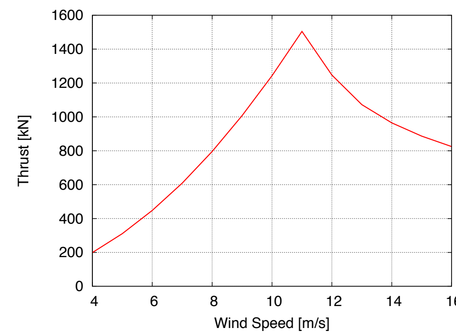
Aerodynamic Design

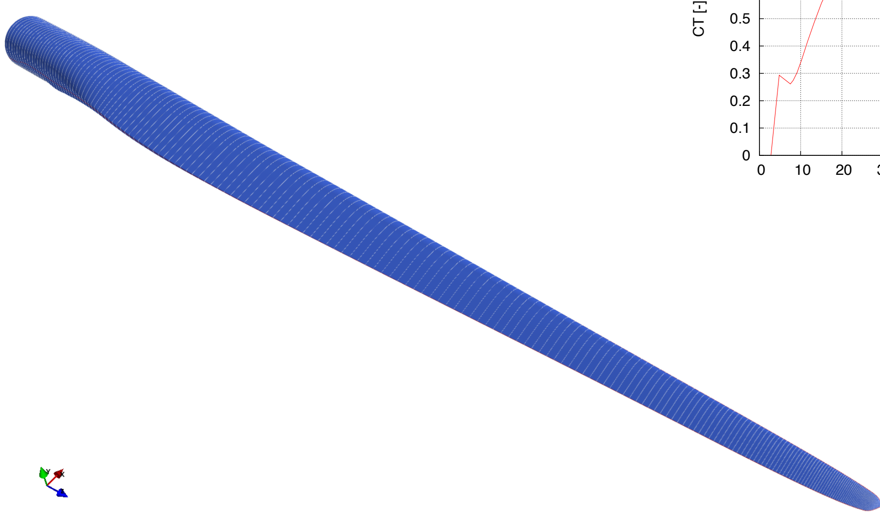


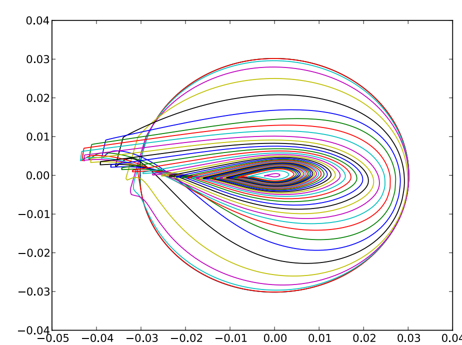






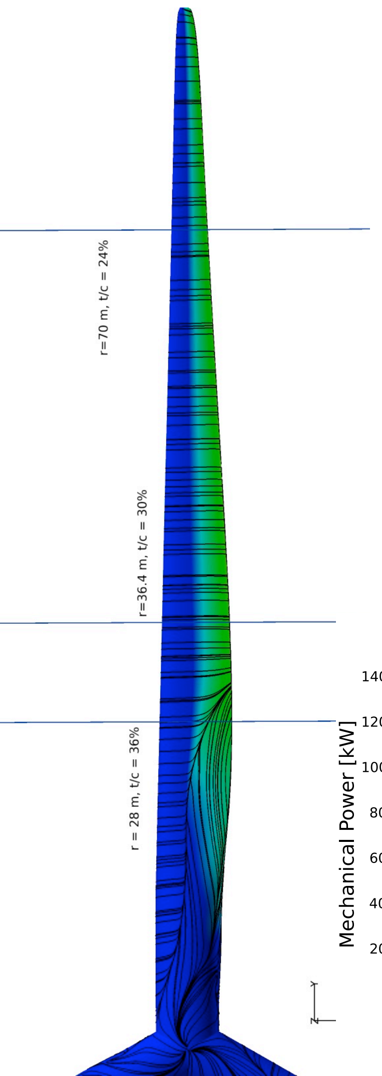


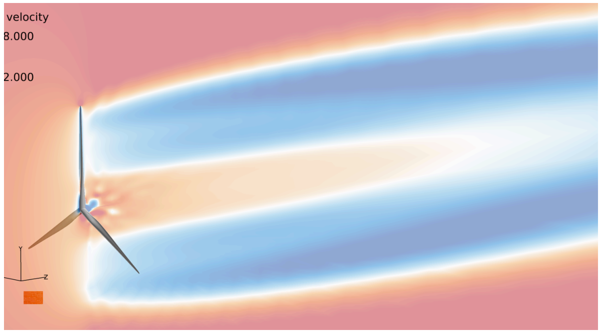


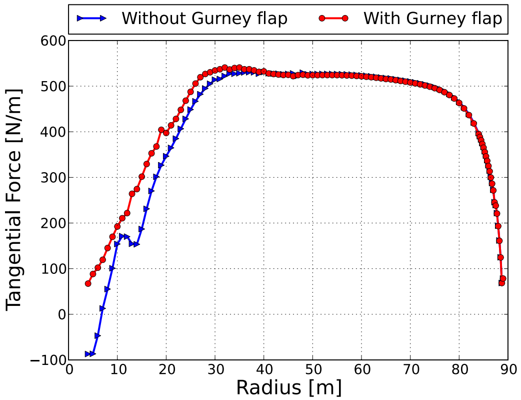


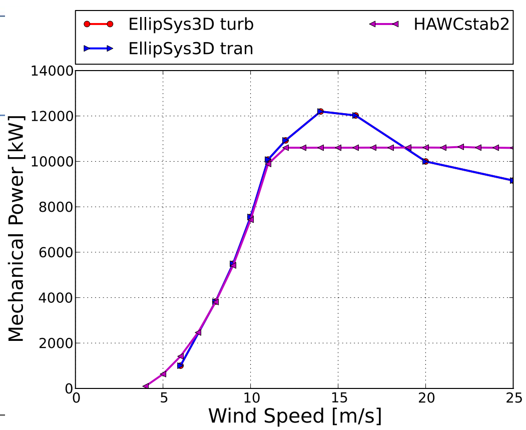
3D CFD Analysis

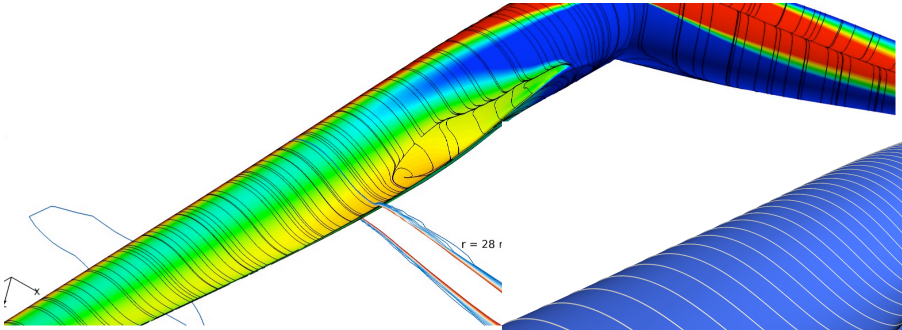
- Automated workflow from 2D blade definition/airfoil family -> 3D shape -> 3D volume mesh,
- 3D CFD validation of performance predicted using BEM,
- Blade performance in the root area was not satisfactory due to use thick airfoils (t/c > .36 for r/R < 0.30).
- Gurney flap were used to remedy this, increase in CP of 1.2% at design TSR.
- Resulted in adjustment of airfoil data and new design iteration adopting the modified root layout.
- (Automated derivation of 3D airfoil data).

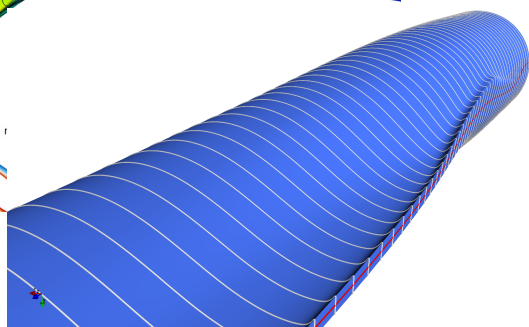




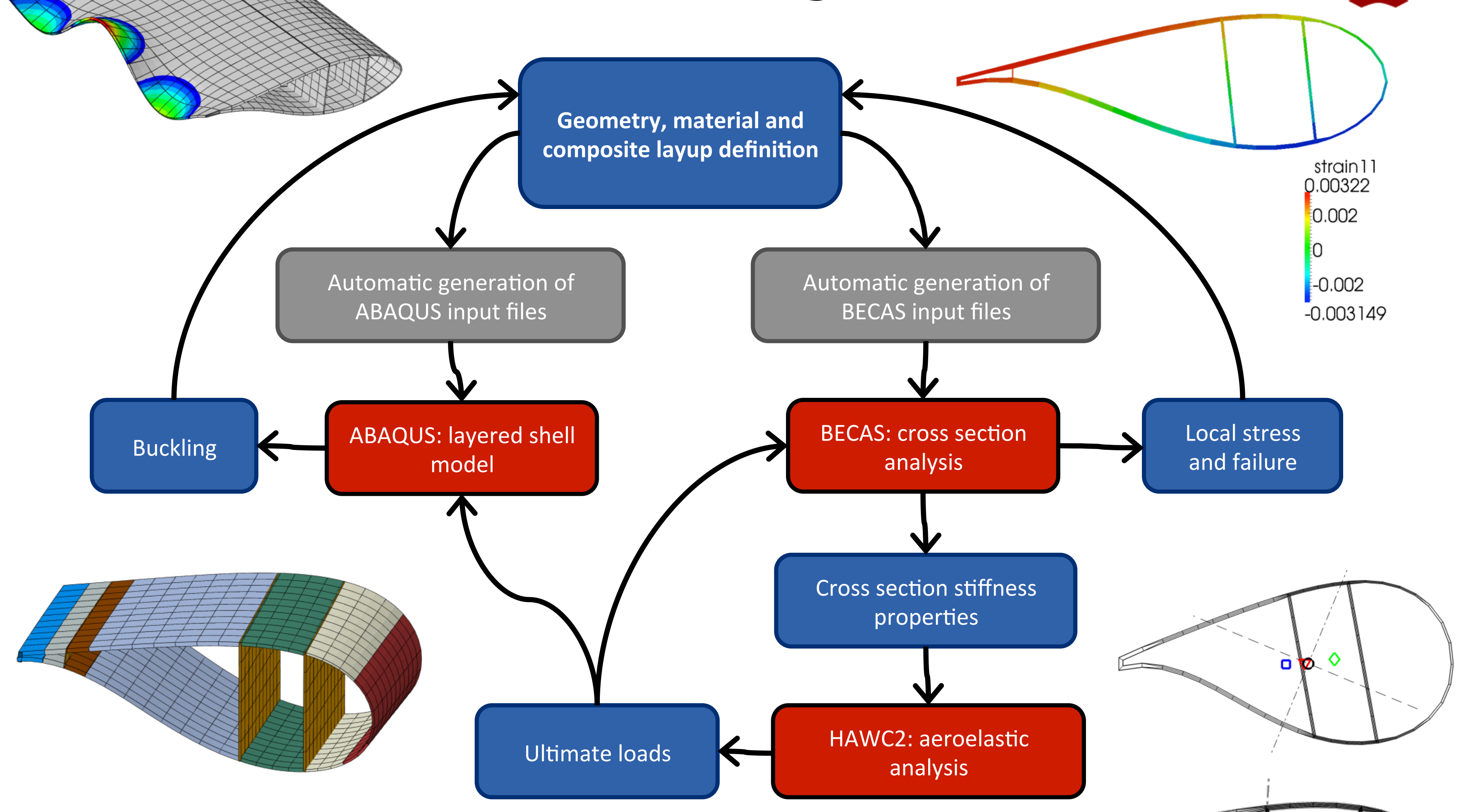


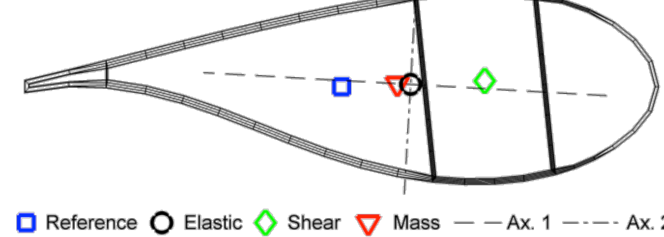






Structural Design

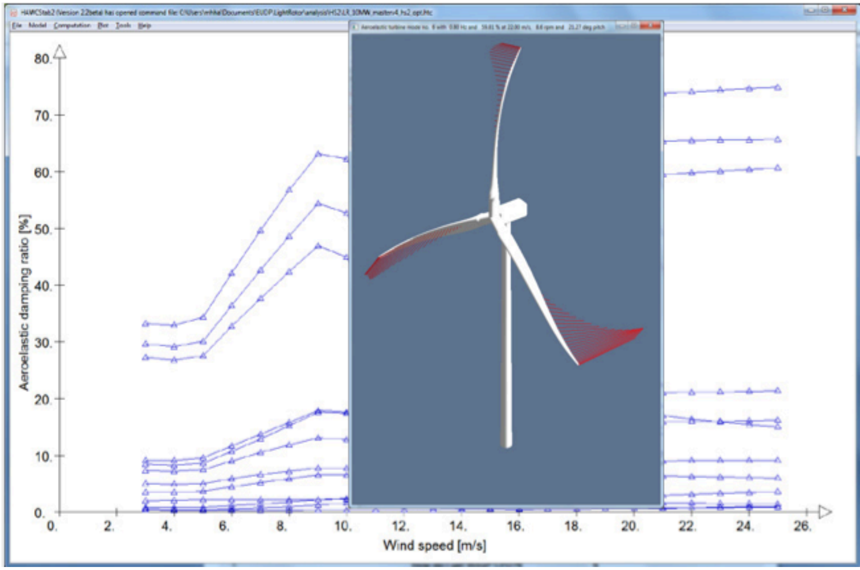


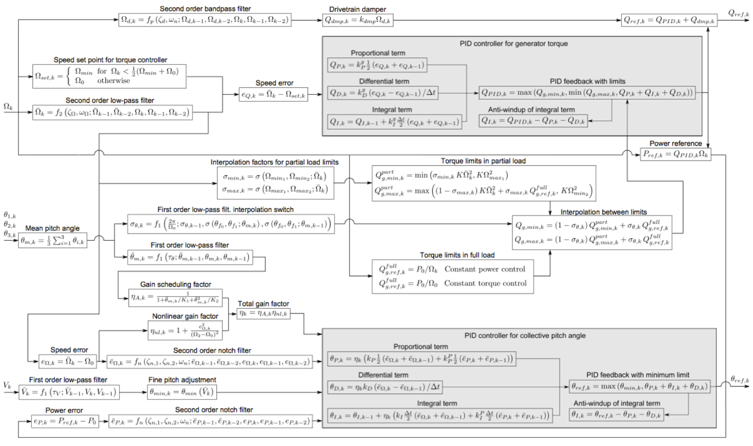


		Load case	γ_F [–]	F_x [MN]	F_y [MN]	F_z [MN]	F_{res} [MN]	M_x [MNm]
F_x	max	dlc5.1	1.35	0.9531	-0.2915	1.0163	0.9967	25.2834
	min	dlc1.3	1.35	-0.8724	0.3672	2.2653	0.9465	-8.9863
F_y	max	dlc1.3	1.35	0.4949	1.6055	2.4138	1.6801	-52.9810
	min	dlc6.1	1.35	0.0504	1.1862	0.2782	1.1872	44.0922

Aero-Servo-Elastic Analysis

- HAWC2 used to evaluate the comprehensive IEC design load basis in parallel on an HPC cluster.
- HawcStab2 used to analyze the modal properties of the wind turbine:
  - frequencies, damping ratios, and mode shapes.
- The DTU Wind Energy controller was revised and tuned specifically for the DTU 10 MW RWT.
- To avoid tower mode excitation from 3P frequency, minumum RPM = 7.
- Report and source code on controller available.





Summary of design challenges

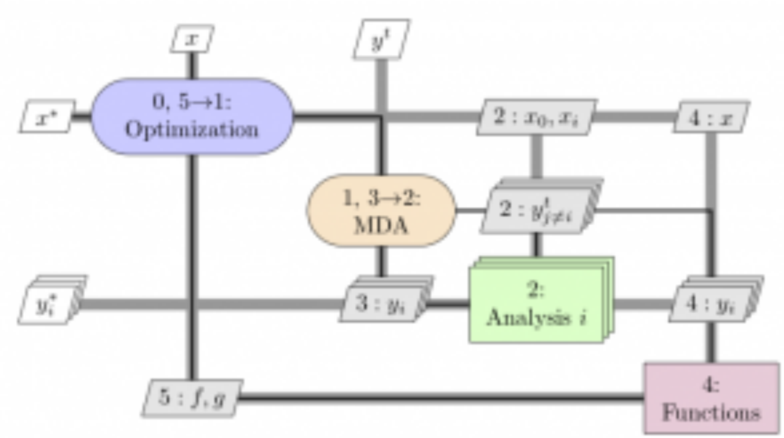
- Transition from laminar to turbulent flow in the boundary layer of the airfoils showed surprising differences between the Xfoil e^n model and the $\gamma - \theta$ correlation based model,
- The efficiency of thick airfoils, i.e. airfoils with relative thickness greater than 30%, is significantly better when using Gurney flaps,
- To the reduce the blade weight, the blade design needs to be ”stress/strain” driven rather than ”tip deflection” driven. This lead to a pre-bend design,
- The control of the rotor must take several instability issues into account, e.g. coinciding frequencies from the tower eigen frequency and 3P at low wind speeds,
- Blade vibrations in stand still

Availability

- The DTU 10 MW RWT has been released to the European InnWind project for review and will be used as the reference turbine in this project.
- Will within weeks be available as a comprehensive release consisting of
  - Fully described 3D rotor geometry,
  - Basic tower and drive train,
  - 3D corrected airfoil data (based on engineering models),
  - 3D CFD surface/volume meshes,
  - Comprehensive description of structural design,
  - Controller,
  - Load basis calculations using HAWC2,
  - Report documenting the design.

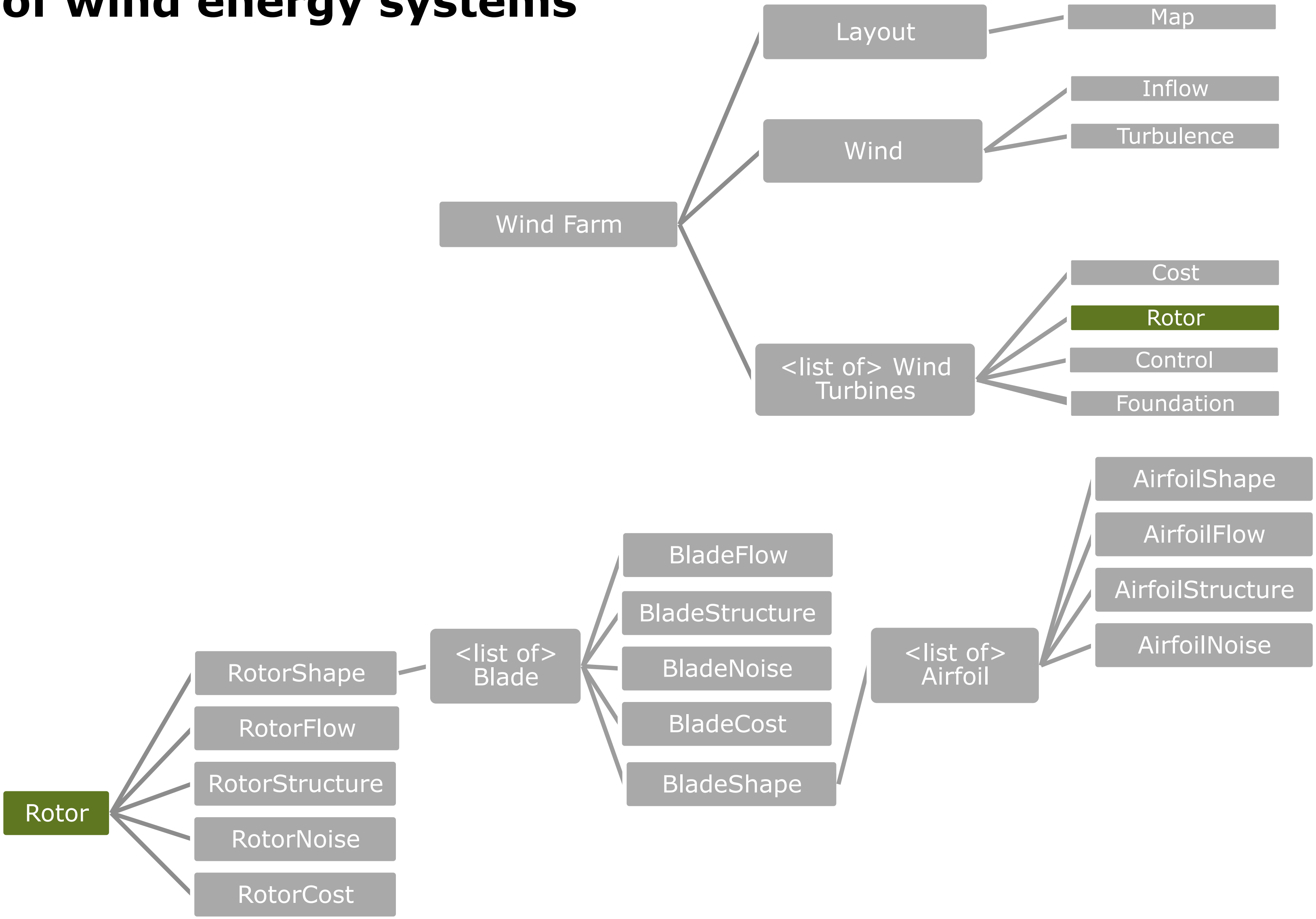
Towards a unified framework for design and analysis of wind energy systems

- Next steps in the Light Rotor project to synthesize the design process enabling employment of more advanced MDO architectures.



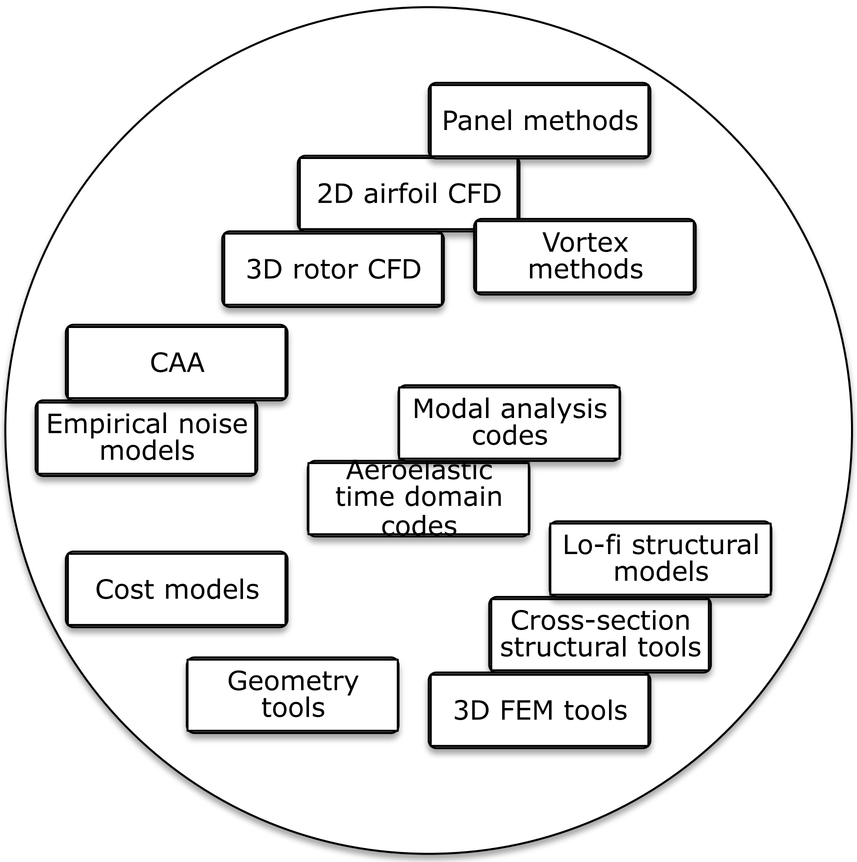
(from openmdao.org)

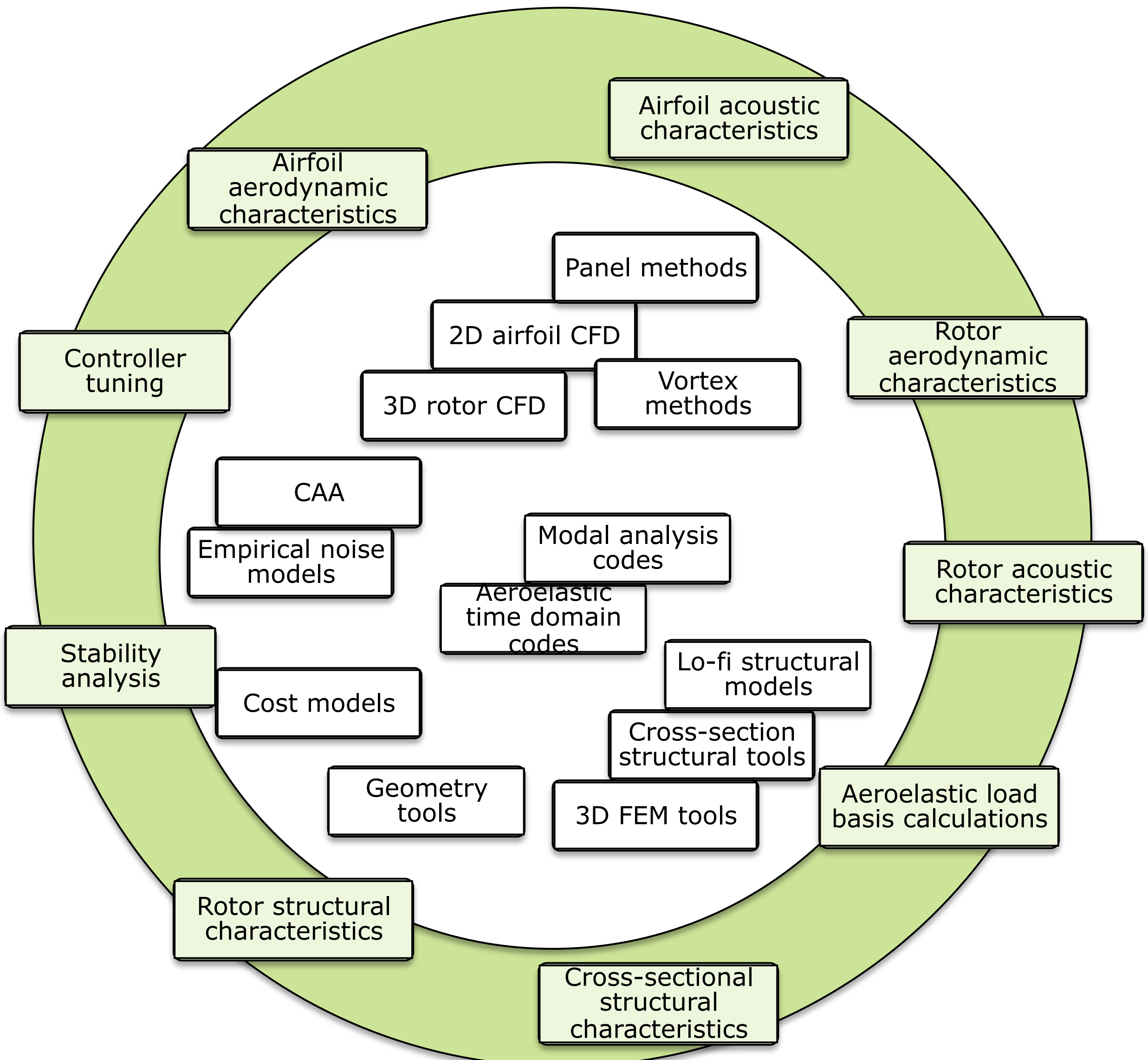
Towards a unified framework for design and analysis of wind energy systems



New Framework

- Development of a new multi-disciplinary MDAO framework for analysis of Wind Energy Systems.
- The idea is to think beyond optimization,
- A common platform for executing *all* codes, regardless of level of fidelity,
- Once a plugin is developed for a code, the code can enter into any type of analysis, parameter study or optimization and can be coupled to other codes,
- Built-in parallelization for comprehensive design space exploration,
- It’s a collaborative platform, **open-source** at the core level,
- Possibility to have **closed-source** modules for commercial tools and **open-source** modules for research tools,
- Base class structure common to all applications,
- Base classes define basic inputs/outputs, geometry and connectivity,
- Plans to collaborate with NREL,
- Based on Python and OpenMDAO.


Panel methods
2D airfoil CFD
3D rotor CFD
Vortex methods
CAA
Empirical noise models
Modal analysis codes
Aeroelastic time domain codes
Lo-fi structural models
Cost models
Cross-section structural tools
Geometry tools
3D FEM tools



Airfoil acoustic characteristics
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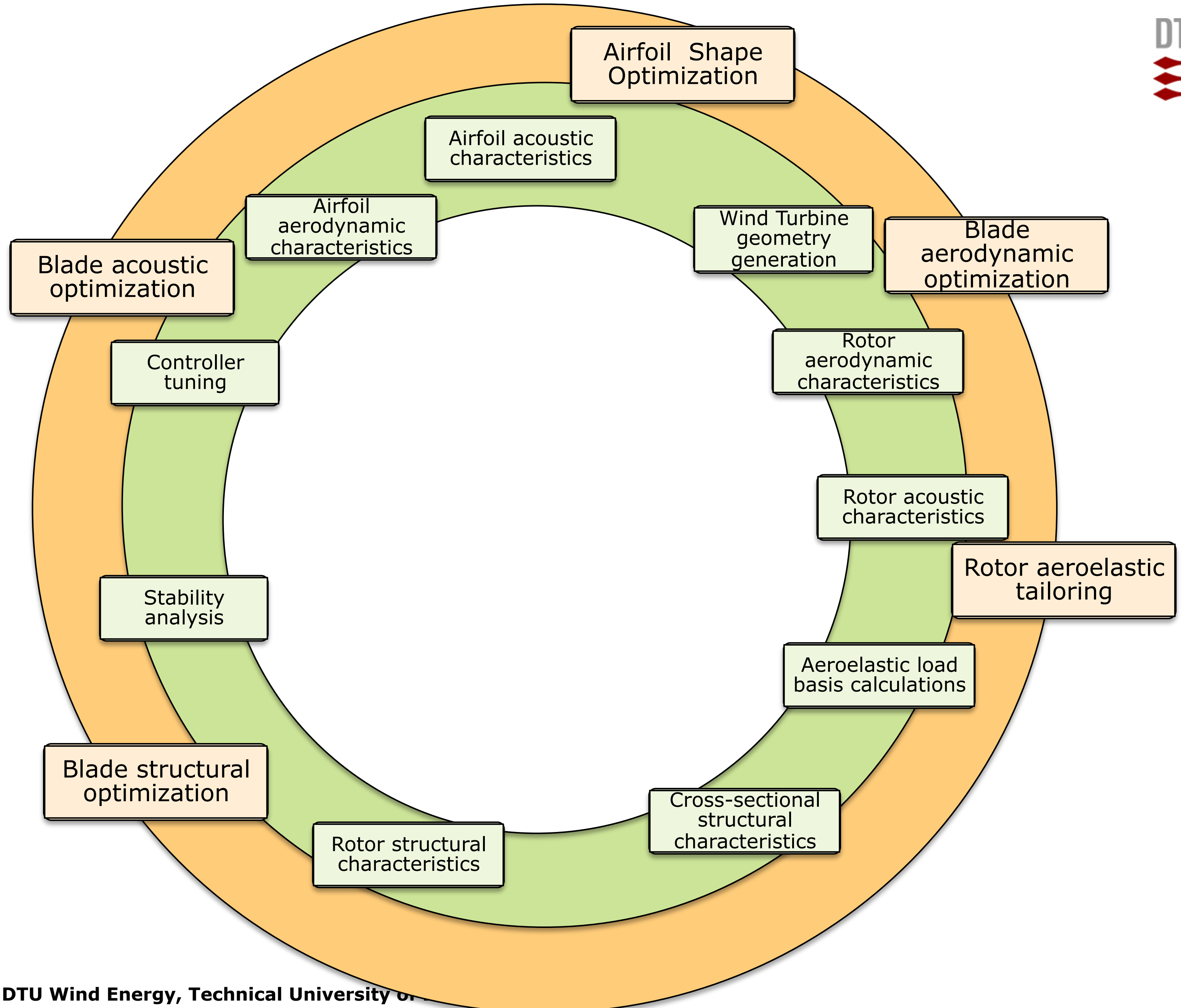

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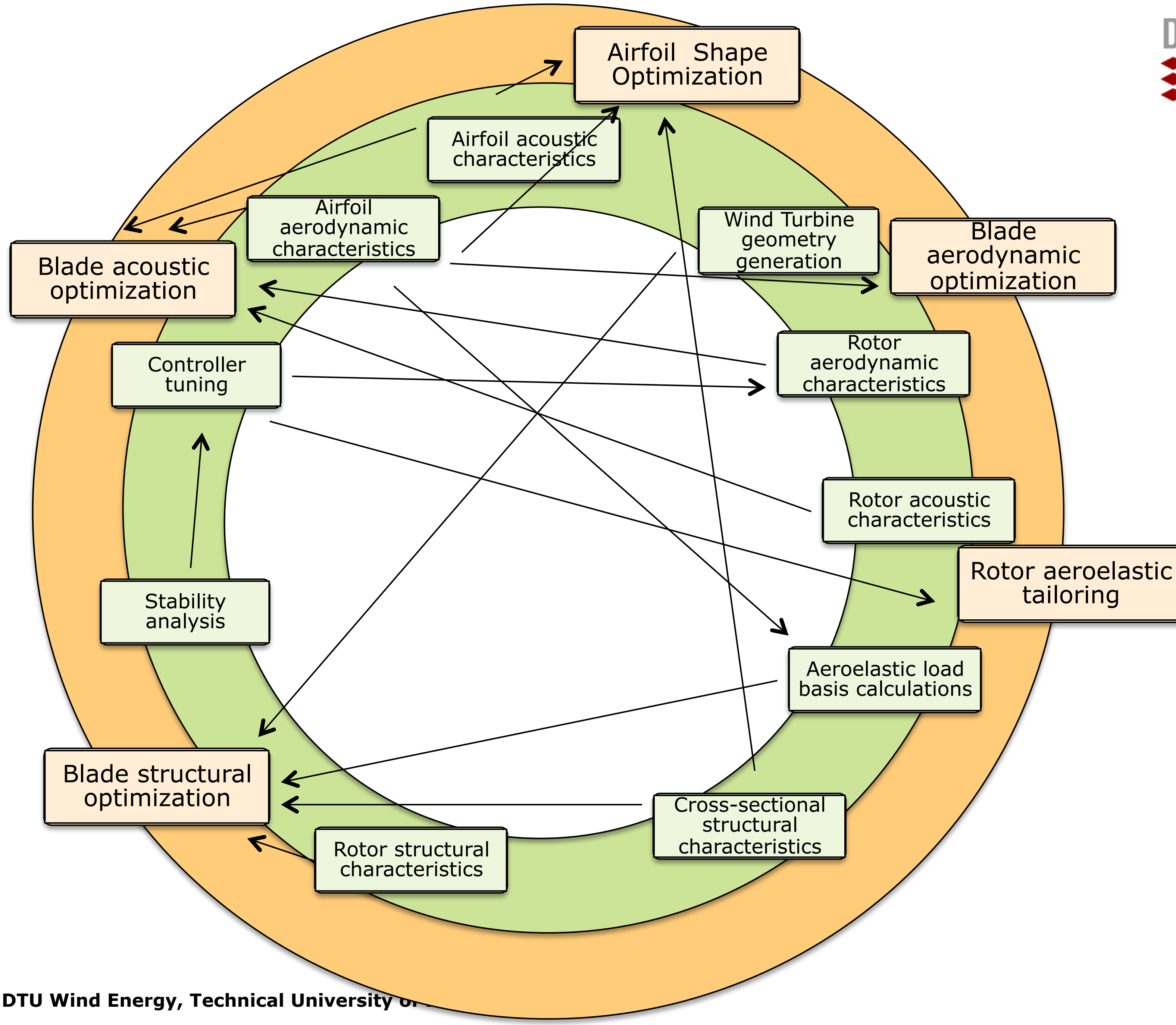
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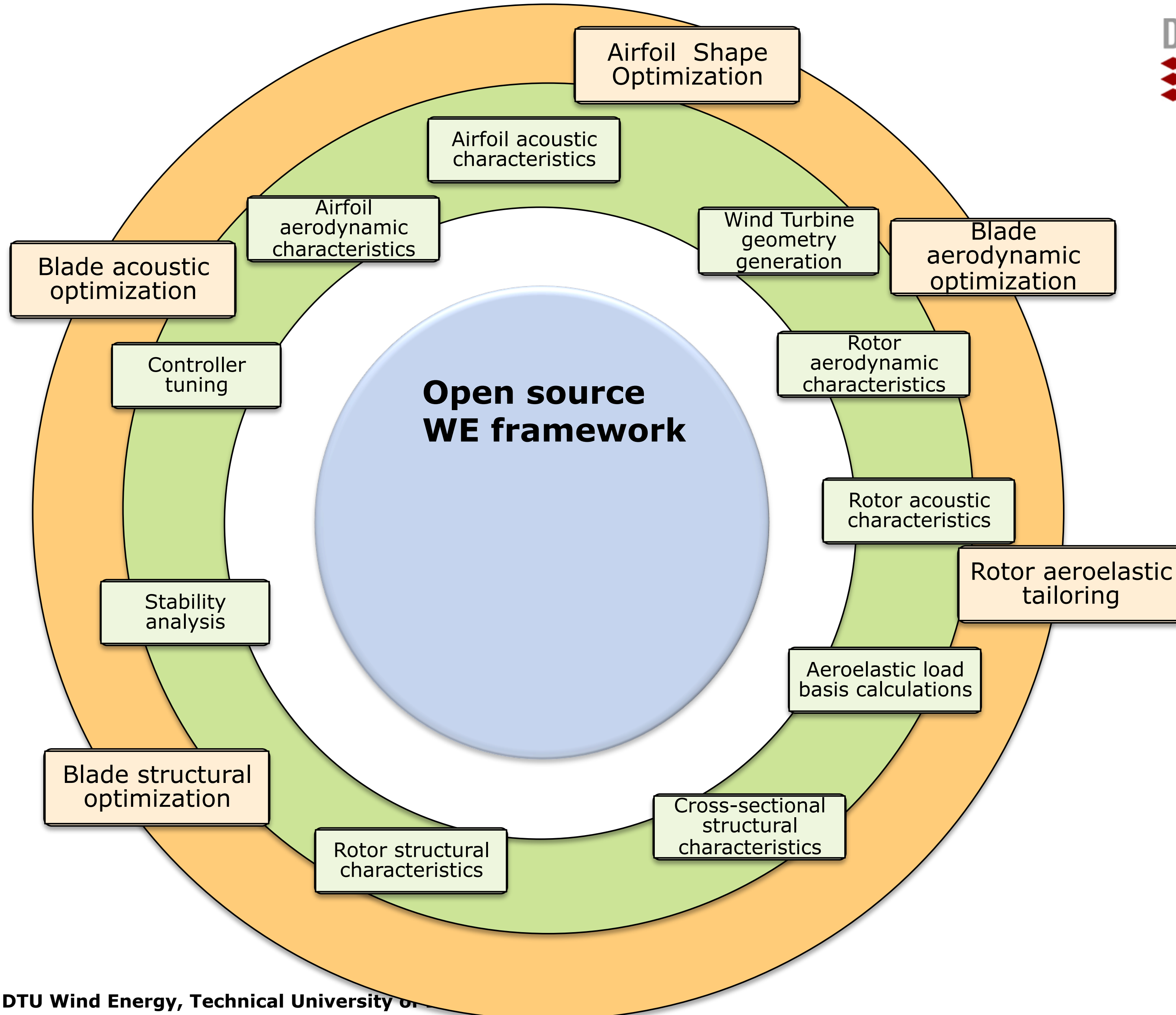
Open source WE framework
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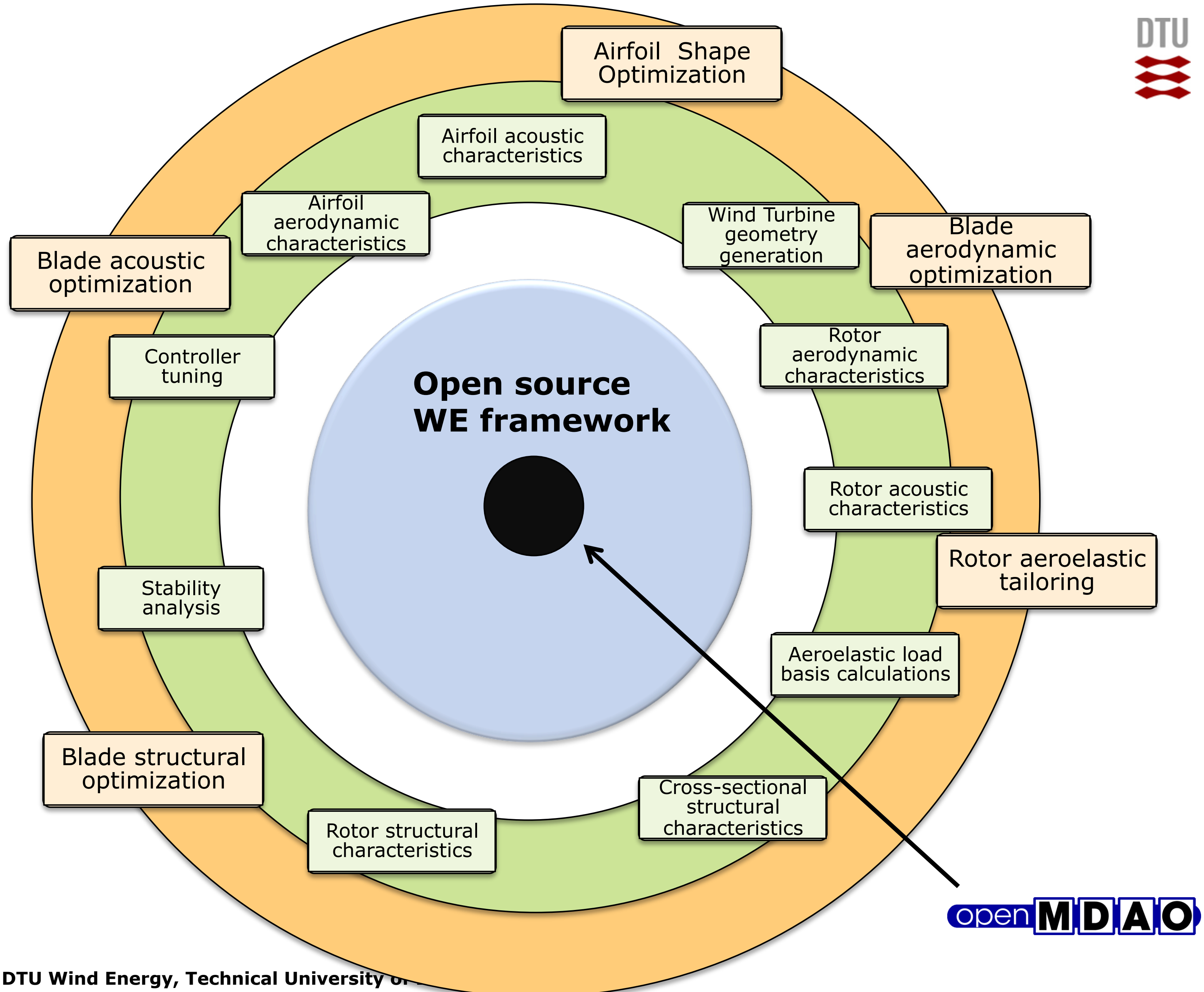
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openMDAO

Conclusions

- The DTU 10 MW RWT design has been finalized – release imminent.
- Design carried out by a team of expert researchers using a sequential approach employing state-of-the-art wind turbine analysis codes
- Highly detailed – useful for researchers for inter-code comparison
- Basis for future designs of optimized large MW turbines

- The activities in the Light Rotor project (as well as other projects) has led to an initiative to synthesize the workflows involving our design codes into a unified framework for design and optimization of wind energy systems.
- Open-source core, mix of open/closed analysis modules
- Facilitate deployment of research codes into research / industry design processes.