



Developing the basis for the design of a 10 MW lightweight rotor

Bak, Christian; Zahle, Frederik; Bitsche, Robert; Kim, Taeseong; Yde, Anders; Henriksen, Lars Christian; Hansen, Morten Hartvig; Blasques, José Pedro Albergaria Amaral; Gaunaa, Mac; Sørensen, Niels N.

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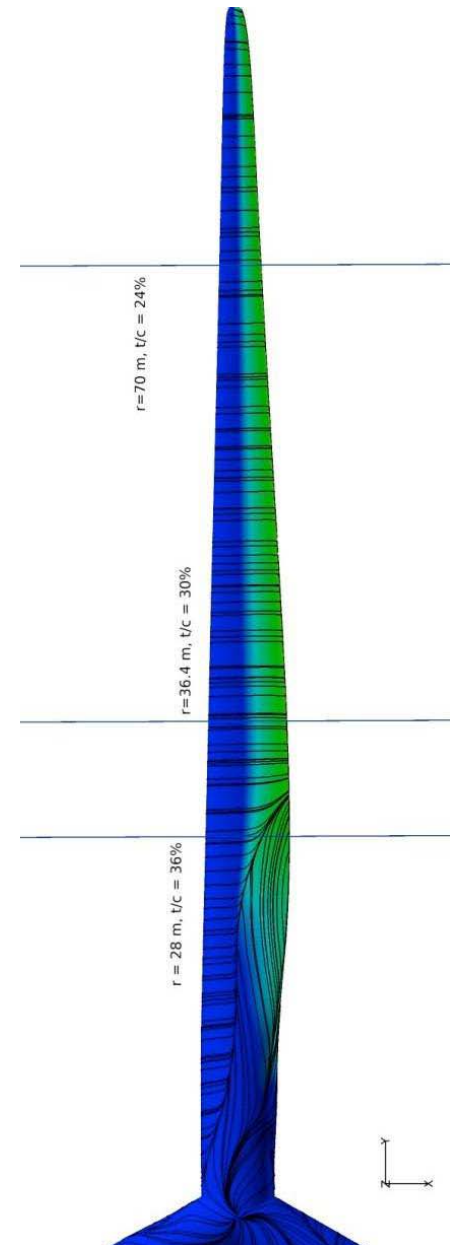
Developing the basis for the design of a 10 MW lightweight rotor

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 DTU Wind Energy – Risø Campus



Introduction

What is going to be presented

- This presentation focuses on the computational tools and methods when designing blades – mainly from the aerodynamic and aeroelastic perspective, but also somewhat from the structural perspective
- It does not focus on e.g.:
 - Materials
 - The manufacturing process
 - The cost
 - The reliability

Outline

- Presentation of the Light Rotor project
- Develop tools, blades and airfoils
 - A system engineering tool
 - Aerodynamic: Thick airfoils
 - Structure: Tools and optimization
 - Rotor: Aeroelastic optimization
- Development of the DTU 10 MW Reference Wind Turbine

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In the process...

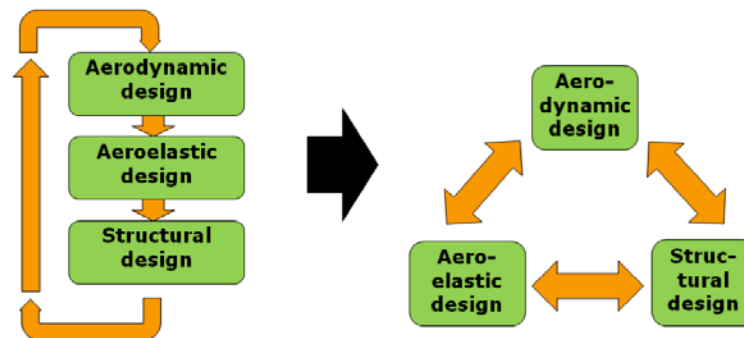
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Presentation of the Light Rotor project

Overall objective

- 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.



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In the process...

Develop tools, blades and airfoils

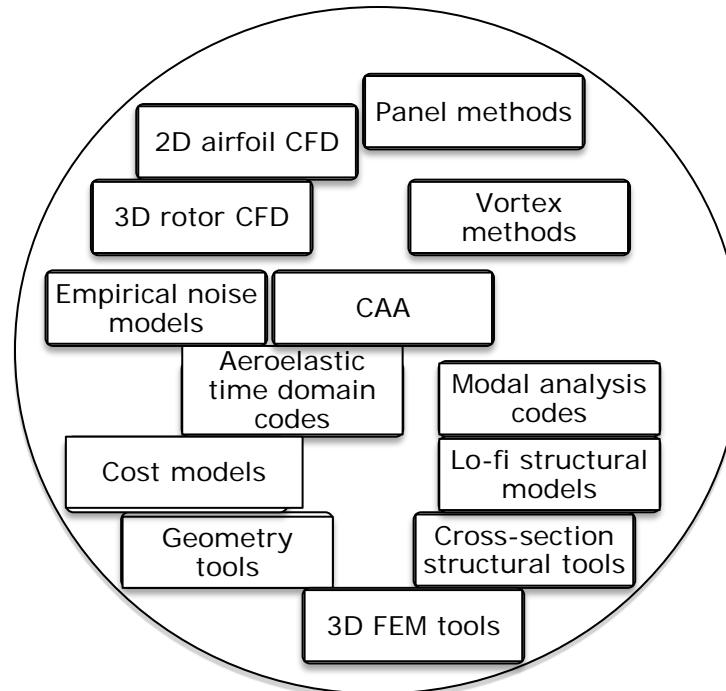
A system engineering tool

- Because traditional blades are rather optimized, any means to optimize blades further are necessary
- The blade needs to be designed as part of the entire system to obtain the wind turbine response directly in the design loop
- Thus, a system engineering tool is needed

Develop tools, blades and airfoils

A system engineering tool

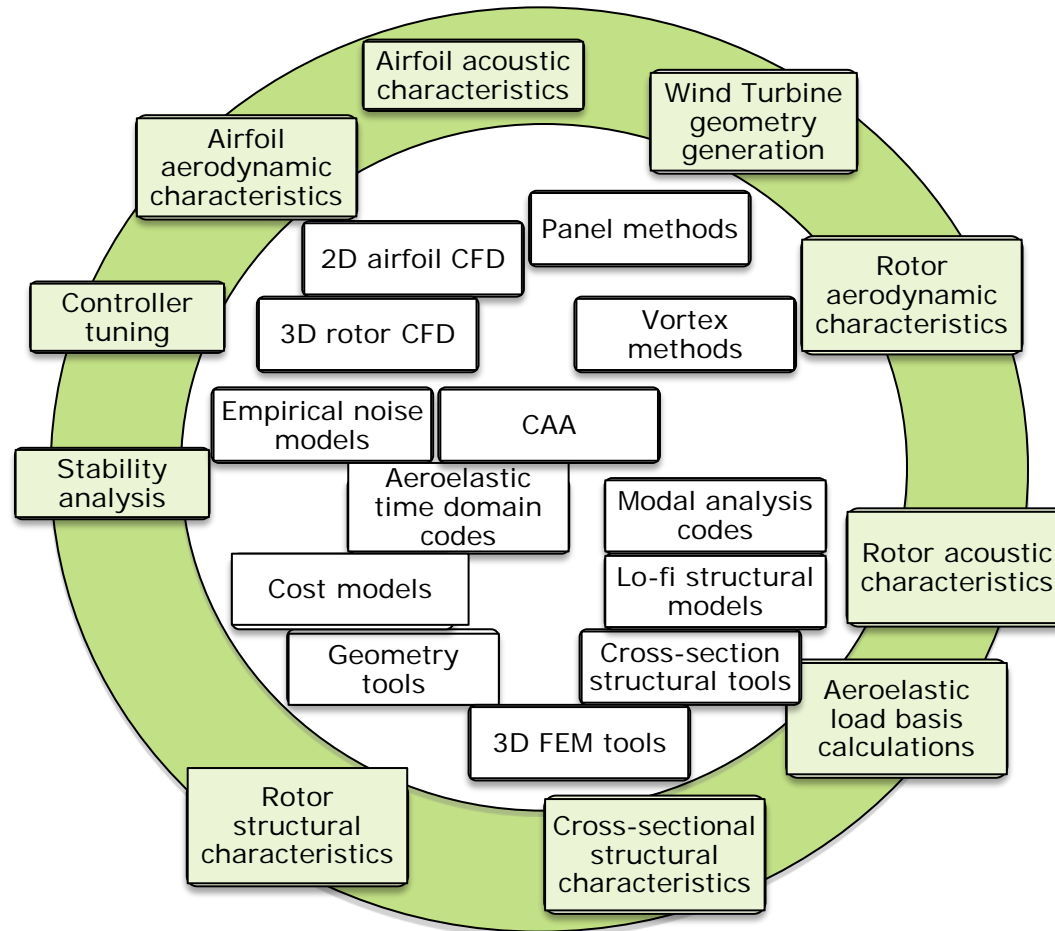
A unified framework for wind energy systems



Develop tools, blades and airfoils

A system engineering tool

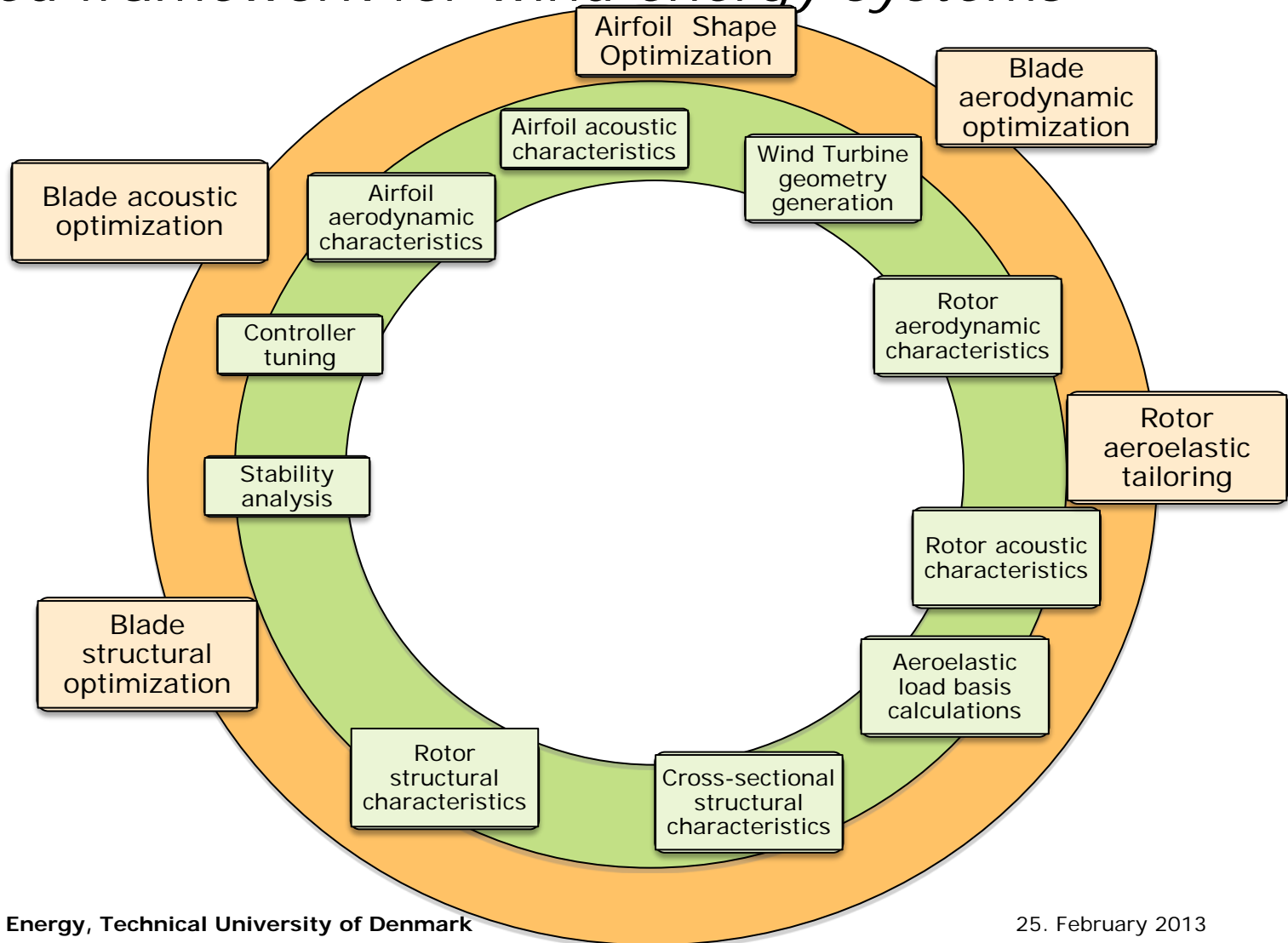
A unified framework for wind energy systems



Develop tools, blades and airfoils

A system engineering tool

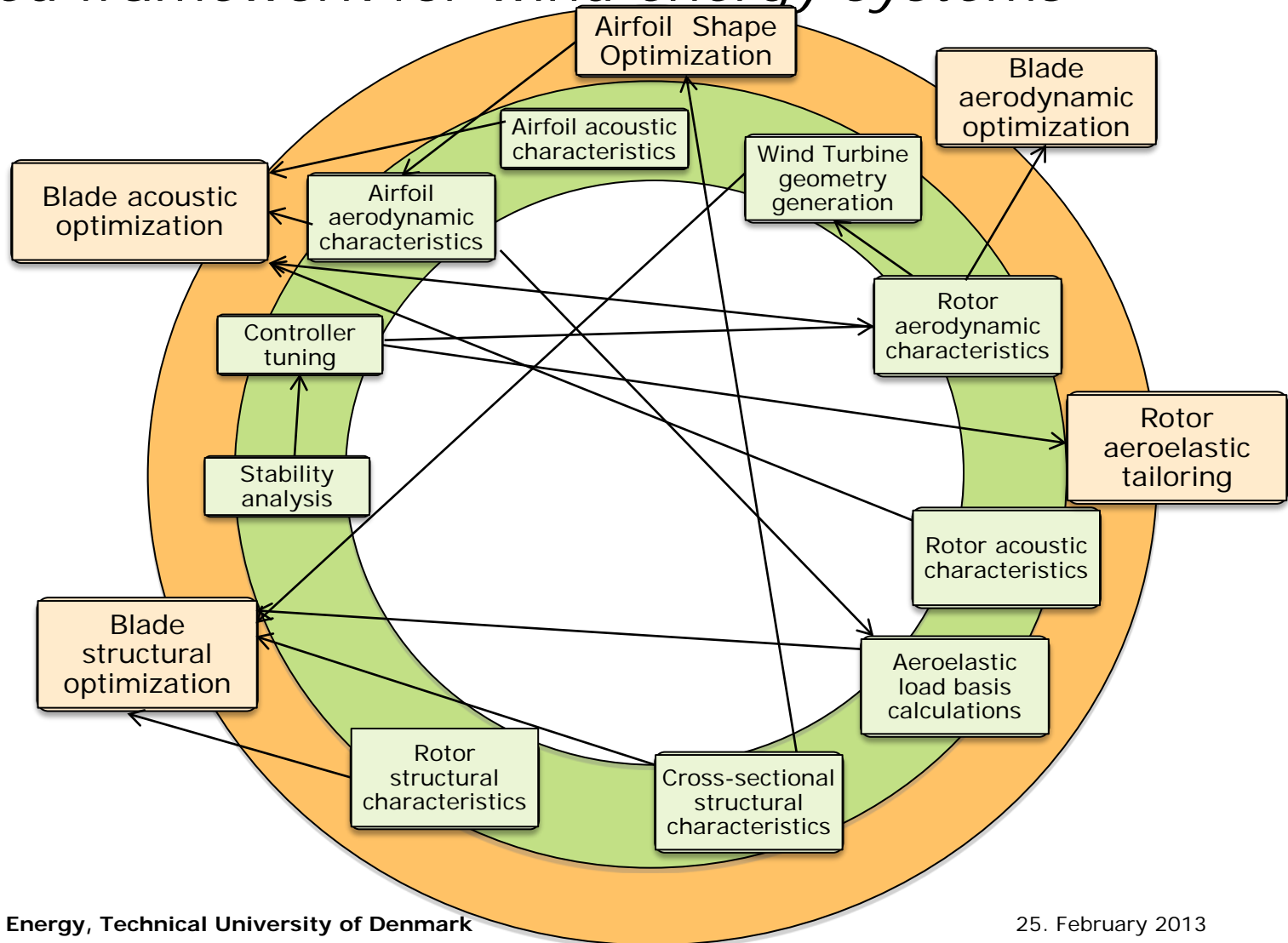
A unified framework for wind energy systems



Develop tools, blades and airfoils

A system engineering tool

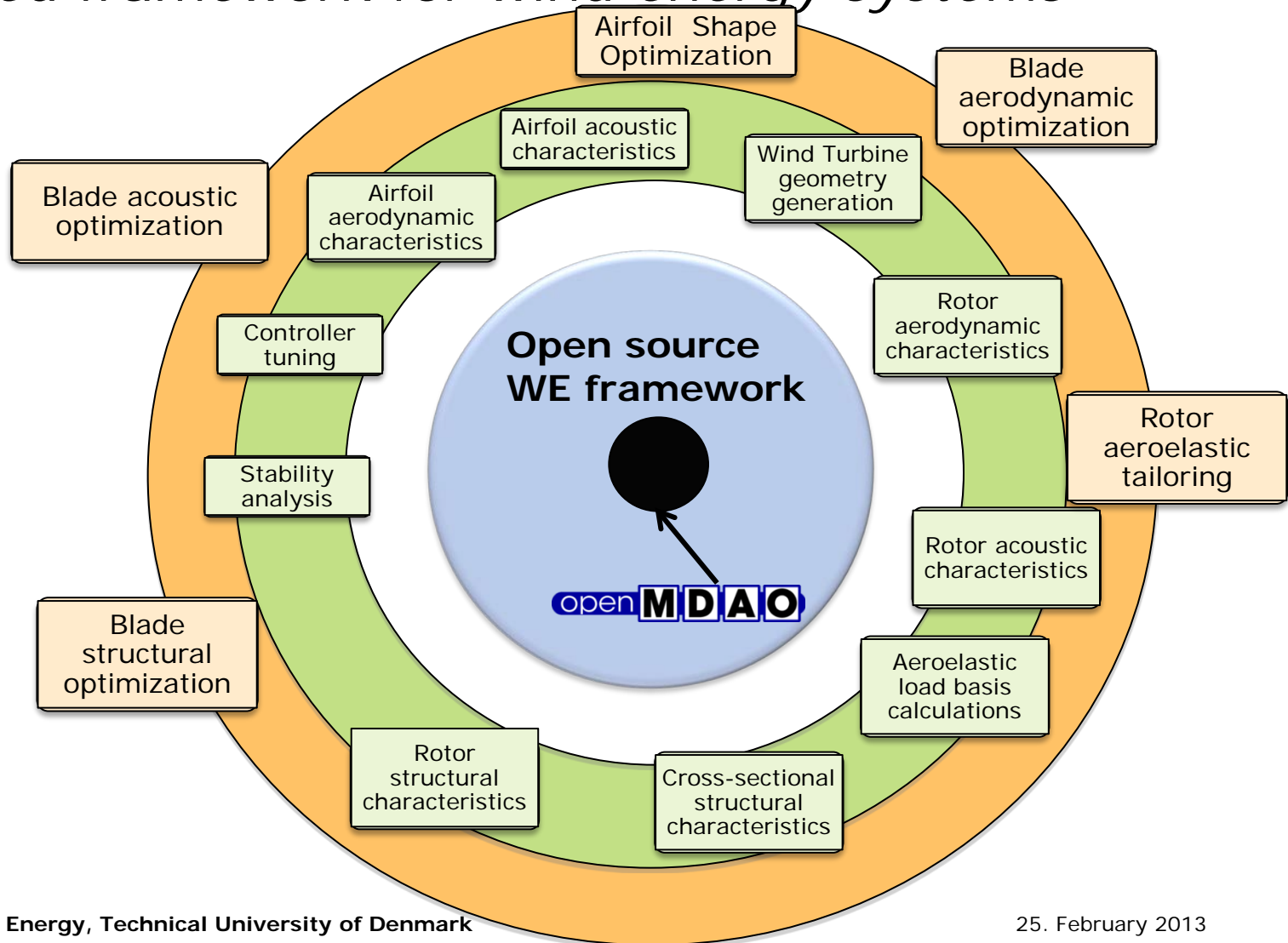
A unified framework for wind energy systems



Develop tools, blades and airfoils

A system engineering tool

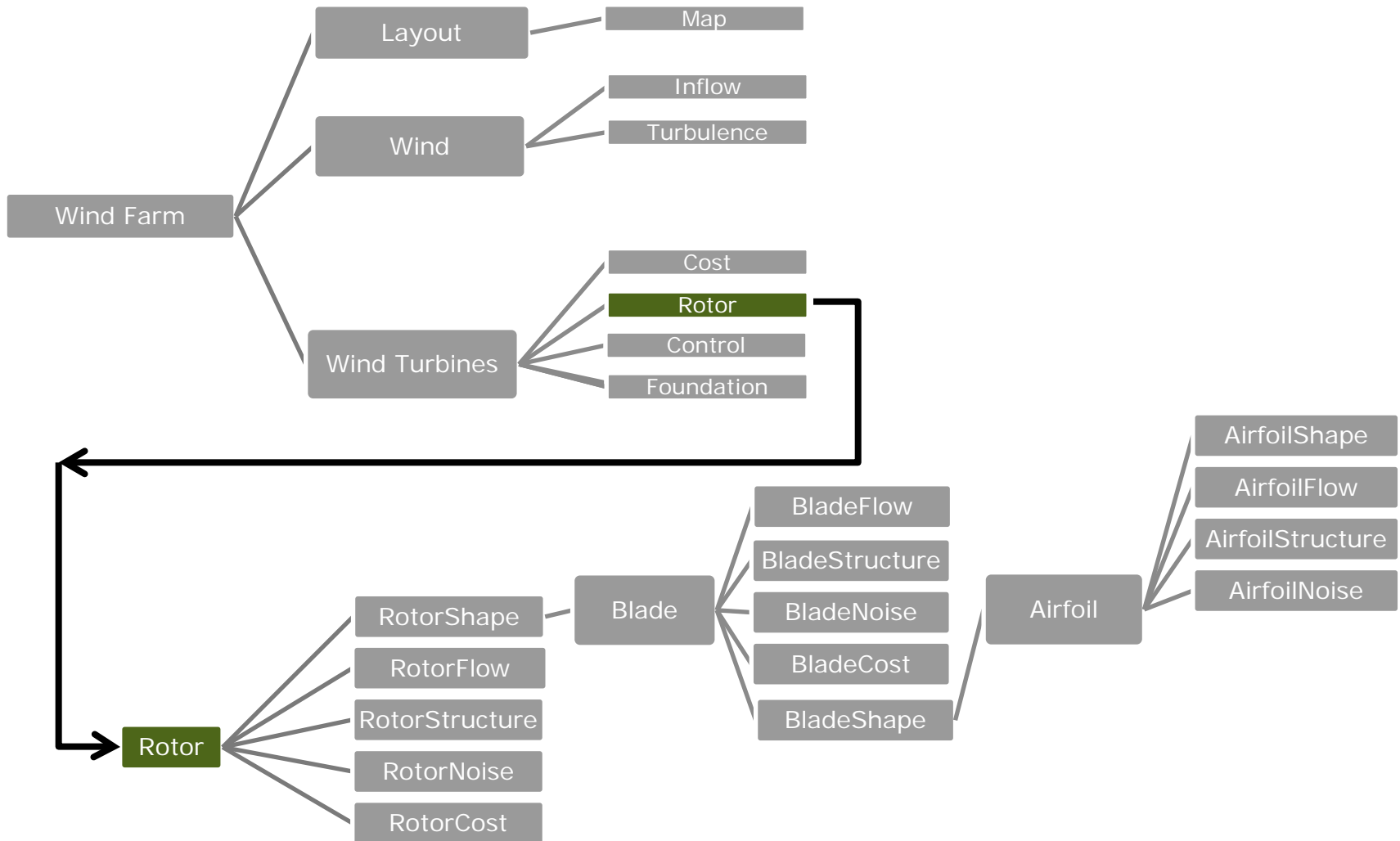
A unified framework for wind energy systems



Develop tools, blades and airfoils

A system engineering tool

A unified framework for wind energy systems



Develop tools, blades and airfoils

A system engineering tool

A unified framework for wind energy systems

- Plans to collaborate with NREL on this development.
- The idea is to think beyond optimization,
- A common platform for executing *all* codes, regardless of level of fidelity,
- 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,
- Based on Python and OpenMDAO.

Outline

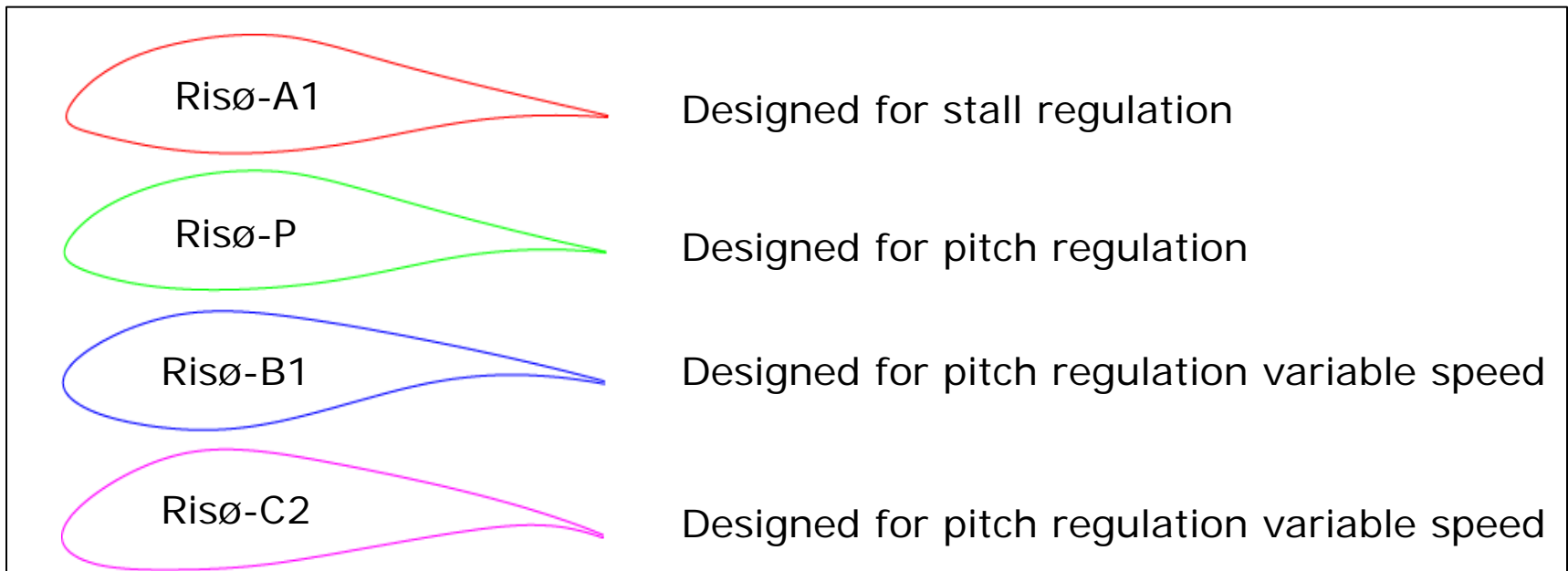
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In the process...

Develop tools, blades and airfoils

Aerodynamic: Thick airfoils

- Four airfoil series have been designed from 1998: Risø-A1, Risø-P, Risø-B1 and Risø-C2.
- They are used in commercial products, where focus is on airfoils from 15% to 30% relative thickness – even though also thick airfoils have been designed
- Now, we will focus on thick airfoils



Develop tools, blades and airfoils

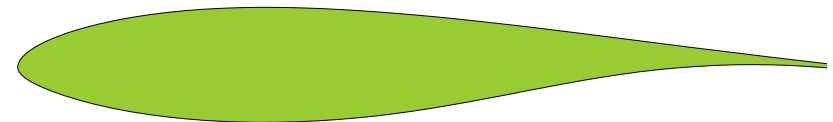
Aerodynamic: Thick airfoils

- Thick airfoils are necessary when looking for light weight rotors with limited cost
- However, thick airfoils are a challenge for the aerodynamic performance and thereby the energy production

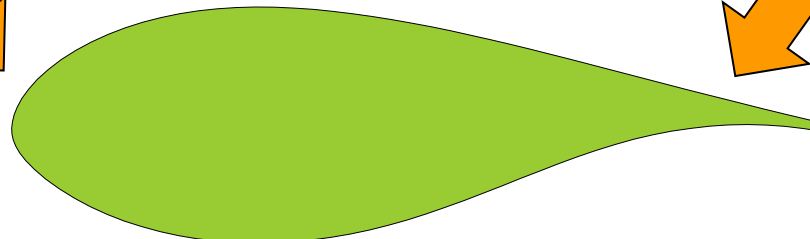
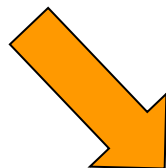
What the structural expert would like



What the aerodynamic expert would like

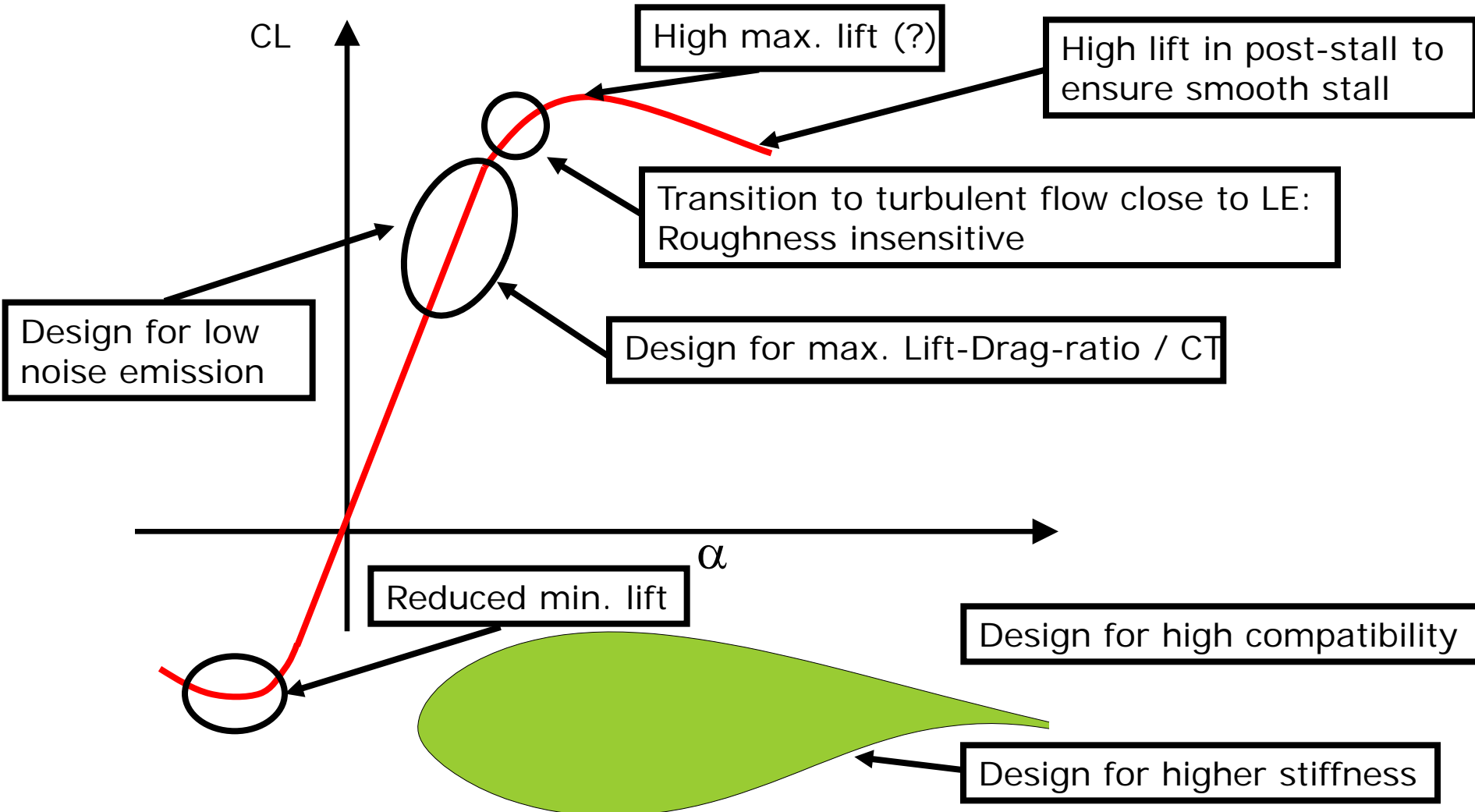


The resulting compromise



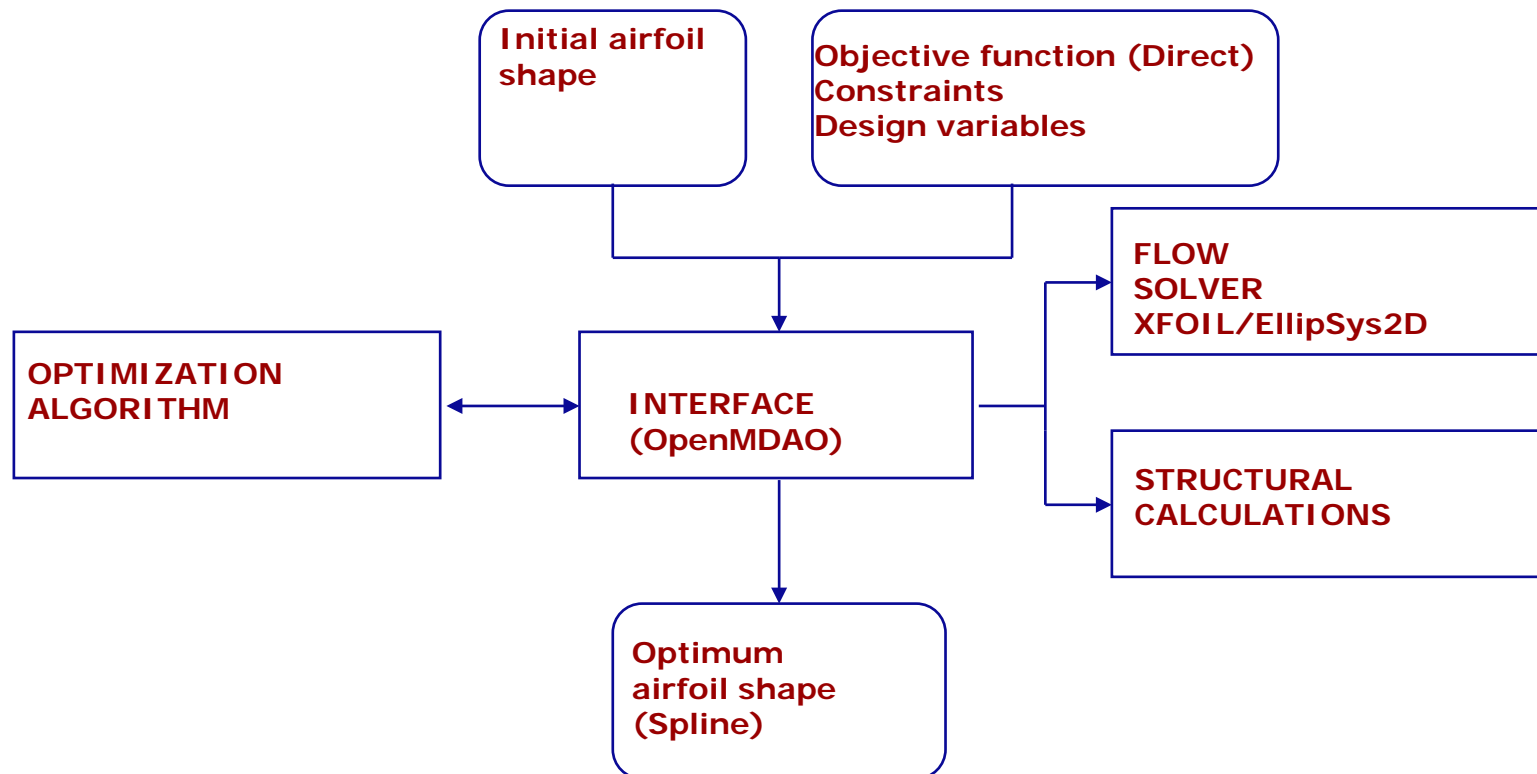
Develop tools, blades and airfoils

Aerodynamic: Thick airfoils



Develop tools, blades and airfoils

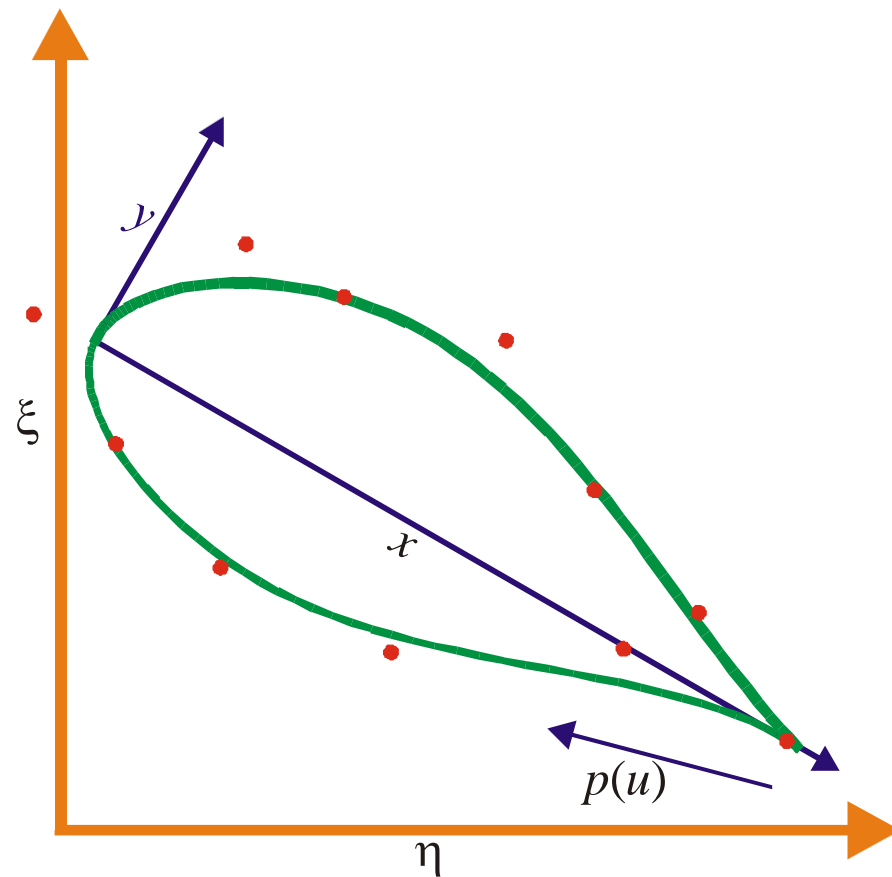
Aerodynamic: Thick airfoils



Develop tools, blades and airfoils

Aerodynamic: Thick airfoils

- Decisions need to be taken:
 - Rotor radius where airfoil will be used?
 - Is high lift more important than high lift-drag ratio?
 - Traditional shape/Flatback?
 - Box girder position?
 - Is noise an issue?



Develop tools, blades and airfoils

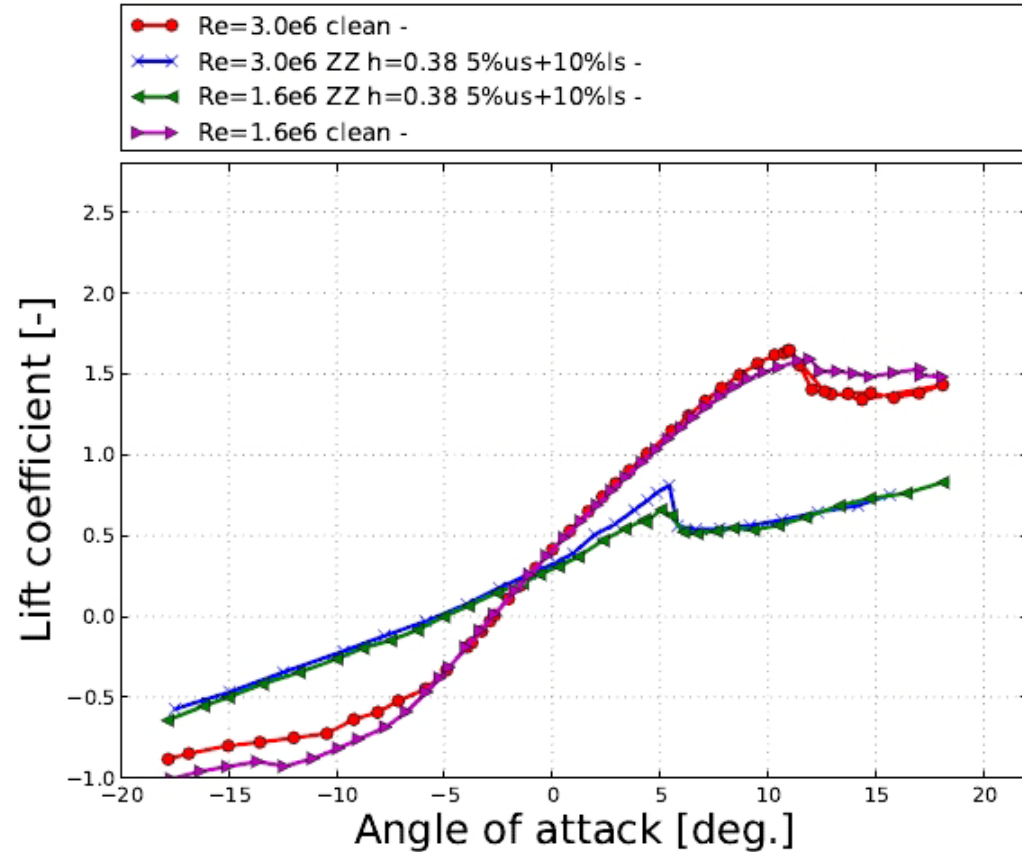
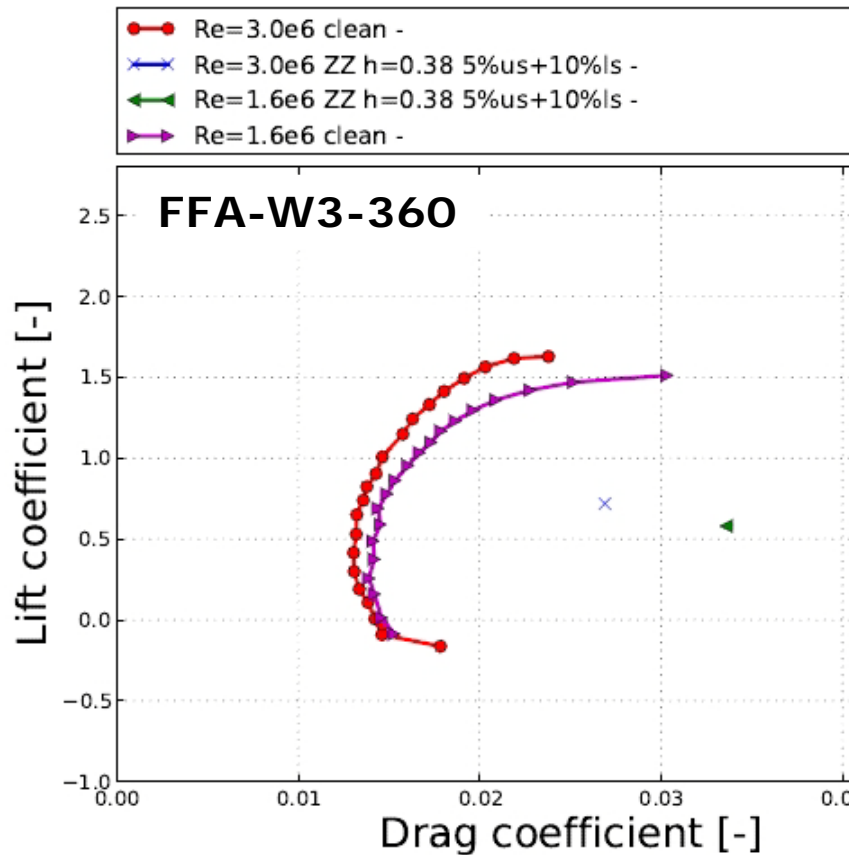
Aerodynamic: Thick airfoils

- Aerodynamic/high-lift devices are investigated
- The devices can be such as
 - Vortex generators
 - Gurney flaps
 - Slats
 - Flaps
- No results from the new airfoil designs yet
- Designs and wind tunnel tests will come later this year
- But results from the known and commonly applied thick FFA-W3-xxx airfoils with high lift devices
- They will work as a reference

Develop tools, blades and airfoils

Aerodynamic: Thick airfoils

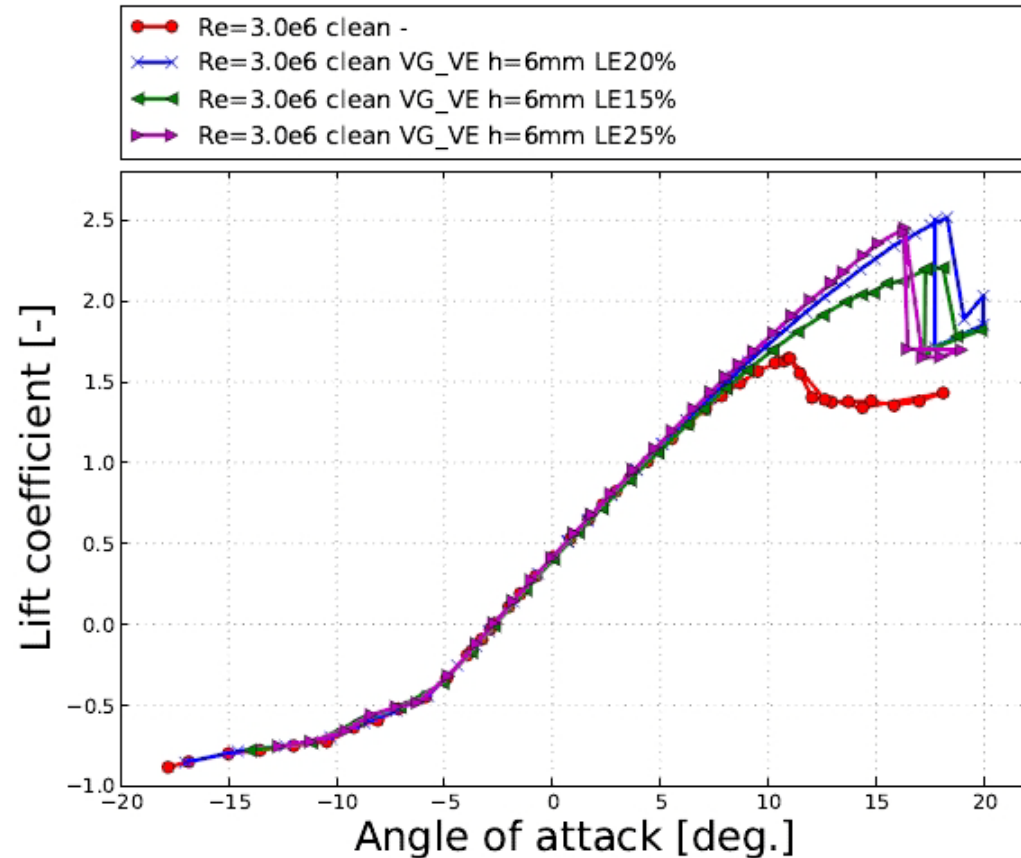
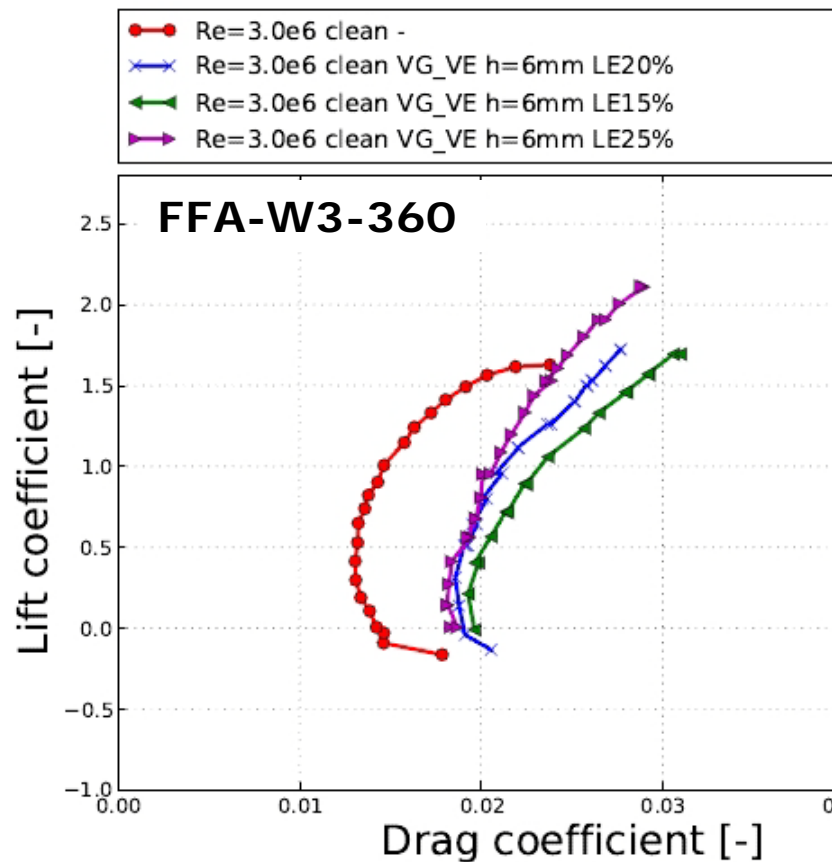
Stuttgart Laminar Wind Kanal



Develop tools, blades and airfoils

Aerodynamic: Thick airfoils

Stuttgart Laminar Wind Kanal



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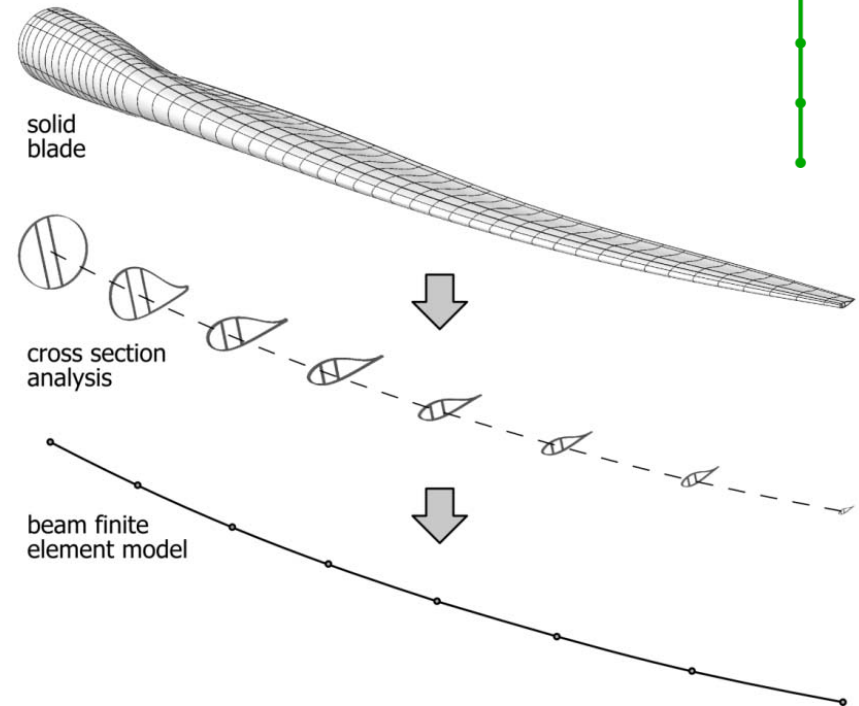
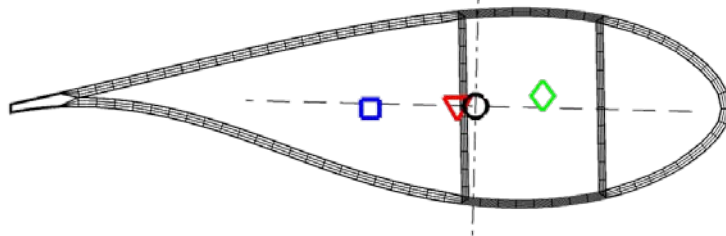
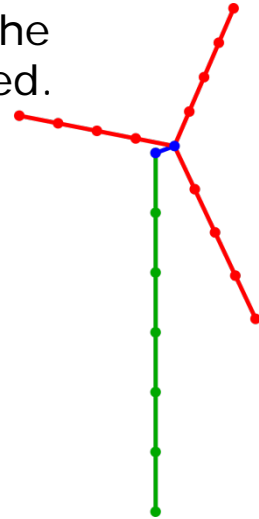
In the process...

Develop tools, blades and airfoils

Structure: Tools and optimization - BECAS

www.becas.dtu.dk

- The aeroelastic model (HAWC2) relies on beam theory to describe the blades of the turbine. → Beam stiffness and mass properties required.
- BECAS is DTU Wind Energy's cross section analysis tool.
- BECAS determines the stiffness and mass properties of arbitrary beam cross sections and correctly accounts for all geometrical and material induced couplings (e.g. bend-twist coupling).
- The light rotor project is supporting the further development of BECAS
- BECAS is "open source", in the sense that all license holders get access to the source code.
- An academic license for BECAS is available free of charge.

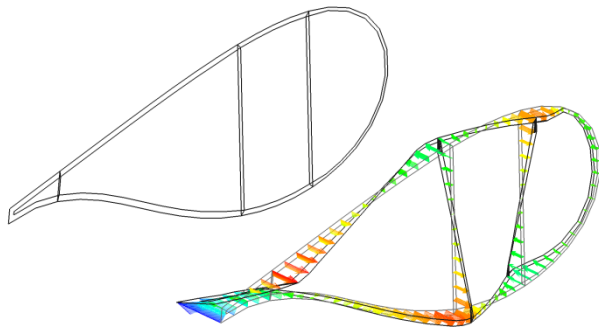


Develop tools, blades and airfoils

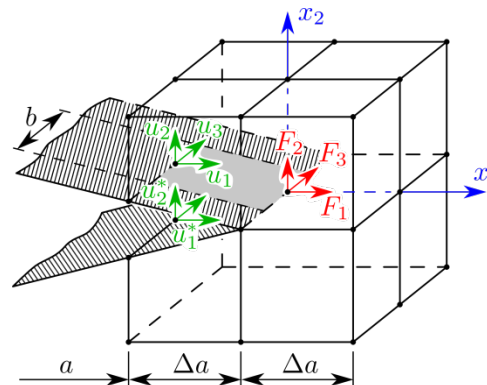
Structure: Tools and optimization - BECAS

- Local 3D stresses and strains can be computed based on cross section forces and moments computed using HAWC2. → Composite failure criteria.
- Planned features:
 - Fracture mechanics analysis (VCCT)
 - New element types
 - Buckling analysis

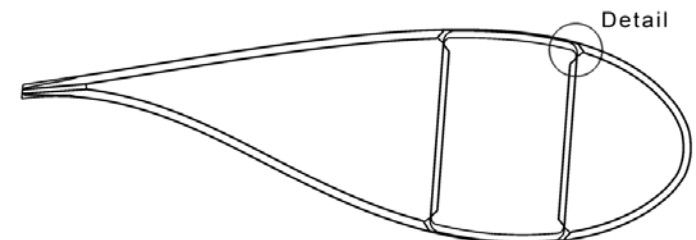
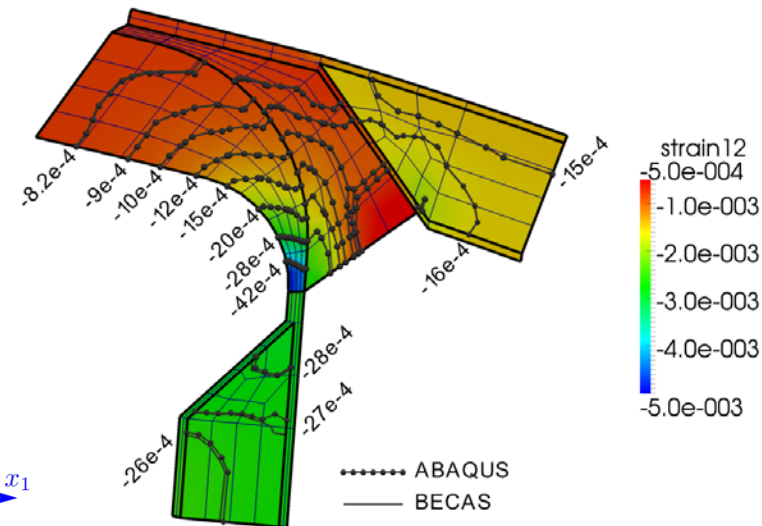
warping deformation



VCCT



local 3D strain field

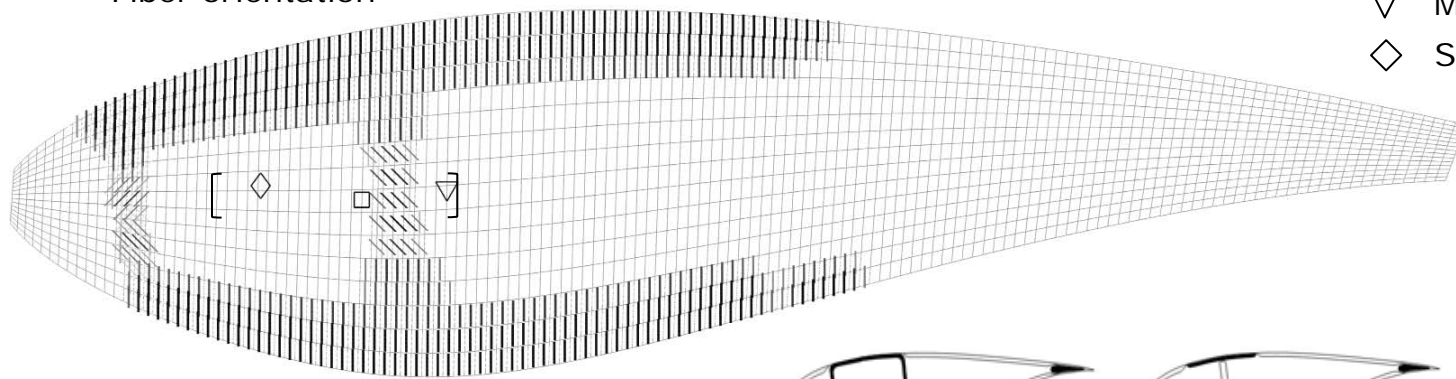


Develop tools, blades and airfoils

Structure: Tools and optimization

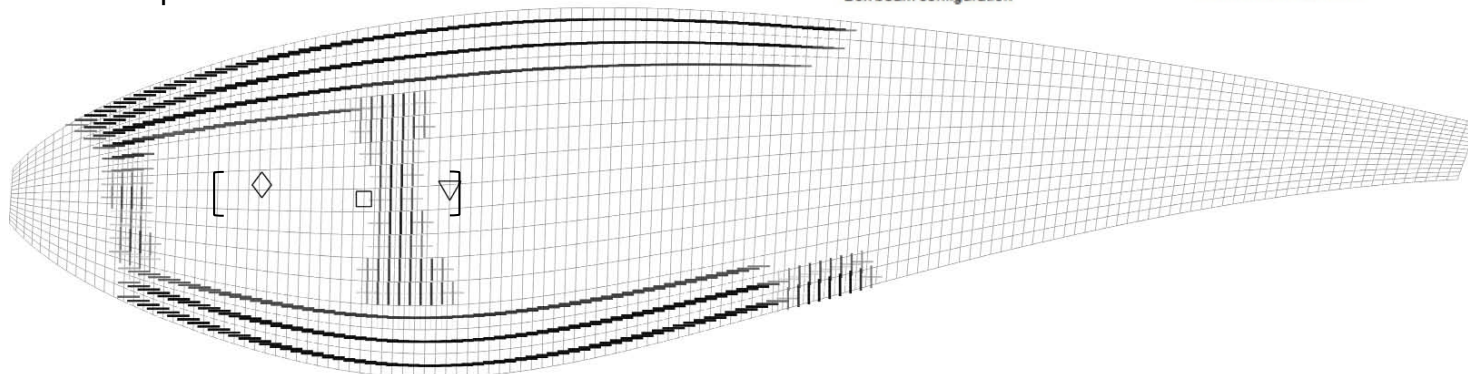
- Minimum compliance optimization with constraints on weight, and shear and mass center positions

Fiber orientation



- Ref. Cent.
- ▽ Mass Cent.
- ◇ Shear Cent.

Fiber plane orientation



Box beam configuration



Shear web configuration

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In the process...

Develop tools, blades and airfoils

Rotor: Parameter variation

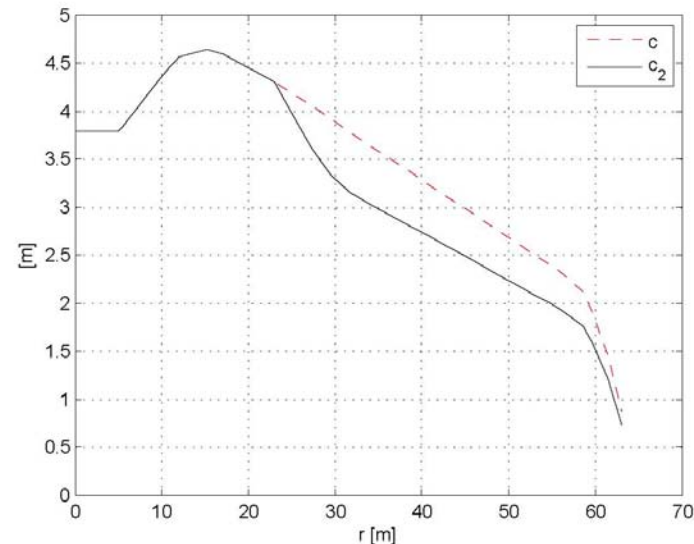
- The chord c and lift coefficient C_l is changed in order to maintain cC_l
 - Unchanged quasi-steady aerodynamics (AOA, power (C_p), annual energy production (AEP) etc.)

$$cC_l = c_2C_{l2} \quad \Rightarrow \quad c_2 = cC_l/C_{l2}$$

- This is done at 9 m/s where $C_l=1.0$ and $C_{l2}=1.2$ for the redefined 2D data at unchanged AOA.
- Very simple definition of c_2 since no optimization is introduced

	AEP [GWh]	
c	21.39	
c_2	21.37	(-0.1%)

Annual energy production



Chord distributions

Develop tools, blades and airfoils

Rotor: Aeroelastic optimization

Load sensor	m	Fatigue, Equivalent moment	Extreme, extrapolated 50 year/ max
Tower bottom, fore-aft bending moment	3	84%	76%
Tower top, fore-aft bending moment	3	89%	89%
Blade root, flap bending moment	10	88%	93%
Blade root, edge bending moment	10	98%	94%

Develop tools, blades and airfoils

Rotor: Aeroelastic optimization

- The coming process of the aeroelastic rotor optimization will:
 - Try to maximize AEP while maintaining the loads
- This will include:
 - Airfoil considerations (high/low lift, structural performance etc)
 - Fiber orientation/twist-flap coupling
 - Blade sweep
 - Blade prebend
 - Mass reduction
 - Internal structure of the blade
 - Etc
- The challenge when optimizing a wind turbine with its components is that the input and thereby the response is inherently stochastic

Outline

- Presentation of the Light Rotor project
- Develop tools, blades and airfoils
 - A system engineering tool
 - Thick airfoils to reduce weight
 - Tools and optimized structure
 - Light weight rotor
- **Development of the DTU 10 MW Reference Wind Turbine**

The DTU 10 MW Reference Wind Turbine Objective

- **The purpose with the design is:**
 - To provide a publicly available representative design basis for next generation of 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.

The DTU 10 MW Reference Wind Turbine

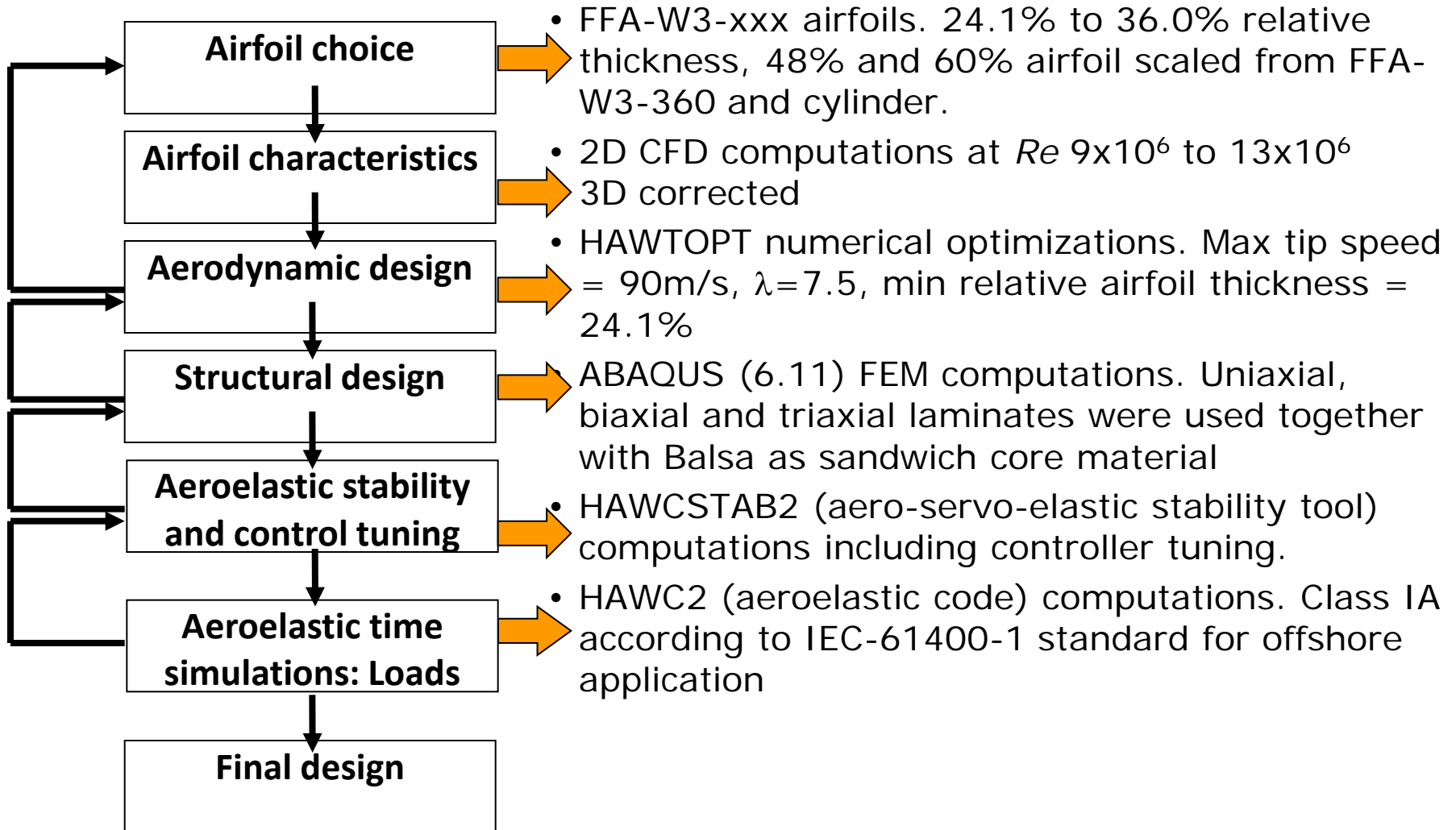
The Design Process

- 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.

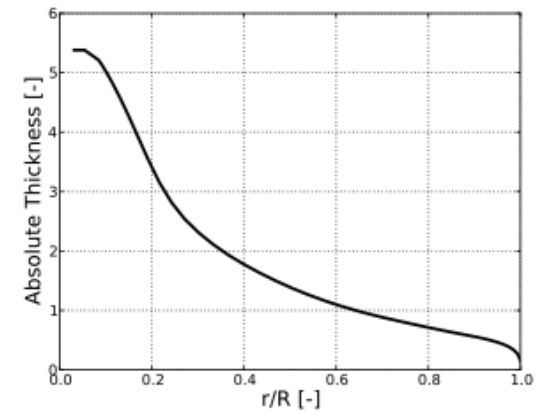
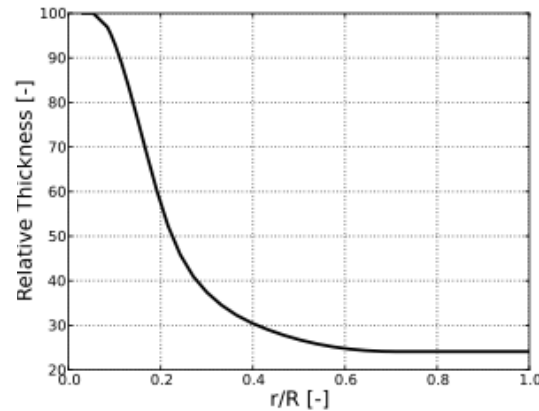
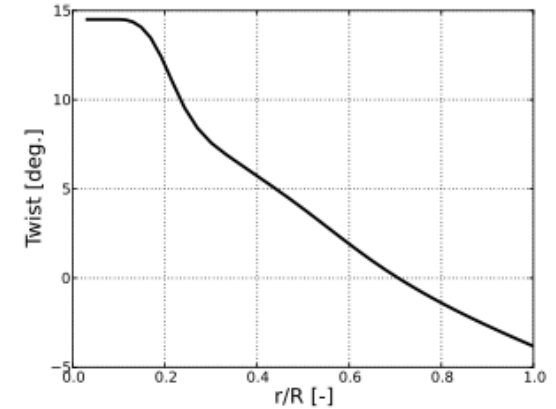
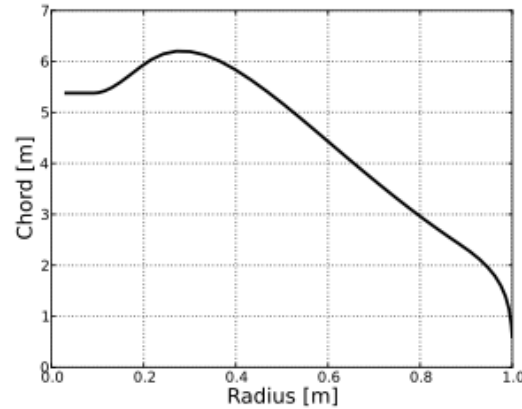
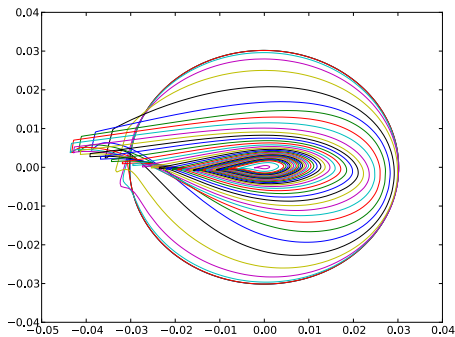
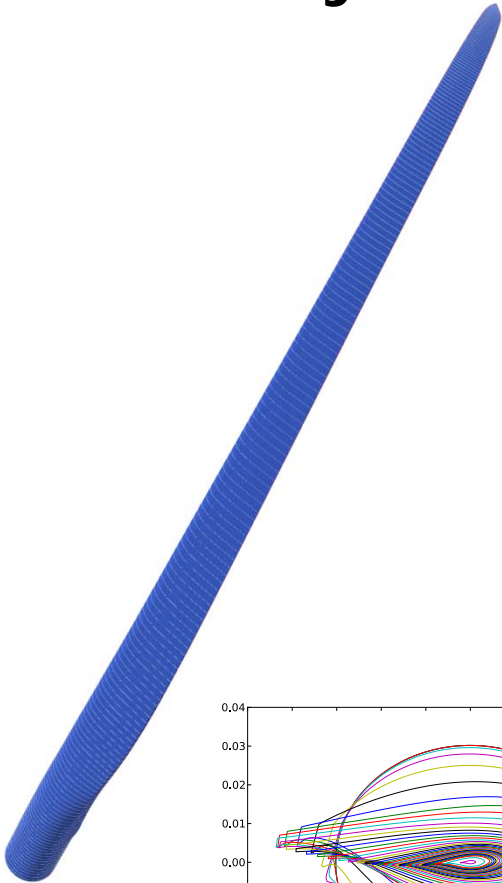
The DTU 10 MW Reference Wind Turbine Design Summary

Description	Value
Rating	10MW
Rotor orientation, configuration	Upwind, 3 blades
Control	Variable speed, collective pitch
Drivetrain	Medium speed, Multiple stage gearbox
Rotor, Hub diameter	178.3m, 5.6m
Hub height	119m
Cut-in, Rated, Cut-out wind speed	4m/s, 11.4m/s, 25m/s
Cut-in, Rated rotor speed	6RPM, 9.6RPM
Rated tip speed	90m/s
Overhang, Shaft tilt, Pre-cone	7.07m, 5°, 2.5°
Pre-bend	~4m
Rotor mass	225tons (each blade ~40tons)
Nacelle mass	446tons
Tower mass	605tons

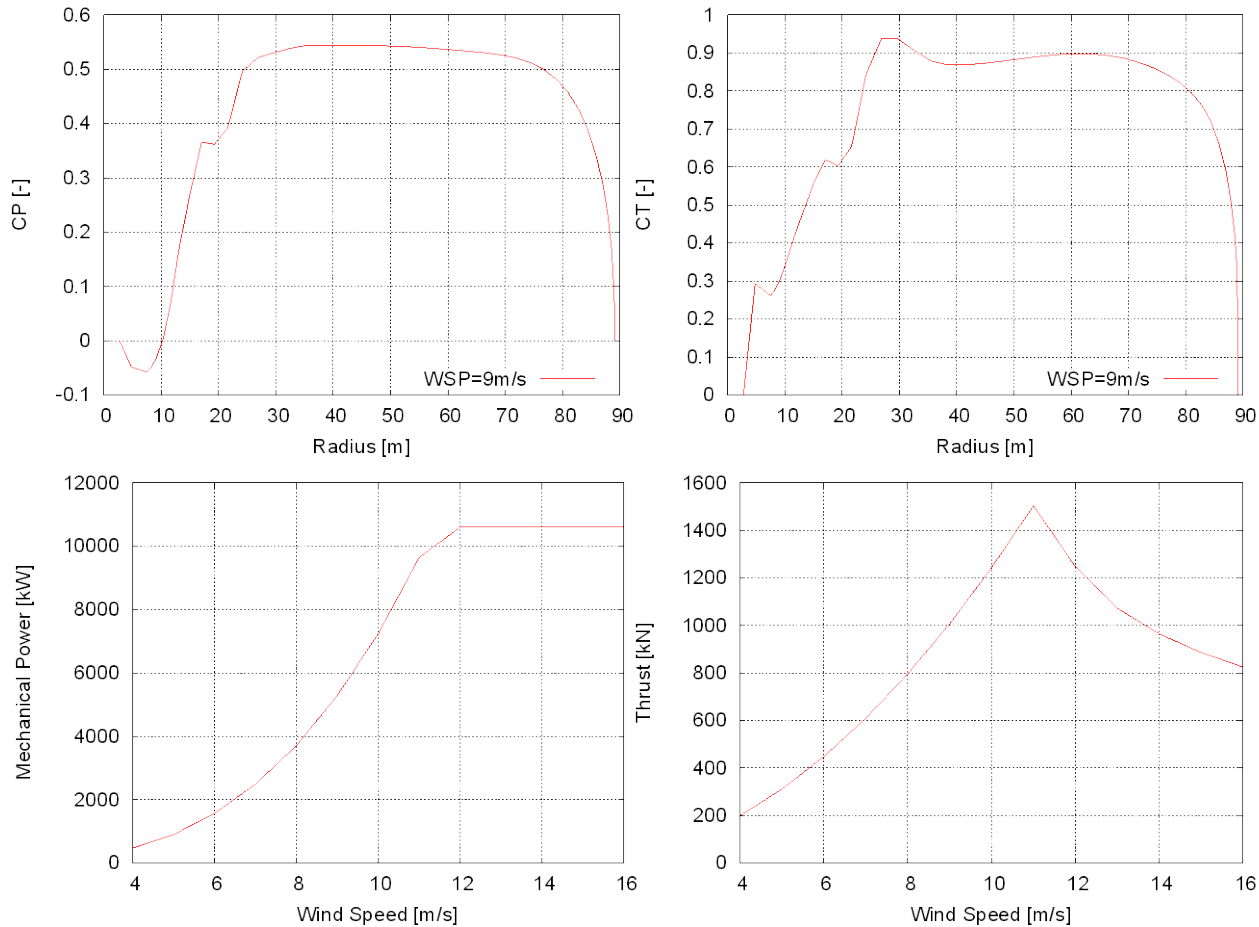
The method



The DTU 10 MW Reference Wind Turbine Aerodynamic Design: Geometry

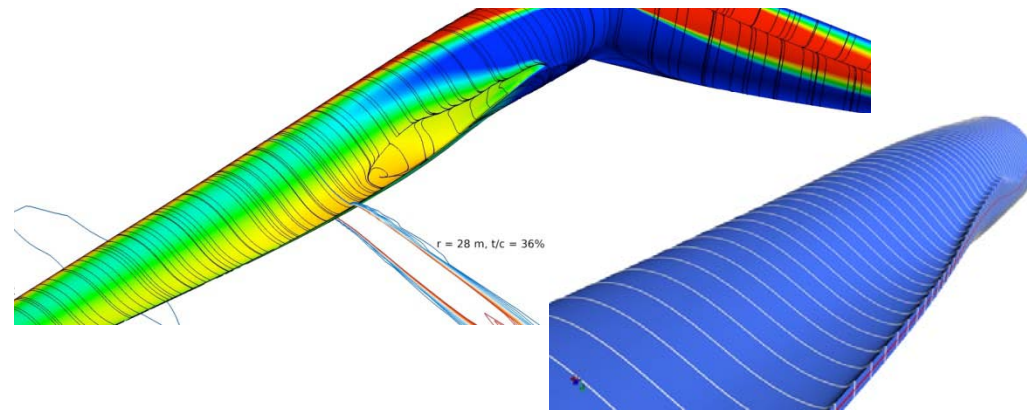
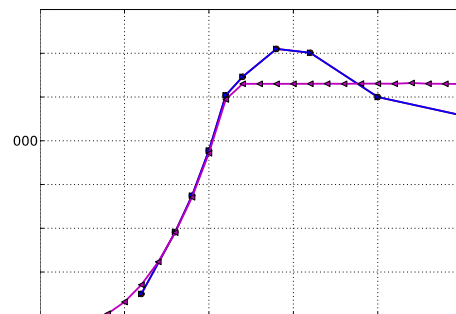
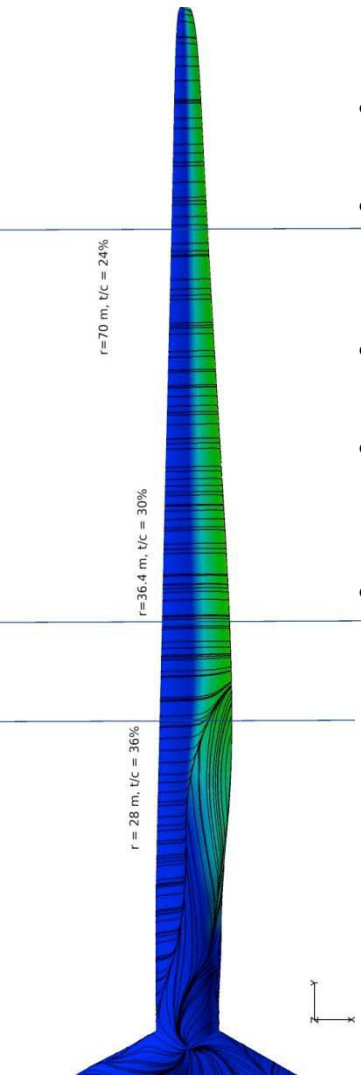
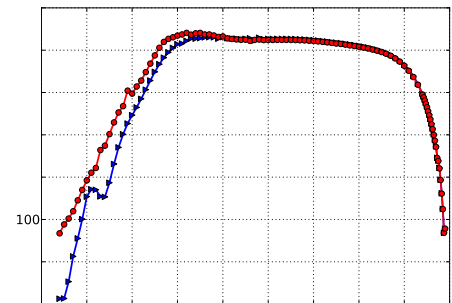
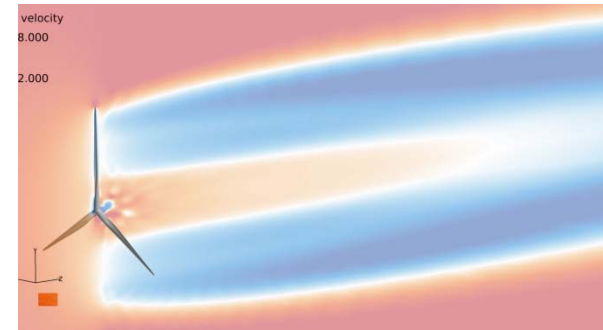


The DTU 10 MW Reference Wind Turbine Aerodynamic Design: Performance



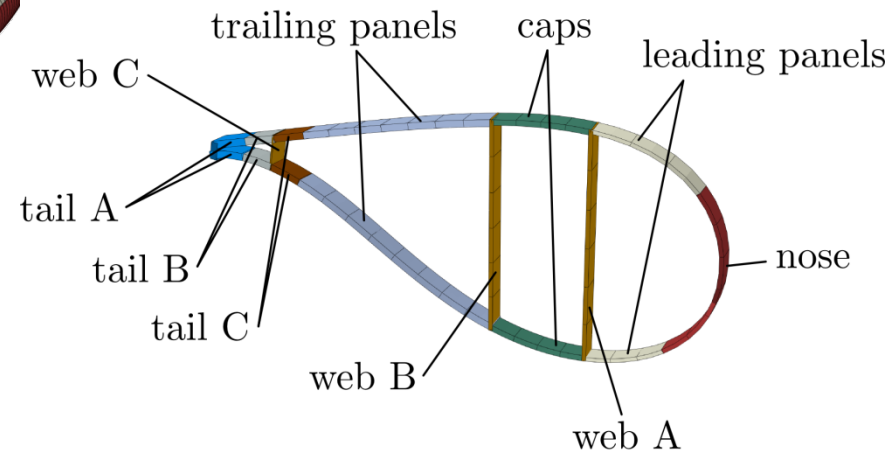
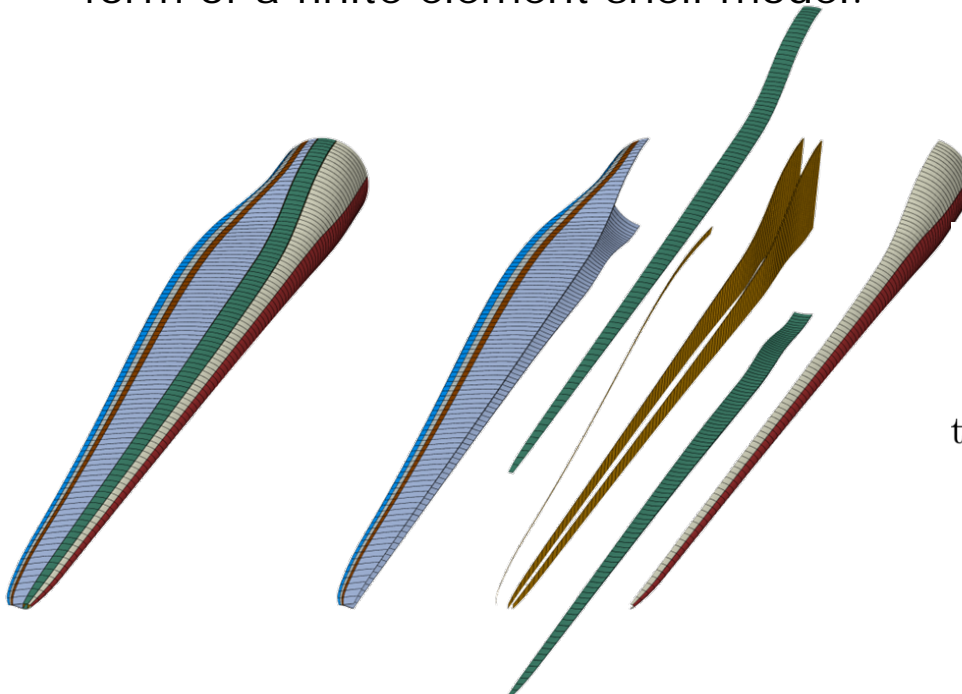
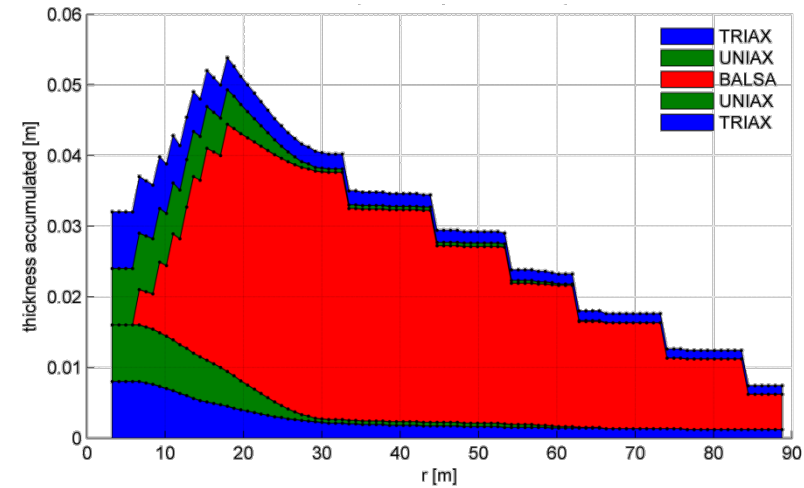
The DTU 10 MW Reference Wind Turbine Aerodynamic Design: 3D CFD analysis

- 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 of thick airfoils ($t/c > 0.36$ 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).

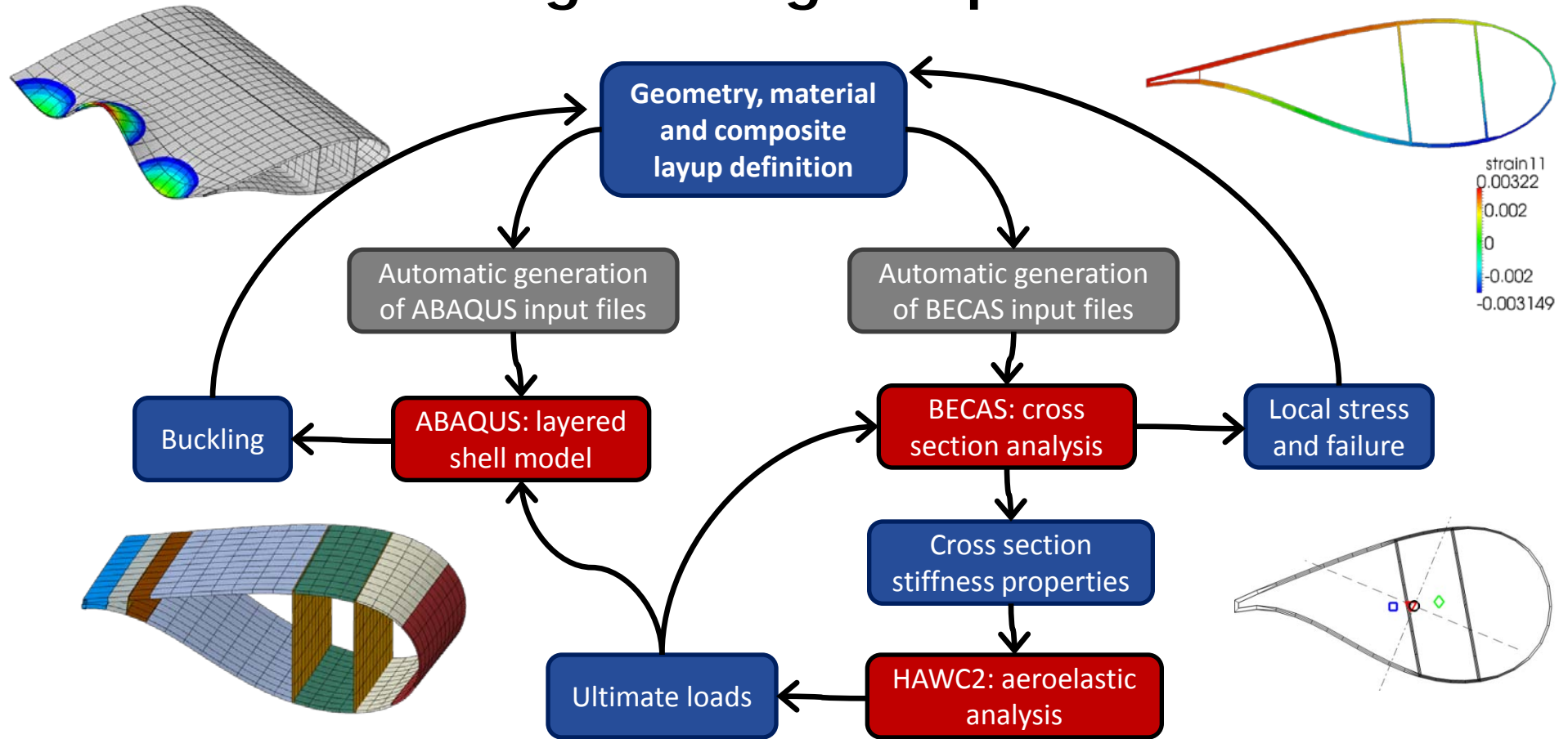


The DTU 10 MW Reference Wind Turbine Structural Design: Basic design choice

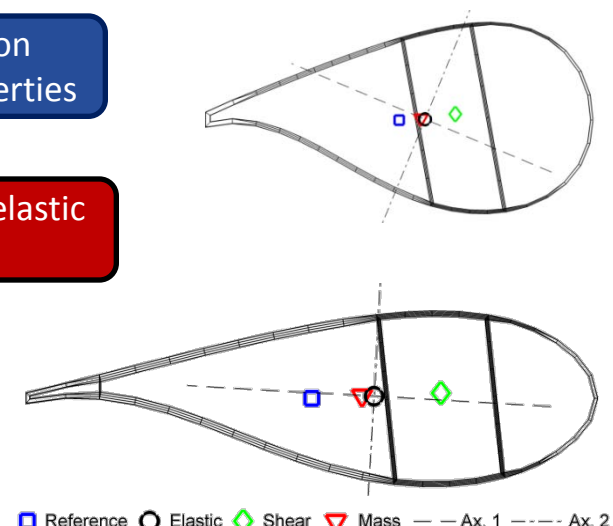
- A "box-girder" design approach is used.
- For layup definition the blade is partitioned into 100 regions radially and 10 regions circumferentially.
- A complete description of the blade's geometry and layup is generated in the form of a finite element shell model.



The DTU 10 MW Reference Wind Turbine Structural Design: Design loop

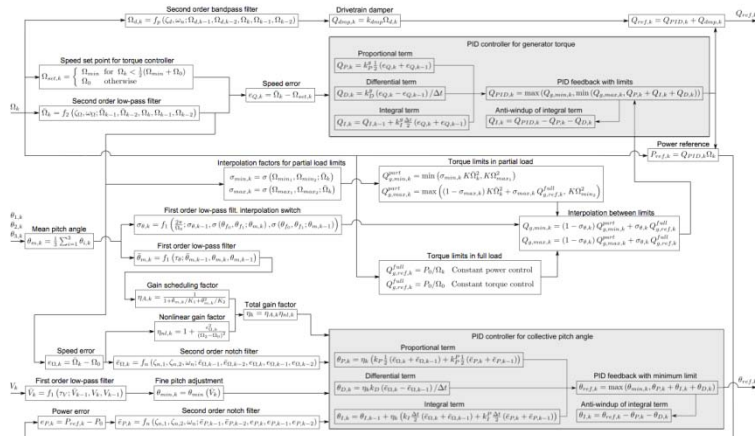
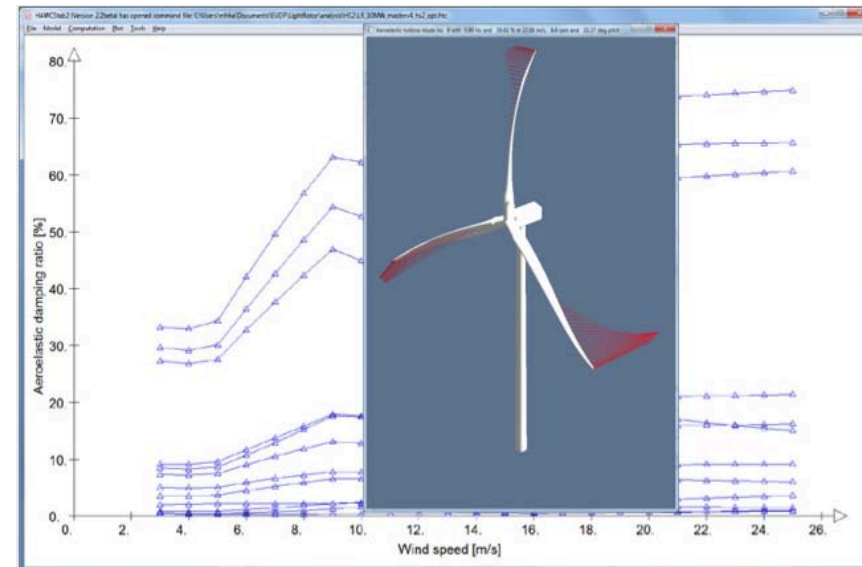


	Load case	γ_F [-]	F_x [MN]	F_y [MN]	F_z [MN]	F_{res} [MN]	M_x [MNm]	
F_x	max	dlc5.1	1.35	0.9531	-0.2915	1.0163	0.9967	25.2834
	min	dlc1.3	1.35	-0.8724	0.3672	2.2653	0.9465	-8.9863
F_y	max	dlc1.3	1.35	0.4949	1.6055	2.4138	1.6801	-52.9810
	min	dlc5.1	1.35	-0.0504	1.1869	0.9799	1.1879	44.0099



The DTU 10 MW Reference Wind Turbine Aero-servo-elastic analysis

- 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, minimum RPM = 6.
- Report and source code on controller available.



The DTU 10 MW Reference Wind Turbine

Load calculations: HAWC2

- DTU 10MW RWT: IA according to IEC-61400-1 (3rd edition)
- The suggested load cases by IEC standard must be verified in order for withstanding all loading situations during its life time.
- Most of design load cases are considered except DLC8, which is for transport, assemble, maintenance, and repair cases, and DLC 1.4, DLC 2.2, DLC 3.1, DLC 3.2, and DLC 3.3 which are very depending on controller.

The DTU 10 MW Reference Wind Turbine

Summary of design challenges

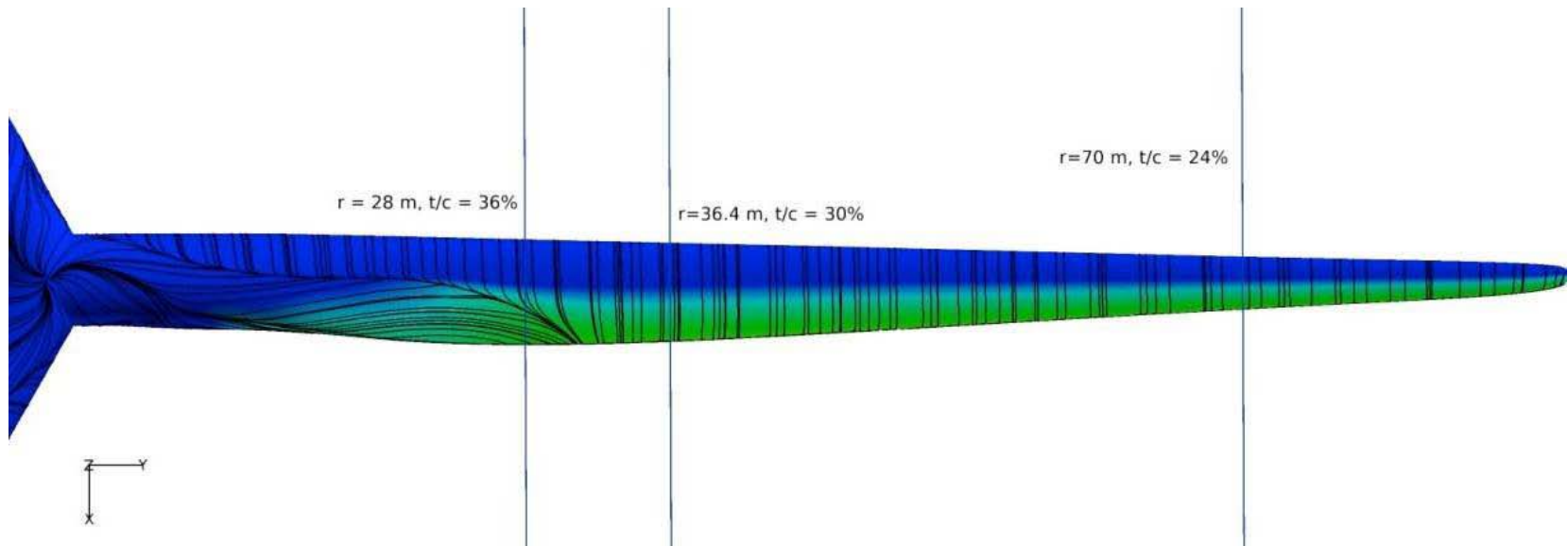
- Transition from laminar to turbulent flow in the boundary layer of the airfoils showed surprising differences between different simulation models: the Xfoil e^n model and the $\gamma - \theta$ correlation based model.
 - The result is uncertainty of the aerodynamic performance and thereby on loads and especially the power
- The efficiency of thick airfoils, i.e. airfoils with relative thickness greater than 30%, is significantly better when using Gurney flaps,
 - The result is an increase of the power of several percent
- To reduce the blade weight, the blade design needs to be "stress/strain" driven rather than "tip deflection" driven.
 - The result is 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,
 - The result is determination of the minimum rotational speed
- Blade vibrations in stand still
 - Vibrations at 90 degrees inflow direction can probably be avoided by pitching each blade differently
 - Vibrations at 30 degrees inflow direction can be reduced by ensuring "smooth" airfoil characteristics

The DTU 10 MW Reference Wind Turbine 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.

Summary

- The activities in the Light Rotor Project are a development of the basis for the design of 10 MW lightweight rotors
- The project has led to an initiative to synthesize the workflows with an open-source core: OpenMDAO
- Tools have been developed and will be connected to the OpenMDAO environment
- Wind tunnel tests of thick airfoils have been carried out showing aerodynamic challenges
- The DTU 10 MW RWT design has been finalized – release imminent.
 - Highly detailed – useful for research and development engineers for inter-code comparison
 - Basis for future designs of optimized large MW turbines



Thank you for your attention!

