Technical University of Denmark

DTU

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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Section for Aeroelastic Design/Structures

Technical University of Denmark

DTU Wind Energy – Risø Campus

DTU Wind Energy
Department of Wind Energy

r=70 m, t/c = 24%

r=36.4 m, t/c = 30%

r = 28 m, t/c = 36%
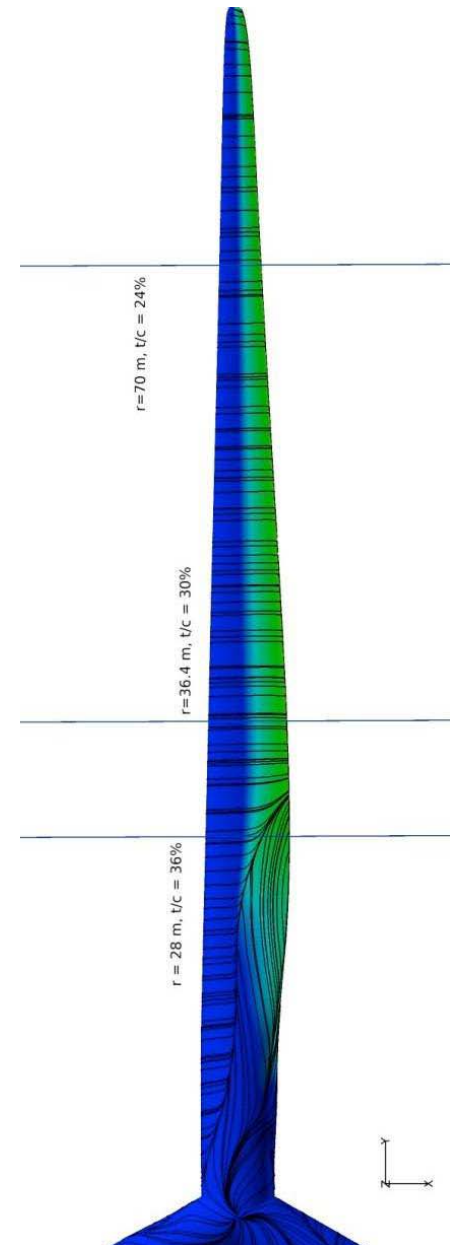
Introduction
What is going to be presented

- 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 reliablity

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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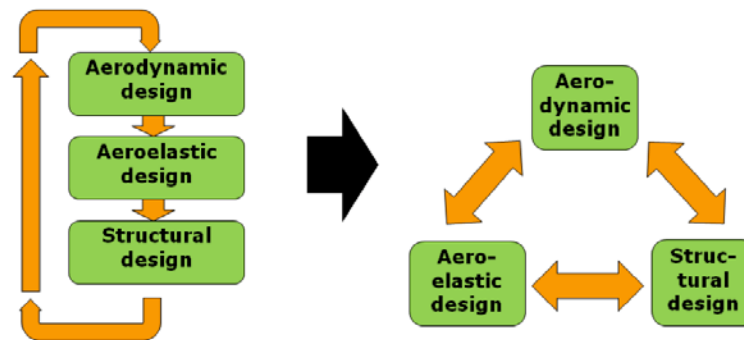
In the process...

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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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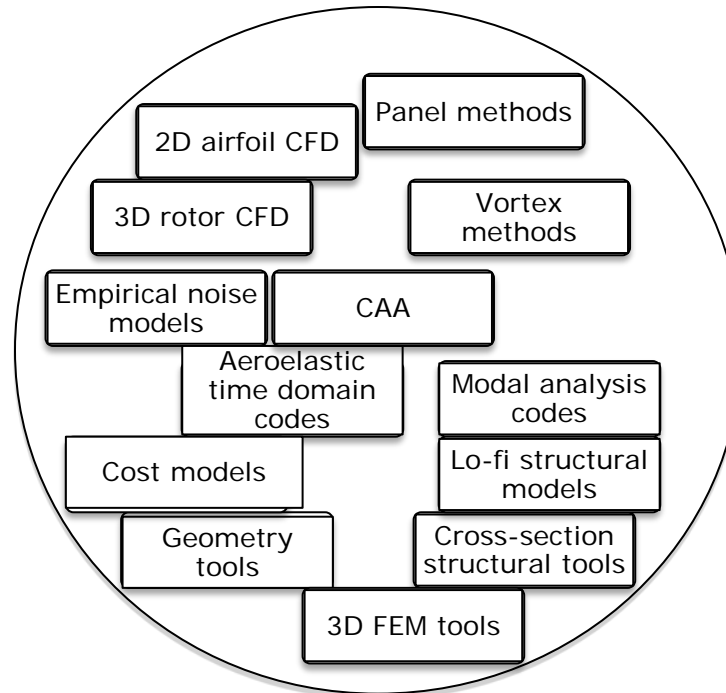
Develop tools, blades and airfoils
A system engineering tool

- 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

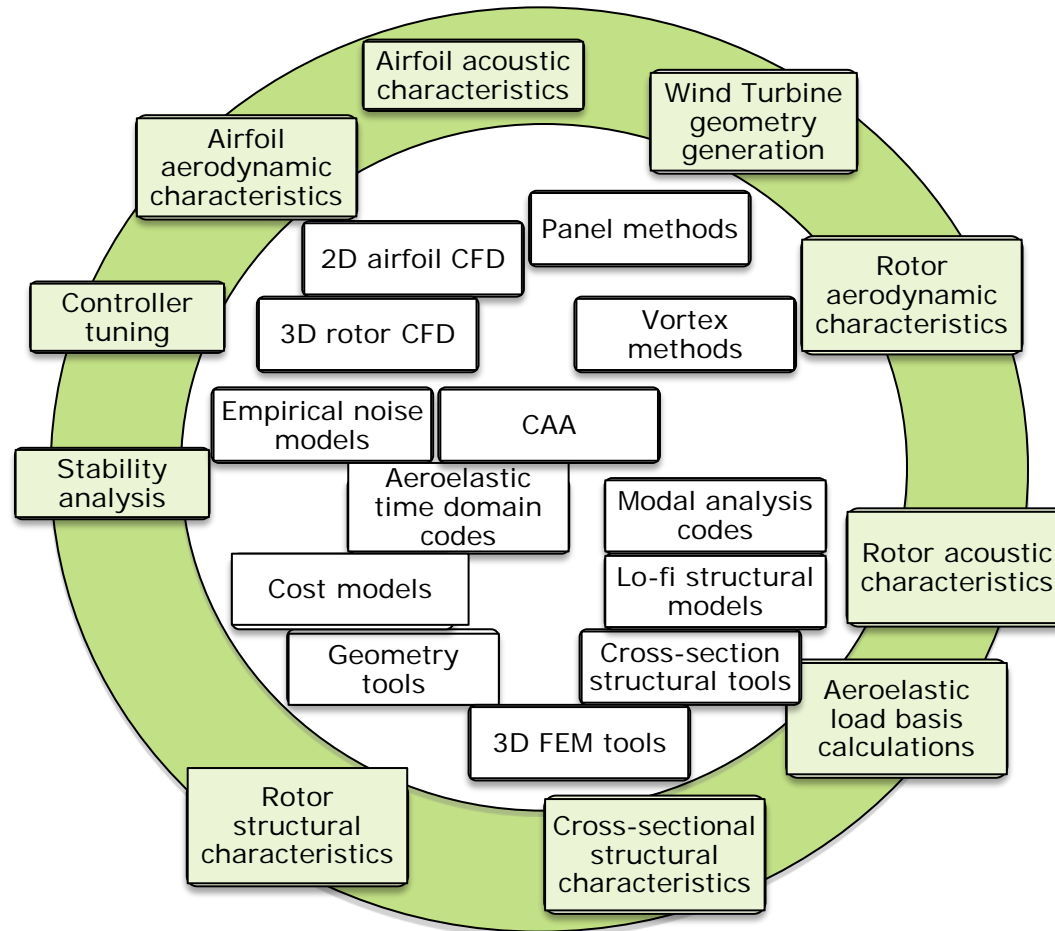# Develop tools, blades and airfoils
A system engineering tool
A unified framework for wind energy systems

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
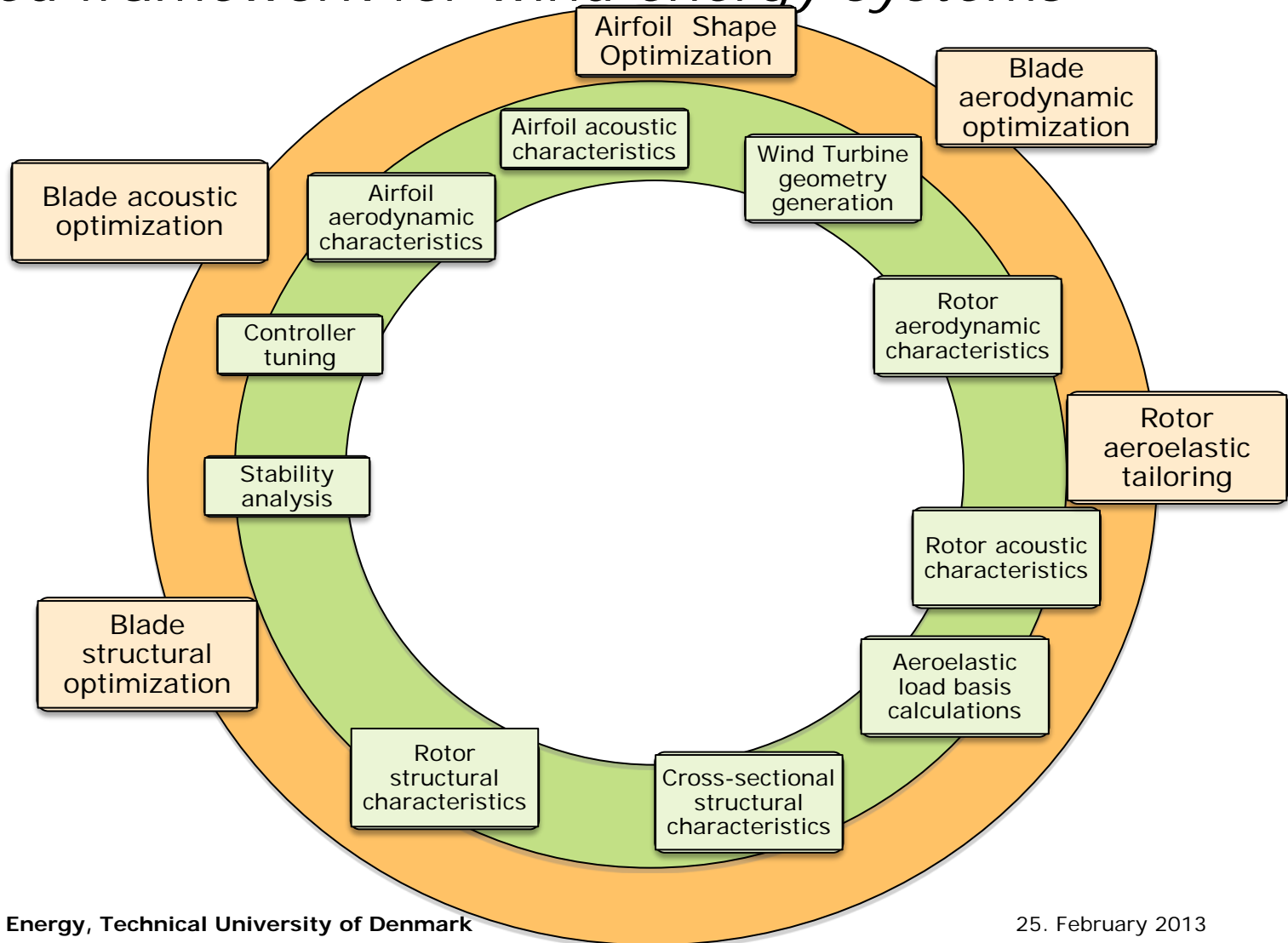## A system engineering tool
A unified framework for wind energy systems

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A system engineering tool
A unified framework for wind energy systems

Develop tools, blades and airfoils
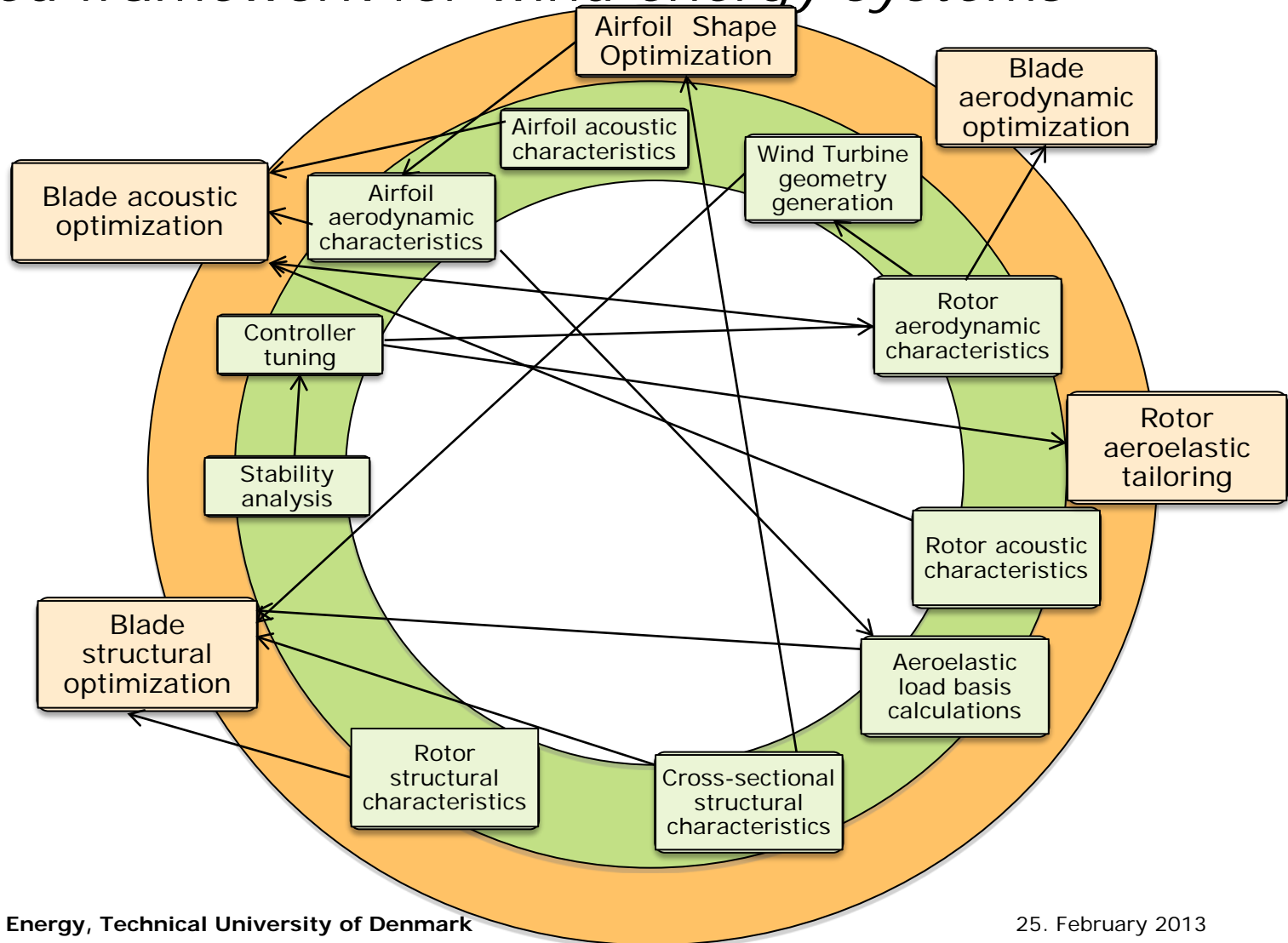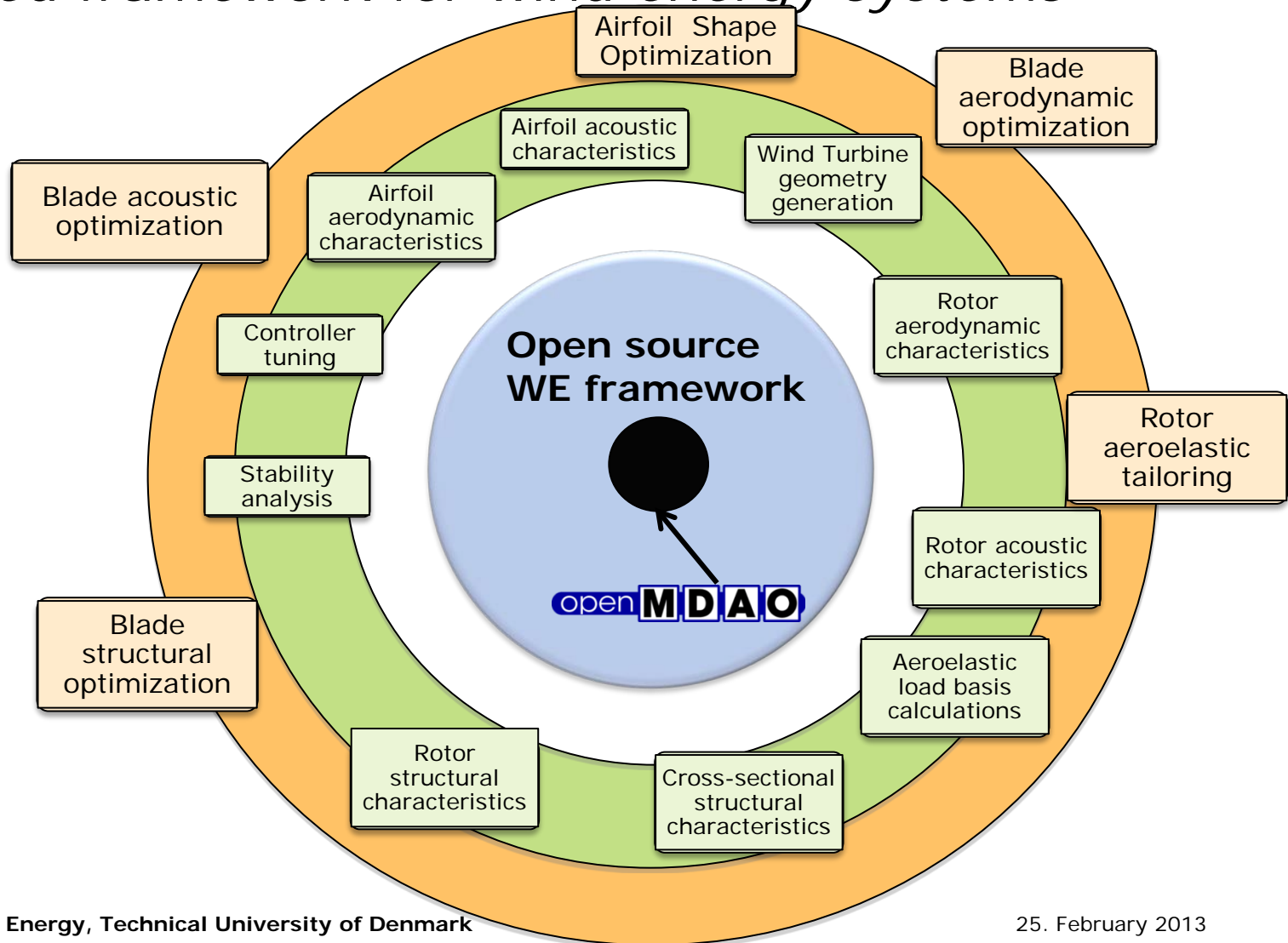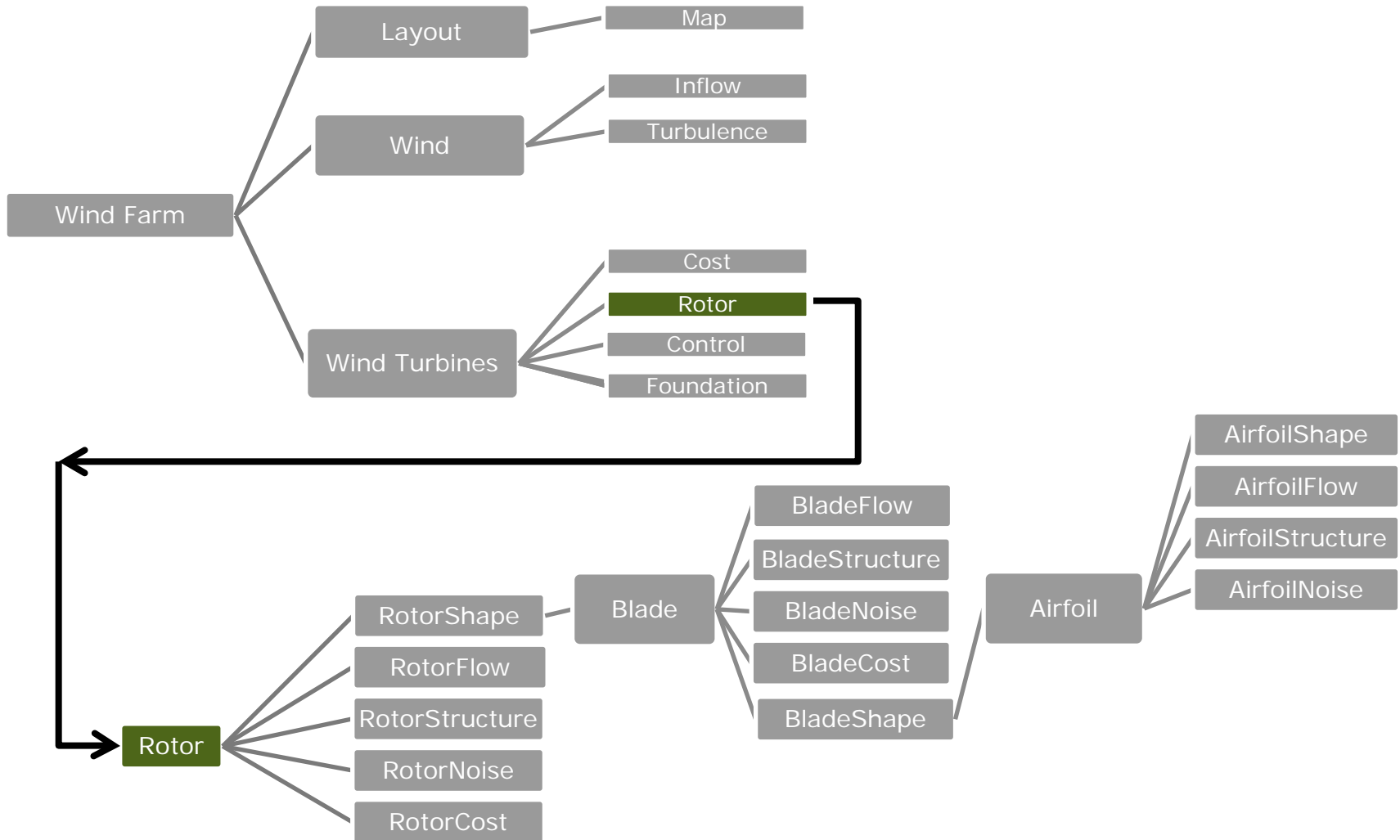# A system engineering tool
A unified framework for wind energy systems

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.

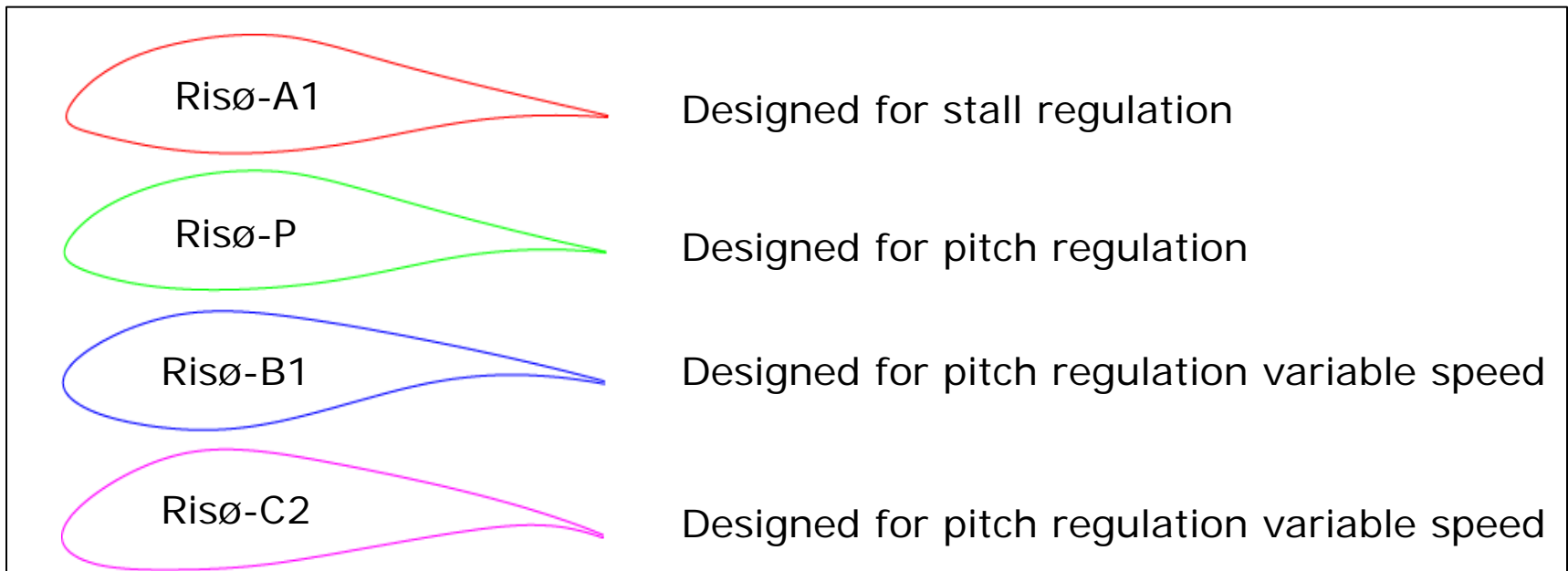# Outline

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  - **A system engineering tool**
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  - **Rotor: Aeroelastic optimization**

• Development of the DTU 10 MW Reference Wind Turbine

In the process…

DTU Wind Energy, Technical University of Denmark   25. February 2013

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

Risø-A1   Designed for stall regulation

Risø-P   Designed for pitch regulation

Risø-B1   Designed for pitch regulation variable speed

Risø-C2   Designed for pitch regulation variable speed

DTU Wind Energy, Technical University of Denmark
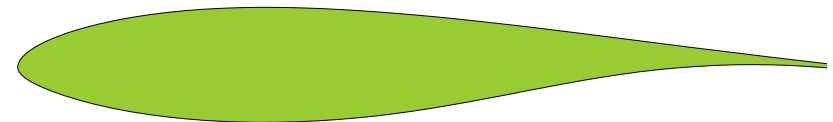
Develop tools, blades and airfoils
Aerodynamic: Thick airfoils

- 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
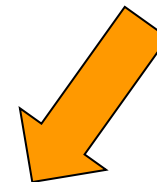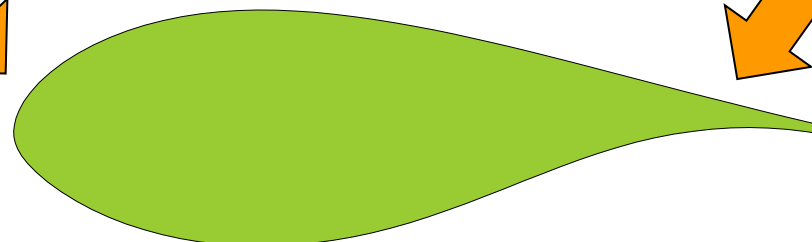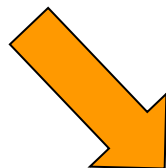
What the structural expert would like

What the aerodynamic expert would like

The resulting compromise

Develop tools, blades and airfoils
Aerodynamic: Thick airfoils

CL

High max. lift (?)

High lift in post-stall to ensure smooth stall

Transition to turbulent flow close to LE: Roughness insensitive

Design for low noise emission

Design for max. Lift-Drag-ratio / CT

α

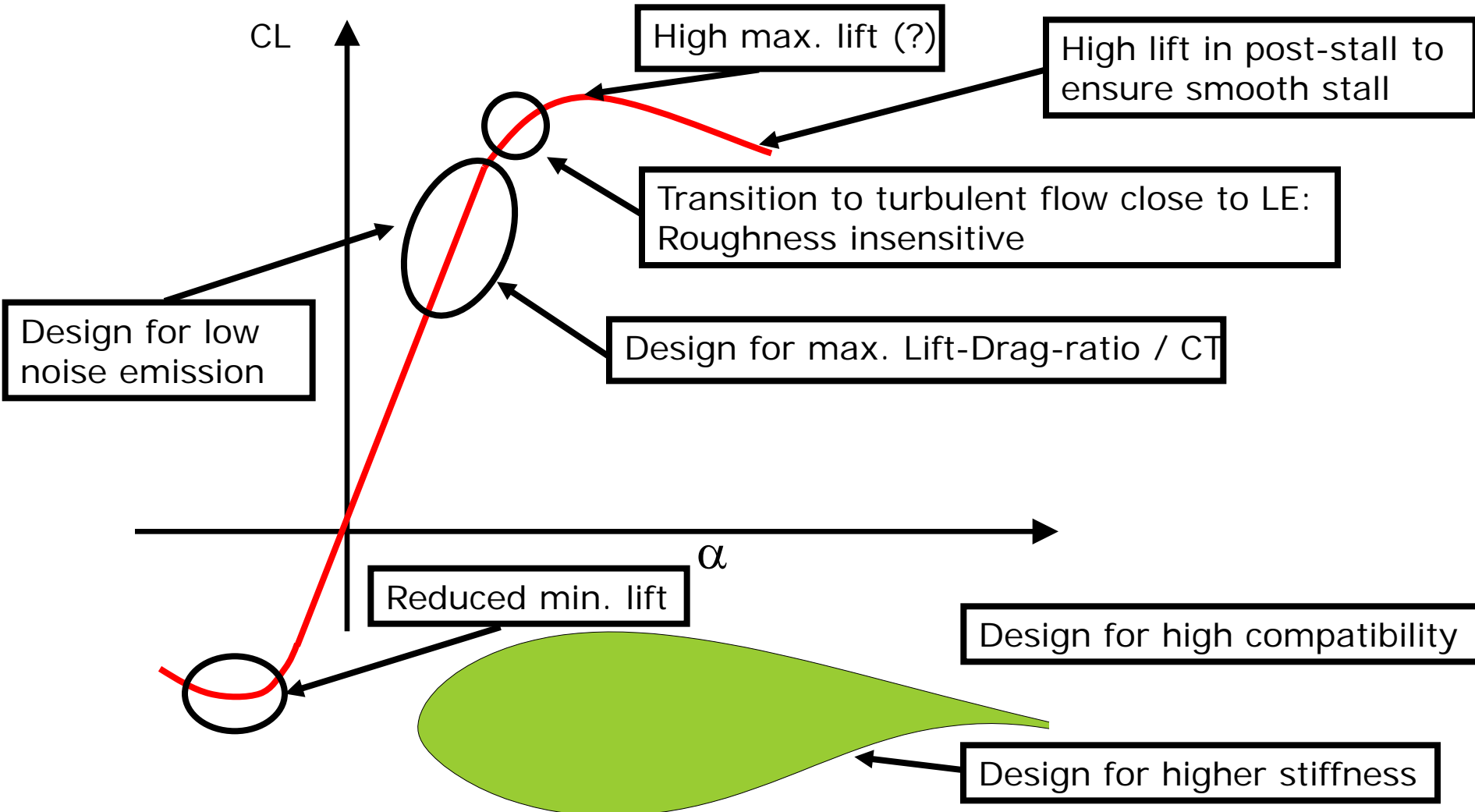Reduced min. lift

Design for high compatibility

Design for higher stiffness

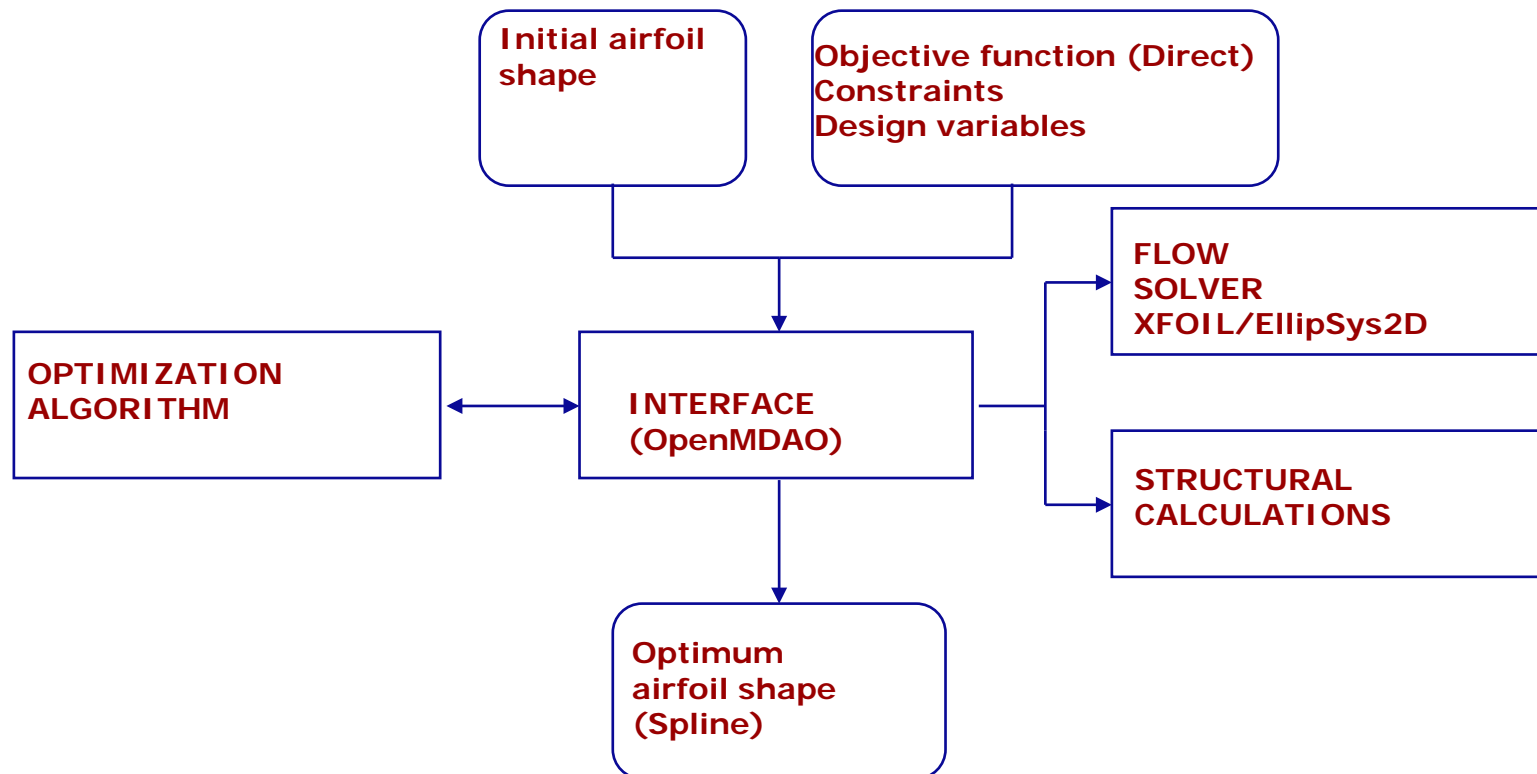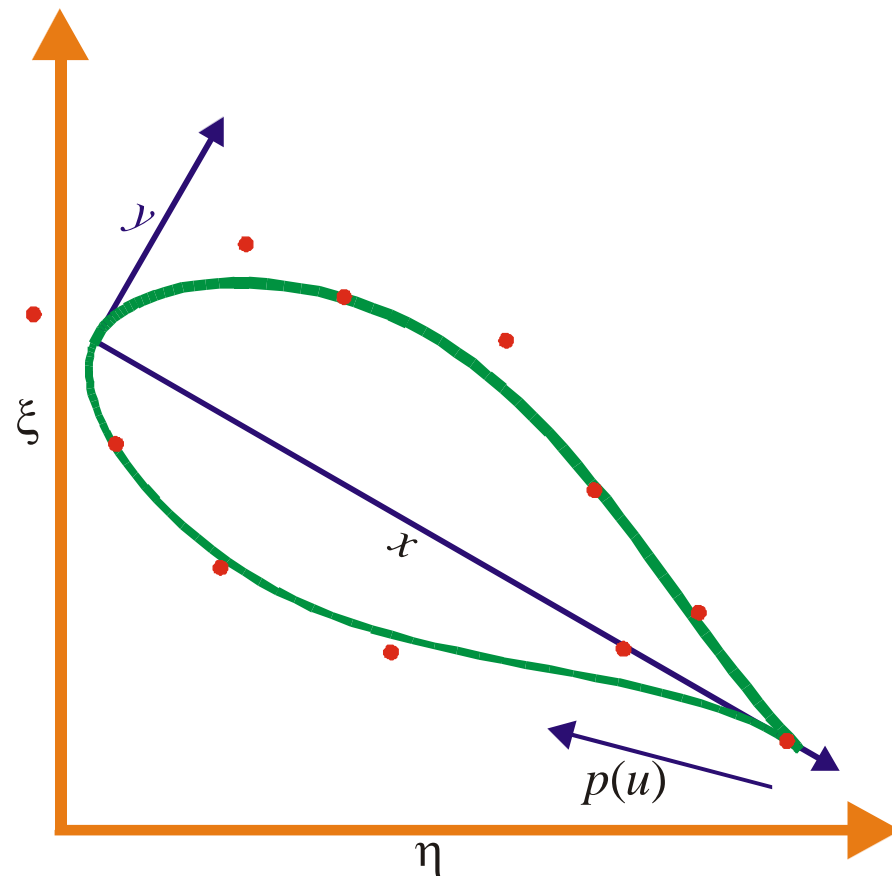# Develop tools, blades and airfoils
Aerodynamic: Thick airfoils

Develop tools, blades and airfoils
Aerodynamic: Thick airfoils

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

Develop tools, blades and airfoils
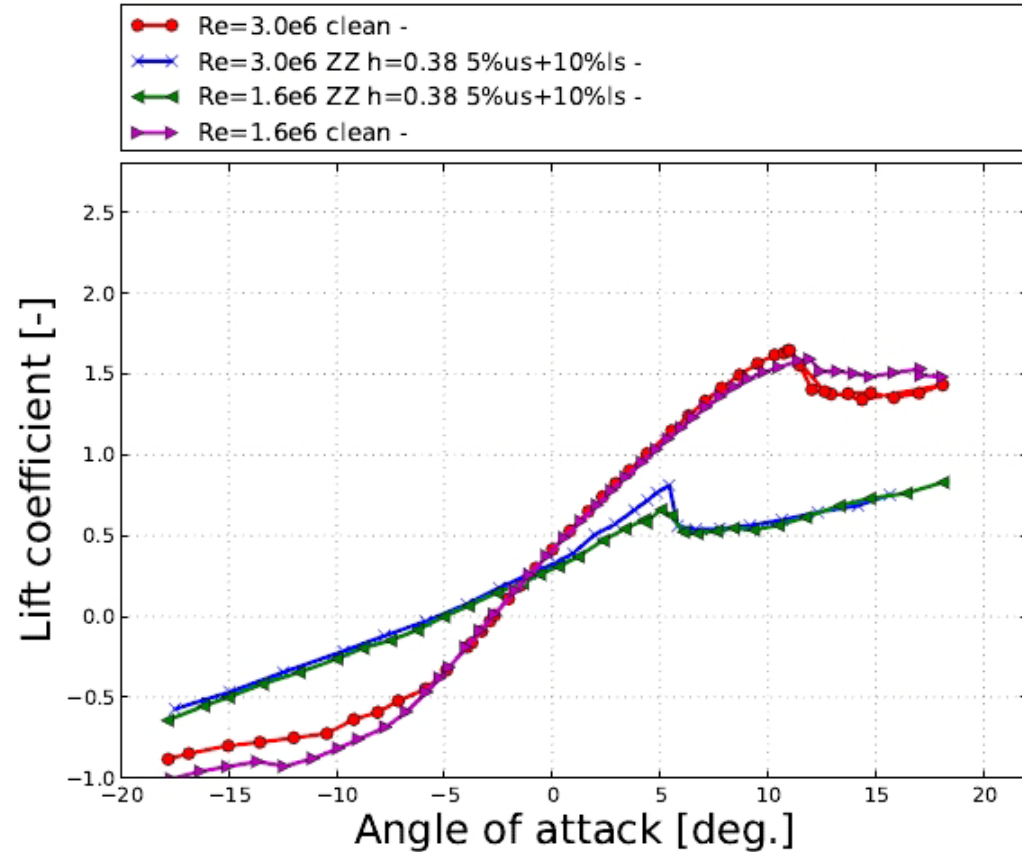## Aerodynamic: Thick airfoils

- 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
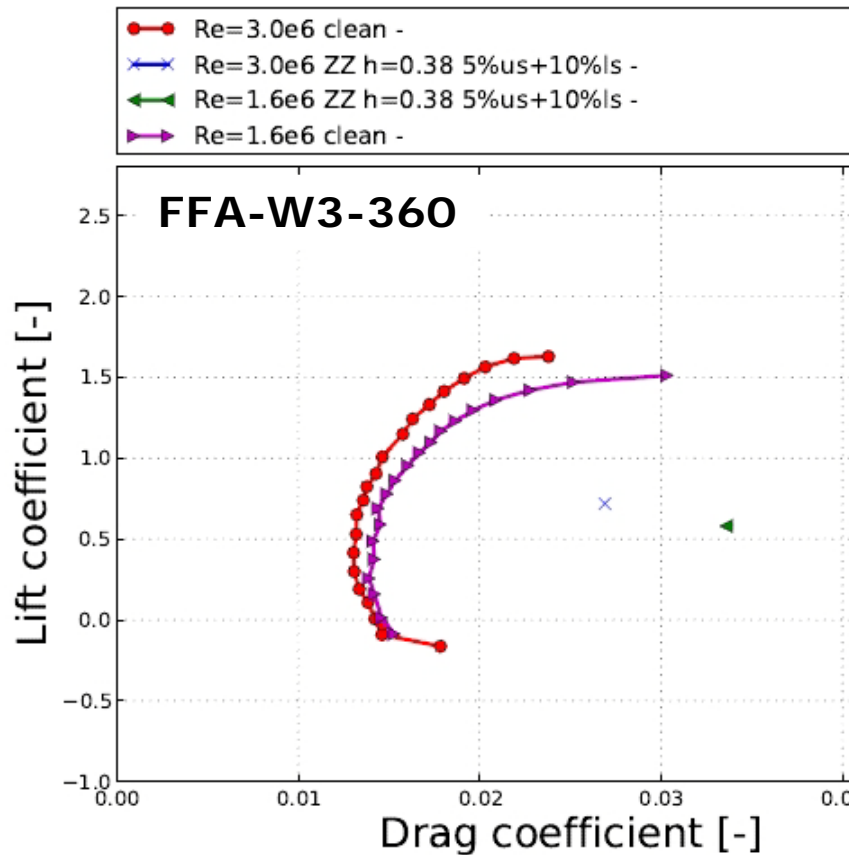
Develop tools, blades and airfoils
Aerodynamic: Thick airfoils

Stuttgart Laminar Wind Kanal

Outline

• Presentation of the Light Rotor project

•Develop tools, blades and airfoils
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  –**Structure: Tools and optimization**
  –**Rotor: Aeroelastic optimization**

• Development of the DTU 10 MW Reference Wind Turbine

In the process...
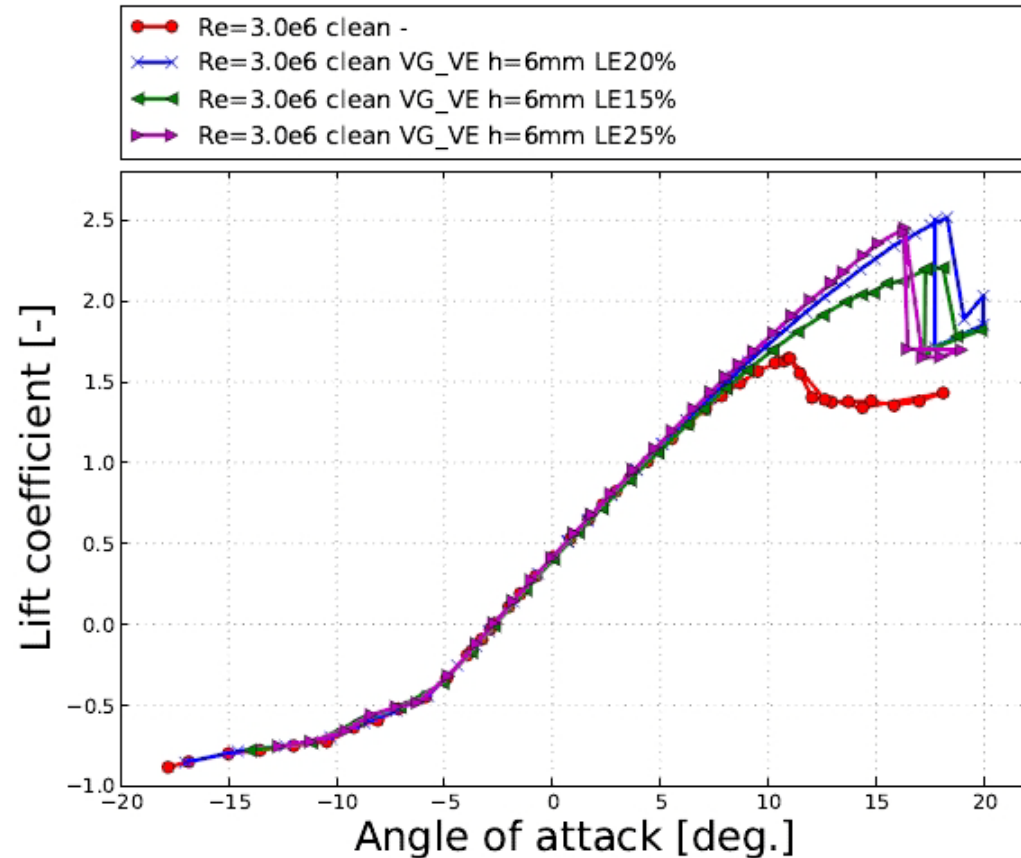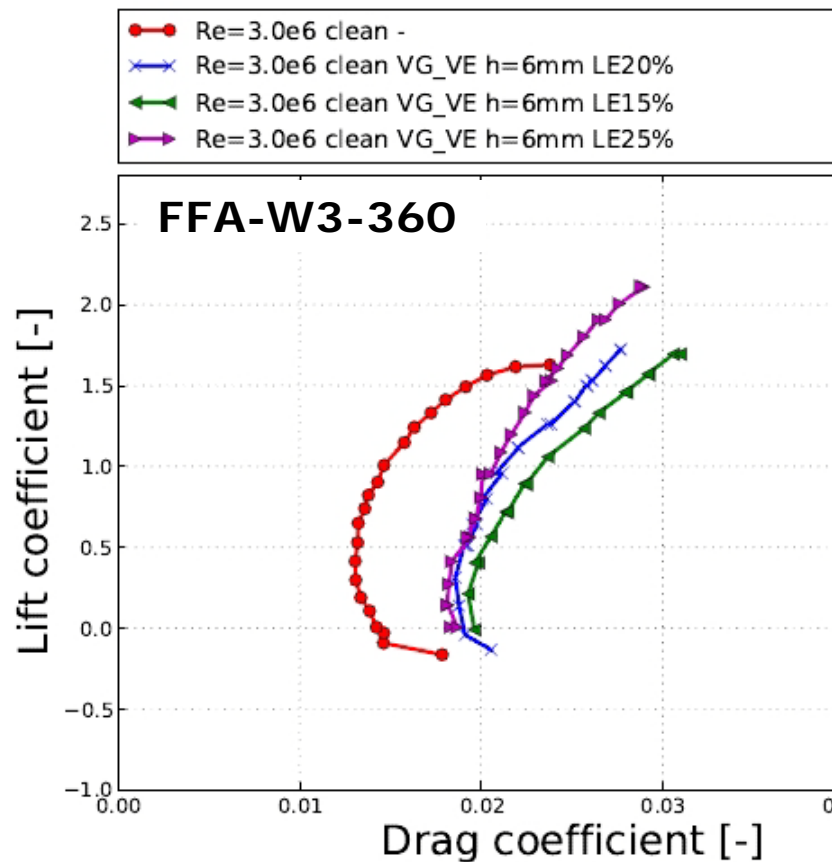
Develop tools, blades and airfoils
Structure: Tools and optimization - BECAS

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.

solid blade

cross section analysis

beam finite element model
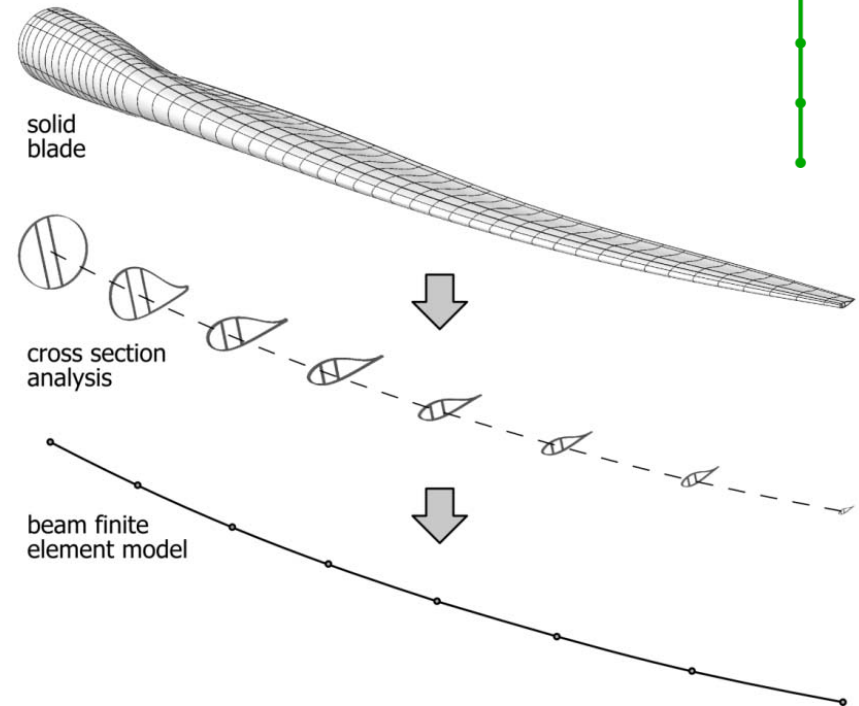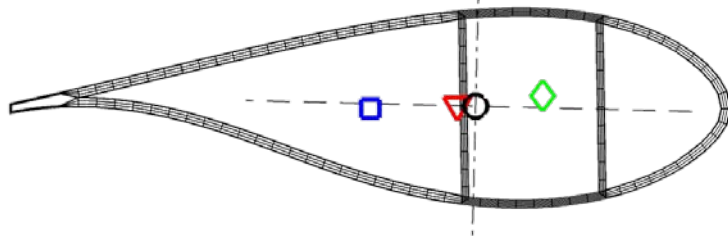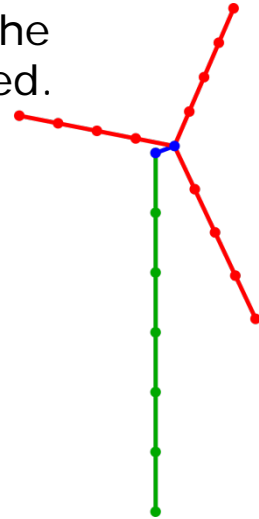
Develop tools, blades and airfoils
Structure: Tools and optimization - BECAS

- Local 3D stresses and strains can be computed based on cross section forces and moments computed using HAWC2. → Composite failure criteria.

- Planed features:
  - Fracture mechanics analysis (VCCT)
  - New element types
  - Buckling analysis

local 3D strain field

warping deformation

VCCT
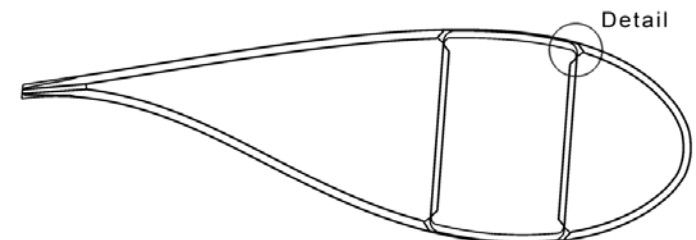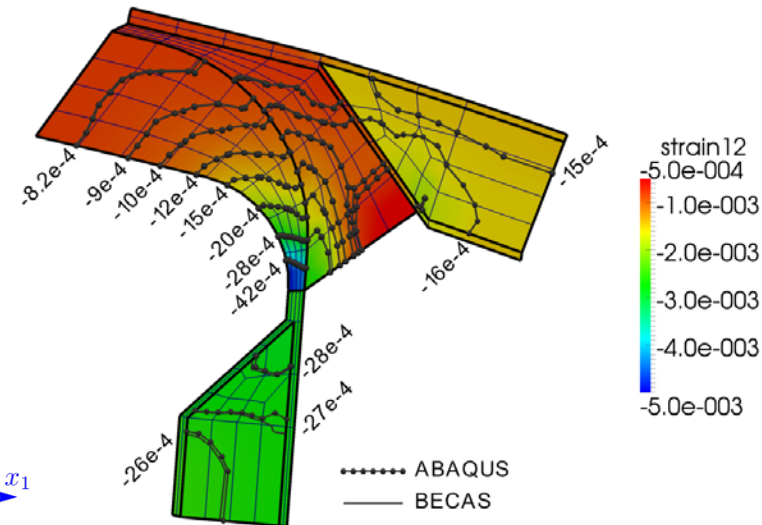
Develop tools, blades and airfoils
Structure: Tools and optimization

- Minimum compliance optimization with constraints on weight, and shear and mass center positions
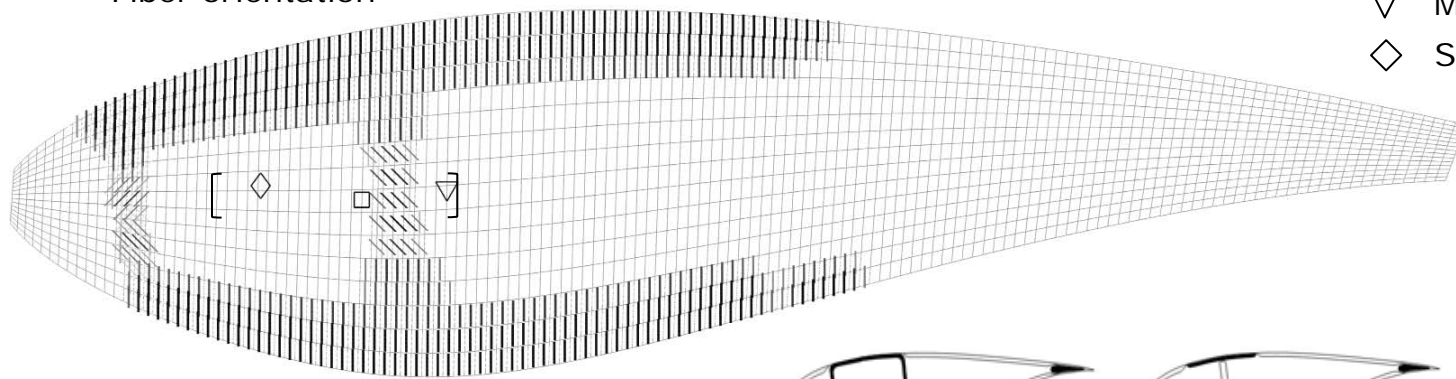
□ Ref. Cent.

▽ Mass Cent.

◇ Shear Cent.

Fiber orientation

Fiber plane orientation
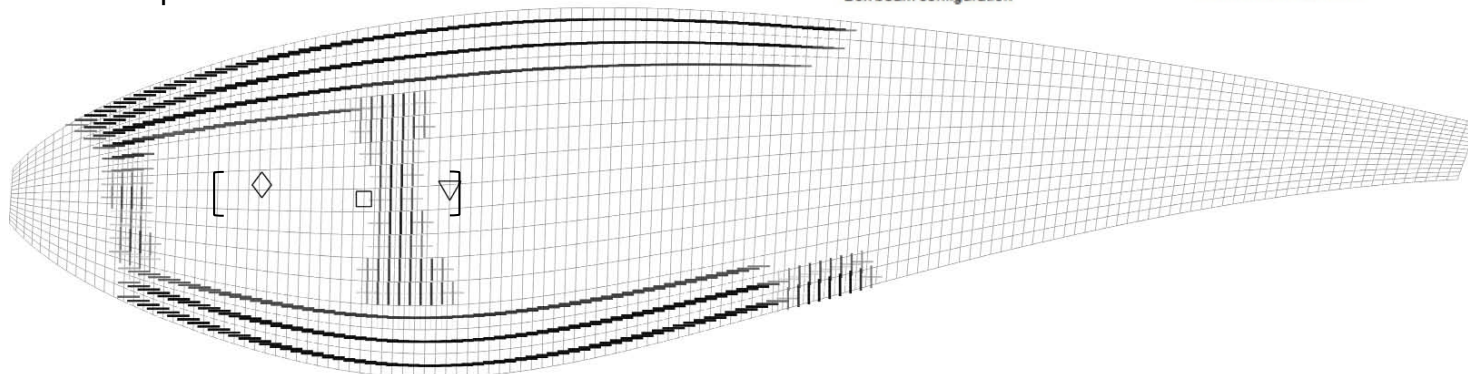
Box beam configuration

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.)

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

- 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
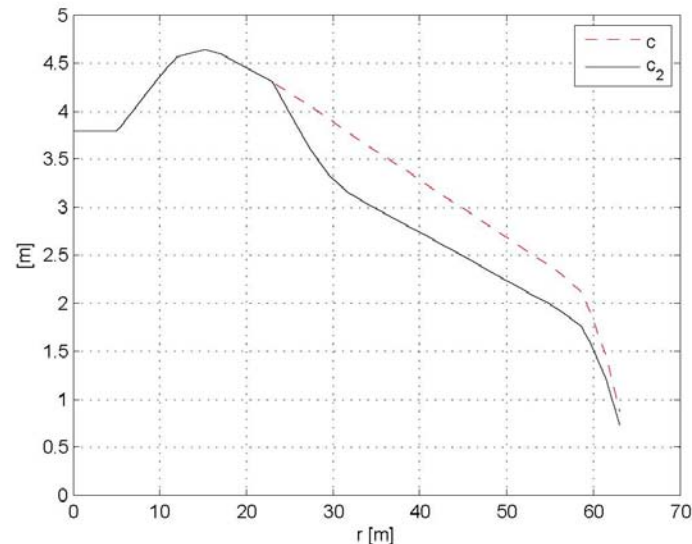
Chord distributions

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.
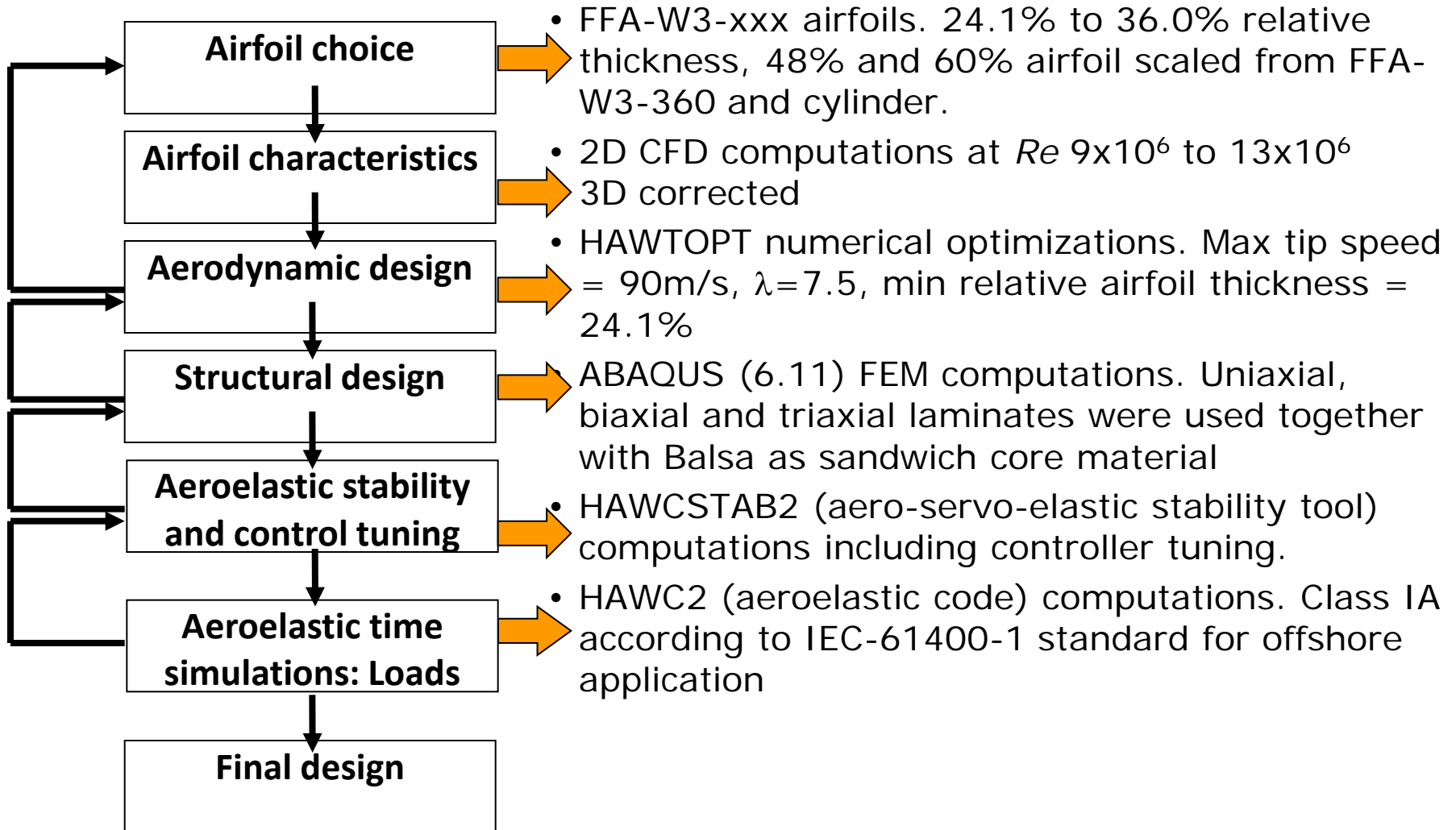
The DTU 10 MW Reference Wind Turbine
The Design Process

- 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.
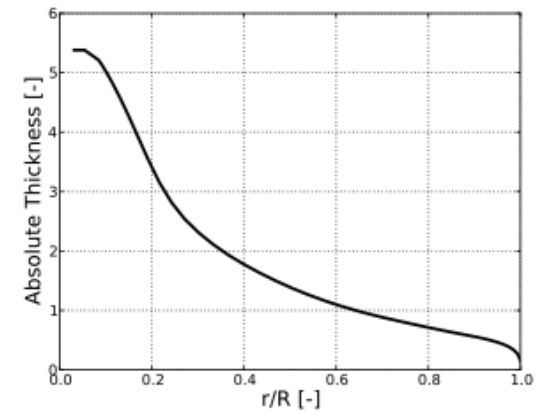
The DTU 10 MW Reference Wind Turbine Design Summary

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

Airfoil choice	• FFA-W3-xxx airfoils. 24.1% to 36.0% relative thickness, 48% and 60% airfoil scaled from FFA-W3-360 and cylinder.
Airfoil characteristics	• 2D CFD computations at Re 9×10^6 to 13×10^6 3D corrected
Aerodynamic design	• HAWTOPT numerical optimizations. Max tip speed = 90m/s, λ=7.5, min relative airfoil thickness = 24.1%
Structural design	ABAQUS (6.11) FEM computations. Uniaxial, biaxial and triaxial laminates were used together with Balsa as sandwich core material
Aeroelastic stability and control tuning	• HAWCSTAB2 (aero-servo-elastic stability tool) computations including controller tuning.
Aeroelastic time simulations: Loads	• HAWC2 (aeroelastic code) computations. Class IA according to IEC-61400-1 standard for offshore application
Final design	

The DTU 10 MW Reference Wind Turbine Aerodynamic Design: Geometry
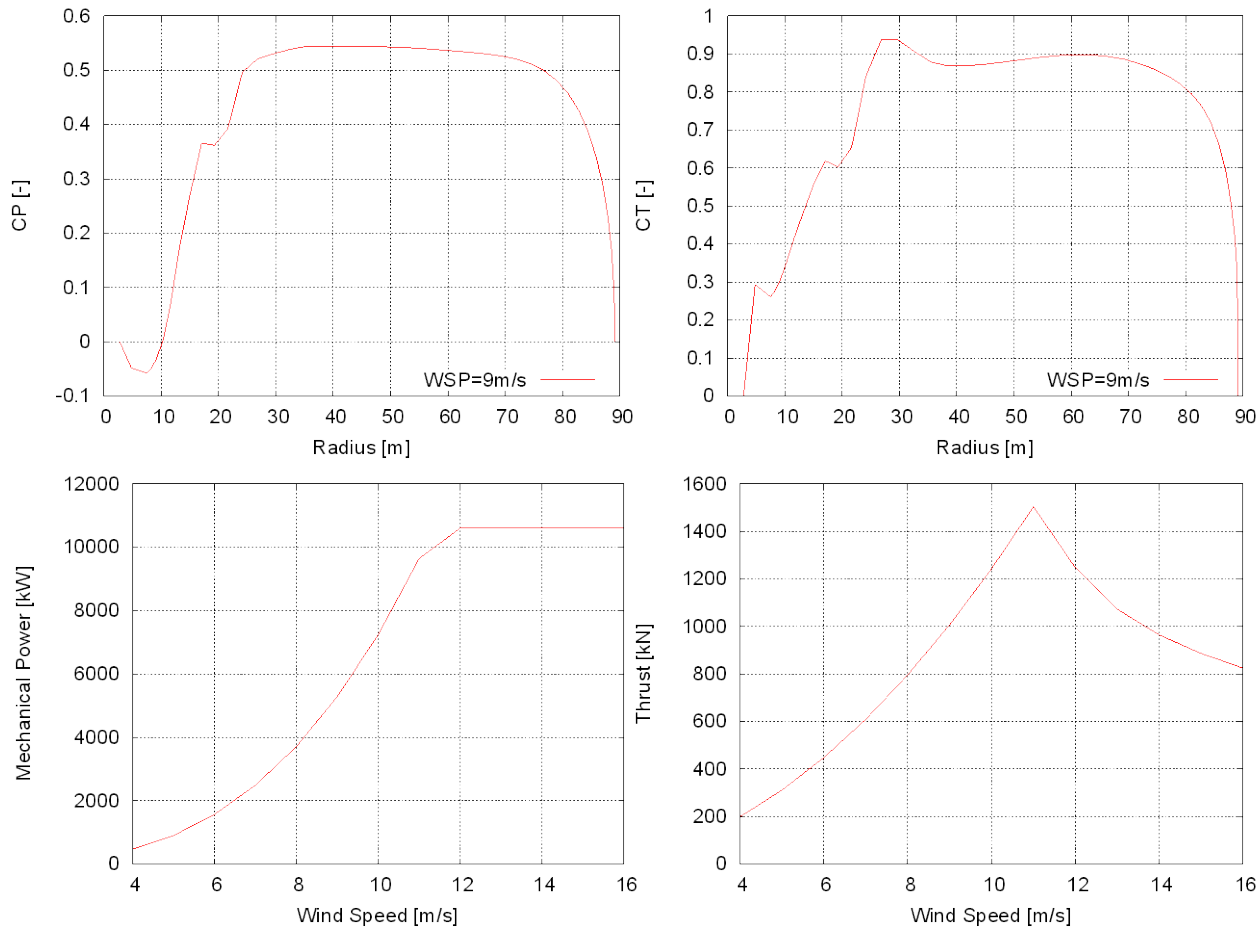

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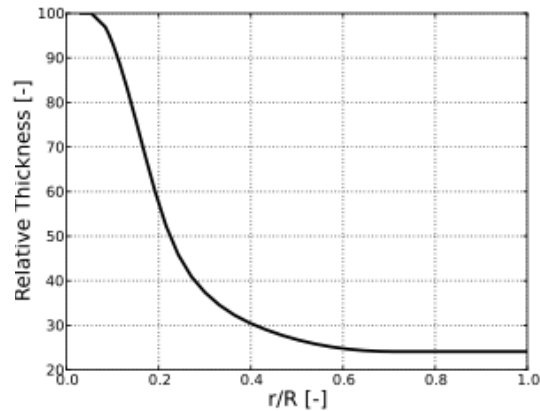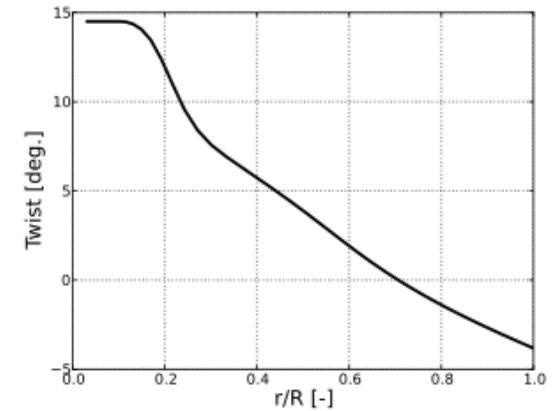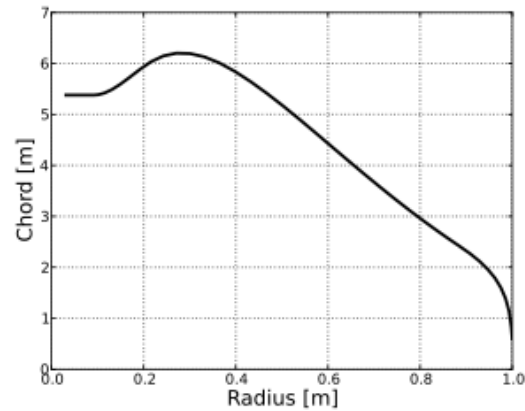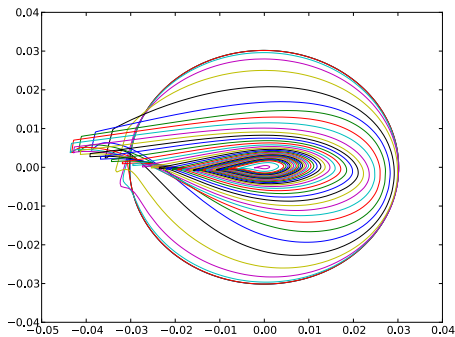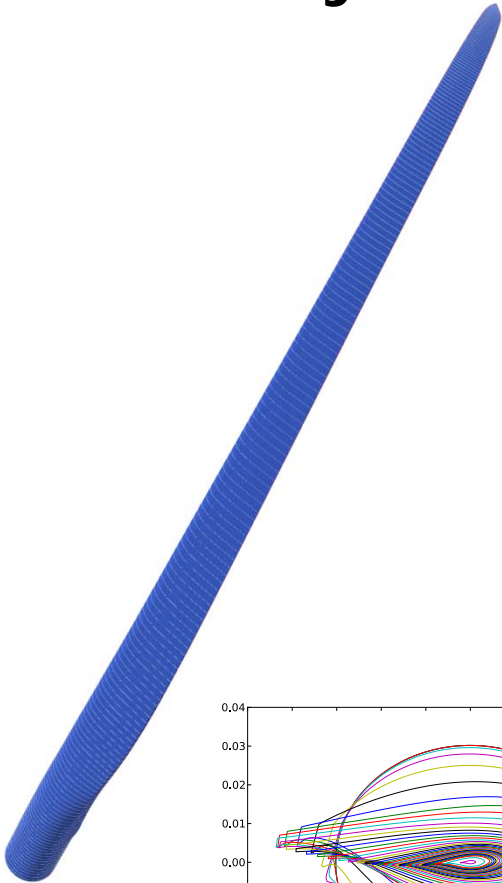
The DTU 10 MW Reference Wind Turbine Aerodynamic Design: Performance

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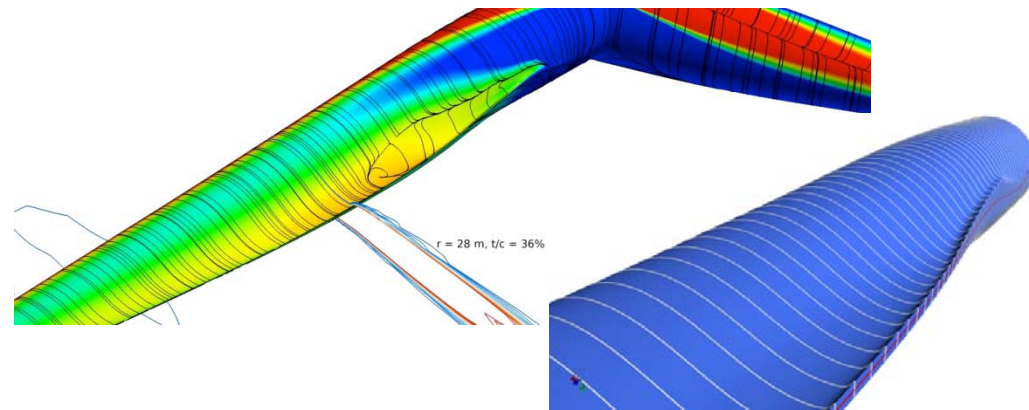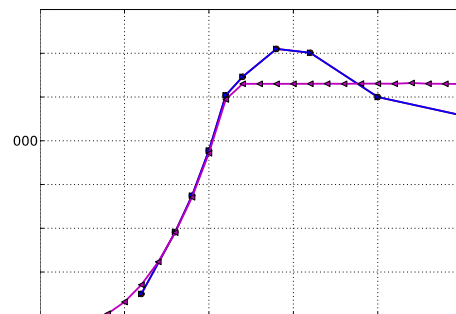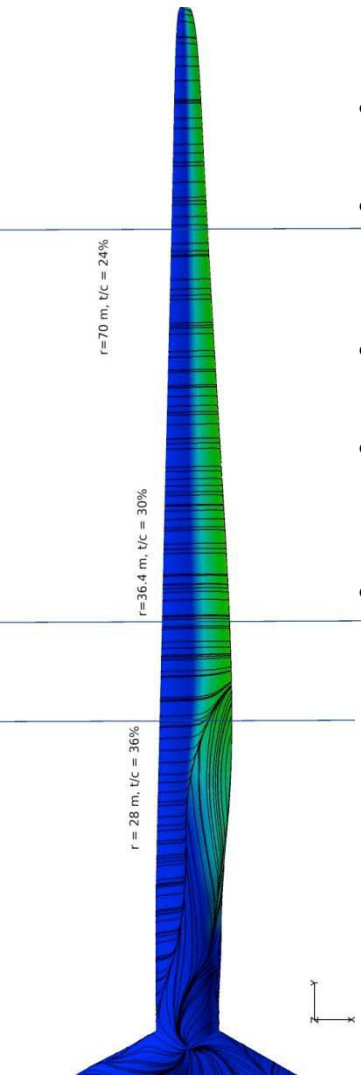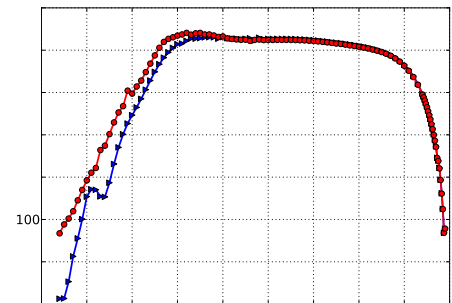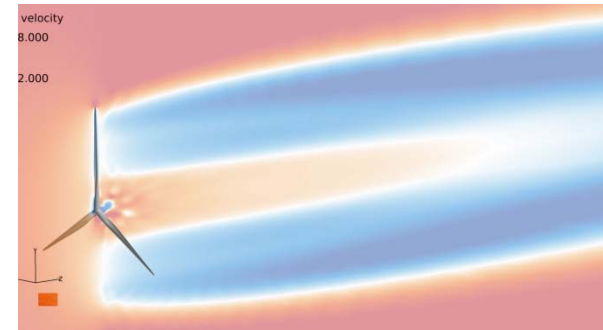
The DTU 10 MW Reference Wind Turbine Structural Design: Basic design choice

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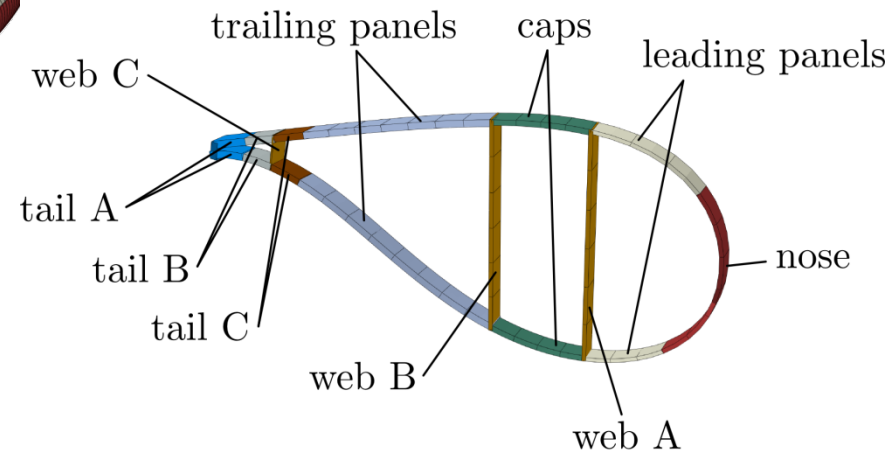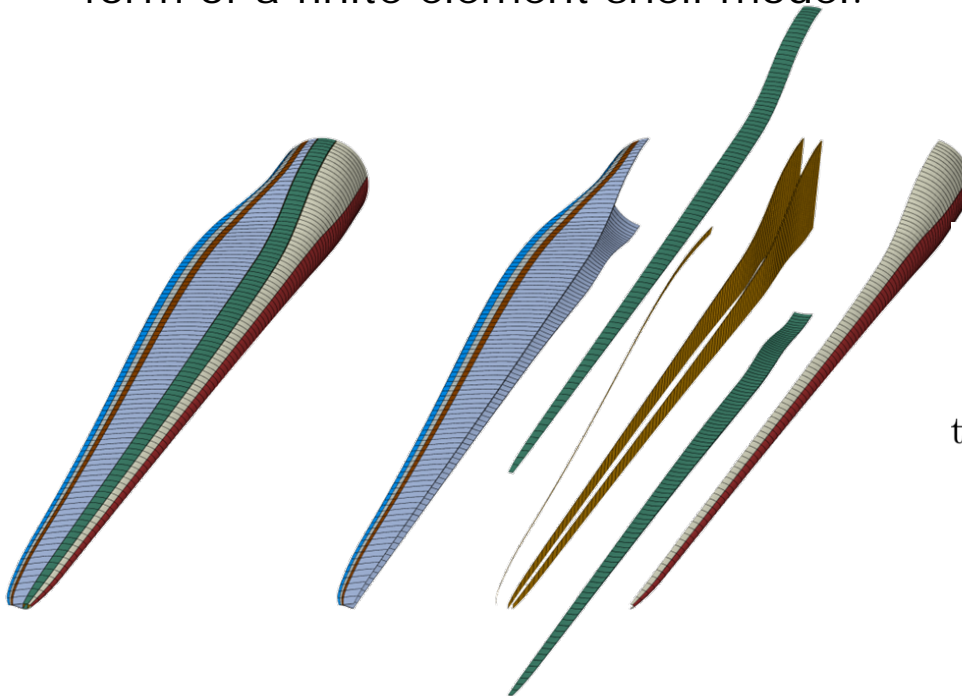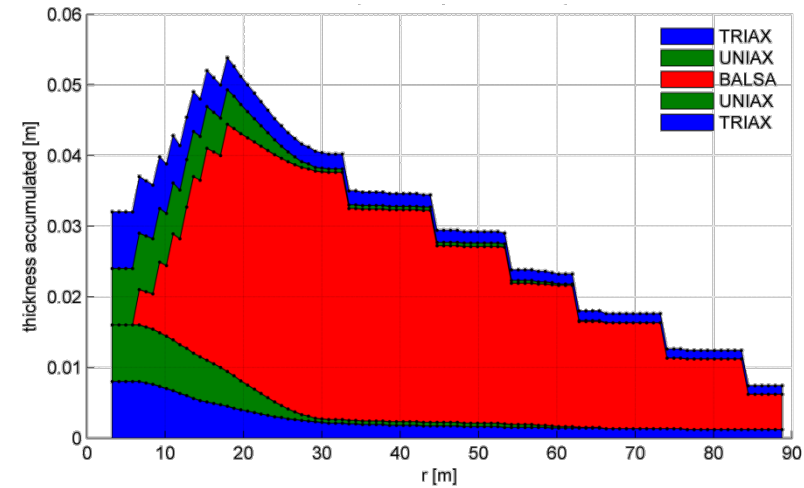
The DTU 10 MW Reference Wind Turbine Structural Design: Design loop

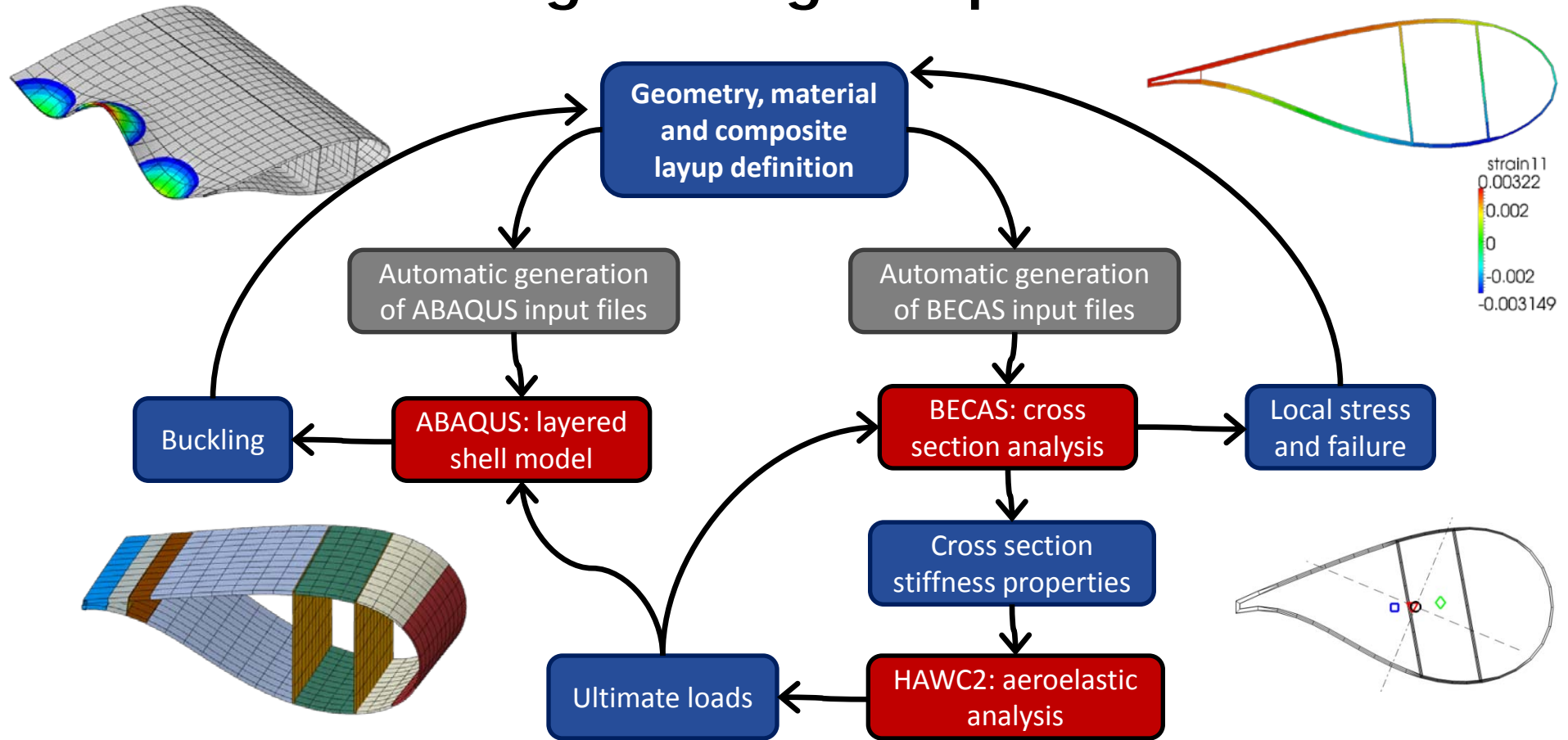**Geometry, material and composite layup definition**

Automatic generation of ABAQUS input files

Automatic generation of BECAS input files

ABAQUS: layered shell model

BECAS: cross section analysis

Buckling

Local stress and failure

Cross section stiffness properties

Ultimate loads

HAWC2: aeroelastic analysis

strain11
0.00322
0.002
0
-0.002
-0.003149

		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	44.0022

Reference Elastic Shear Mass — Ax. 1 —·— Ax. 2

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.
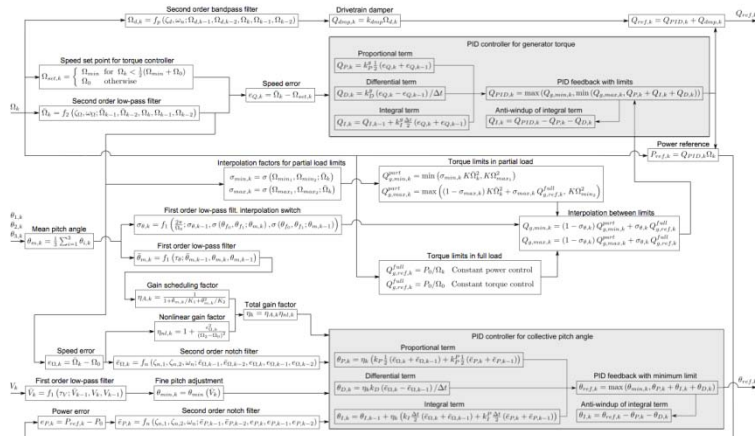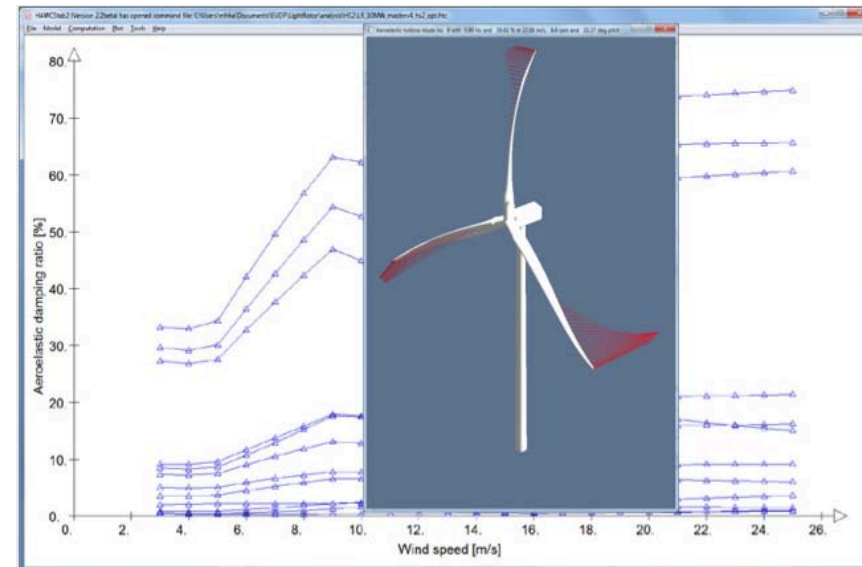
The DTU 10 MW Reference Wind Turbine Load calculations: HAWC2

- 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.

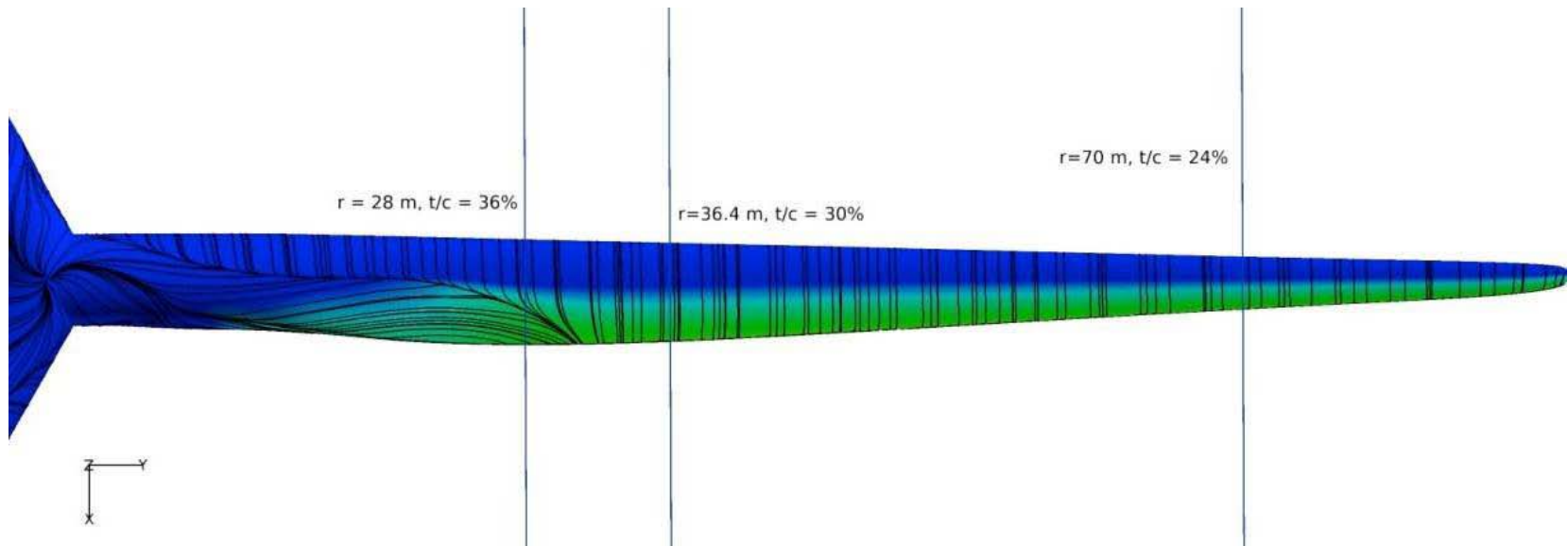# The DTU 10 MW Reference Wind Turbine Summary of design challenges

- 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!