Cp-Max: an MDO framework for the design of wind turbines

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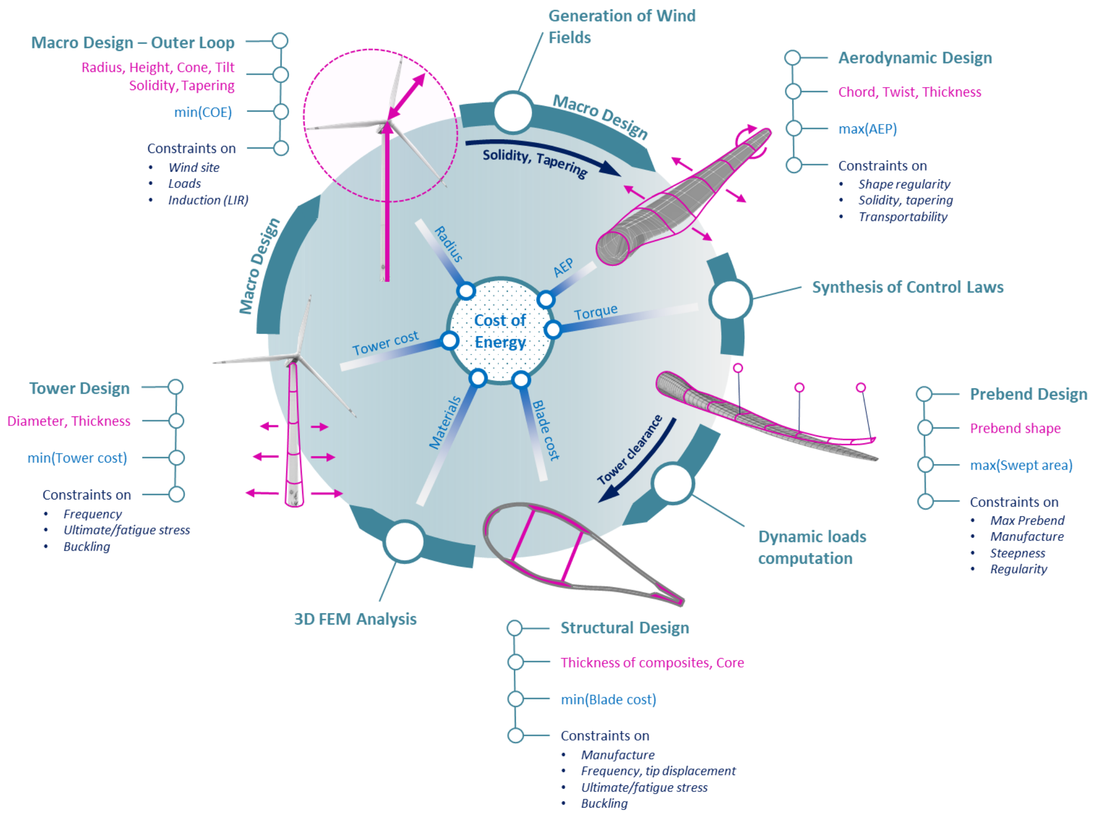
RESEARCH FRAMEWORK

Research framework

- **Wind turbines are steadily upscaling**
- **Some design challenges:**
  - High flexibility of elements
  - Unsteady, non-uniform inflow
  - Increased aero-elastic couplings
  - Increased dynamic complexity

Research framework

- **Multi-disciplinary design algorithms (MDO):**
  - Improve physical description (*modelling fidelity)*
  - Implement a system-level design based on COE
  - Manage a wide number of different variables
  - Significant research in the last years



CP-MAX:
A MULTI-DISCIPLINARY DESIGN PHILOSOPHY

Cp-Max Timeline

2011: Roll-out of the 2MW-45m blade

2012: Roll-out of the 700kW-23m blade

2014: Roll-out of the 330kW-16m blade

2007: First implementation, parametric design only

2011: External 3D FEM module

2012 - 2015: Studies about aero-structural design

2016: Cp-Max in its new multi-level architecture

2017: Prebend design module

2017-2019: Extensive testing and design studies

Cp-Max development team

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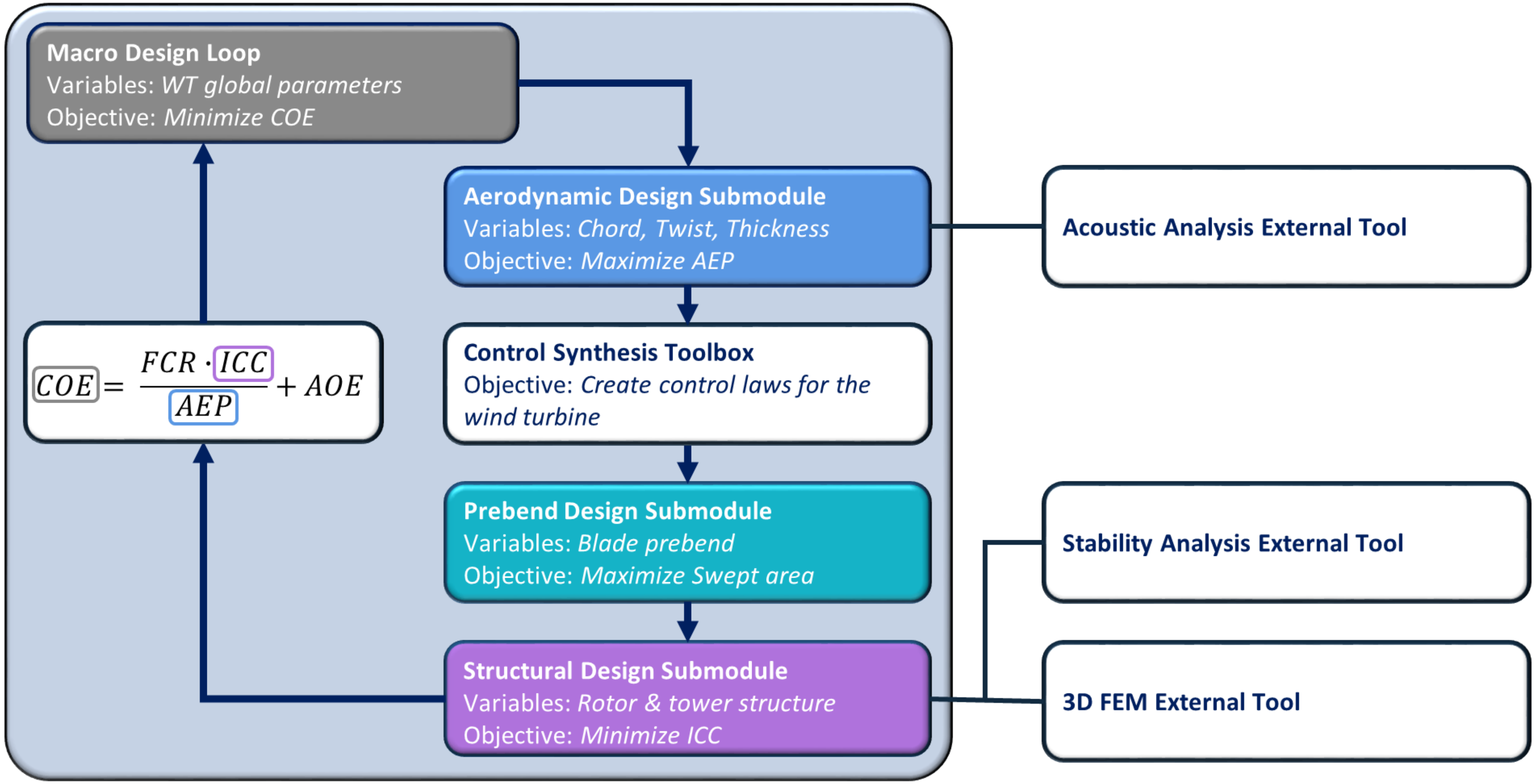
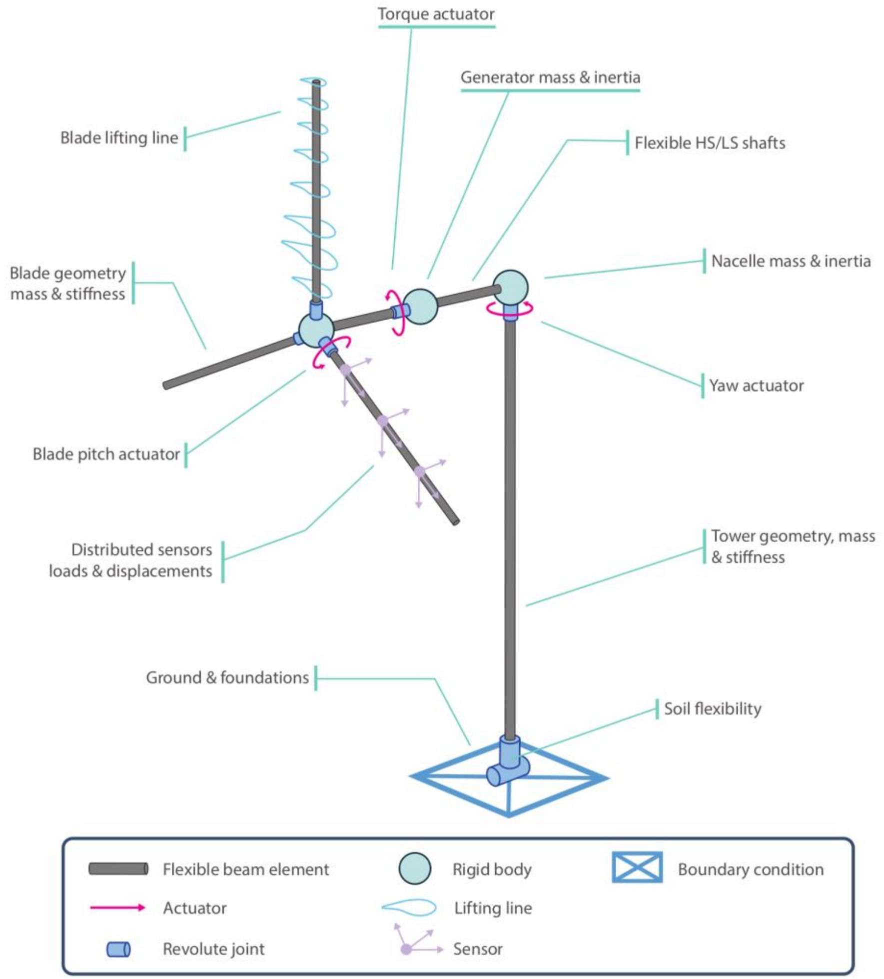
Software architecture



Multi-body modelling of wind turbines

Simulation tool: Cp-Lambda

- Multibody solver
- Lifting line + BEM Inflow
- Spatial grid + wind time history
- Nonlinear beam formulation (Bauchau et al. 2001)
- Fully-populated mass/stiffness matrix



MACRO DESIGN LOOP

Macro Design Loop (MDL)

- **Optimizes** *global features* **of the turbine to minimize COE**

- **Macro design variables:**

$$\boldsymbol{p_g} = [\ R,\ H,\ \varphi,\ \gamma,\ \sigma_c^g,\ \tau_c^g,\ \sigma_t^g,\ \tau_t^g\ ]$$

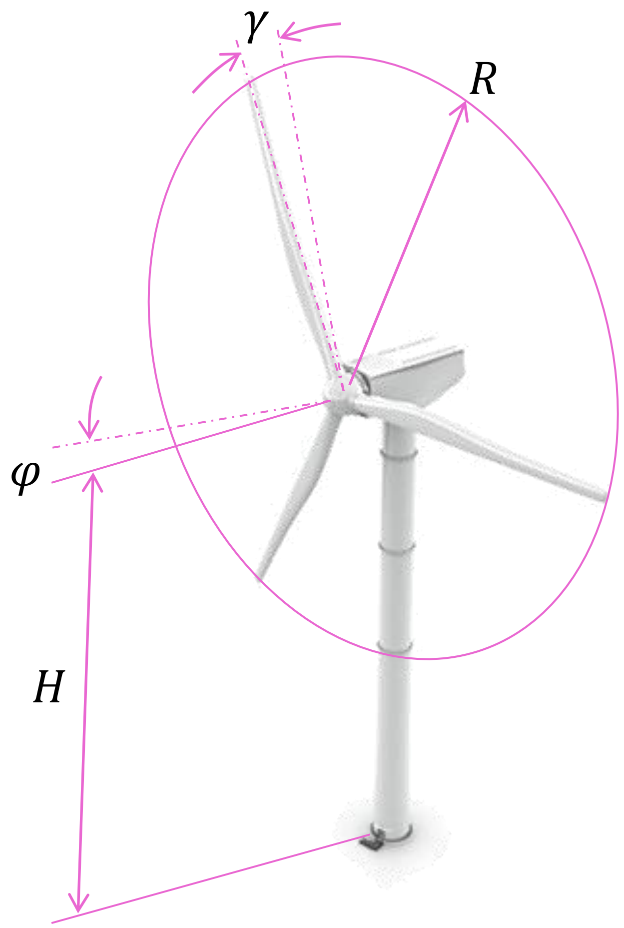
Rotor radius (R)

Hub height (H)

Rotor tilt angle (φ)

Blade coning (γ)

Shape parameters ($\sigma_c^g,\ \tau_c^g,\ \sigma_t^g,\ \tau_t^g$)



Macro Design Loop (MDL)

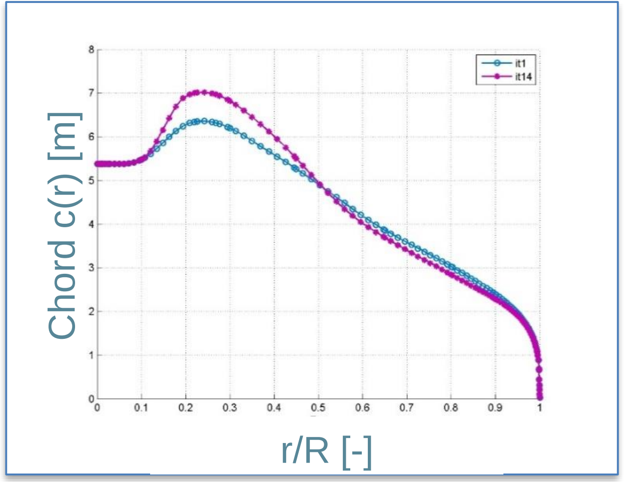
- **The shape parameters are computed from *chord* and *thickness* distributions:**

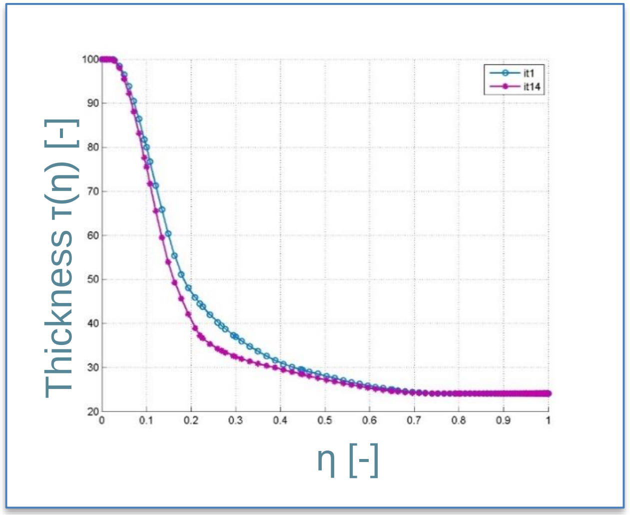
Rotor *solidity* $$\sigma_c^g = \frac{3\int_0^R c(r)dr}{\pi R^2}$$

Rotor *tapering* $$\tau_c^g = \frac{\int_0^R rc(r)dr}{\int_0^R c(r)dr}$$

Thickness solid area $$\sigma_t^g = \frac{1}{100}\int_0^1 t(\eta)d\eta$$

Thickness weighted area $$\tau_t^g = \frac{\int_0^1 \eta t(\eta)d\eta}{\int_0^1 t(\eta)d\eta}$$





- **They link the MDL with the submodules**

Macro Design Loop (MDL)

- **Simplified workflow of the MDL:**

MDL $(COE^*, \boldsymbol{p}_g^*) = MinCOE(\boldsymbol{p}_a, \boldsymbol{p}_b, \boldsymbol{p}_s, \boldsymbol{p}_g, \boldsymbol{D})$

ADS $(\boldsymbol{p}_a^*, AEP^*) = MaxAEP(\boldsymbol{p}_a, \boldsymbol{p}_b, \boldsymbol{p}_s, \boldsymbol{p}_g, \boldsymbol{D})$

CST $(\boldsymbol{r}_\varepsilon^*) = CreateControlLaws(\boldsymbol{p}_a^*, \boldsymbol{p}_b, \boldsymbol{p}_s, \boldsymbol{p}_g, \boldsymbol{D})$

PDS $(\boldsymbol{p}_b^*, A_\delta^*) = OptimizePrebend(\boldsymbol{p}_a^*, \boldsymbol{p}_b, \boldsymbol{p}_s, \boldsymbol{p}_g, \boldsymbol{D}, \boldsymbol{r}_\varepsilon^*)$

SDS $(\boldsymbol{p}_s^*, ICC^*) = MinICC(\boldsymbol{p}_a^*, \boldsymbol{p}_b^*, \boldsymbol{p}_s, \boldsymbol{p}_g, \boldsymbol{D}, \boldsymbol{r}_\varepsilon^*)$

$$COE = CostModel(AEP^*, ICC^*, \boldsymbol{p}_a^*, \boldsymbol{p}_b^*, \boldsymbol{p}_s^*, \boldsymbol{p}_g, \boldsymbol{D}, \boldsymbol{r}_\varepsilon^*)$$

- **Available cost models:**

    Scaling (NREL, 2006), Industrial (SANDIA), Refined scaling (INNWIND)

DESIGN SUBMODULES

Aerodynamic Design Submodule (ADS)

- Optimizes the aerodynamic design variables p_a of the rotor to maximize AEP

$$(p_a^*, AEP^*) = \max_{p_a}(AEP(p_a, p_b, p_s, p_g))$$

s.t.:

$$v_{tip} \leq v_{tip}^{max}$$
$$g_a(p_a, p_g) \leq 0$$

Design variables:

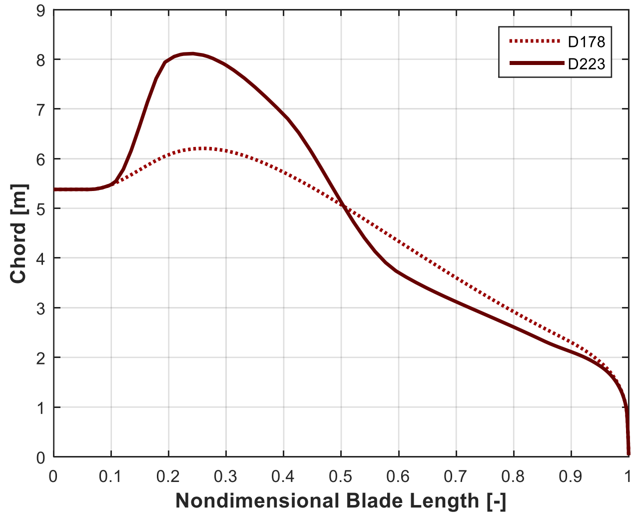
- Chord
- Twist
- Thickness (position of airfoils)

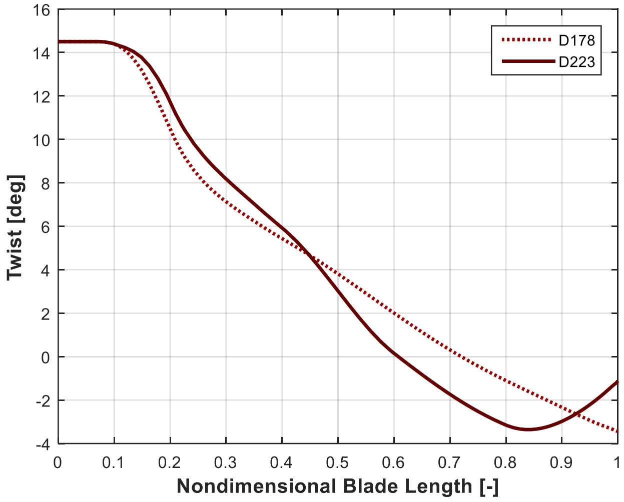
Aerodynamic Design Submodule (ADS)

Chord, twist and thickness are parameterized by multiplicative/additive *bumping* functions

$$c(\eta) = s_c(\eta)c_{bl}(\eta)$$
$$\theta(\eta) = s_\theta(\eta)\theta_{bl}(\eta)$$
$$t(\eta) = s_t(\eta)t_{bl}(\eta)$$

$$s_c(\eta) = \boldsymbol{n}_c(\eta)\boldsymbol{c}$$
$$s_\theta(\eta) = \boldsymbol{n}_\theta(\eta)\boldsymbol{\theta}$$
$$s_t(\eta) = \boldsymbol{n}_t(\eta)\boldsymbol{t}$$





n **are spline shape functions**

θ, c and t are the associated nodal parameters

Aerodynamic Design Submodule (ADS)

- **Theoretical AEP from flexible *Cp-TSR* curves**
- **The structure is frozen**
- **Blade shape and thickness constrained by the MDL:**

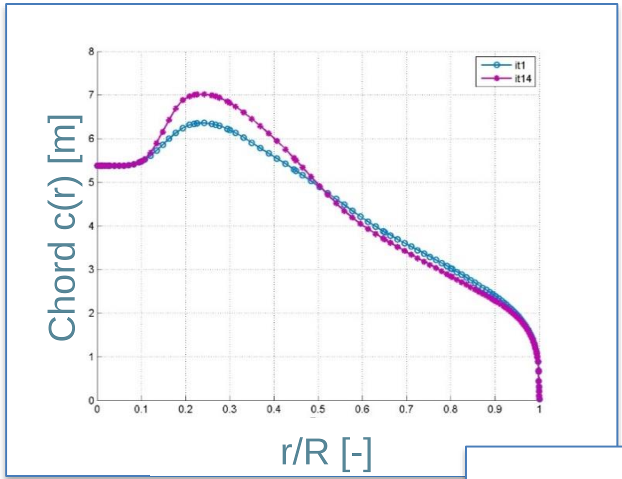
$$\sigma_c^{Aero}(c(\eta), R) = \sigma_c^g$$

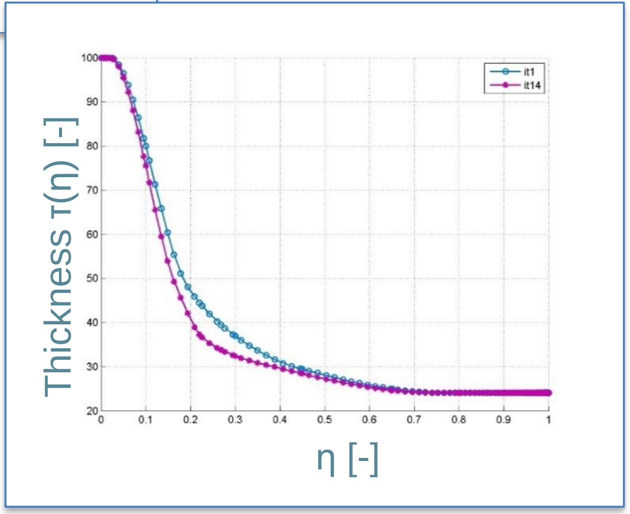
$$\tau_c^{Aero}(c(\eta), \eta, R) = \tau_c^g$$

$$\sigma_t^{Aero}(t(\eta), R) = \sigma_t^g$$

$$\tau_t^{Aero}(t(\eta), \eta, R) = \tau_t^g$$

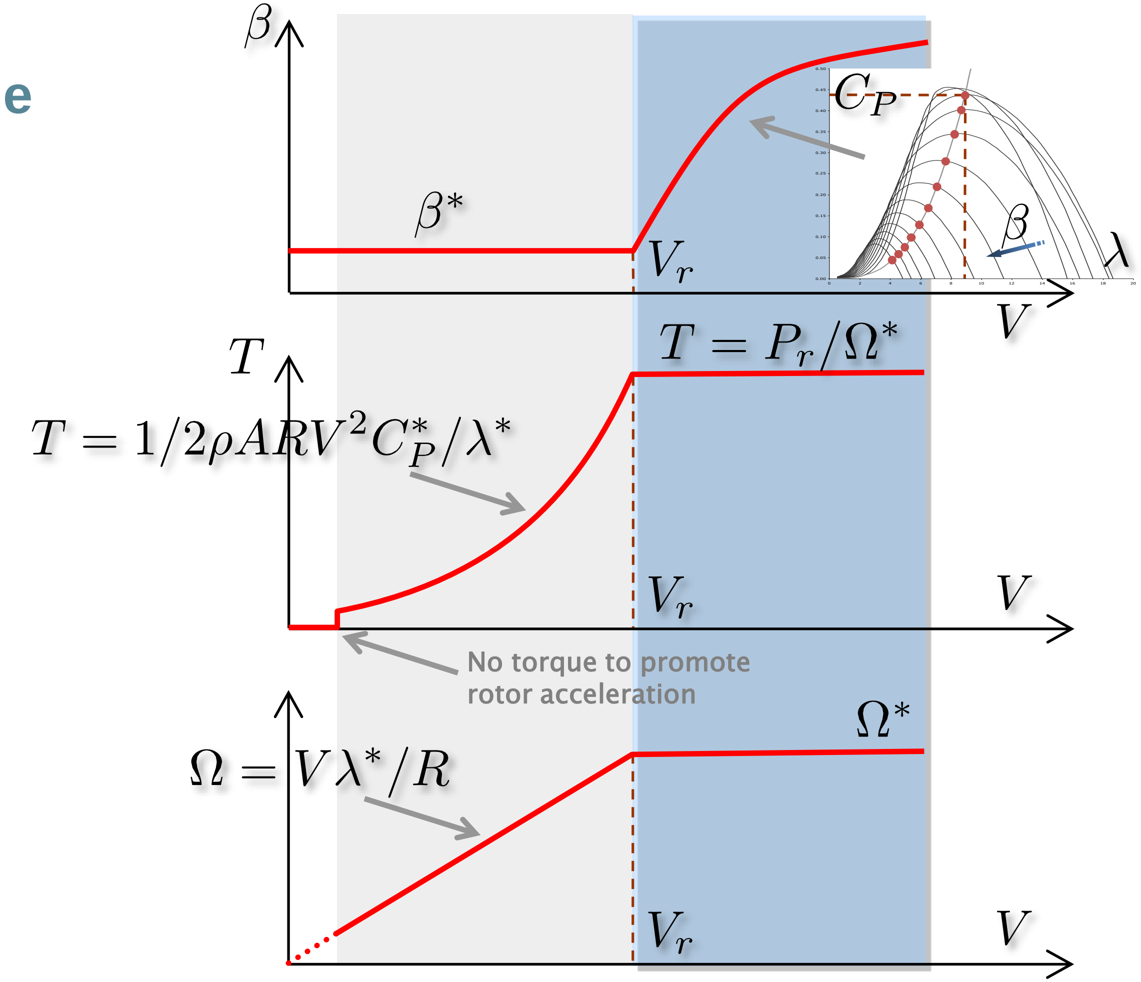
- **Other constraints on max chord, tip speed, shape regularity**





Control Synthesis Tool (CST)

- **Determines the control laws r_ε^* of the turbine**
- **Required to perform DLC simulations**
- **Available options:**
  - PID on pitch + LUT on torque
  - PID on pitch + PID on torque (DTU)
  - MIMO-LQR model based
  - Individual Pitch Control



Prebend Design Submodule (PDS)

- Optimizes prebend to maximize the deformed swept area

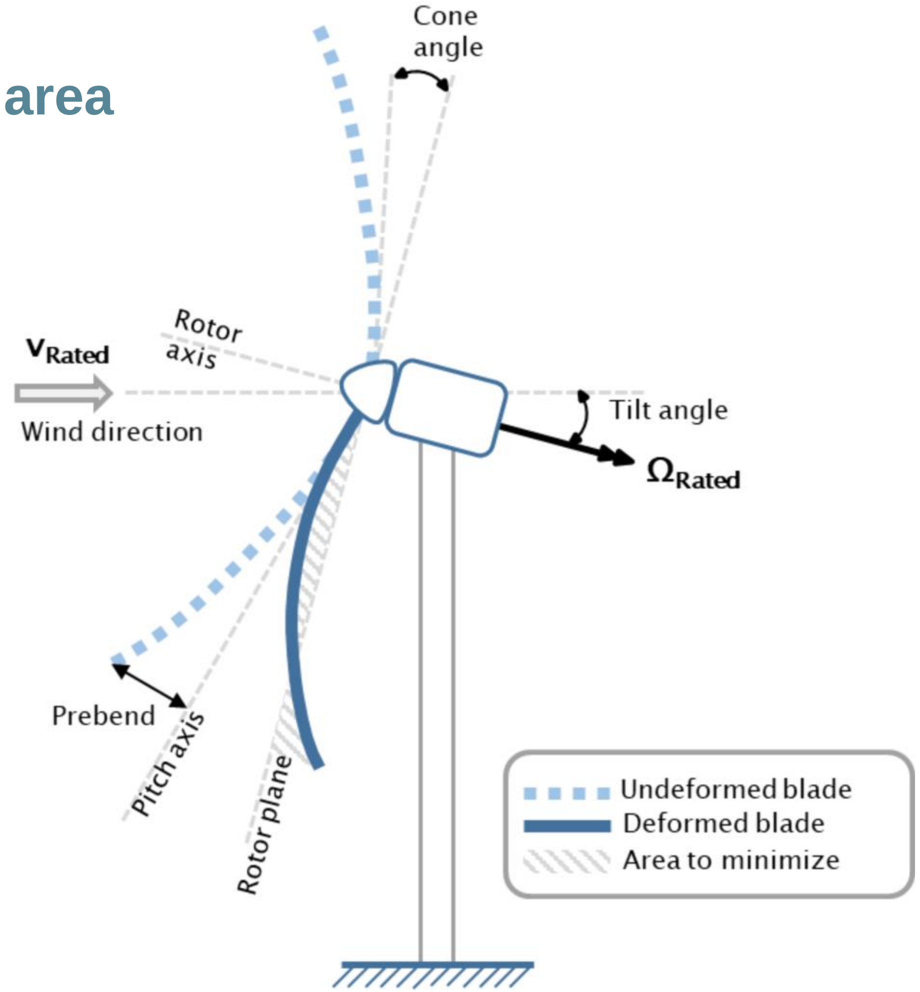
$$(\boldsymbol{p}_b^*, A_\delta^*) = \min_{\boldsymbol{p}_b}(A_\delta^*(\boldsymbol{p}_a^*, \boldsymbol{p}_b, \boldsymbol{p}_s, \boldsymbol{p}_g, r_\varepsilon^*))$$

s.t.:

$$\boldsymbol{g}_a(\boldsymbol{p}_a, \boldsymbol{p}_g) \leq \boldsymbol{0}$$

Design variables:

- **Prebend shape**



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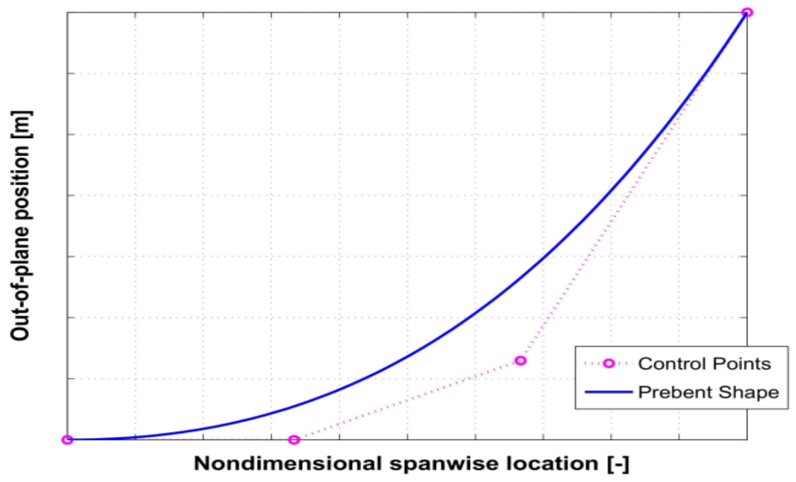
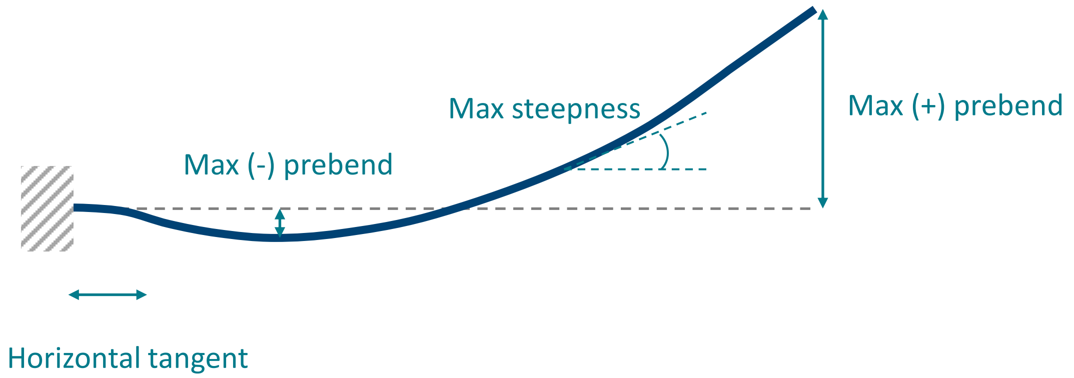
Prebend Design Submodule (PDS)

- **Prebend is parameterized by a Bézier curve**
- **Static analysis at rated conditions**
- **Possible constraints on:**
  - Max tip prebend
  - Max steepness
  - Shape regularity
- **No associated variables in the MDL**





Structural Design Submodule (SDS)

- Optimizes *internal structure* of blade, tower to minimize the ICC

$$(\boldsymbol{p}_s^*, ICC^*) = \min_{\boldsymbol{p}_s}(ICC(\boldsymbol{p}_a^*, \boldsymbol{p}_b^*, \boldsymbol{p}_s, \boldsymbol{p}_g, r_\varepsilon^*))$$

s.t.:

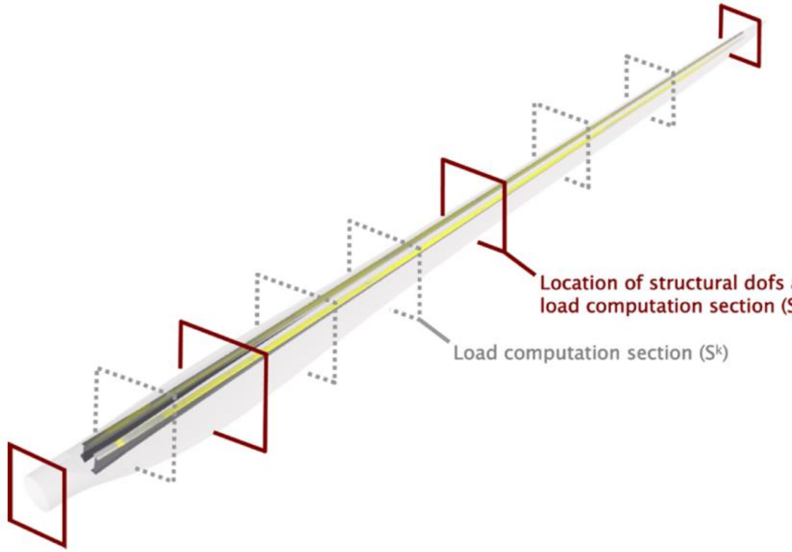
$$\boldsymbol{g}_s(\boldsymbol{p}_a^*, \boldsymbol{p}_b^*, \boldsymbol{p}_s, \boldsymbol{p}_g, r_\varepsilon^*) \leq \boldsymbol{0}$$

Design variables:

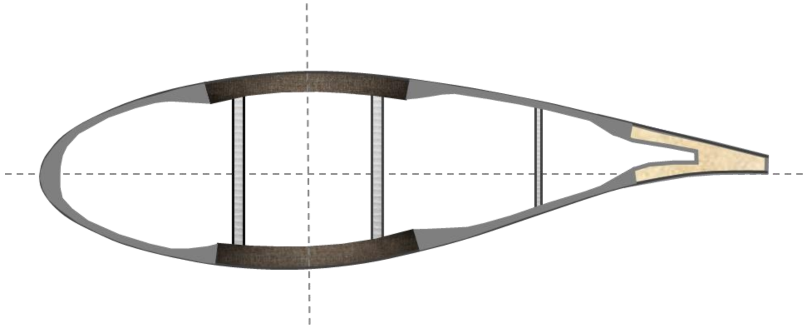
- **Thickness of blade structural components**
- **Wall thickness of tower segments**
- **Diameter of tower segments**

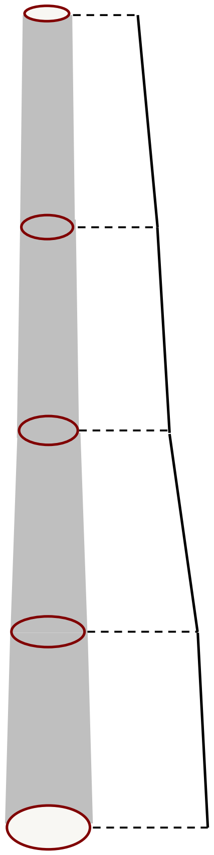
Structural Design Submodule (SDS)

- Thickness of elements is defined at selected stations
- Sectional mass, stiffness computed by ANBA



- Sectors defined along tower height
- Mass, stiffness, stress/strain and buckling computed analytically
- Loads and deformations from *Cp-Lambda* sensors





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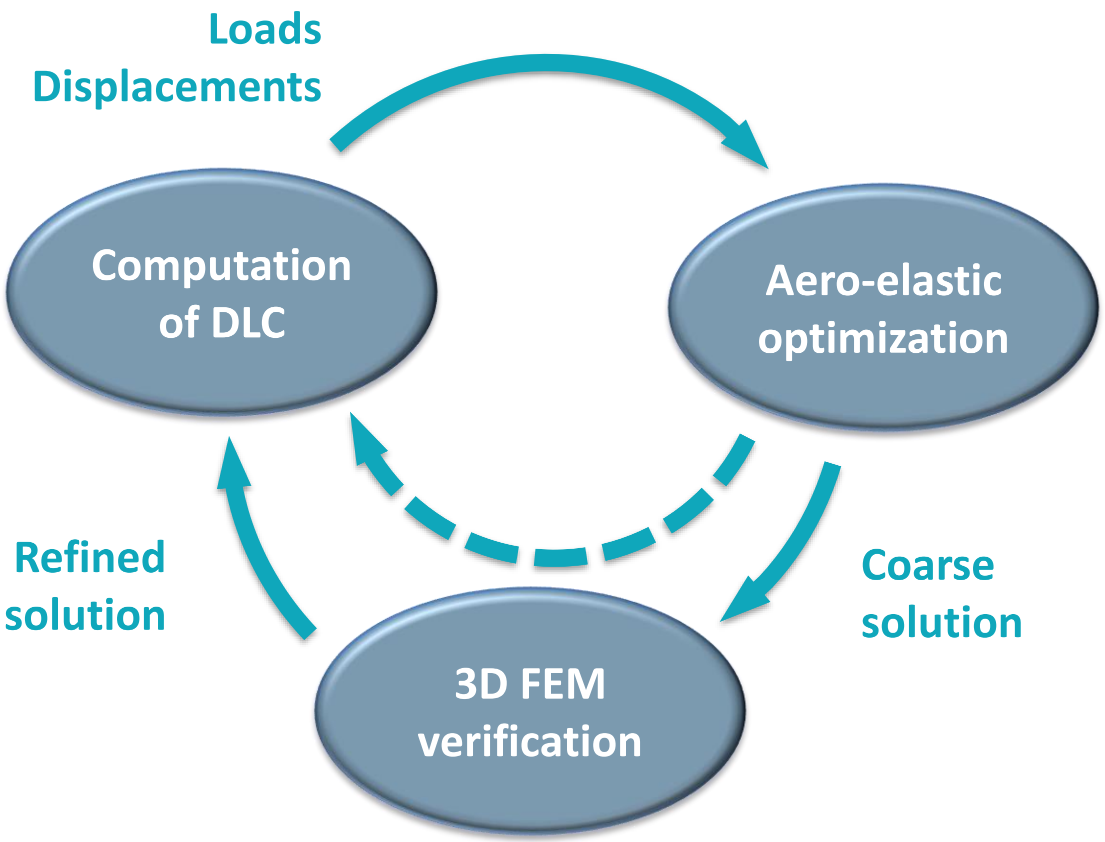
Structural Design Submodule (SDS)



Constraints:

- Blade tip deflection
- Frequencies
- Manufacturing limits
- Ultimate stress, strain
- Fatigue damage
- Buckling

AN EXAMPLE: DESIGN OF THE POLIMI 20MW BASELINE WT

Definition of the initial 20 MW model

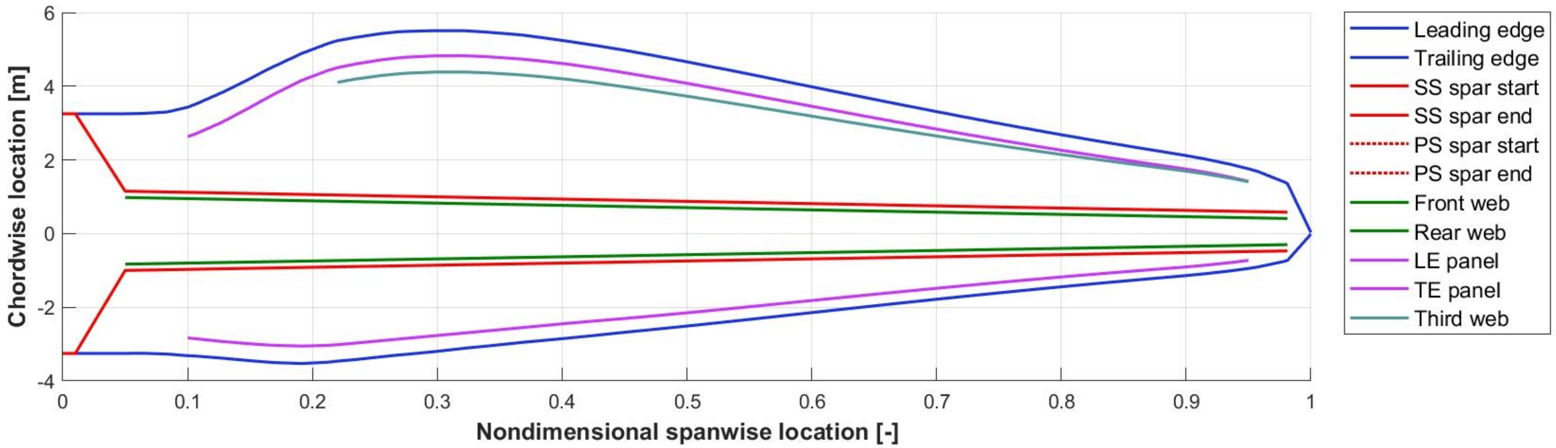
- Initial aeroelastic definition obtained from upscaling the INNWIND.EU 10 MW

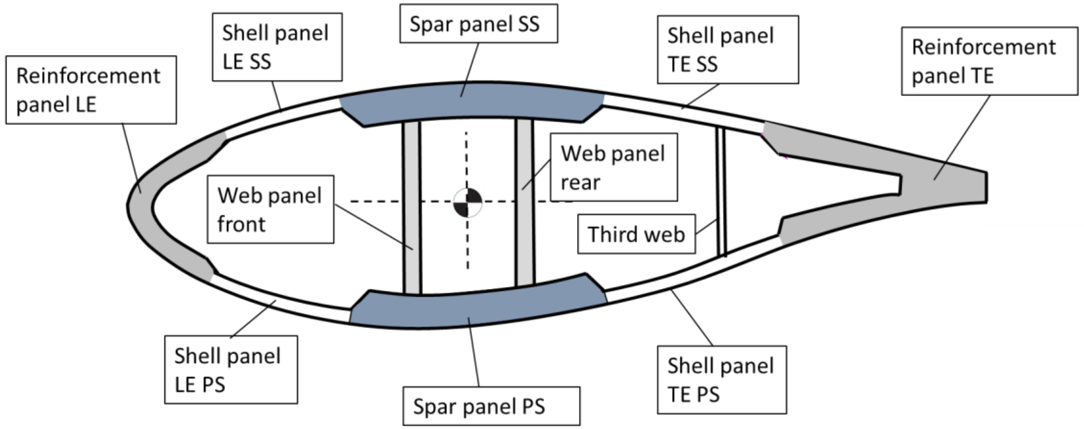
Rated power	20 MW	**Rotor radius**	126 m
IEC Class	IC	**Hub radius**	3.95 m
Rotor orientation	Clockwise, upwind	**Hub height**	168 m
Control	Variable speed	**Tower height**	163 m
Cut-In speed	4 m/s	**Blade mass**	118 ton
Cut-Out speed	25 m/s	**Hub mass**	278 ton
Rated wind speed	11.4 m/s	**Nacelle mass**	1098 ton
Max tip speed	90 m/s	**Tower mass**	1779 ton
Cone angle	2.5°	**Generator Inertia**	8488 kg/m2
Tilt angle	5°	**Generator efficiency**	94%

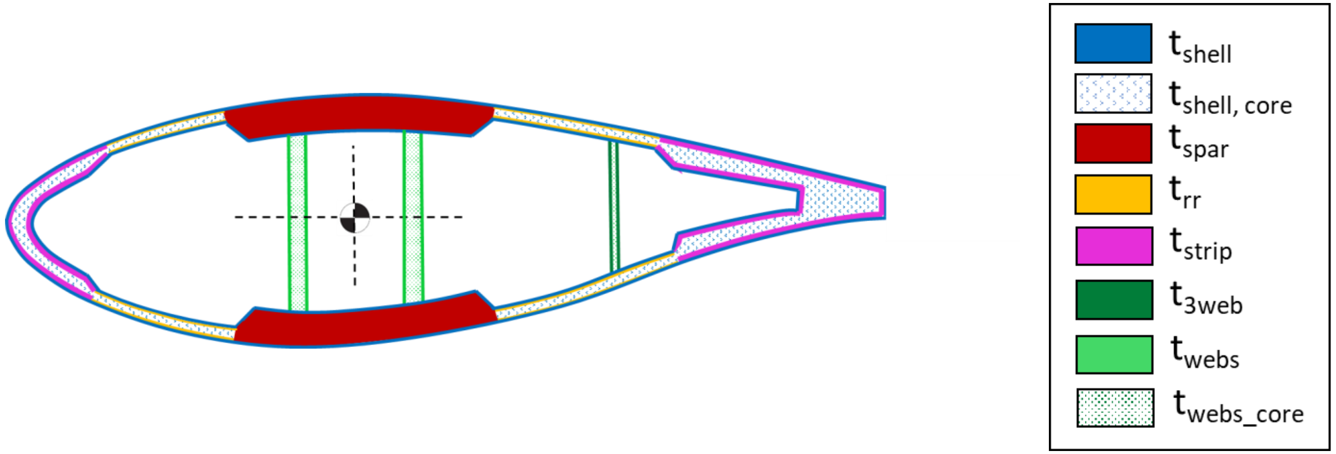
Reference: INNWIND Deliverable 1.25: *PI-based assessment (application) on the results of WP2-WP4 for 20 MW wind turbines*, June 2017

Design assumptions

- **Classic *spar-box* layout**
- **No initial prebend**
- **Fixed-radius optimization**

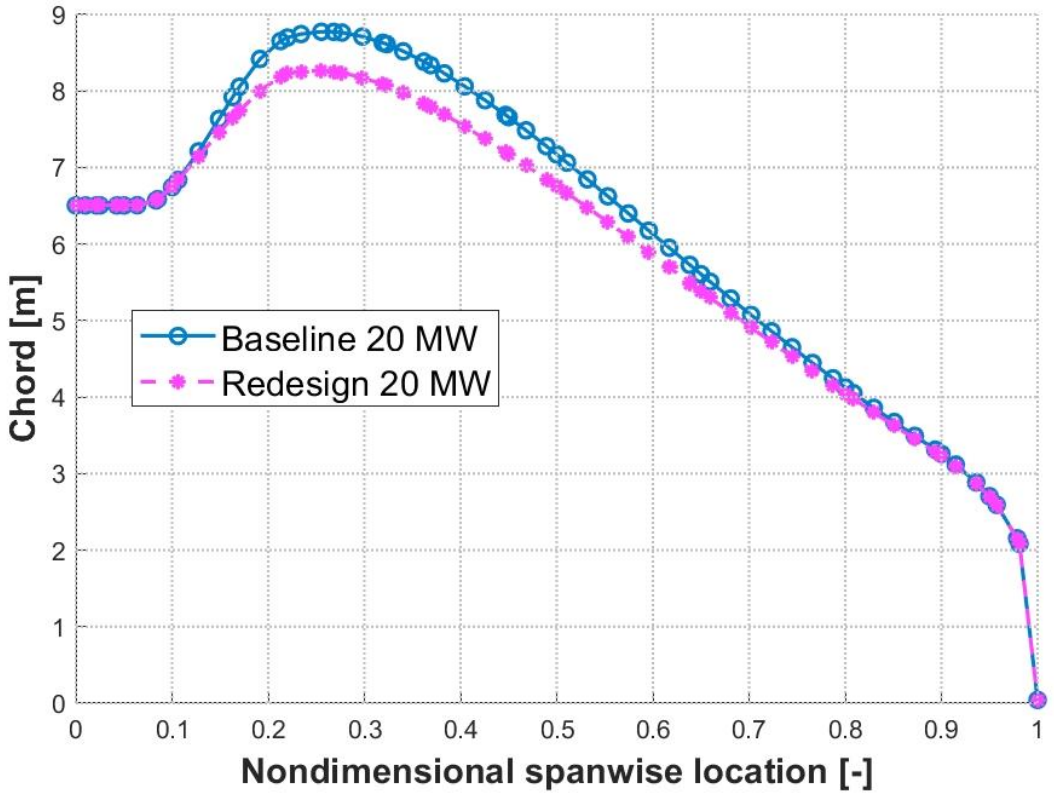




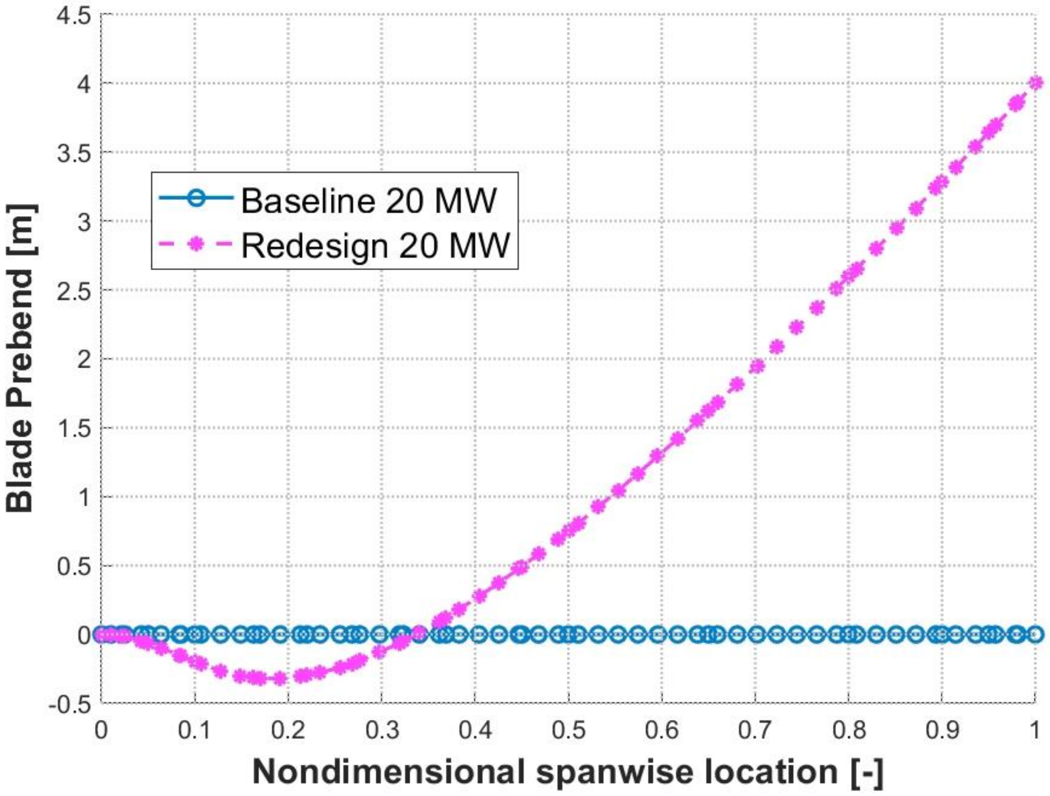


Baseline vs. Redesign comparison

Chord

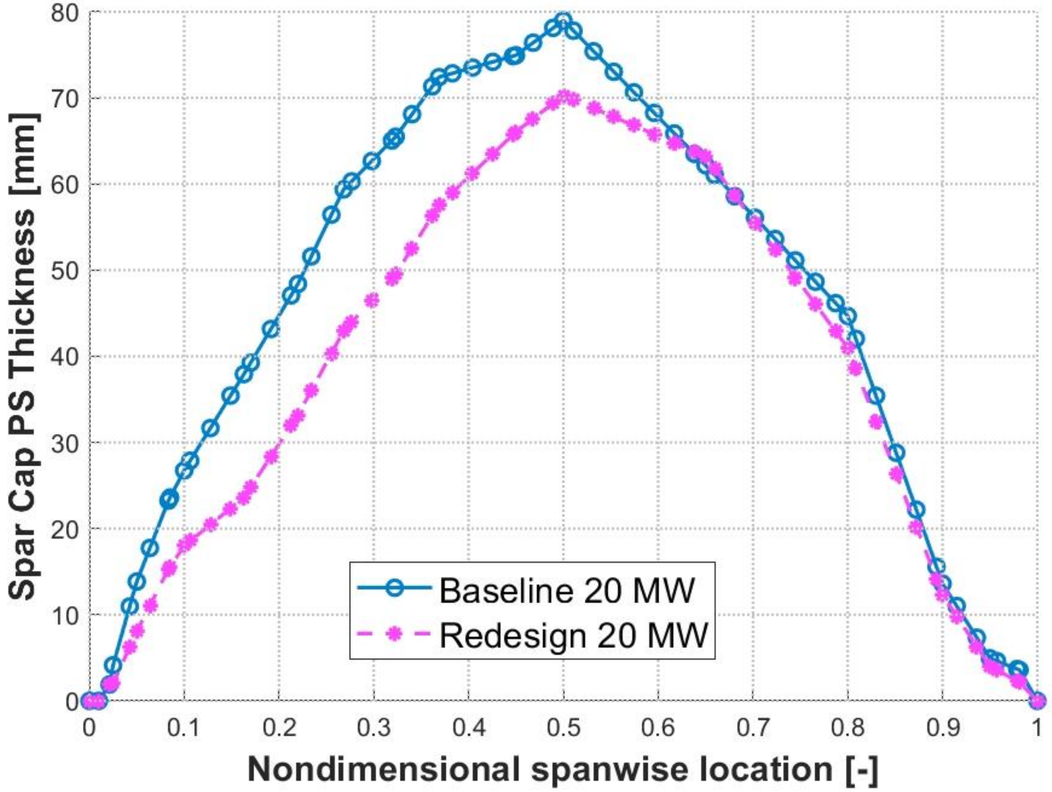


Prebend

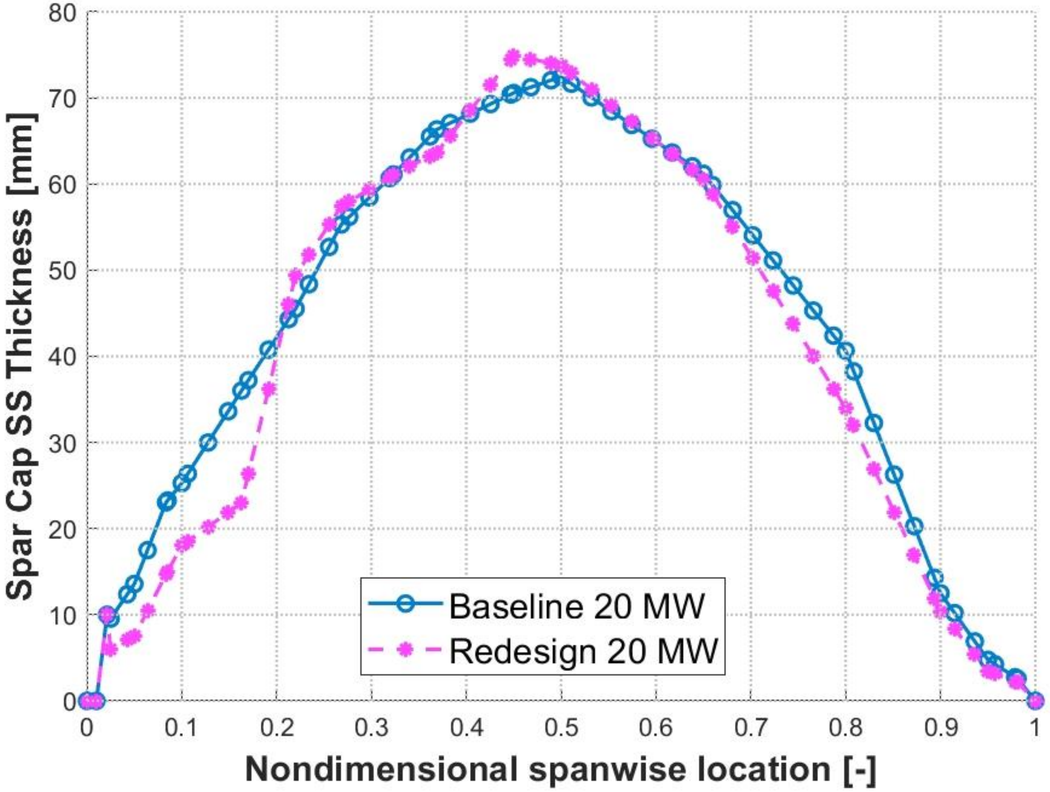


Baseline vs. Redesign comparison

PS Spar Cap thickness

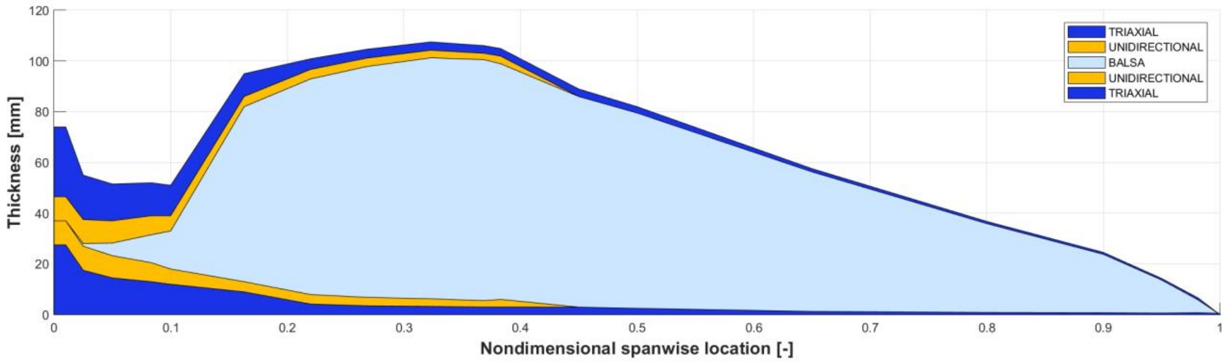


SS Spar Cap thickness

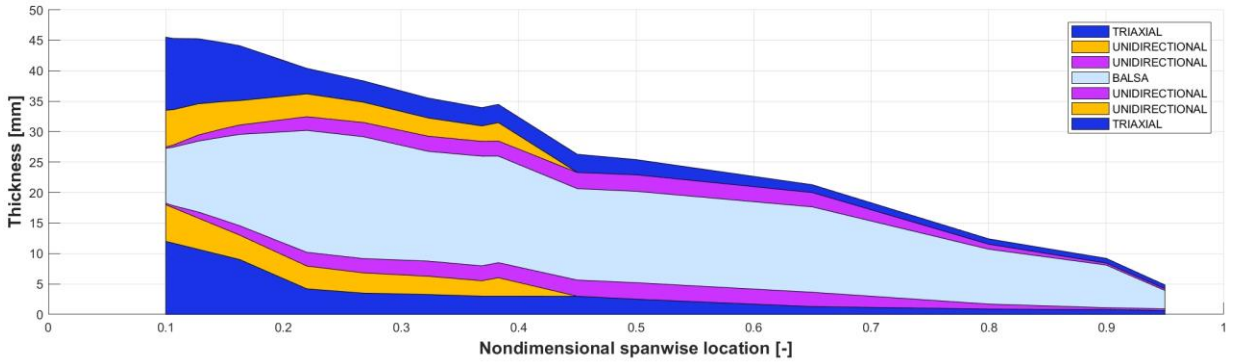


Structural solution of the redesigned rotor

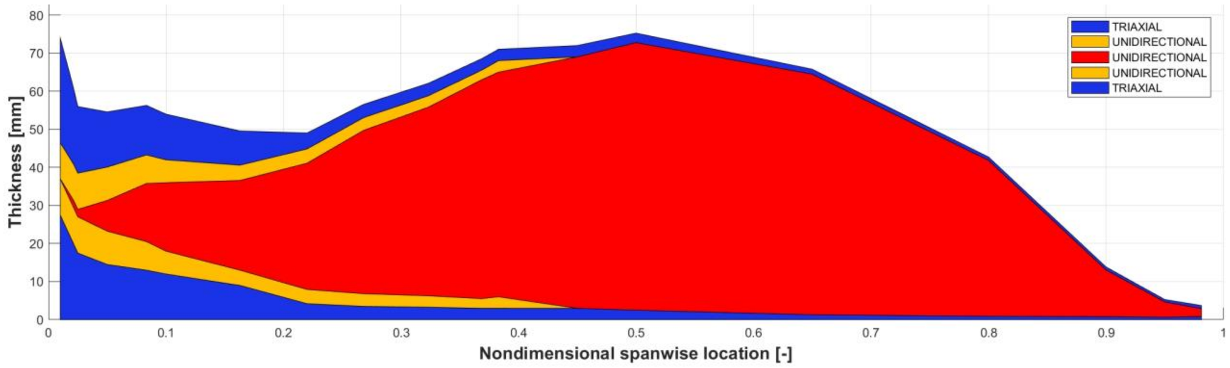
Shell Panels



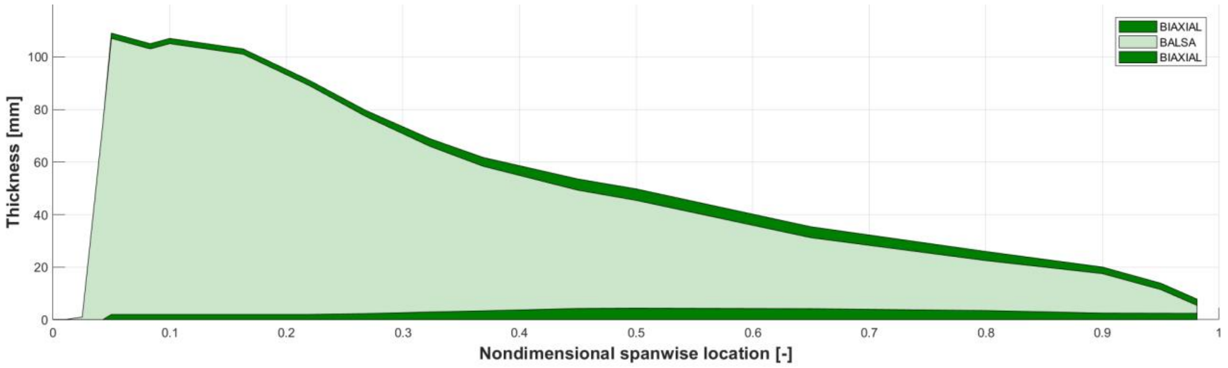
LE Panels



Spar Panels



Shear Webs

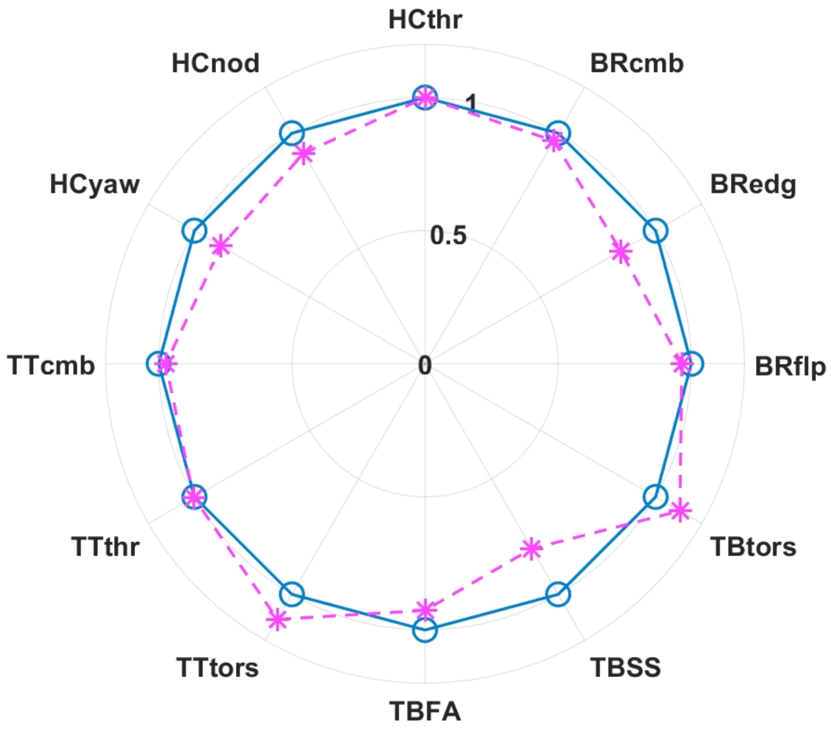


Baseline vs. Redesign comparison

		Units	Baseline 20 MW	Redesign 20 MW	Var. %
Regulation	Rotor speed	[RPM]	6.77	6.82	+ 0.74
	Max tip speed	[m/s]	89.4	89.93	+ 0.59
	Optimal TSR	[-]	7.73	7.86	+ 1.68
	Rated wind speed	[m/s]	11.56	11.45	- 0.95
Design parameters	Max chord	[m]	8.77	8.27	- 5.70
	Prebend at tip	[m]	0	4	-
	Spar caps fiber angle	[deg]	0	6	-
KPIs	Total blade mass	[ton]	113.5	107.8	- 5.05
	AEP	[GWh/yr]	91.63	91.74	+ 0.12
	COE	[€/MWh]	84.92	84.56	- 0.42

Baseline vs. Redesign comparison

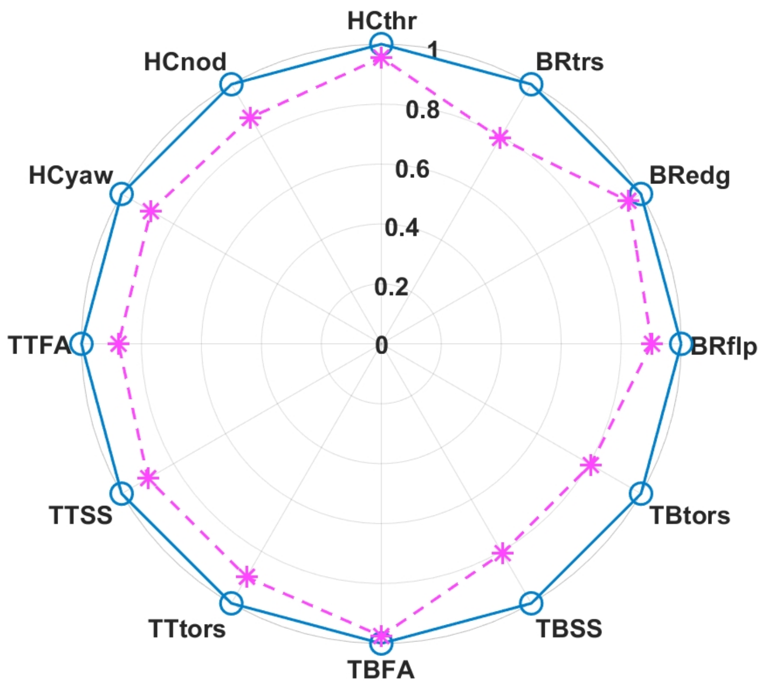
Ultimate loads



BR	Blade Root
HC	Hub Center
TT	Tower Top
TB	Tower Base

Baseline 20 MW
Redesign 20 MW

Fatigue loads



STATE OF THE ART AND OUTLOOK

Completed research projects

- **Definition of 10~20 MW reference wind turbines**
- **Definition of a 3.4 MW reference WT for the IEA-Task 37 project**
- **Integration of active/passive load mitigation in the design**
- **Development of upwind/downwind two-bladed rotors**
- **Study of the impact of WF control on a single WT design**
- **Global WT design with noise emissions constraints**

AdVanced Aerodynamic Tools for lArge Rotors

INNWIND.EU

CL-Windcon

iea wind

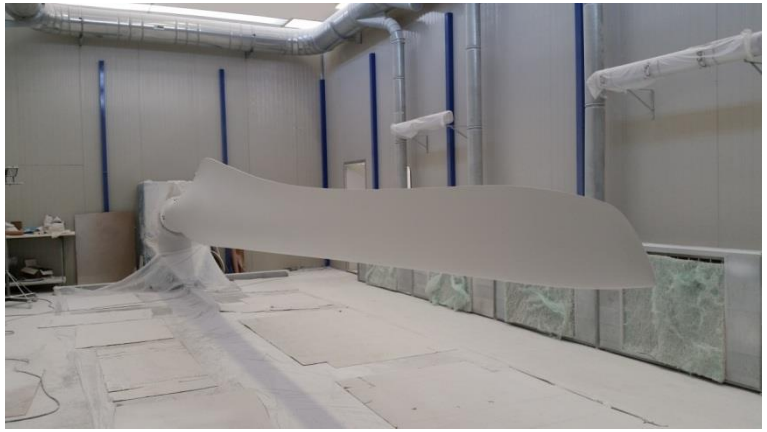
Completed industrial projects

1m (for wind tunnel)

300kW – 16m

700kW – 24m

100kW – 10m

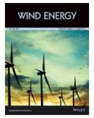


2MW – 45m

Ongoing activities

- **Integration of airfoil design**
- **Development of numerical tools for aero-acoustic modelling and design**
- **Application of the design to down-scaled WTs for wind tunnel**
- **Integration of WF-level simulation and design modules**
- **Integration of additional sub-component design modules (DT & generator, support structure)**

Selected references



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THANK YOU FOR YOUR ATTENTION