MULTI-DISCIPLINARY DESIGN OPTIMIZATION OF WIND TURBINES

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POLItecnico di Milano

Outline

- Introduction and motivation
- Approach:
  - Constrained multi-disciplinary optimization
  - Simulation models
  - Aerodynamic optimization
  - Structural optimization
  - Combined aero-structural optimization
- Applications and results
- Conclusions and outlook

Introduction and Motivation

Wind Turbine Design

Aerodynamics
- Annual Energy Production (**AEP**)
- **Noise**
- …

Systems
- **Generator** (RPM, weight, torque, drive-train, …)
- Pitch and yaw **actuators**
- Brakes
- …

Structures
- **Loads**: **envelope** computed from large number of Design Load Cases (DLCs, IEC-61400)
- **Fatigue** (25 year life), Damage Equivalent Loads (DELs)
- Maximum blade tip **deflections**
- Placement of **natural frequencies** wrt rev harmonics
- **Stability**: flutter, LCOs, low damping of certain modes, local buckling
- Complex **couplings** among rotor/drive-train/tower/foundations (off-shore: hydro loads, floating & moored platforms)
- **Weight**: massive size, composite materials (but shear quantity is an issue, fiberglass, wood, clever use of carbon fiber)
- **Manufacturing** technology, constraints

Controls

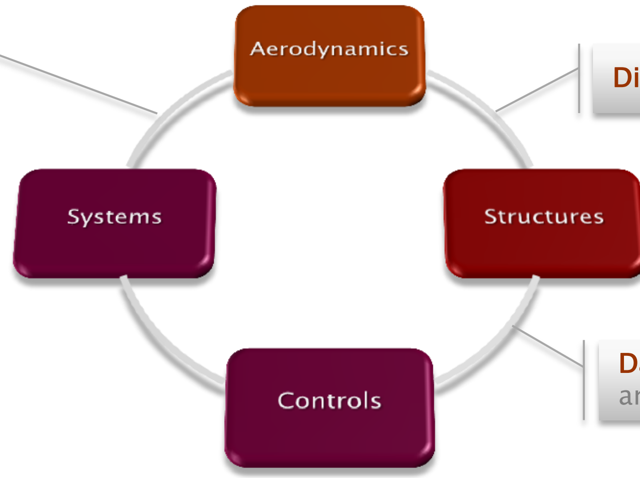
Pitch-torque control laws:
- **Regulating** the machine at different set points depending on wind conditions
- Reacting to **gusts**
- Reacting to wind **turbulence**
- Keeping actuator **duty-cycles** within admissible limits
- Handling **transients**: run-up, normal and emergency shut-down procedures
- …

Introduction and Motivation

Current approach to design: discipline-oriented specialist groups

Lengthy loops to satisfy all requirements/constraints (months)

Different simulation models



Data transfer/compatibility among groups

There is a need for **multi-disciplinary optimization tools**, which must:

- Be fast (hours/days)
- Provide workable solutions in all areas (aerodynamics, structures, controls) for specialists to refine/verify
- Account ab-initio for all complex couplings (no fixes a posteriori)
- Use fully-integrated tools (no manual intervention)

They will **never replace** the experienced designer! … but would greatly speed-up design, improve exploration/knowledge of design space

Introduction and Motivation

Focus of present work: integrated multi-disciplinary (**holistic**) **constrained** design of wind turbines, i.e. optimal coupled sizing of:

- Aerodynamic shape
- Structural members (loads, aero-servo-elasticity and controls)

Constraints: ensure a viable design by enforcing all necessary design requirements

Applications:

- Sizing of a new machine
- Improvement of a tentative configuration
- Trade-off studies (e.g. performance-cost)
- Modifications to exiting models

Previous work:

Duineveld, Wind Turbine Blade Workshop 2008; Fuglsang & Madsen, JWEIA 1999; Fuglsang, EWEC 2008; etc.

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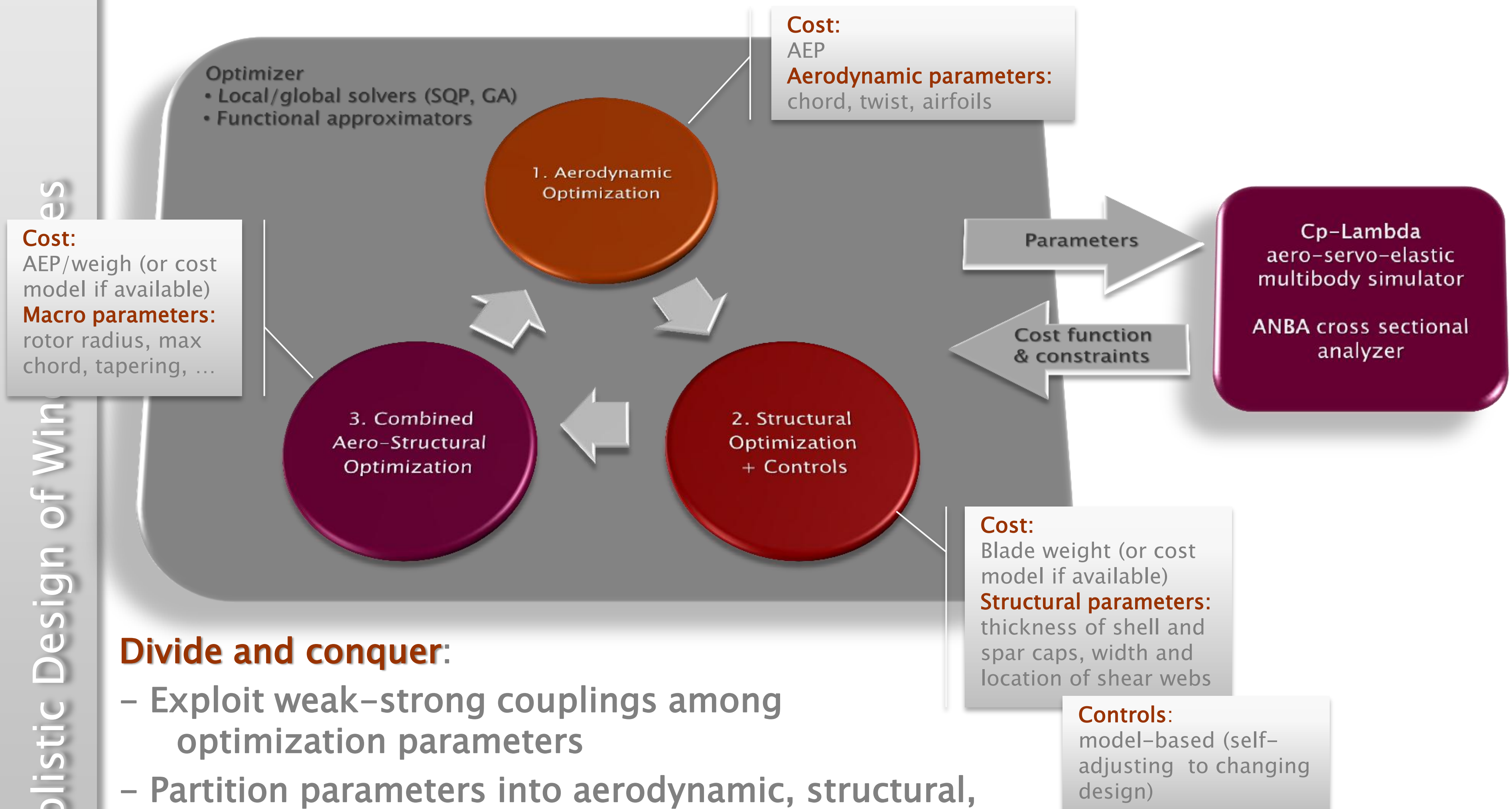
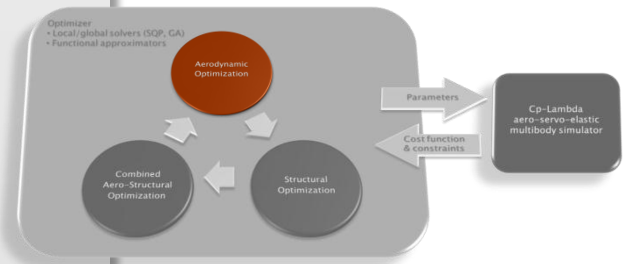
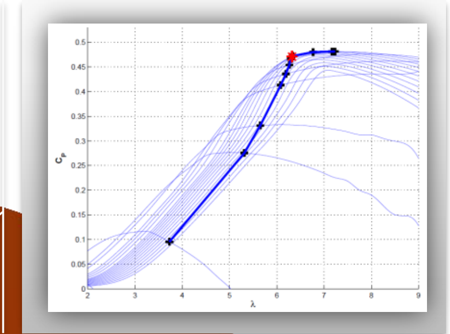
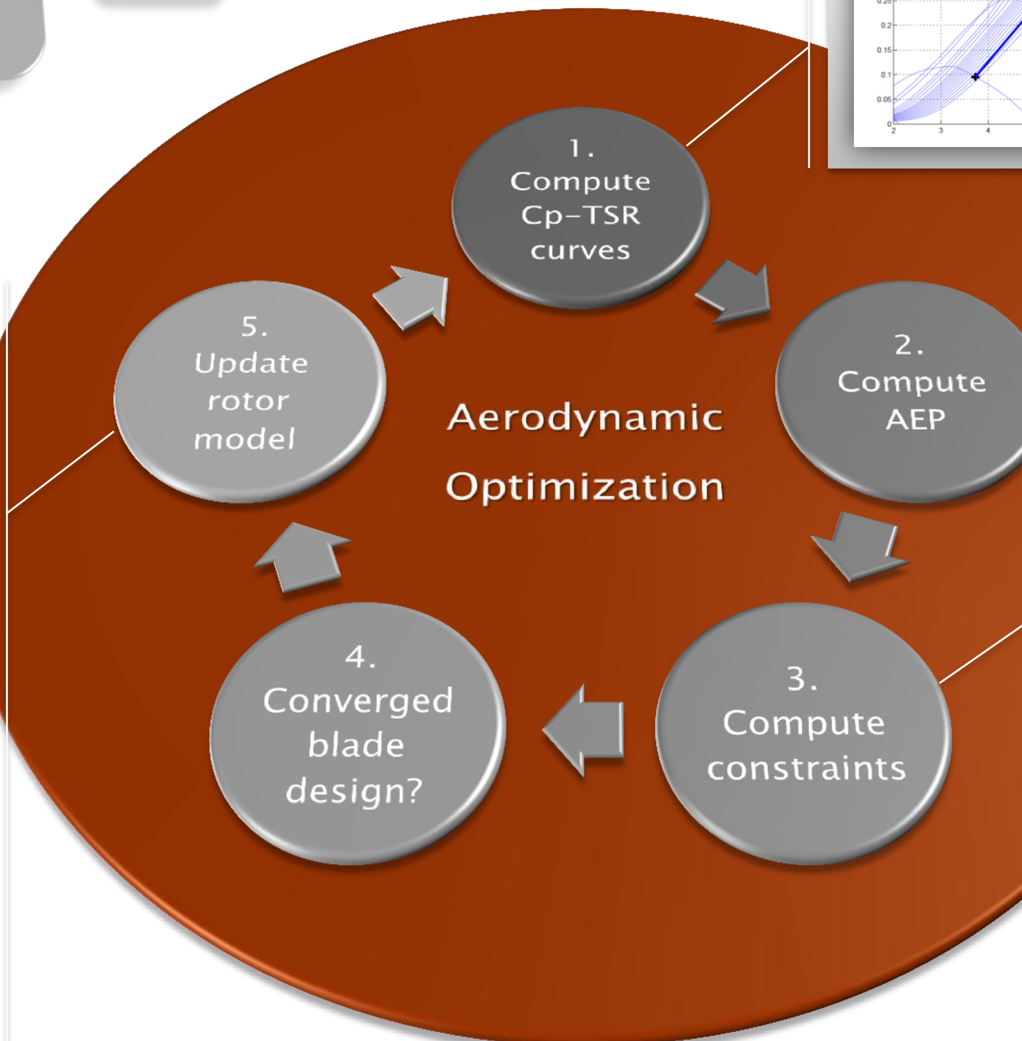
Approach



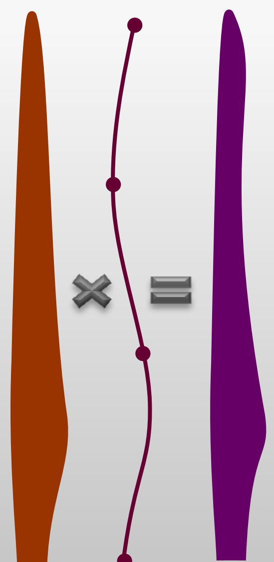
Divide and conquer:
- Exploit weak-strong couplings among optimization parameters
- Partition parameters into aerodynamic, structural, macro (i.e. combined aero-structural)





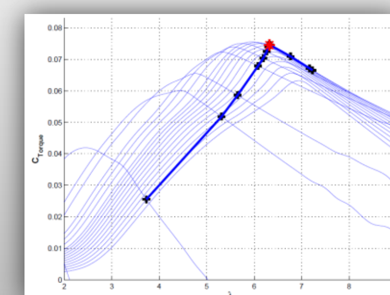


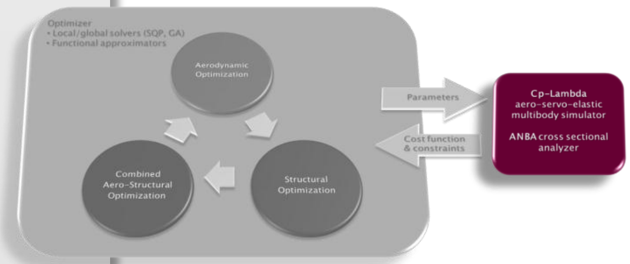
Blade parameterization:
Chord and twist shape functions deform a **baseline** configuration



Richer shape with fewer dofs

Constraints:
- Noise constraint (V tip): regulation in region II1/2
- Torque-TSR stability
- Max chord
- …

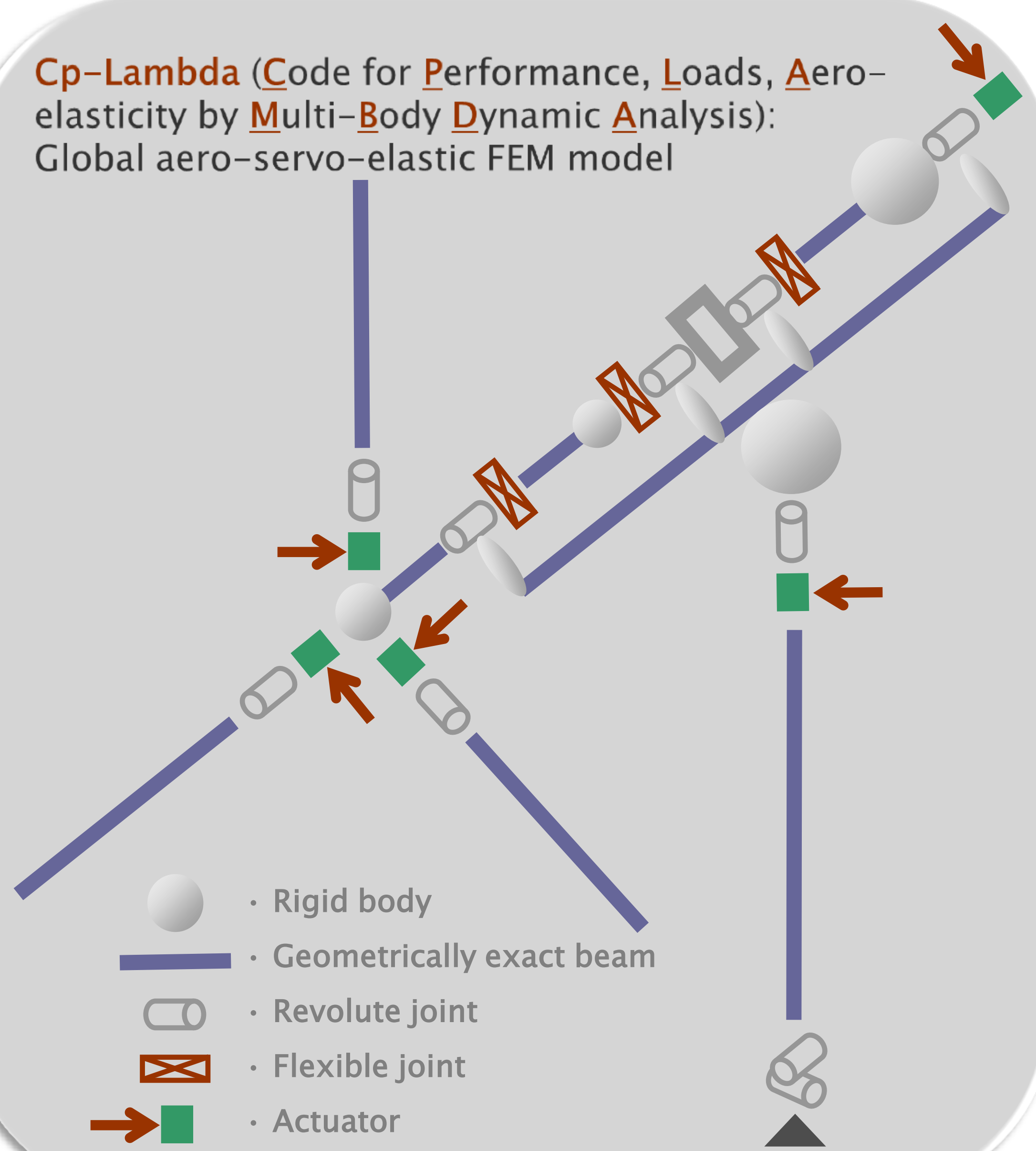


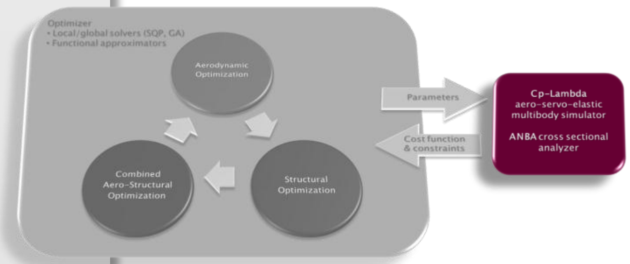


Cp-Lambda highlights:

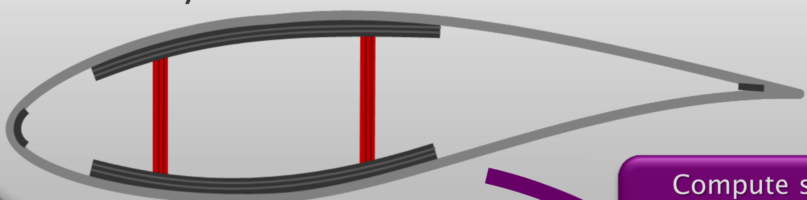
- Geometrically exact composite-ready beam models
- Generic topology (Cartesian coordinates+Lagrange multipliers)
- Dynamic wake model (Peters-He, yawed flow conditions)
- Efficient large-scale DAE solver
- Non-linearly stable time integrator
- Fully IEC 61400 compliant (DLCs, wind models)

Cp-Lambda (Code for Performance, Loads, Aero-elasticity by Multi-Body Dynamic Analysis):
Global aero-servo-elastic FEM model





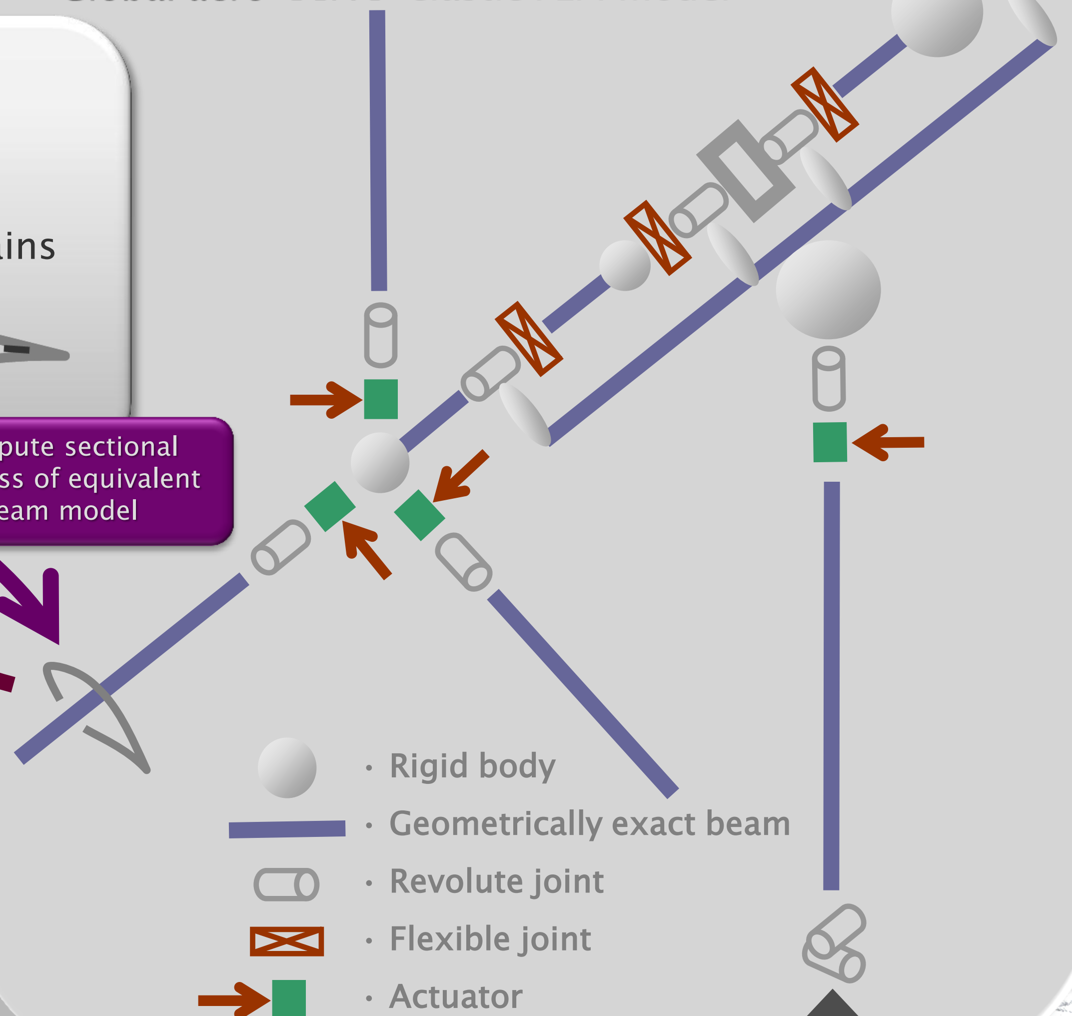
ANBA (**An**isotropic **B**eam **A**nalysis) cross sectional model (Giavotto et al., 1983):
- Evaluation of cross sectional stiffness (6 by 6 fully populated)
- Recovery of sectional stresses and strains

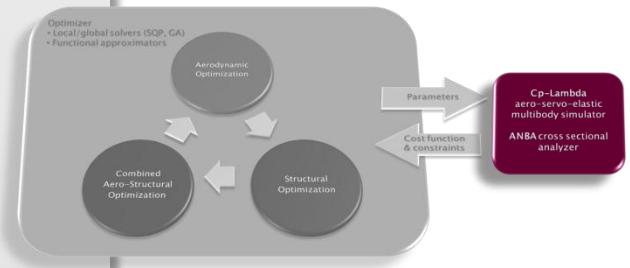


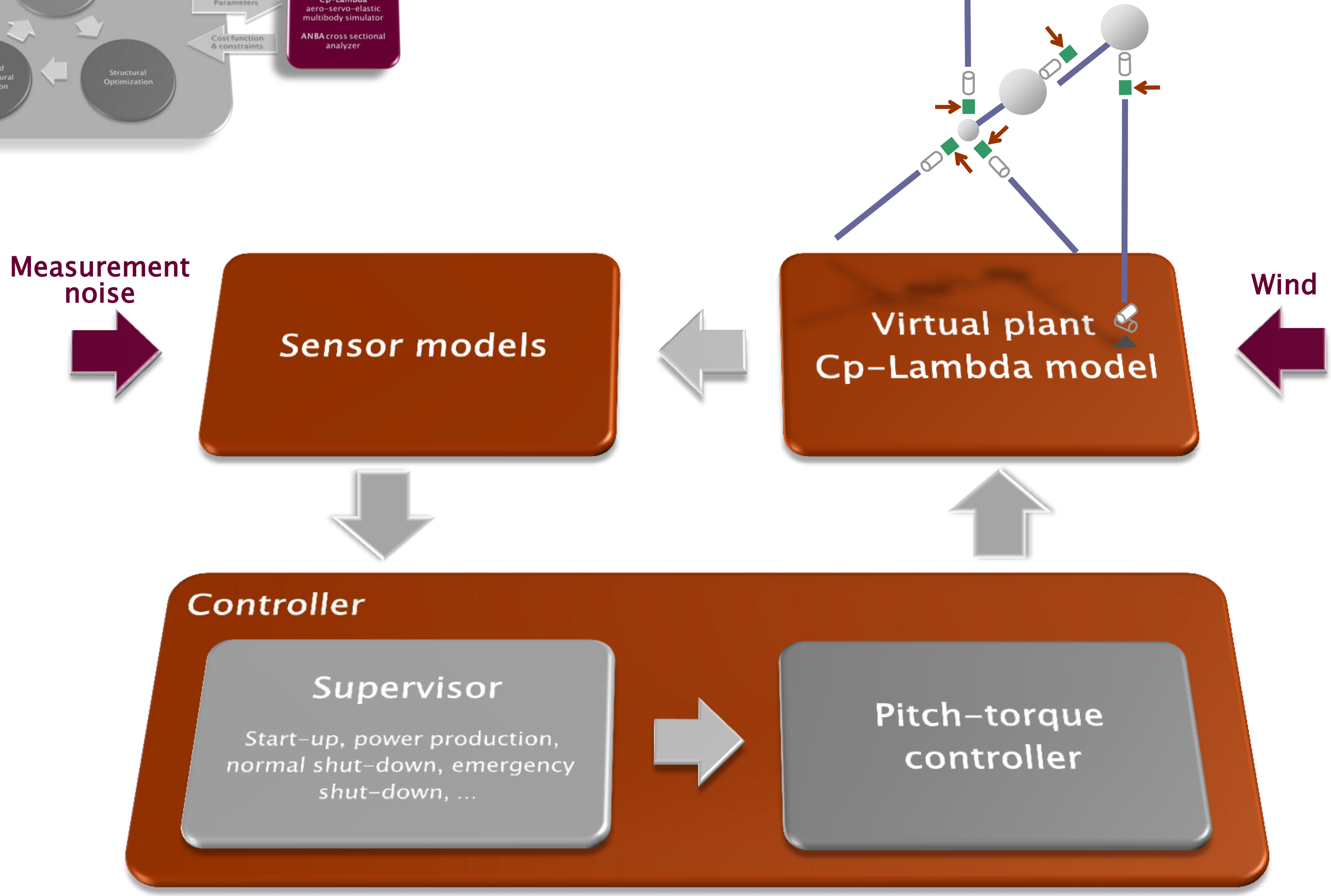
Compute sectional stiffness of equivalent beam model

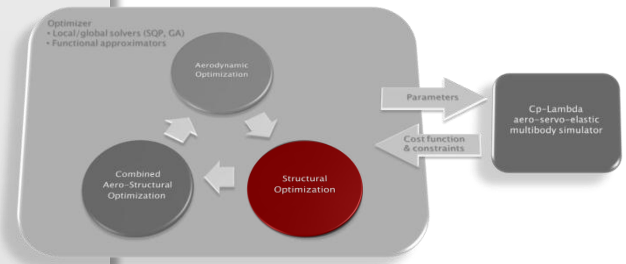
Compute cross sectional stresses and strains

Cp-Lambda (**C**ode for **P**erformance, **L**oads, **A**ero-elasticity by **M**ulti-**B**ody **D**ynamic **A**nalysis):
- Global aero-servo-elastic FEM model



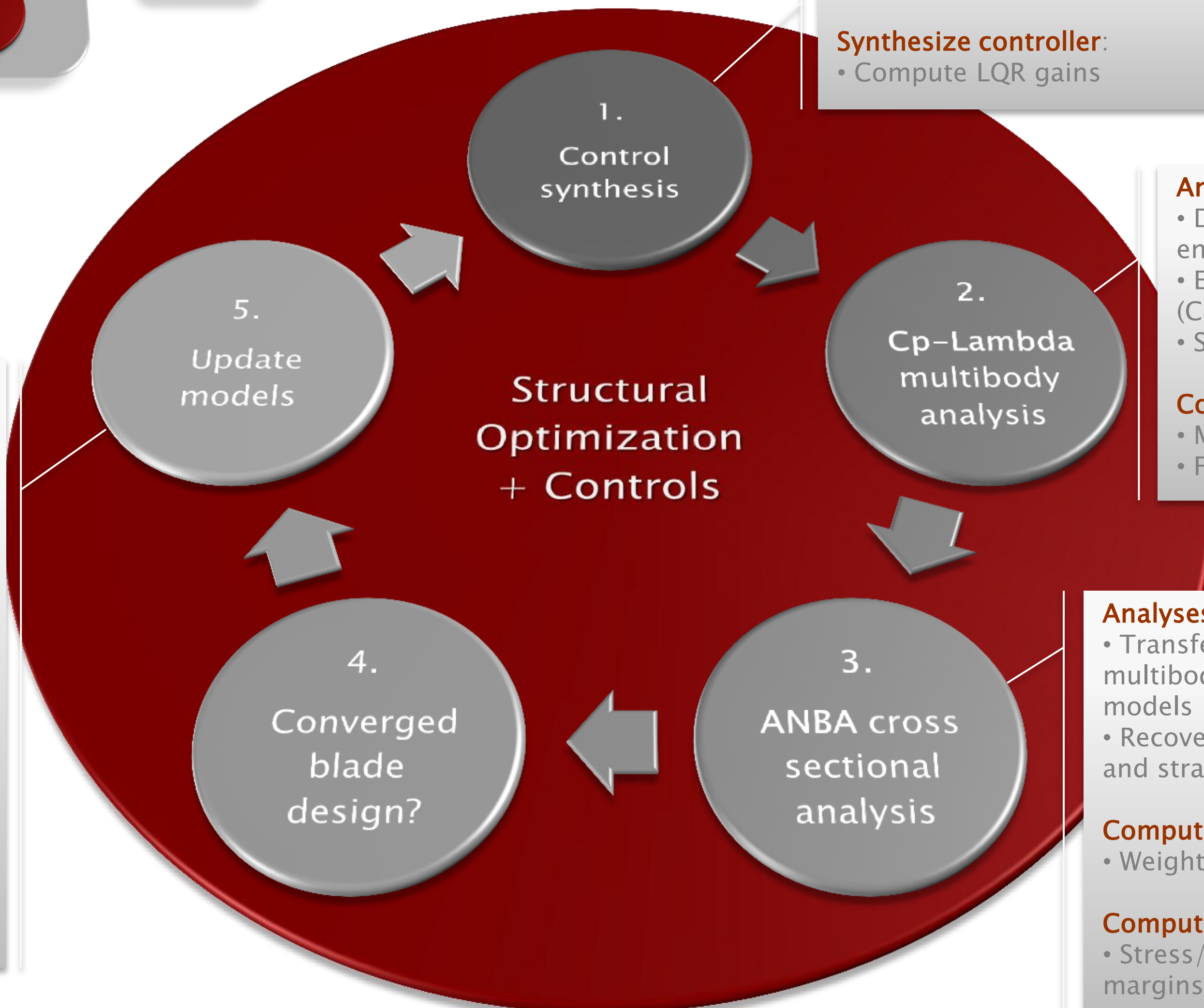

Optimizer
• Local/global solvers (SQP, GA)
• Functional approximators
Aerodynamic Optimization
Combined Aero-Structural Optimization
Structural Optimization
Parameters
Cost function & constraints
Cp-Lambda aero-servo-elastic multibody simulator
ANBA cross sectional analyzer


Measurement noise
Sensor models
Virtual plant Cp-Lambda model
Wind
Controller
Supervisor
Start-up, power production, normal shut-down, emergency shut-down, …
Pitch-torque controller



Modeling:
- Extract reduced model from multibody one
- Linearize reduced model

Synthesize controller:
- Compute LQR gains



Analyses:
- DLCs (IEC61400: load envelope, fatigue DELs)
- Eigenfrequencies (Campbell diagram)
- Stability

Compute constraints:
- Max tip deflection
- Frequency placement

Update process:

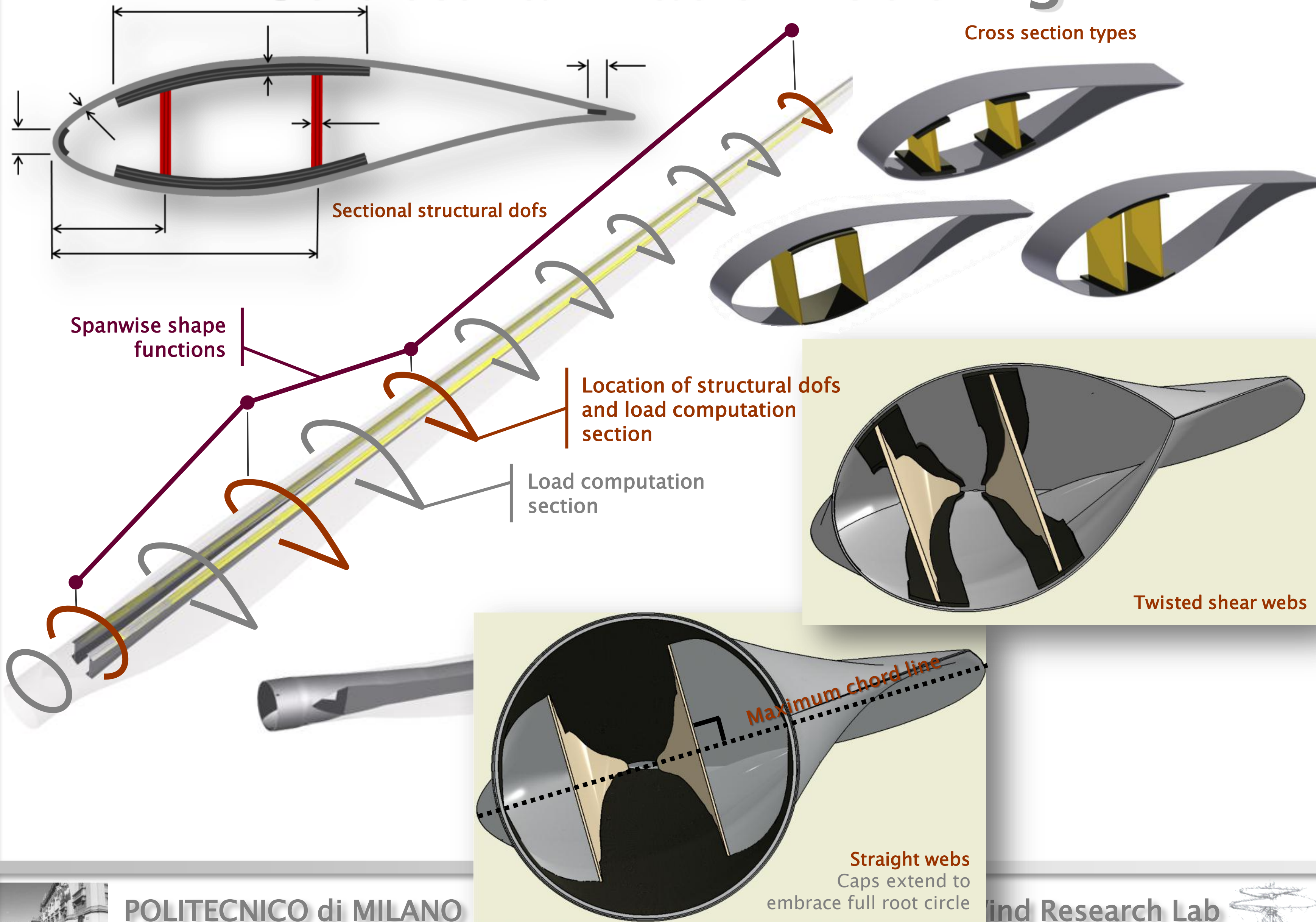
Update cross sectional models
↓
Compute beam stiffness and inertial properties
↓
Update multibody model

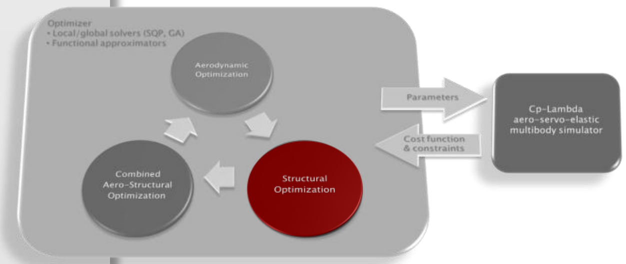
Analyses:
- Transfer loads from multibody to cross sectional models
- Recover sectional stresses and strains

Compute cost function:
- Weight

Compute constraints:
- Stress/strains safety margins

Structural Blade Modeling



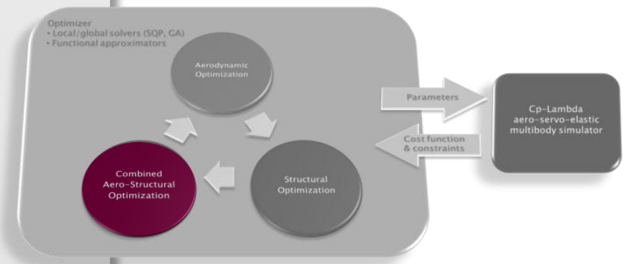


Efficient optimization:
Load envelope evaluation
external to weight optimization
Converges typically in 2/3
iterations

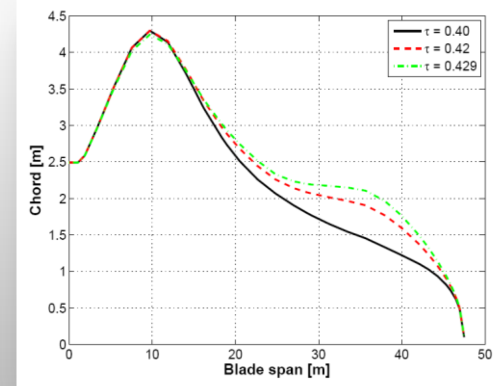
$$\textbf{Function}\ (\boldsymbol{p}_s^*, w^*) = \texttt{MinBladeWeight}\ (\boldsymbol{p}_a, \boldsymbol{p}_s, D):$$
$$\boldsymbol{E} = \texttt{LoadEnvelope}(\boldsymbol{p}_a, \boldsymbol{p}_s, D)$$
$$\textbf{do}$$
$$(\boldsymbol{p}_s^*, w^*) = \texttt{MinBladeWeightFrozenLoads}(\boldsymbol{p}_a, \boldsymbol{p}_s, D, \boldsymbol{E})$$
$$\boldsymbol{E}' = \texttt{LoadEnvelope}(\boldsymbol{p}_a, \boldsymbol{p}_s^*, D)$$
$$\Delta p_s = \|\boldsymbol{p}_s^* - \boldsymbol{p}_s\|, \quad \Delta E = \|\boldsymbol{E}' - \boldsymbol{E}\|$$
$$\boldsymbol{p}_s = \boldsymbol{p}_s^* \quad \boldsymbol{E} = \boldsymbol{E}$$
$$\textbf{while}\ (\Delta p_s \geq \text{tol}_{p_s}\ \textbf{and}\ \Delta E \geq \text{tol}_E)$$

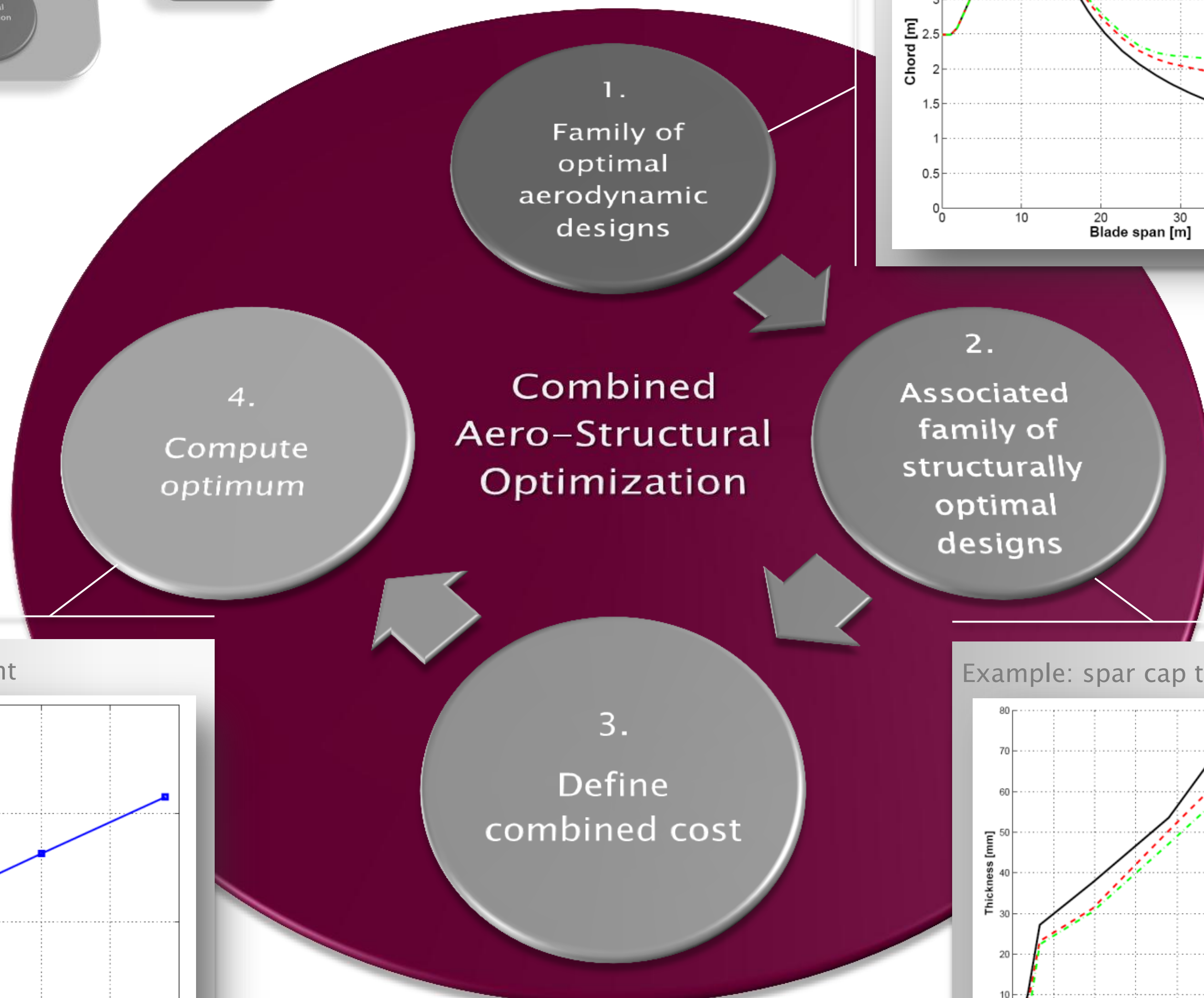
$$\textbf{Function}\ (\boldsymbol{p}_s^*, w^*) = \texttt{MinWeightBladeFrozenLoads}\ (\boldsymbol{p}_a, \boldsymbol{p}_s, D, \boldsymbol{E}):$$
$$\boldsymbol{p}_s^* = \min_{\boldsymbol{p}_s} W(\boldsymbol{p}_s, D) \quad (\text{and } w^* = \arg\min_{\boldsymbol{p}_s} W)$$
$$\text{s.t.:}\quad \boldsymbol{g}_s(\boldsymbol{p}_s) \leq \boldsymbol{0}$$
$$\boldsymbol{\omega}(\boldsymbol{p}_s, D) \in [\boldsymbol{\omega}_L, \boldsymbol{\omega}_U]$$
$$\boldsymbol{\sigma}(\boldsymbol{p}_s, \boldsymbol{E}, D) \leq \boldsymbol{\sigma}_{\text{adm}}$$
$$\boldsymbol{\epsilon}(\boldsymbol{p}_s, \boldsymbol{E}, D) \leq \boldsymbol{\epsilon}_{\text{adm}}$$
$$\boldsymbol{\delta}_{\text{tip}_{\max}}(\boldsymbol{p}_s, \boldsymbol{E}, D) \leq \boldsymbol{\delta}_{\text{tip}_{\text{adm}}}$$

Geometric constraints
Frequency placement
Admissible stresses
Admissible strains
Maximum tip deflection

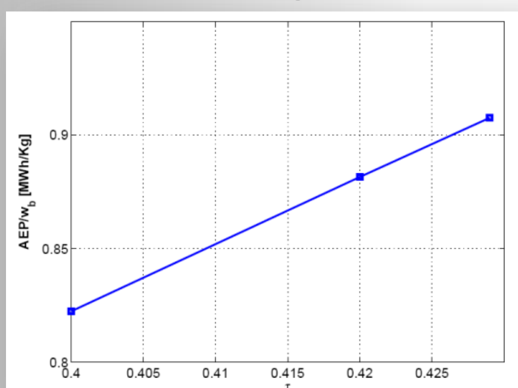


Parameter: radius, max chord, etc.
Example: tapering

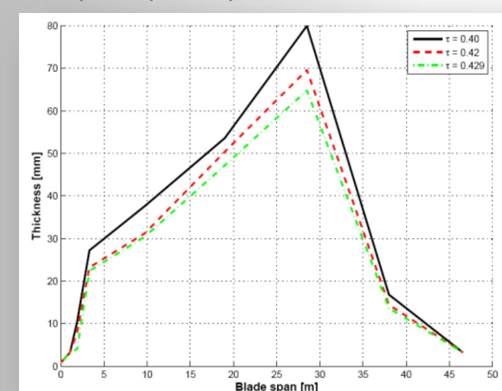




Example: AEP over weight



Example: spar cap thickness



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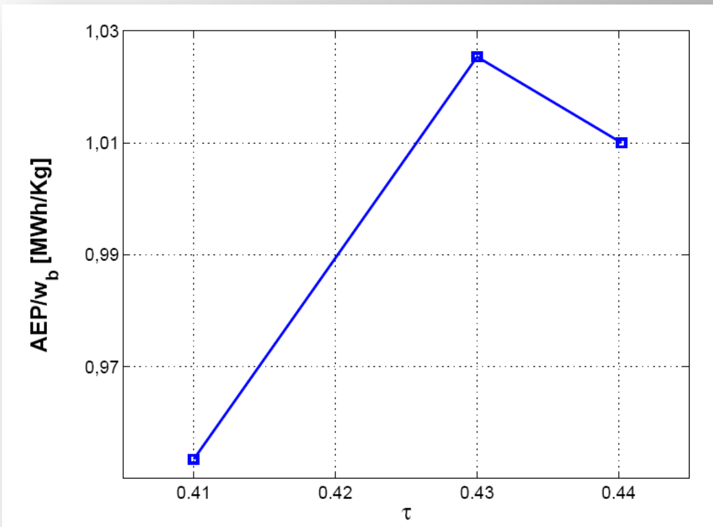
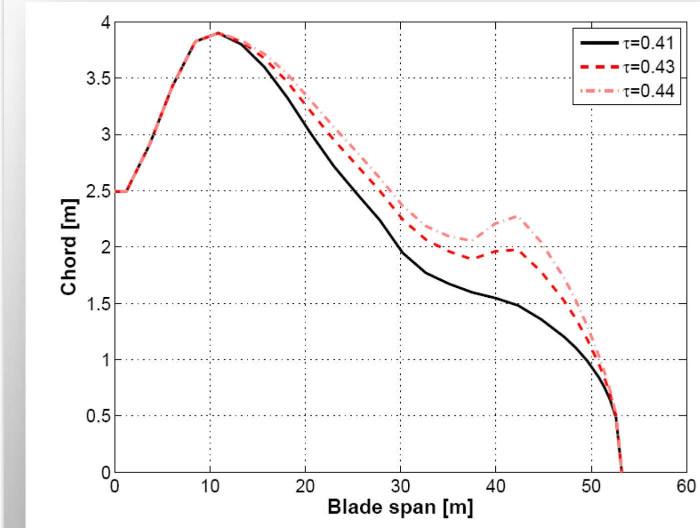
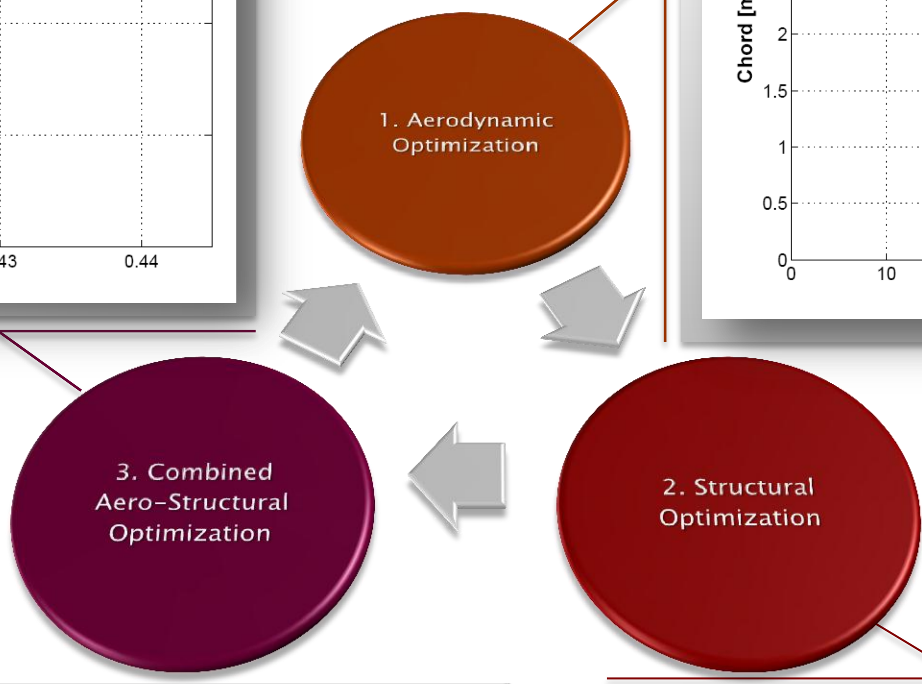
Optimization of a 3MW Wind Turbine



Parameter: blade tapering, constrained max chord





Long blade span (D=106.4m) and small maximum chord (3.9m) is penalized by **excessive outboard chords** (lower flap frequency/increased tip deflections)

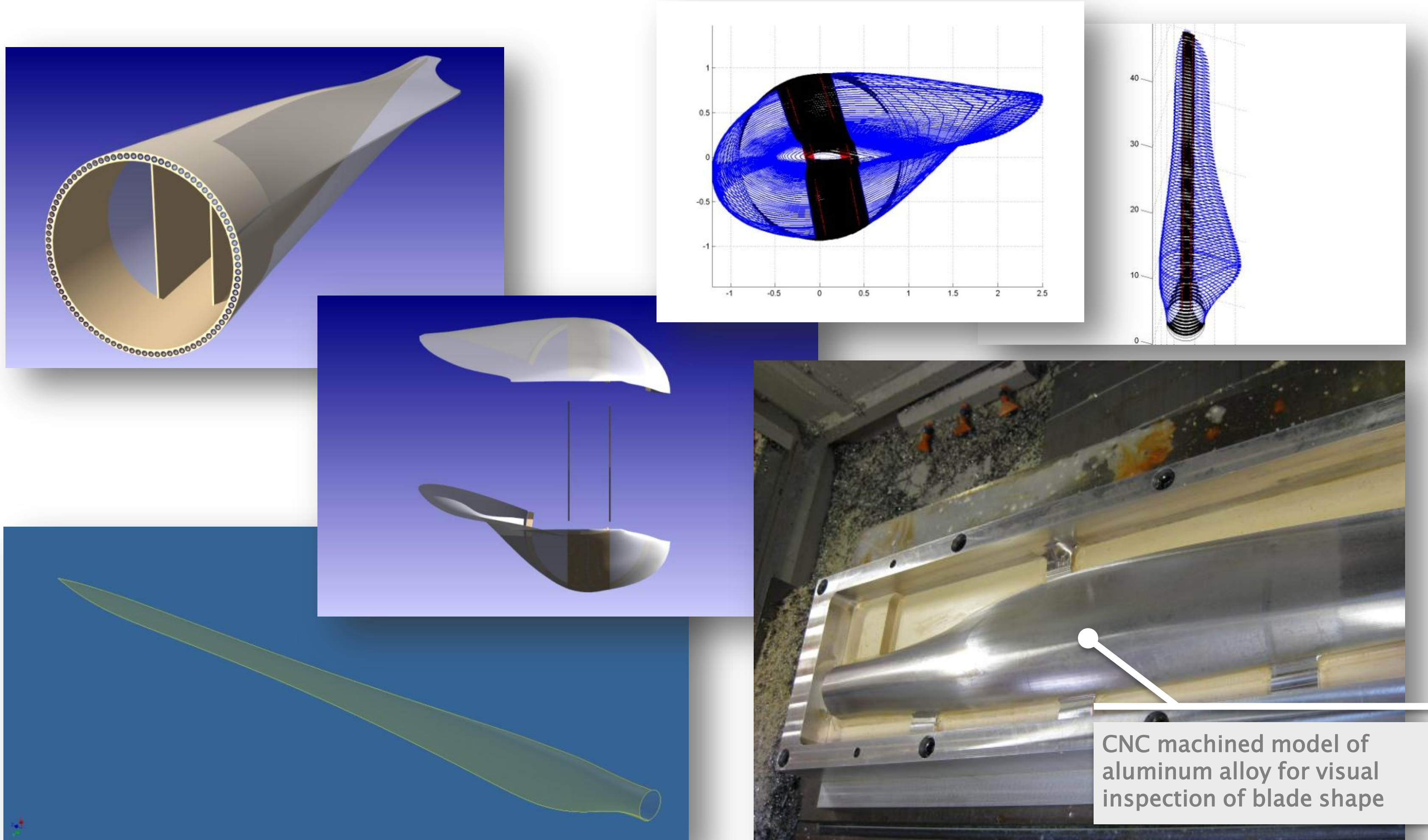
Optimal solution: **intermediate taper**

τ	P_y^* [MWh]	C_P^{II}	λ^{II}	$V_{II^{1/2}}$ [m/sec]	V_r [m/sec]	w_b^* [Kg]
0.41	1.334e4	0.4930	9.241	8.2	11.5	13993
0.43	1.354e4	0.4898	8.396	9.0	10.9	13206
0.44[a]	1.356e4	0.4877	8.191	9.2	10.8	13426

[a] No constraint on τ.

2MW 45m Wind Turbine Blade

Production of First Prototype 3rd Quarter 2010

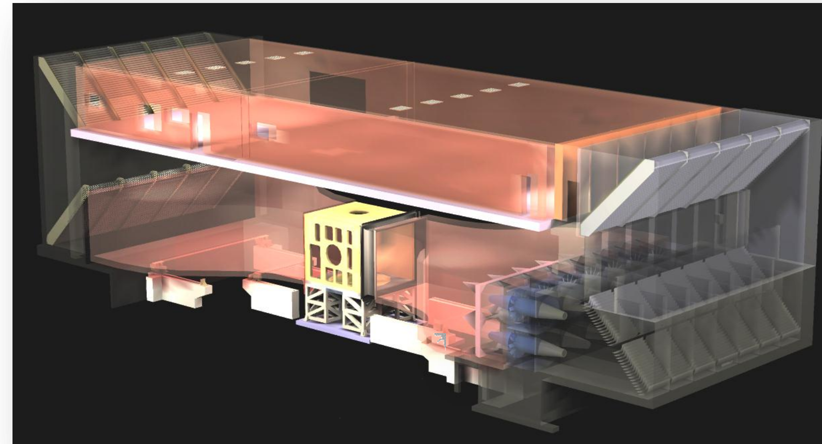


Design developed in partnership with Gurit (UK)

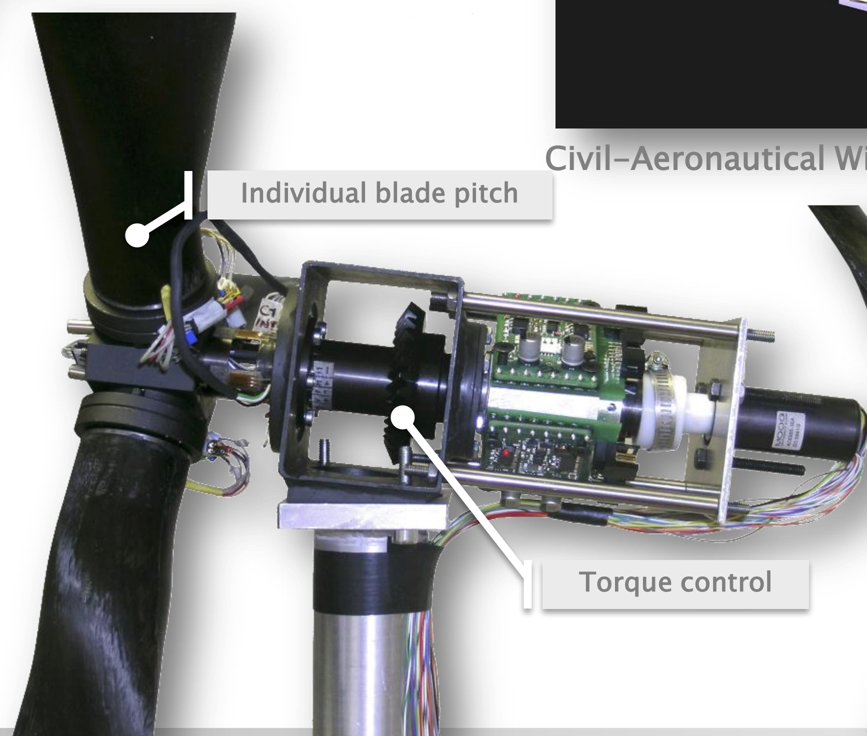
WT², the Wind Turbine in a Wind Tunnel

Aero-elastically scaled wind turbine model for:

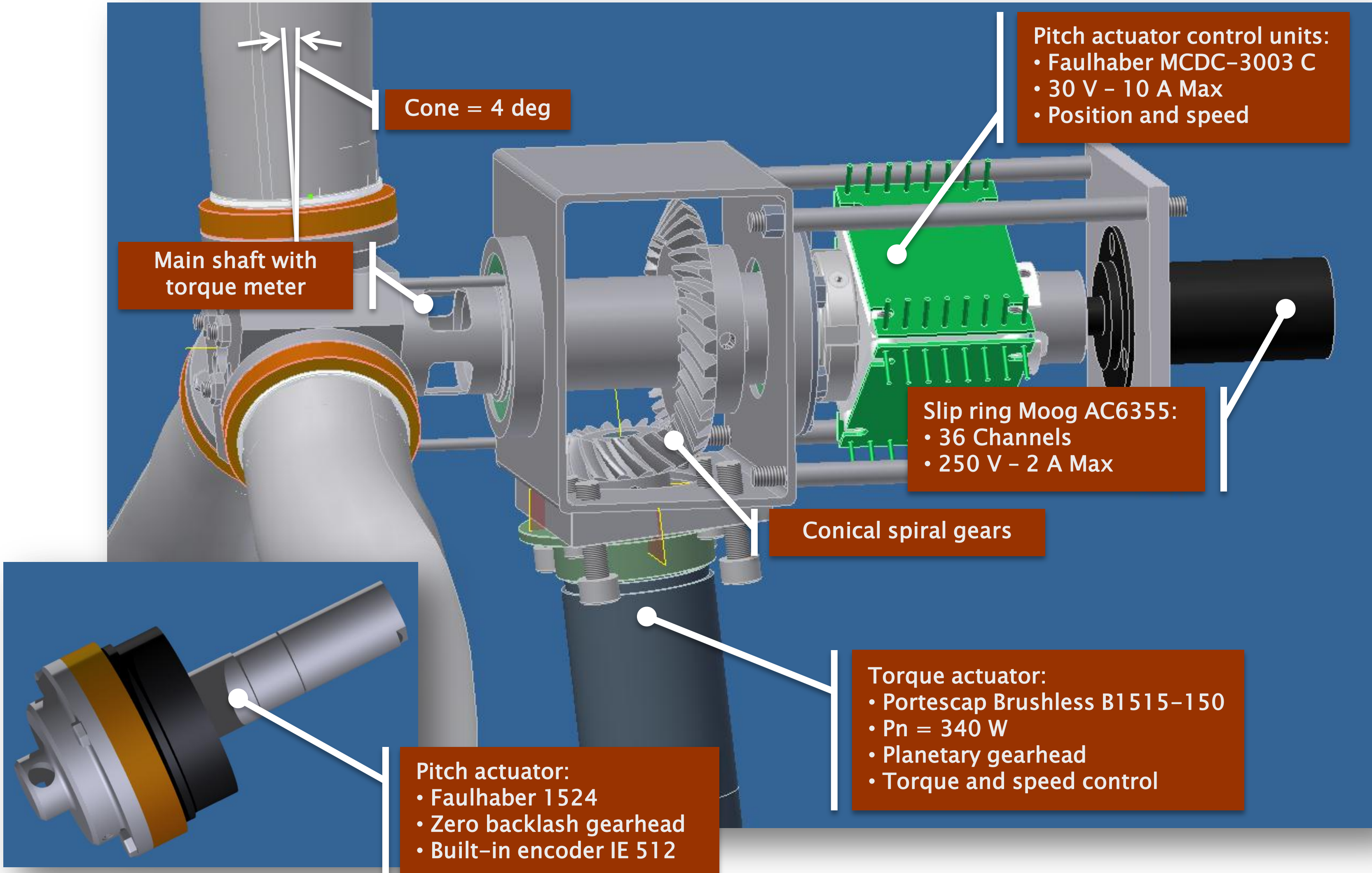
- Testing and comparison of advanced control laws and supporting technologies
- Testing of extreme operating conditions



Civil-Aeronautical Wind Tunnel – Politecnico di Milano

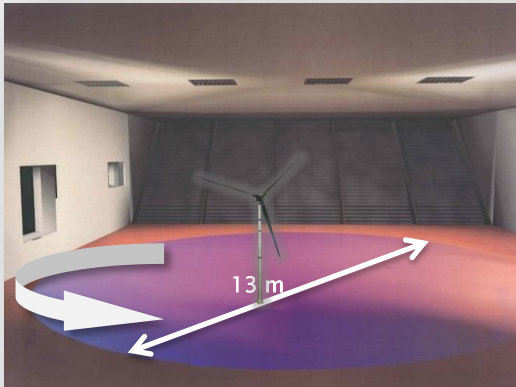


WT², the Wind Turbine in a Wind Tunnel

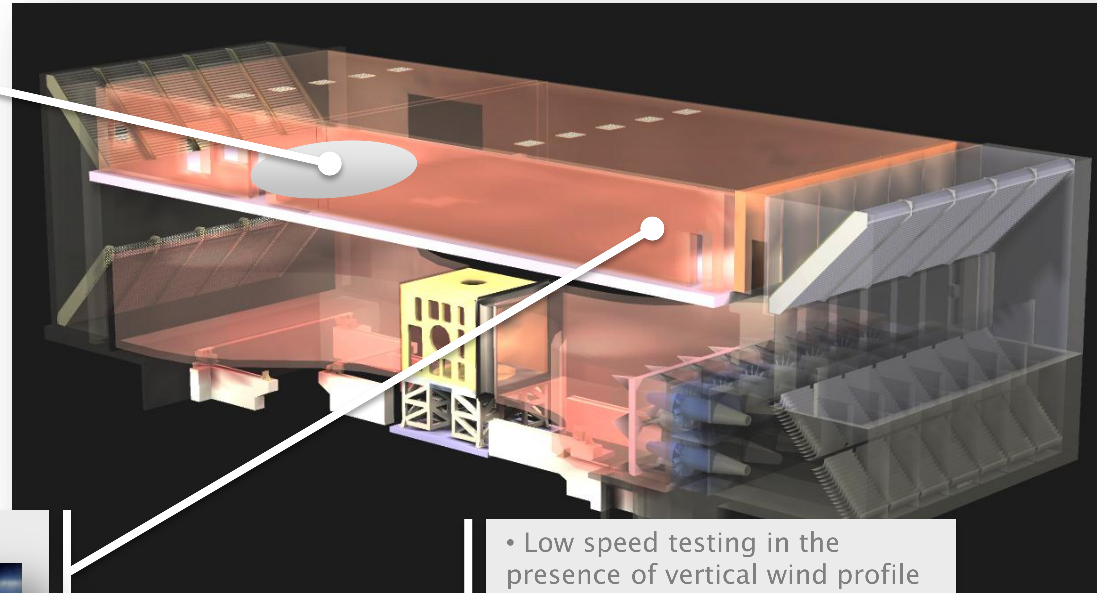


WT², the Wind Turbine in a Wind Tunnel

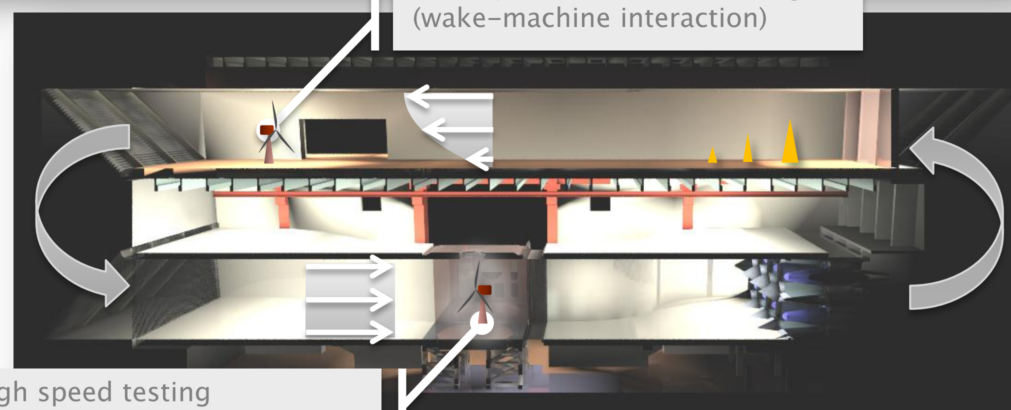
Turn-table



Turbulence (boundary layer) generators

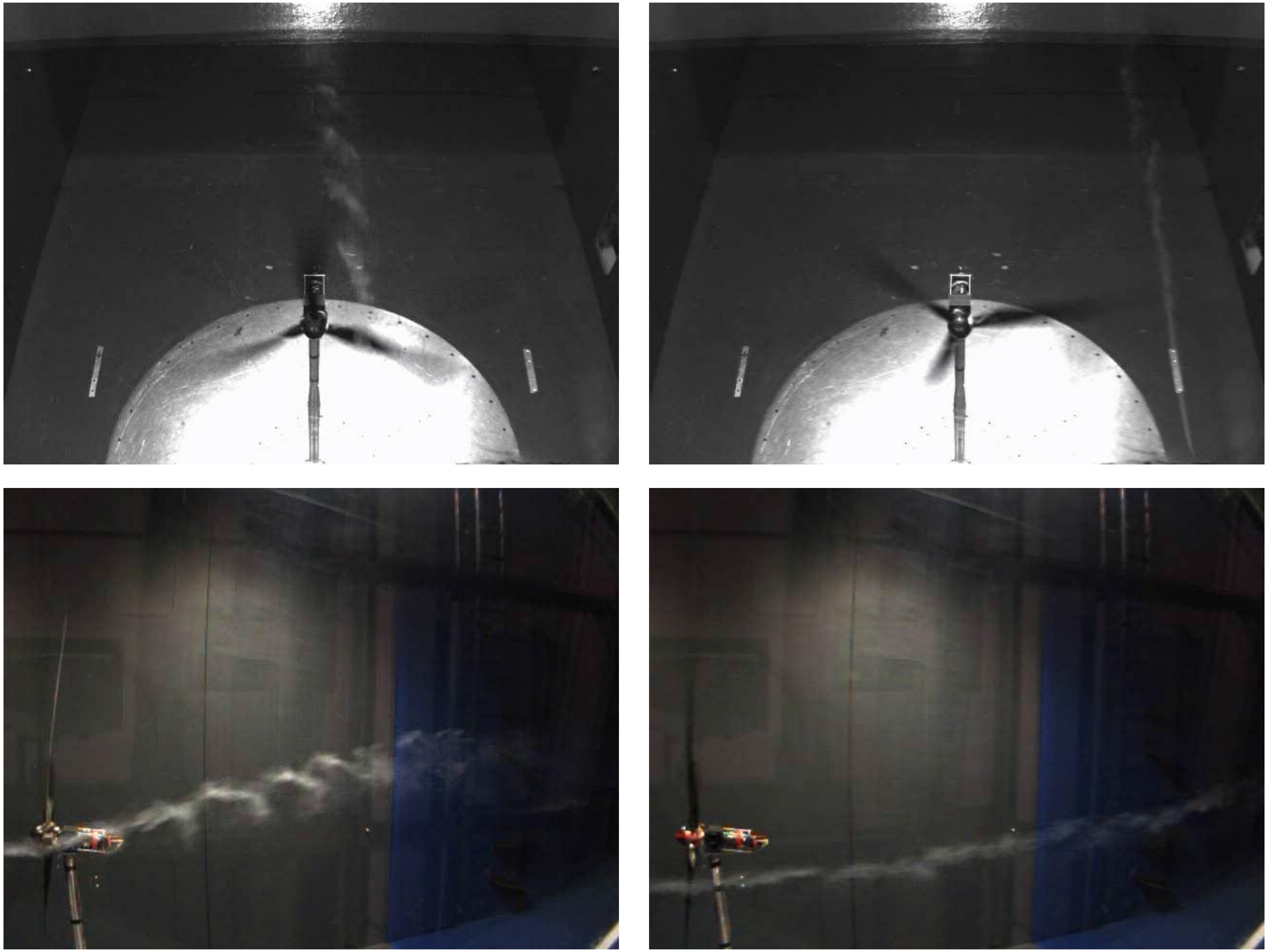


- Low speed testing in the presence of vertical wind profile
- Multiple wind turbine testing (wake-machine interaction)



- High speed testing
- Aerodynamic characterization (C_p–TSR–β & C_F–TSR–β curves)

WT^2, the Wind Turbine in a Wind Tunnel



First wind tunnel entry April 2010

Design of an Aero-elastically Scaled Composite Blade

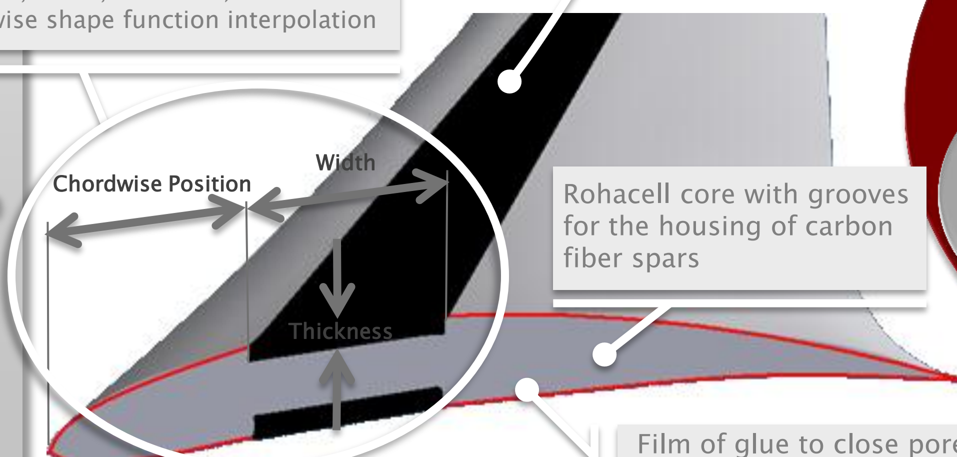
Carbon fiber spars

Airfoil cross section

Carbon fiber spars for desired stiffness

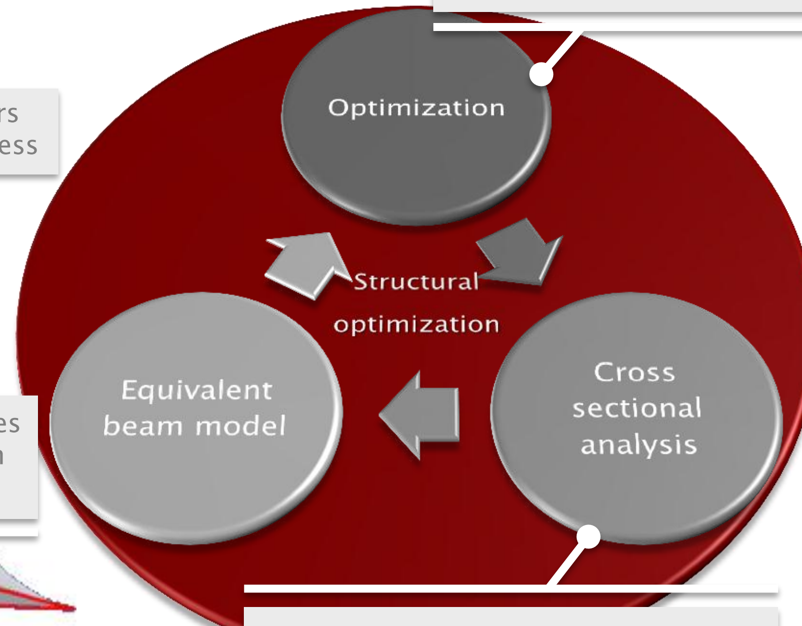
Objective: size spars (width, chordwise position & thickness) for desired sectional stiffness within mass budget
Cost function: sectional stiffness error wrt target (scaled stiffness)
Constraints: lowest 3 frequencies

Sectional optimization variables (position, width, thickness)
Span-wise shape function interpolation



Rohacell core with grooves for the housing of carbon fiber spars

Film of glue to close pores and ensure smooth finish

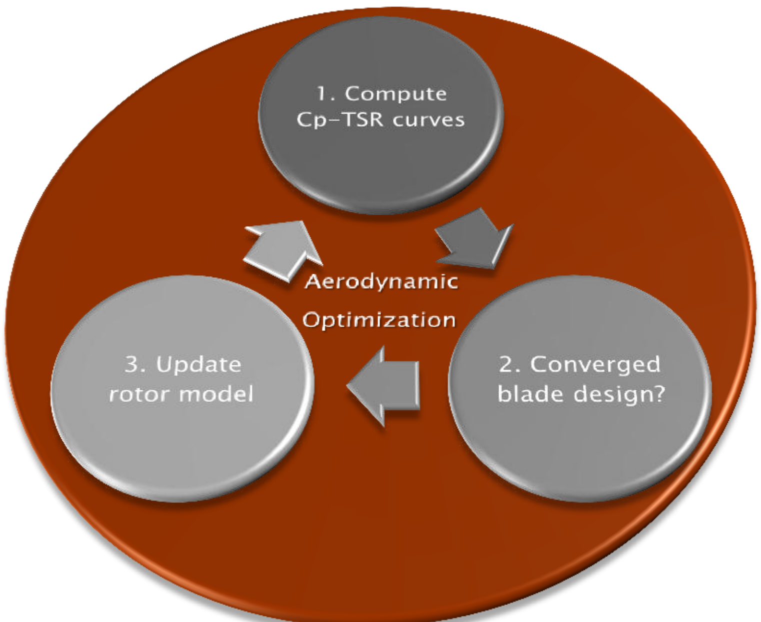


ANBA (ANisotropic Beam Analysis) FEM cross sectional model:
- Evaluation of cross sectional stiffness (6 by 6 fully populated matrix)

Aerodynamic Design of Model Blade

	WT^2	V90
Rotor Diameter	2 [m]	90 [m]
Blade Length	977.8 [mm]	44 [m]
Rotor Speed	367 [rpm]	16 [rpm]
Average Reynolds	≈ 5÷6 e4	≈ 4÷5 e6

Reynolds mismatch:
- Use low-Re airfoils (AH79 & WM006) to minimize aerodynamic differences
- Keep same chord distribution as original V90 blade but
- Adjust blade twist to optimize axial induction factor



Conclusions

Presented **holistic optimization procedures** for wind turbines:

• **Refined models**: **aero-servo-elastic multibody** + **FEM cross sectional analysis** can account for complex effects and couplings from the very inception of the design process (no a-posteriori fixes)

• **Fully automated**: no manual intervention, including **self-tuning model-based controller** that adjusts to changes in the design

• **Fast design loop**: can perform a full design in 1-2 days on standard desktop computing hardware

• **General and expandable**: can readily add constraints to include further design requirements

• **Ready-to-use multibody aero-servo-elastic model of final design**: available for further analyses/verifications, evaluation of loads for design of sub-components, etc.

Outlook

Real-life applications:

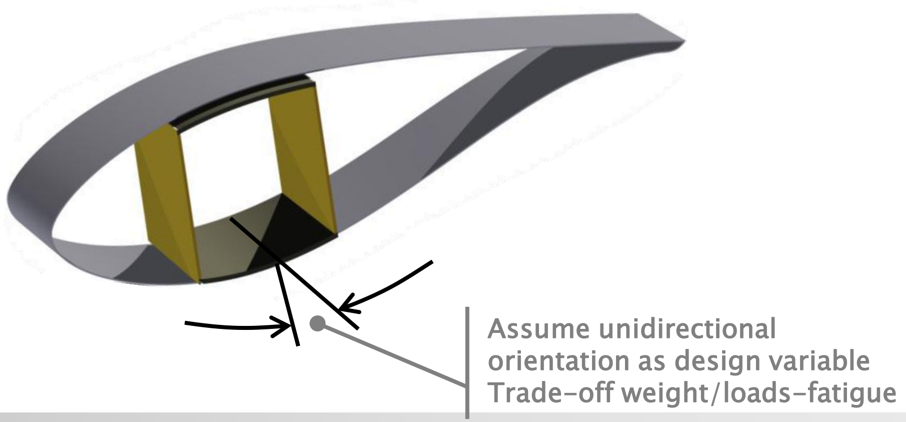
- Completed design of **45m** blade (to be manufactured 3rd quarter 2010)
- Design of **16.5m** blade under development

Software enhancements:

- Buckling and fatigue within optimization loop
- Automated generation of 3D FEM model for detailed verification

Future applications:

- Aeroelastic tailoring: optimal blade design with flap-pitch coupling (embedded load alleviation)



Acknowledgements

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Thanks to **A. Croce** and **F. Campagnolo** and to the **POLI-Wind** team