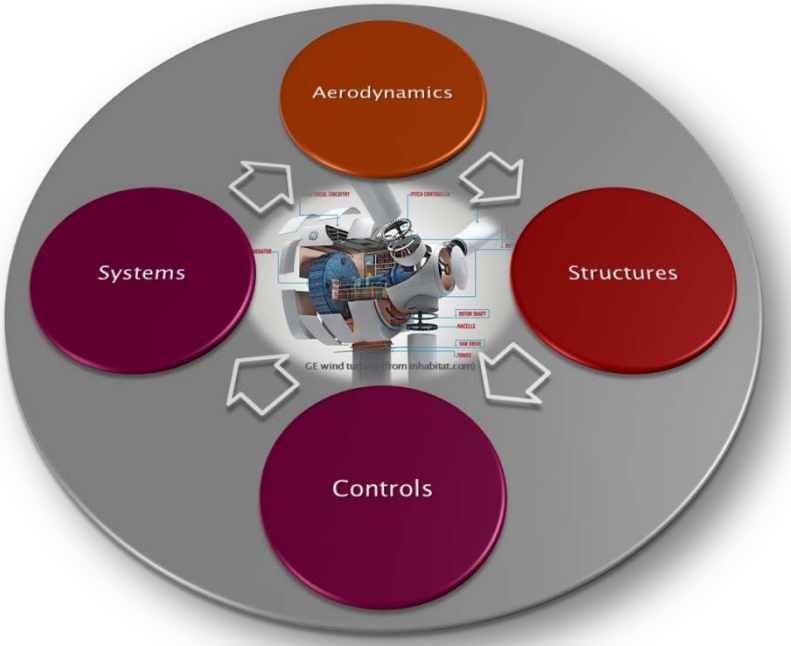
MULTIDISCIPLINARY DESIGN OPTIMIZATION OF WIND ENERGY SYSTEMS

Carlo L. Bottasso
Politecnico di Milano



2nd NREL Wind Energy Systems Engineering Workshop
Broomfield, CO, 29–30 January 2013

POLItecnico di MILano

Outline

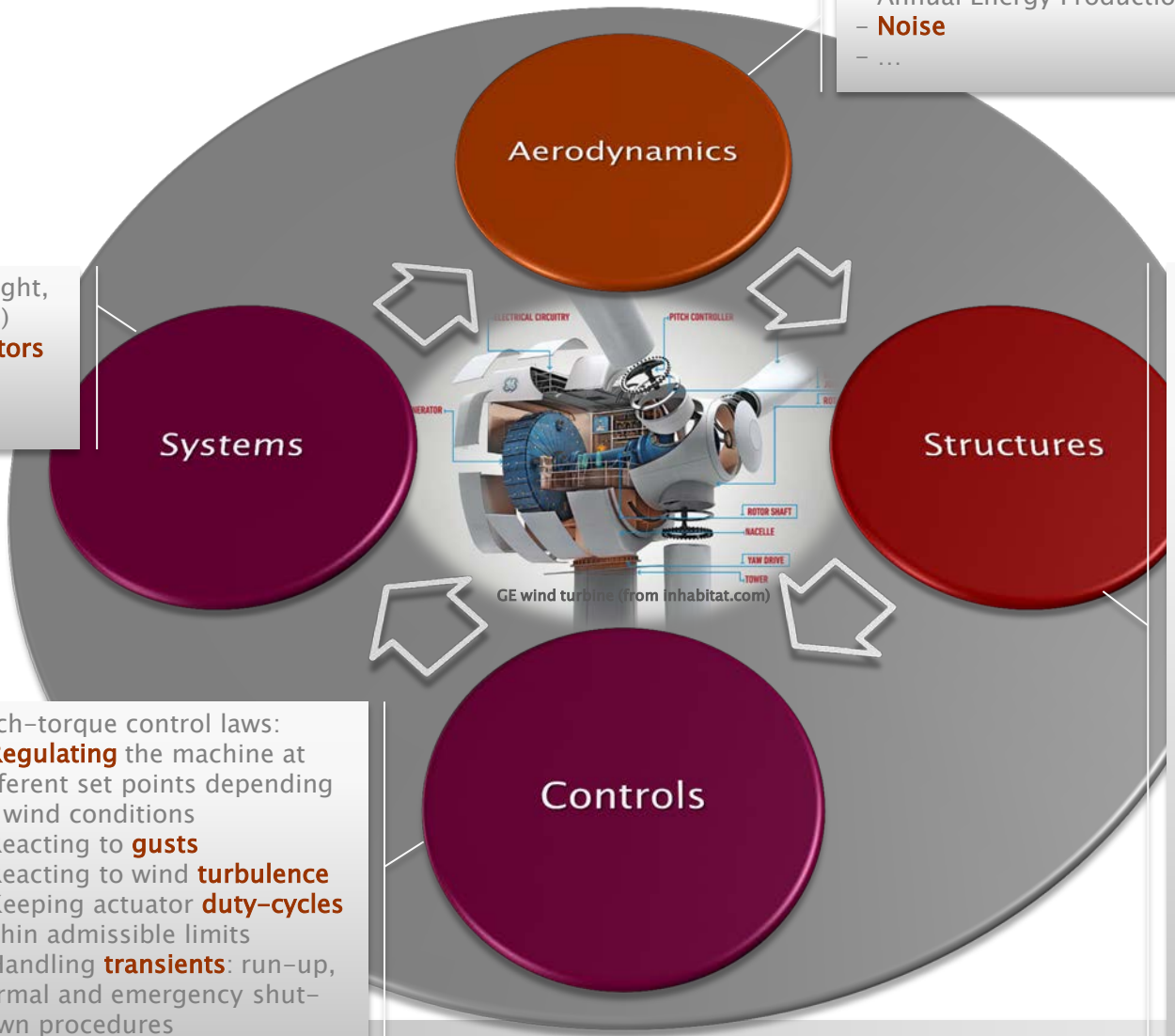
- Introduction and motivation
- Approach:
  - Constrained multi-disciplinary optimization by physics-based cost of energy (CoE) models
  - Multi-level analysis (1D spatial beams+2D sections, 3D FEM)
  - Comprehensive wind turbine simulation tools
  - Tool validation/calibration by wind tunnel testing
- Applications and results
- Conclusions and outlook

Outline

- Introduction and motivation
- Approach:
  - Constrained multi-disciplinary optimization by physics-based cost of energy (CoE) models
  - Multi-level analysis (1D spatial beams+2D sections, 3D FEM)
  - Comprehensive wind turbine simulation tools
  - Tool validation/calibration by wind tunnel testing
- Applications and results
- Conclusions and outlook

Holistic Design of Wind Turbines

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



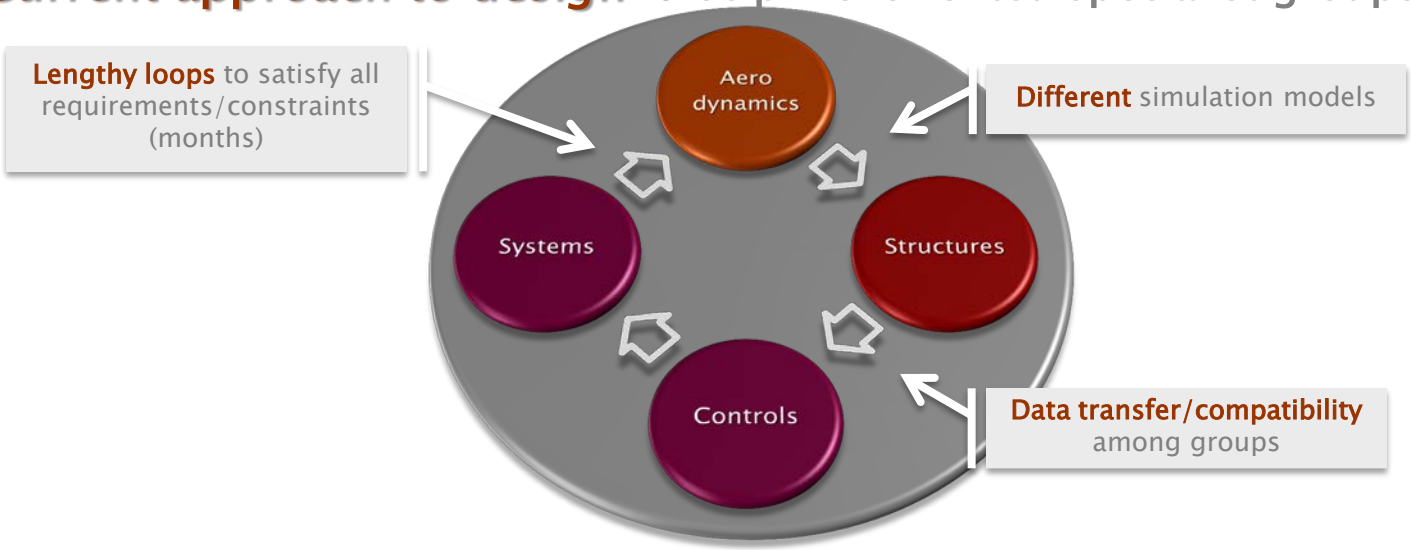
- **Generator** (RPM, weight, torque, drive-train, …)
- Pitch and yaw **actuators**
- Brakes
- …

- **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

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
- …

Holistic Design of Wind Turbines

Current approach to design: discipline-oriented specialist groups



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

- Be fast (hours/days) (on standard desktop hardware!)
- 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

Holistic Design of Wind Turbines

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

Figure of merit: physics-based model of the cost of energy

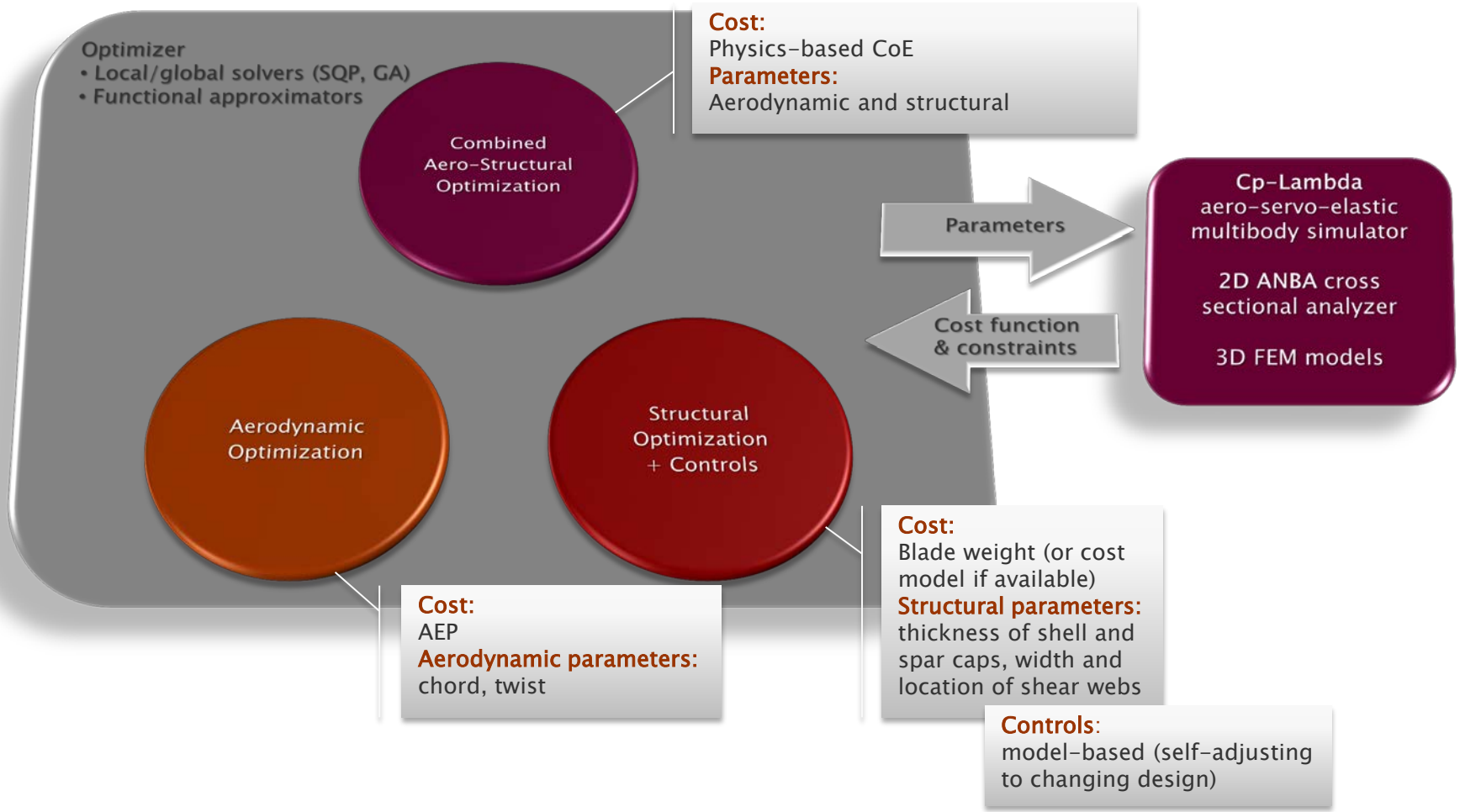
Applications:

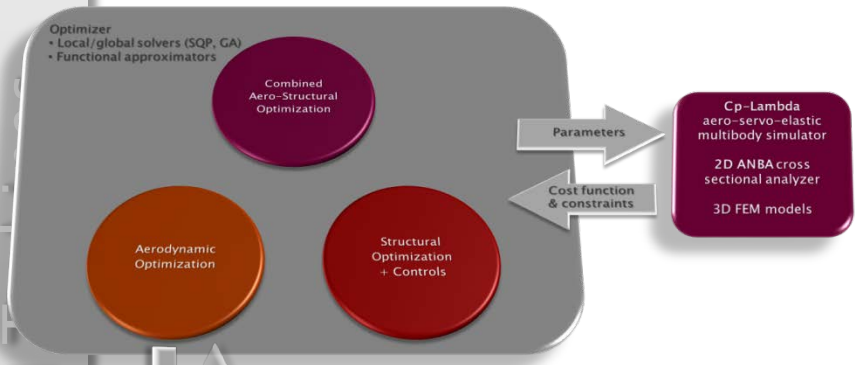
- Sizing of a new machine
- Improvement of a tentative configuration
- Trade-off studies (e.g. performance-cost)
- Modifications to exiting models

Outline

- Introduction and motivation
- Approach:
  - Constrained multi-disciplinary optimization by physics-based cost of energy (CoE) models
  - Multi-level analysis (1D spatial beams+2D sections, 3D FEM)
  - Comprehensive wind turbine simulation tools
  - Tool validation/calibration by wind tunnel testing
- Applications and results
- Conclusions and outlook

Optimization-Based Multi-Level Blade Design

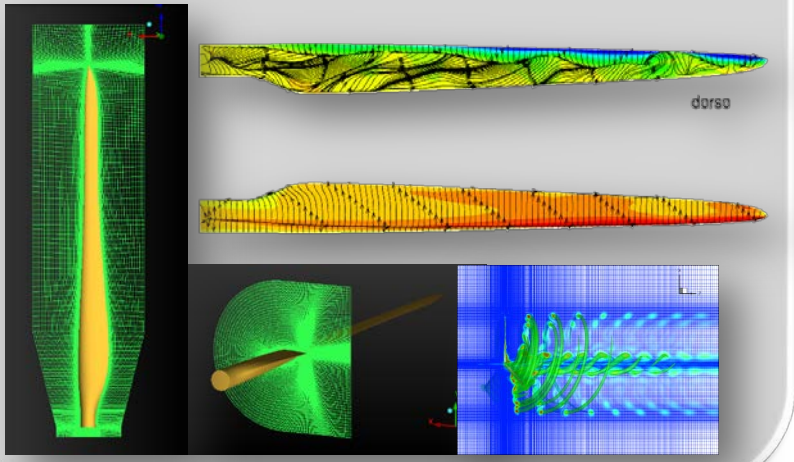




Only weak up link
(e.g. 3D root corrections)

Aerodynamic verification (RANS & LES)

Applications: tip, 3D root effects, wind tunnel

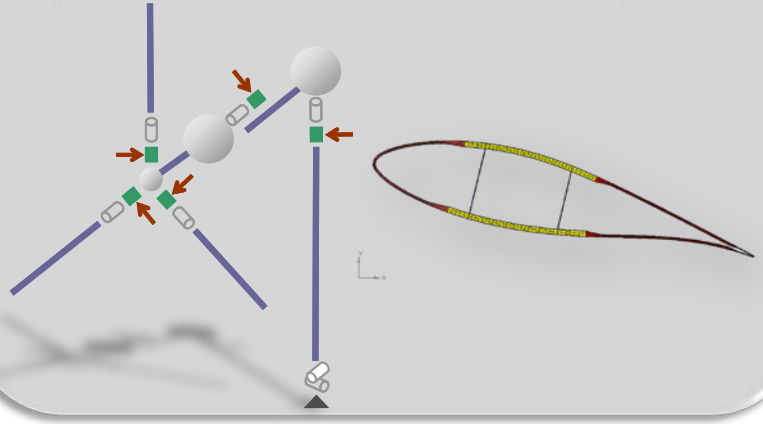


Multi-level analysis

"Coarse" aero-servo-elastic level:

1D spatial beam +2D sectional models

Applications: loads, performance, aeroleasticity

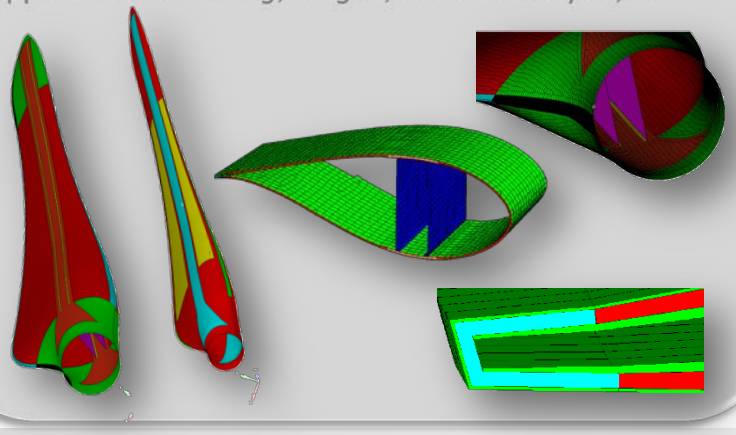


Up-down fully
automated links

"Fine" 3D structural level:

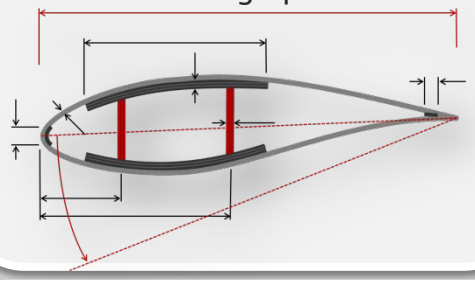
CAD+ 3D FEM

Applications: buckling, fatigue, detailed analysis, ...

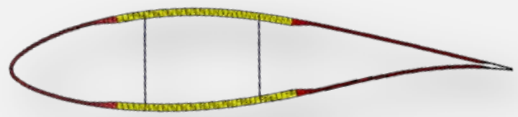


Aeroservoelastic-Level Optimization

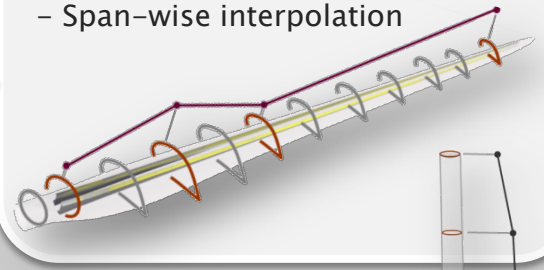
Blade: definition of aerodynamic & structural design parameters



Blade:
- ANBA 2D FEM sectional analysis
- Compute 6x6 stiffness matrices



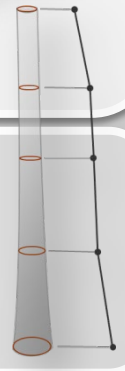
Blade:
- Geometrically exact beam model
- Span-wise interpolation



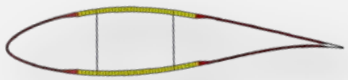
Tower: definition of structural design parameters

Tower:
- Compute stiffness matrices

Tower:
- Geom. exact beam model
- Height-wise interpolation



Blade constraints:
- Maximum tip deflection
- Natural frequencies
- Max stresses/strains (ANBA)
- Fatigue (ANBA)



▸ Update blade mass & cost

Tower constraints:
- Natural frequencies
- Max stresses/strains
- Fatigue

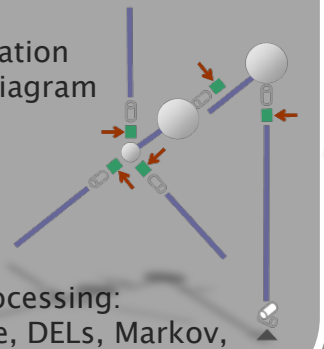
▸ Update tower mass & cost

SQP optimizer

min cost
subject to constraints

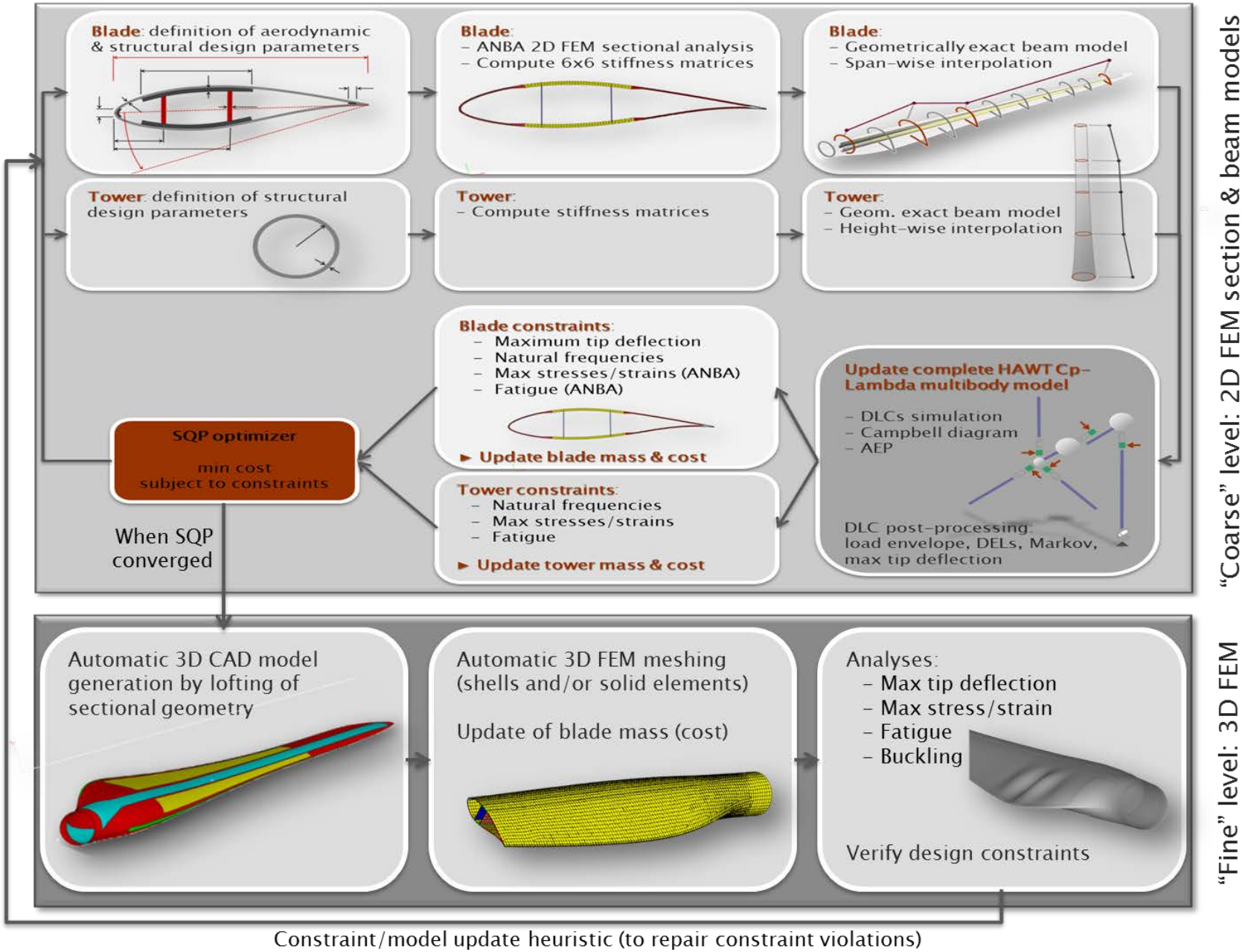
Update complete HAWT Cp-Lambda multibody model

- DLCs simulation
- Campbell diagram
- AEP



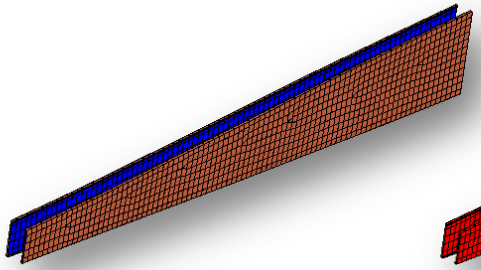
DLC post-processing:
load envelope, DELs, Markov, max tip deflection

Multi-Level Optimization

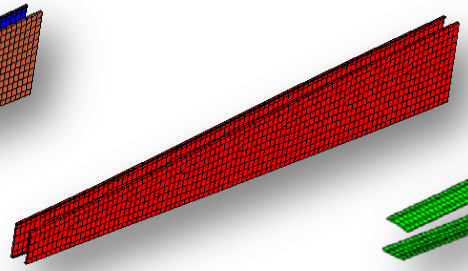


3D FEM Blade Modeling

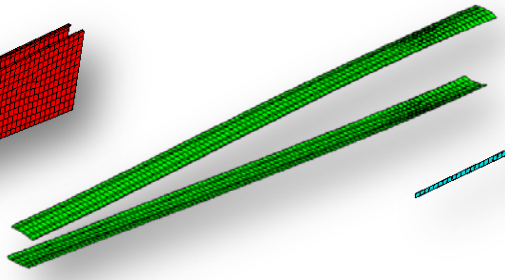
3D CAD with solid and shell (with or without offsets) meshing directly from coarse-level model data:



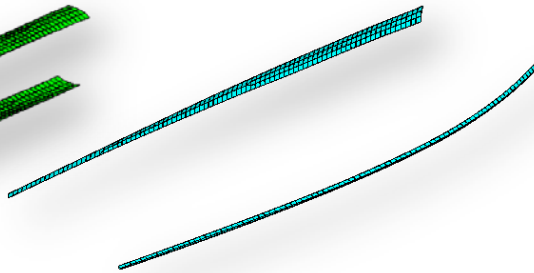
Webs +



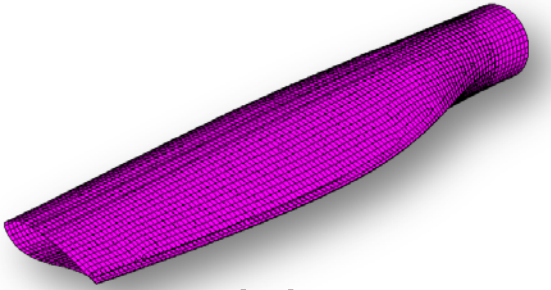
Web core +



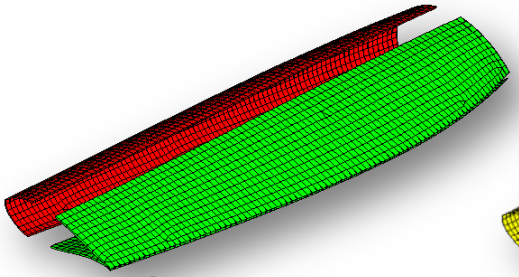
Spar caps +



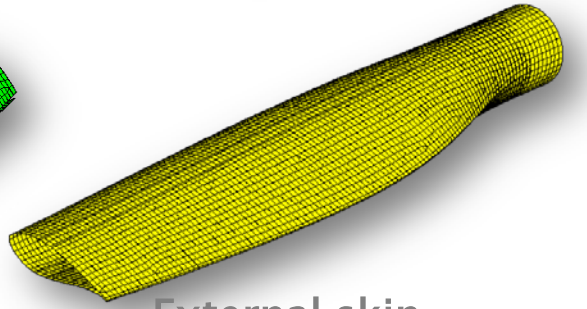
LE & TE reinforcements



Internal skin +

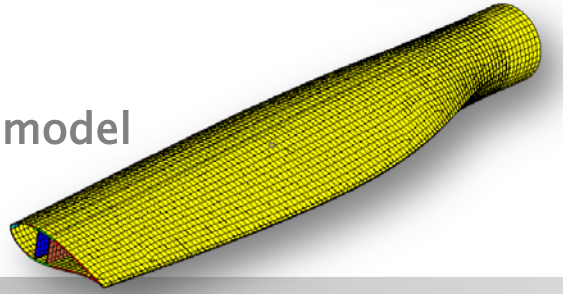


Skin core +

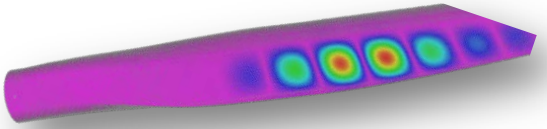


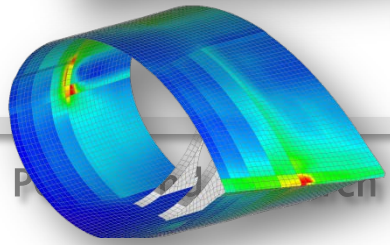
External skin

= Complete model



⇒ Analyses





Physics-based Cost Function

Cost model (Fingersh at al., 2006):

$$CoE = \frac{FixedChangeRate * InitialCapitalCost(p)}{AEP(p)} + AnnualOperatingExpenses(p)$$

where p = design parameters (at the moment for rotor and tower)

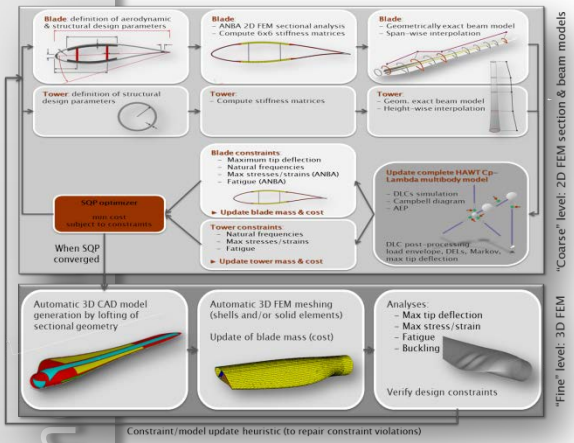
When possible, **avoid scaling relationships** and compute cost item **directly from model information**

Example:

- Detailed blade geometry ⇒ bill of materials ⇒ blade material cost
- Detailed tower geometry ⇒ bill of materials ⇒ tower material cost
- Torque ⇒ Gear-box mass (from mass scaling model)
- Etc. …

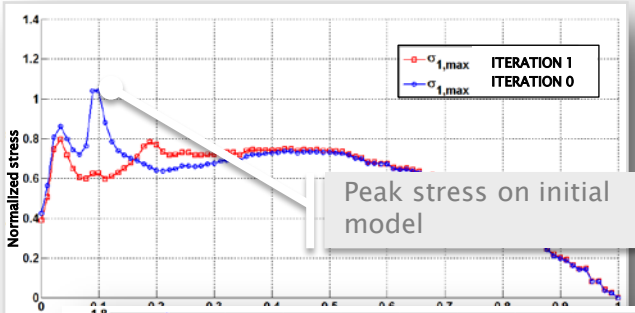
Ideally this should be done for all major components (when not possible, use scaling relationships)

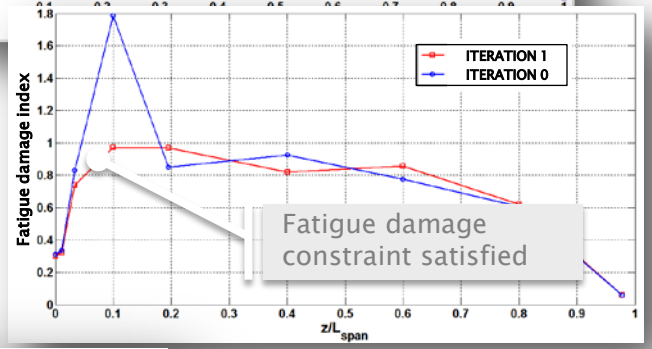
The Importance of Multi-Level Blade Design



Stress/strain/fatigue:

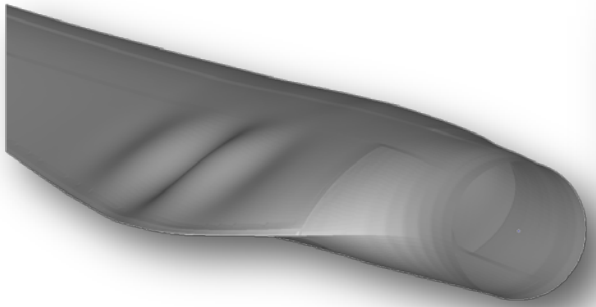
- Fatigue constraint not satisfied at first iteration on 3D FEM model
- Modify constraint based on 3D FEM analysis
- Converged at 2nd iteration

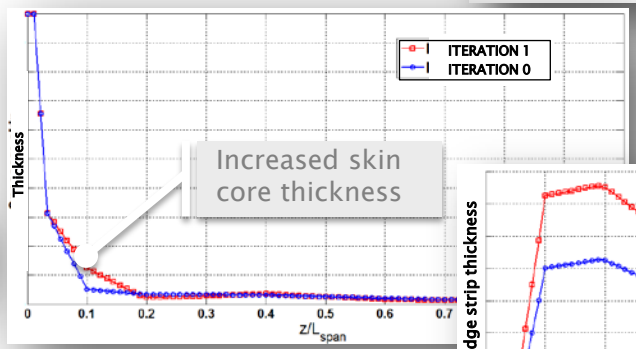


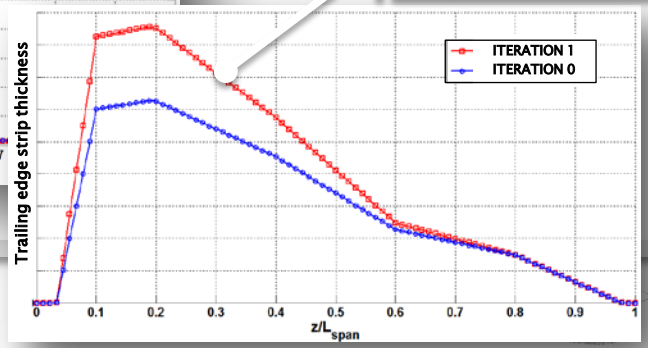


Buckling:

- Buckling constraint not satisfied at first iteration
- Update skin core thickness
- Update trailing edge reinforcement strip
- Converged at 2nd iteration



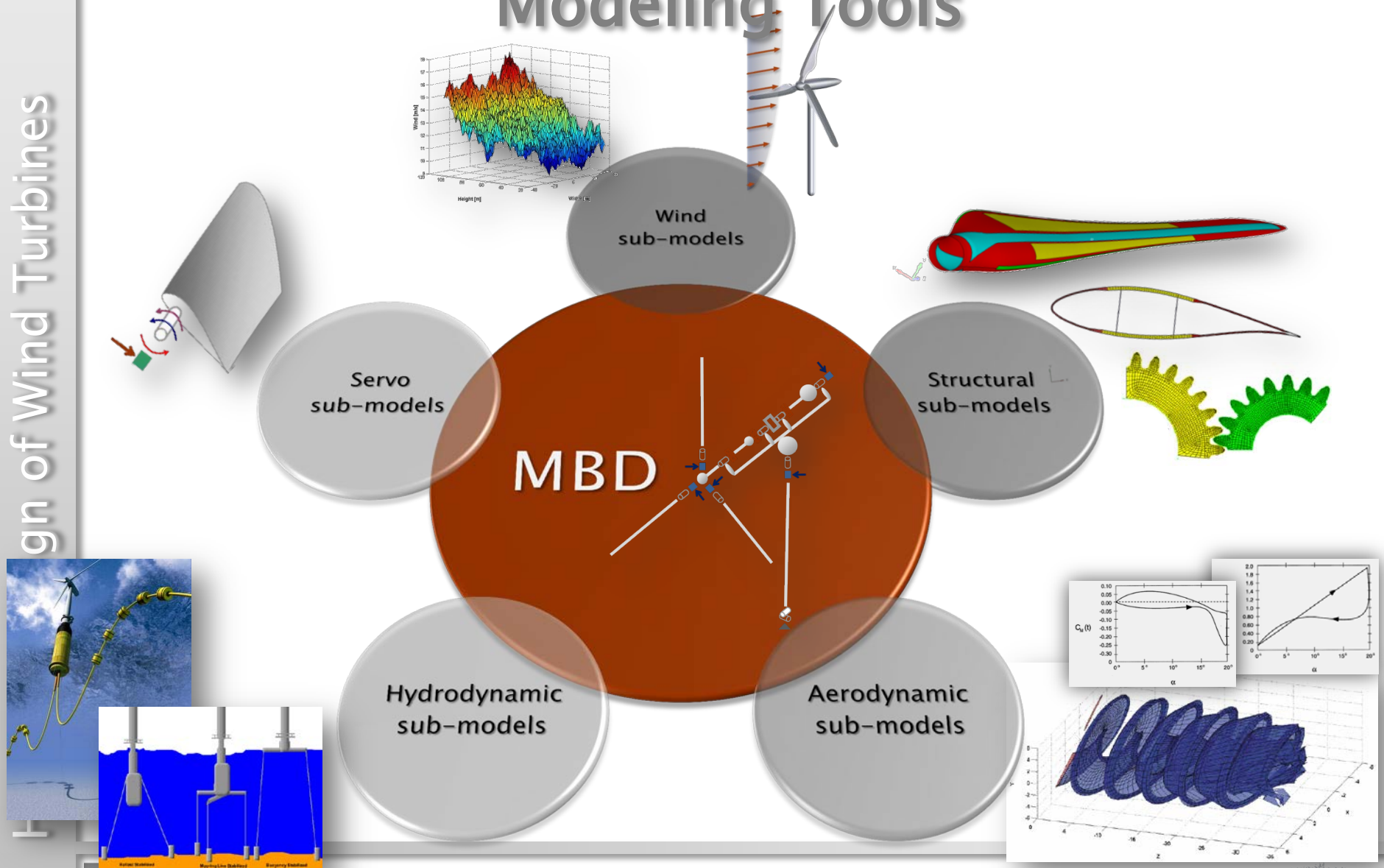


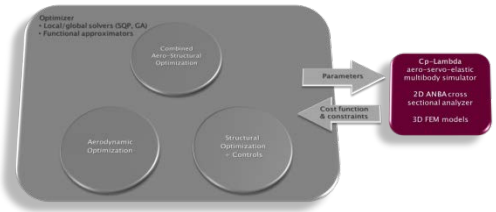


Outline

- Introduction and motivation
- Approach:
  - Constrained multi-disciplinary optimization by physics-based cost of energy (CoE) models
  - Multi-level analysis (1D spatial beams+2D sections, 3D FEM)
  - Comprehensive wind turbine simulation tools
  - Tool validation/calibration by wind tunnel testing
- Applications and results
- Conclusions and outlook

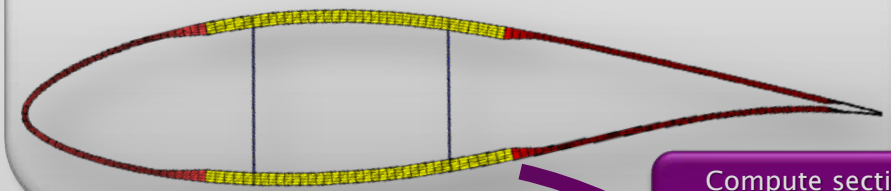
Comprehensive Wind Turbine Modeling Tools





ANBA (Anisotropic Beam Analysis) cross sectional model (Giavotto et al., 1983):

- Evaluation of cross sectional stiffness (6 by 6 fully populated)
- Recovery of sectional stresses and strains

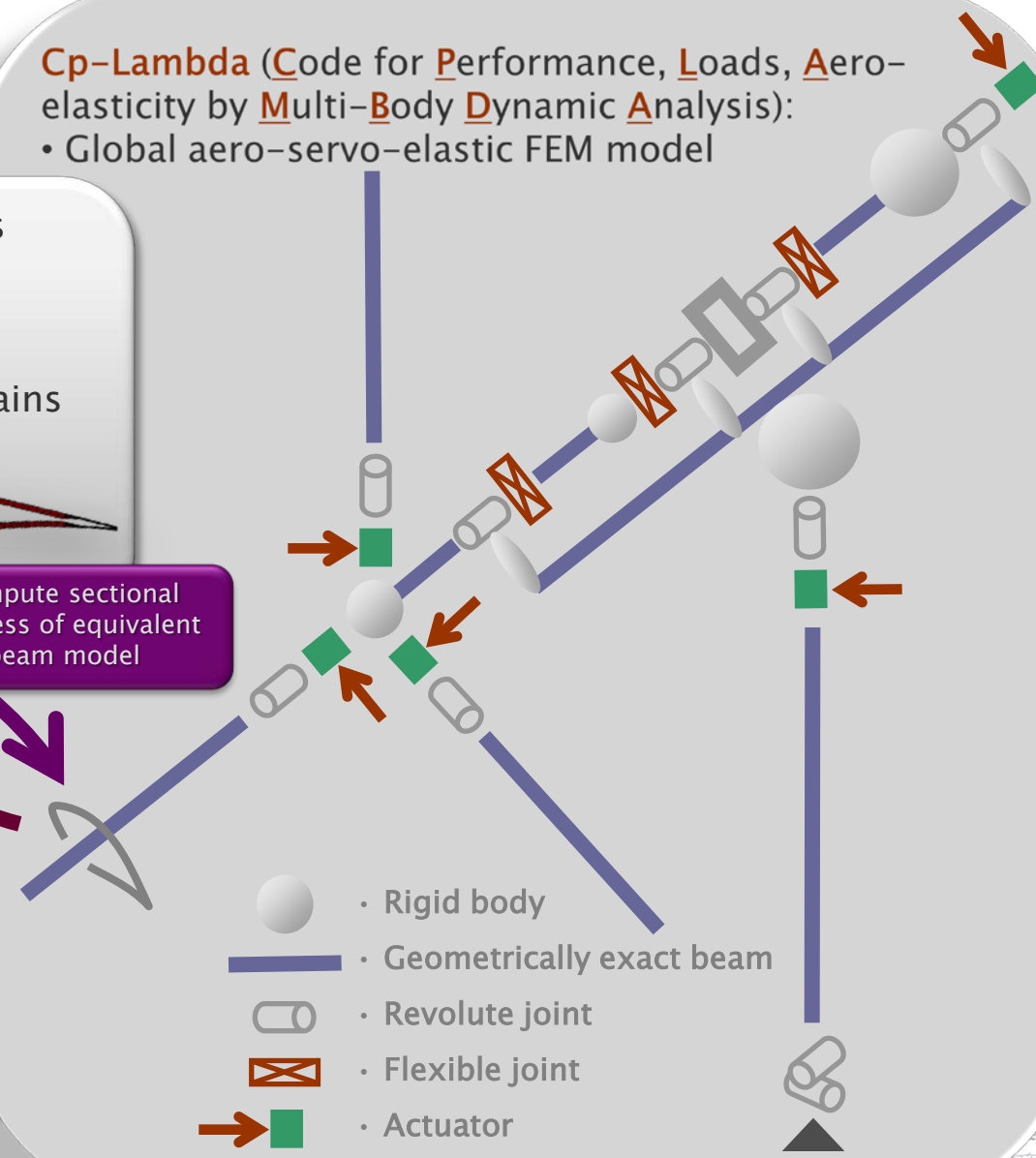


Compute sectional stiffness of equivalent beam model

Compute cross sectional stresses and strains

Cp-Lambda (Code for Performance, Loads, Aero-elasticity by Multi-Body Dynamic Analysis):

- Global aero-servo-elastic FEM model



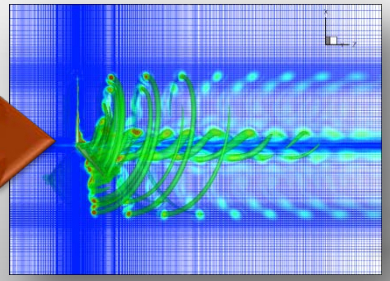
Outline

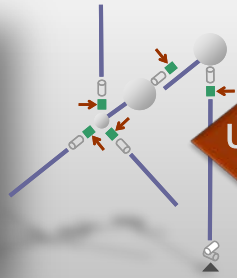
- Introduction and motivation
- Approach:
  - Constrained multi-disciplinary optimization by physics-based cost of energy (CoE) models
  - Multi-level analysis (1D spatial beams+2D sections, 3D FEM)
  - Comprehensive wind turbine simulation tools
  - Tool validation/calibration by wind tunnel testing
- Applications and results
- Conclusions and outlook

Validation/Calibration of Modeling Tools by Wind Tunnel Testing

Field (full-scale) testing

Validated mathematical models





Upscaling

Wind tunnel (scaled) testing

Wind tunnel testing:

– Cons:

Usually impossible to exactly match all relevant physics due to scaling

+ Pros:

Better control/knowledge of conditions/errors/disturbances

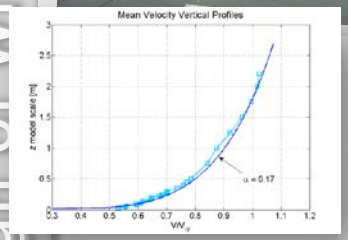
Much lower costs

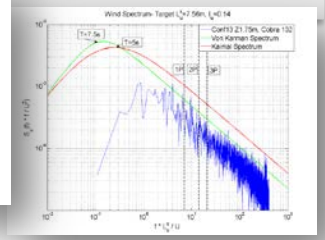
Does not replace simulation nor field testing, but works in **synergy** with them

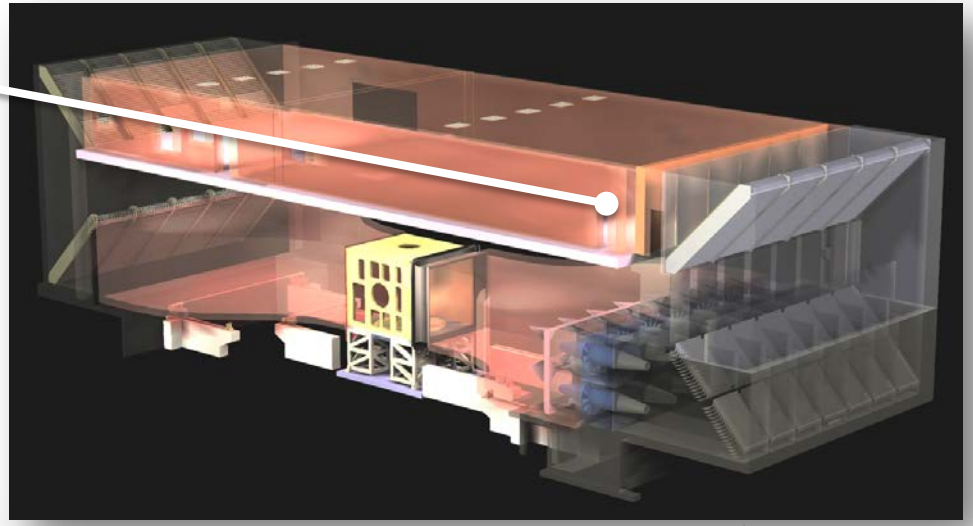
Wind tunnel role is <u>not limited to aerodynamics</u>

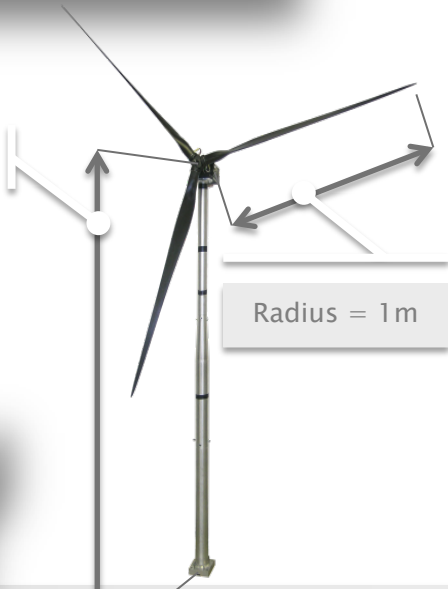
Wind Turbine Wind Tunnel Models

Turbulence (boundary layer) generators



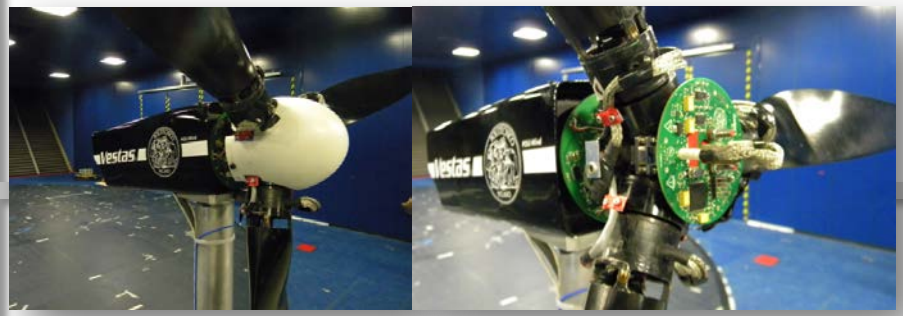


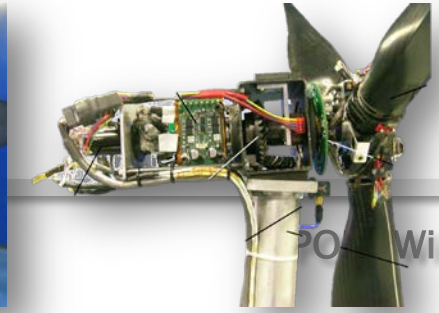




Wind tunnel model of the Vestas V90 wind turbine

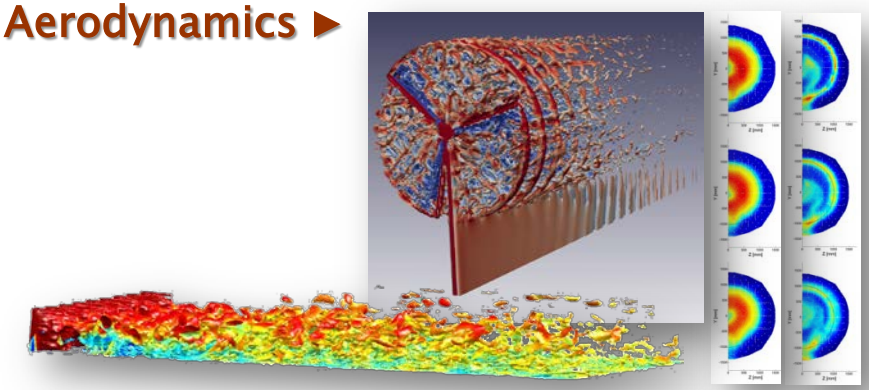
- **Aeroelastically-scaled**
- **Real-time individual blade pitch and torque control**





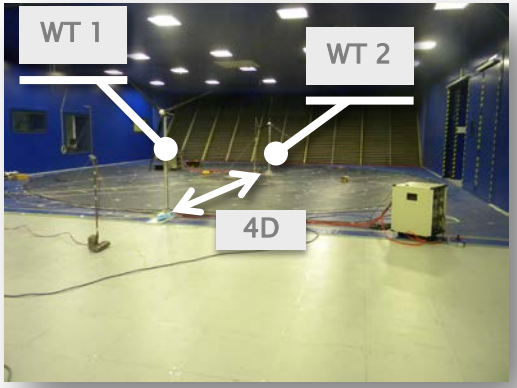
Applications: Aerodynamics and Beyond

Aerodynamics ▶

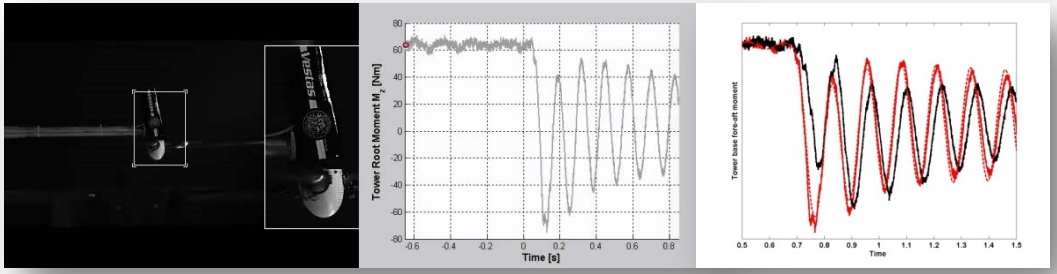


LES+lifting line (Schito & Zasso 2012)

Wake interference conditions ▶

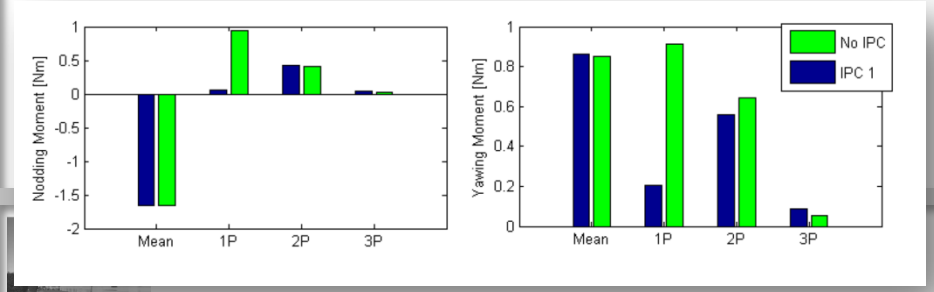


Emergency shutdown ▼

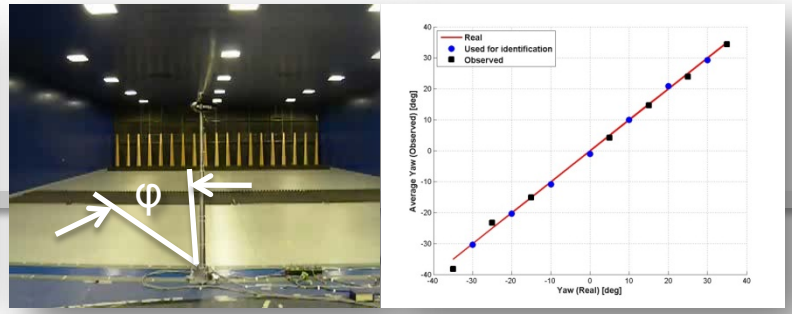


Floating wind turbine ▼

Individual blade pitch control ▼



Wind direction observer ▼



Outline

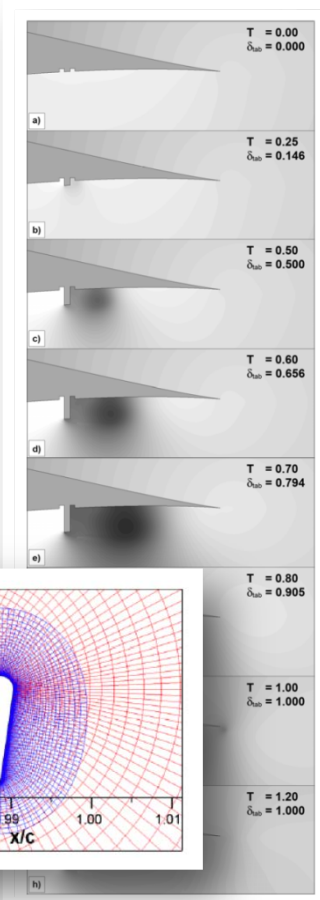
- Introduction and motivation
- Approach:
  - Constrained multi-disciplinary optimization by physics-based cost of energy (CoE) models
  - Multi-level analysis (1D spatial beams+2D sections, 3D FEM)
  - Comprehensive wind turbine simulation tools
  - Tool validation/calibration by wind tunnel testing
- Applications and results
- Conclusions and outlook

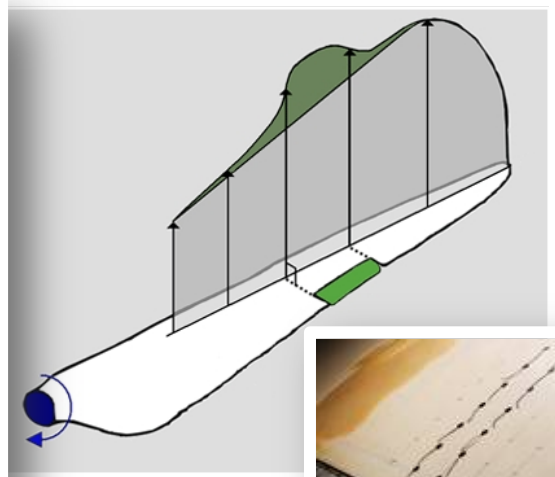
Active Load Mitigation: Smart Blades

Flow control devices:

- TE flaps
- Microtabs
- Vortex generators
- Active jets (plasma, synthetic)
- Morphing airfoils
- …

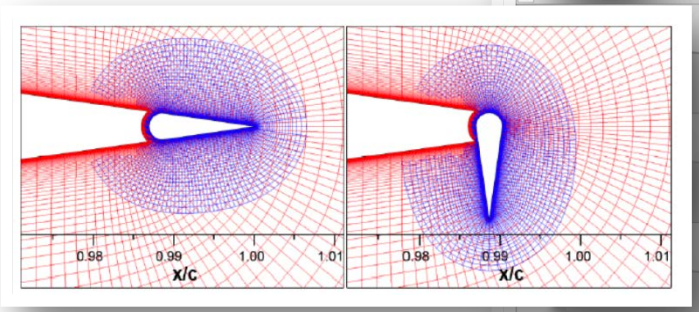
(Chow and van Dam 2007)

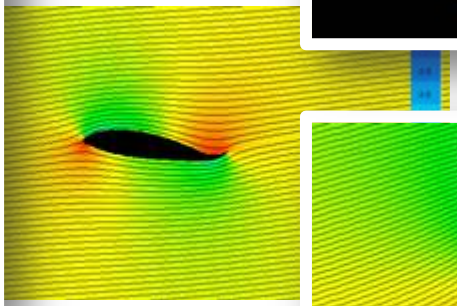


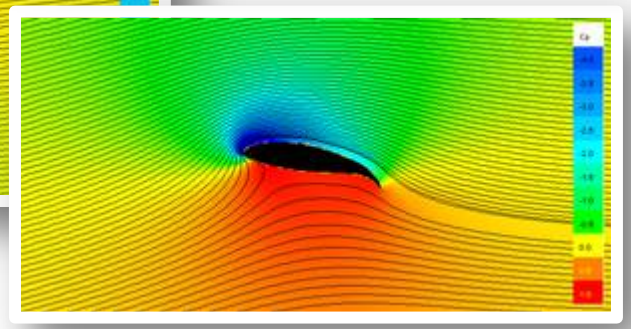


(Credits: Risoe DTU)

(Credits: Risoe DTU)







(Credits: Smart Blade GmbH)

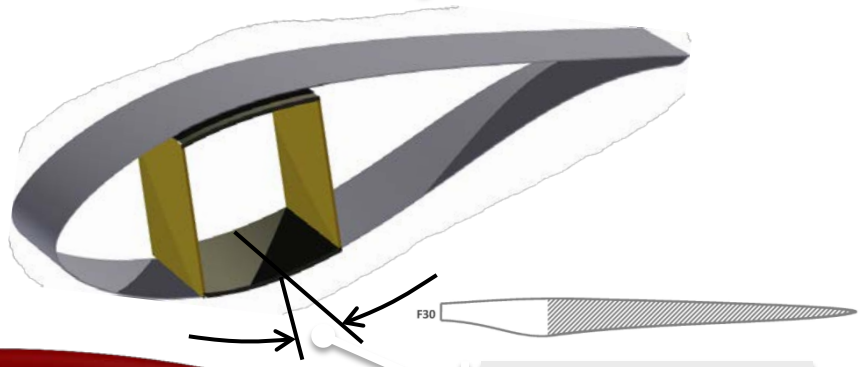
However: complexity/availability/maintenance

Really applicable offshore in the foreseeable future?

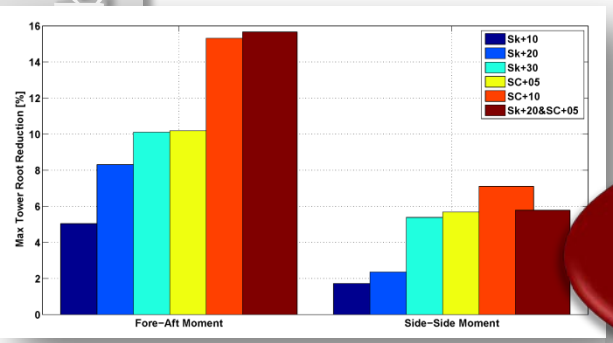
Passive Load Alleviation by BTC

Passive load alleviation: optimal blade design with Bend-Twist Coupling (BTC)

Note: all designs satisfy exactly the same requirements

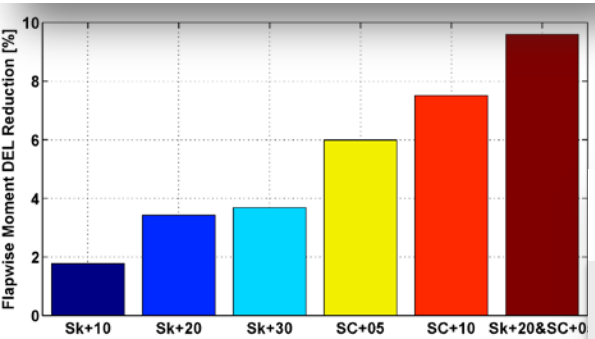


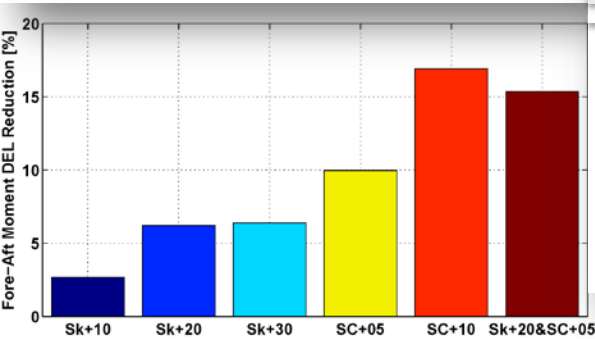
Assume fiber angle as design variable in skin and spar caps

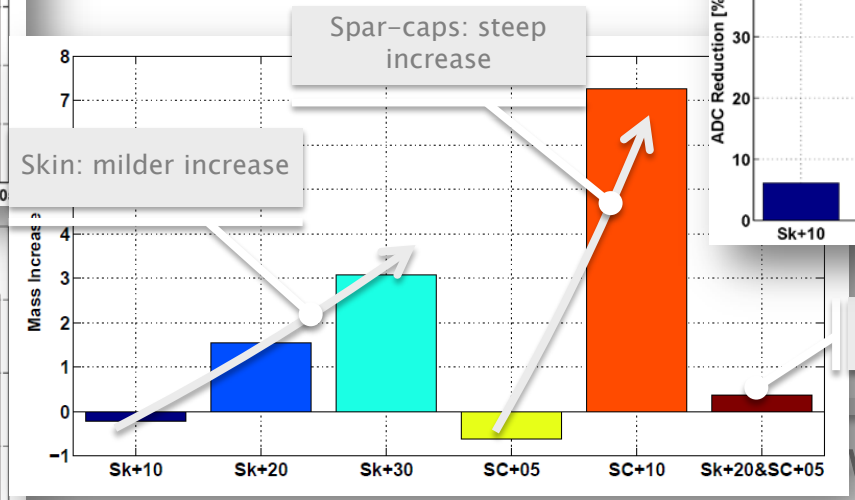


Design trade-offs

+ Decreased load envelope and fatigue
+ Decreased actuator duty cycle
+ Decreased weight
But same power



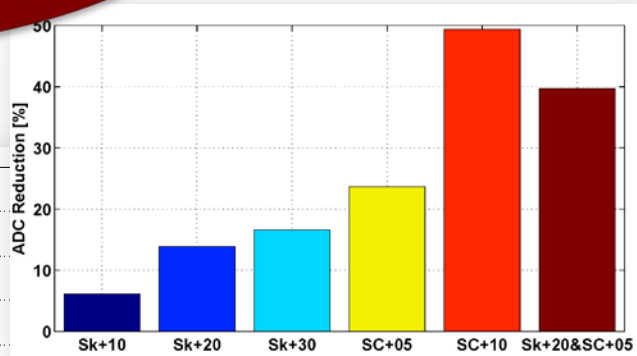




Spar-caps: steep increase

Skin: milder increase

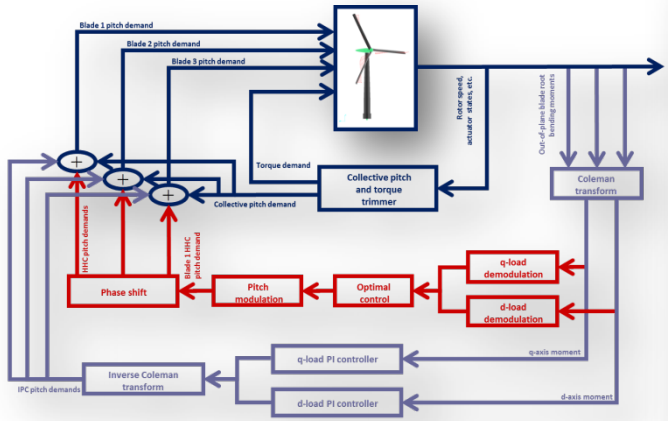
Spar-cap/skin synergy



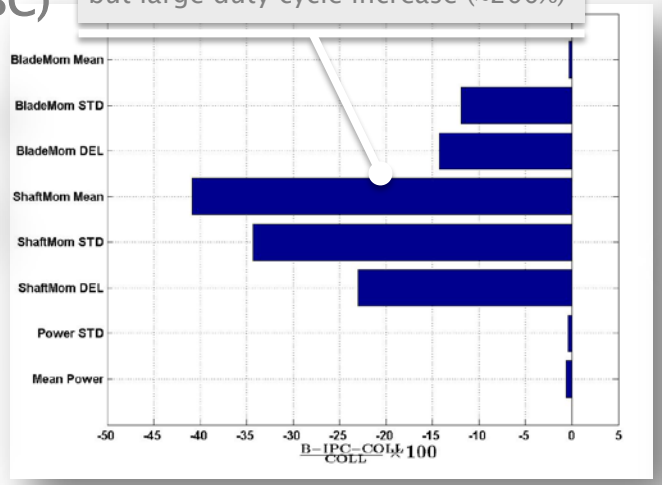
Integrated Passive and Active Load Alleviation

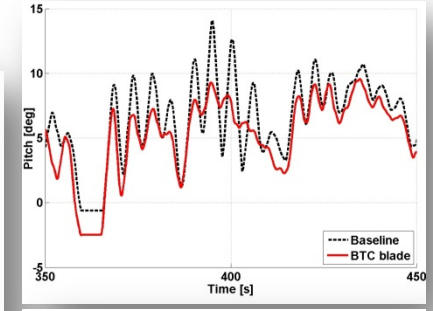
Holistic Design of Wind Turbines

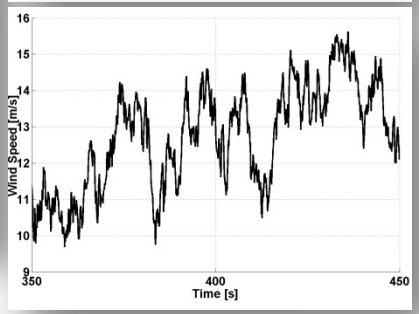
Active load alleviation:
Individual Blade pitch Control (IBC)



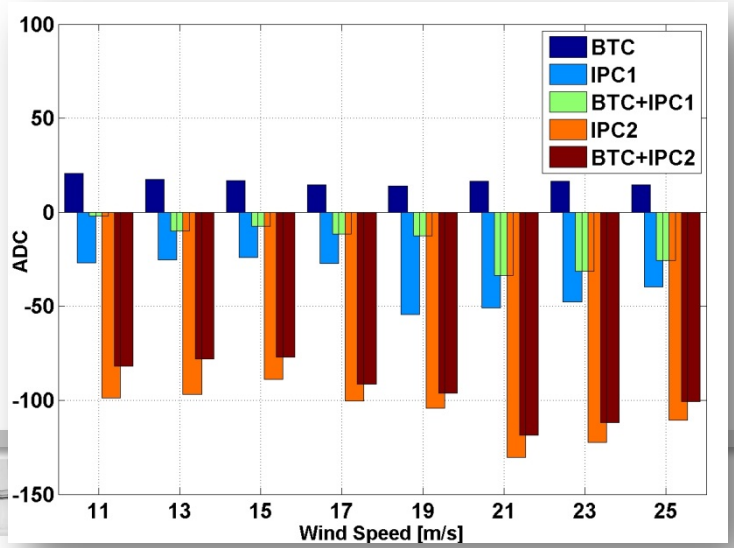
Significant life-time improvement, but large duty cycle increase (≈200%)

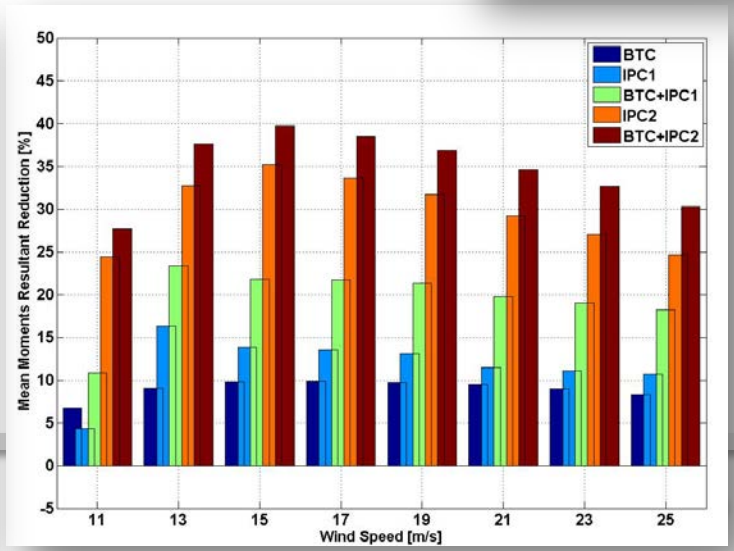






Integrated Passive-Active load alleviation: IBC of BTC blade





Conclusions

- **Optimization-based design tools**: enable automated design of wind turbines with a-priori satisfaction of all desired design requirements
- **Physics-base CoE**: tries to avoid as much as possible scaling relationships in favor of direct sizing of each principal component
- **Multi-level design**: aeroservoelastic models for fast pre-design, followed by detailed FEM to capture local effects
- **Computational cost**: reasonable for an industrial environment (a couple of days to complete a design loop), using standard low cost computing hardware
- **Outlook**:
  - Working on multiple applications to build confidence in tools
  - Expand physics-based sizing of sub-systems (generator, nacelle, …)

Acknowledgements

Work in collaboration with:
M. Bassetti, **P. Bettini**, **M. Biava**, **D. Boroni**, **F. Campagnolo**, **S. Calovi**, **S. Cacciola**, **A. Croce**, **F. Cadei**, **G. Campanardi**, **M. Capponi**, **G. Galetto**, **A. Gonzalez de Céspedes**, **F. Gualdoni**, **L. Maffenini**, **P. Marrone**, **M. Mauri**, **V. Petrovic**, **C.E.D. Riboldi**, **S. Rota**, **G. Sala**, **A. Zasso**

Funding provided by **Vestas Wind Systems A/S**, **Clipper Windpower**, **Alstom Wind**, **DOE National Renewable Energy Laboratory**, **Italian Ministry of Education University and Research**, partial support provided by **Bachmann GmbH**