Technische Universität München
Wind Energy Institute

Wind Turbine Design

Origins of Systems Engineering and MDAO for Wind Energy Applications

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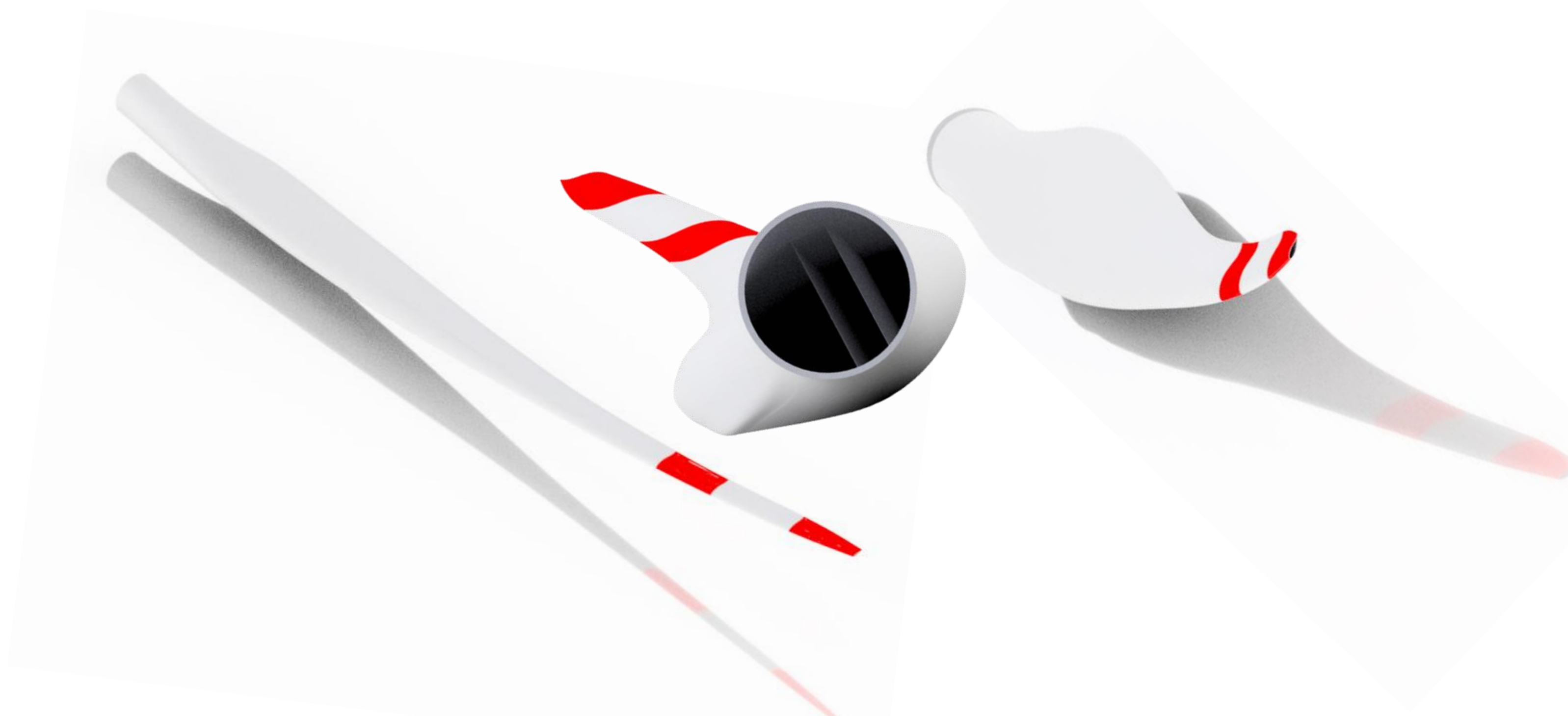
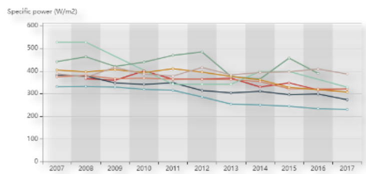


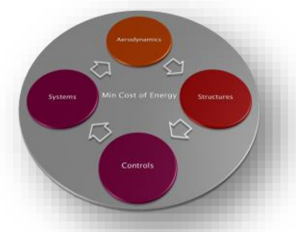
WESE Workshop, Pamplona, Spain, 2-3 October 2019

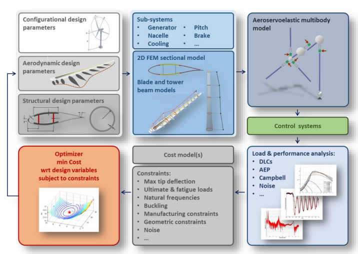
Outline



◄ Some technical reasons behind the falling prices of energy from wind

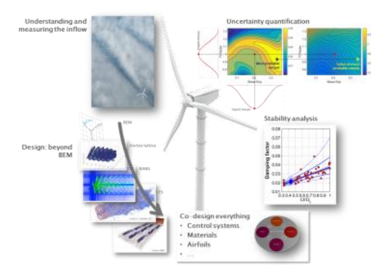
Multidisciplinarity and the need for MDAO ►



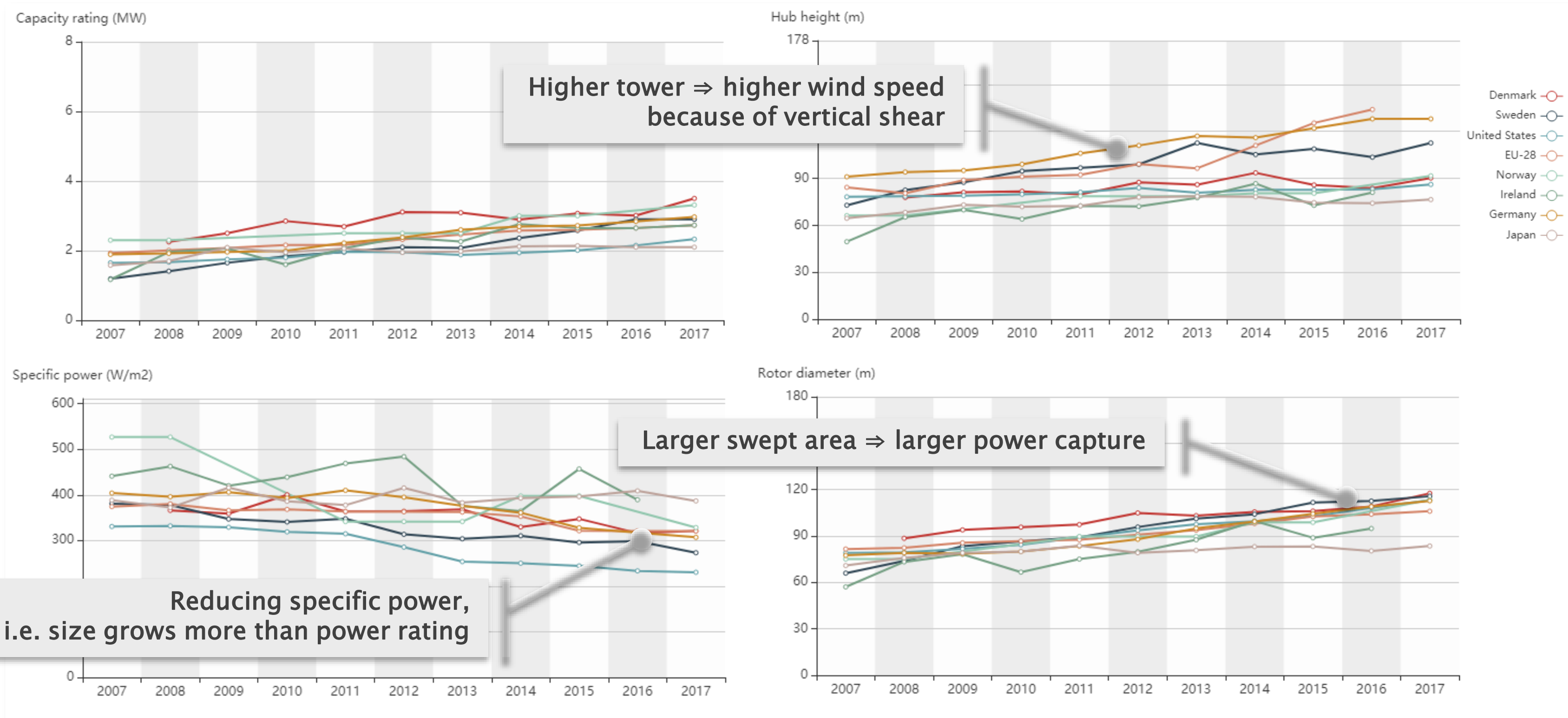


◄ MDAO tools: architectures, methods, limits and gaps

Conclusions and outlook ►

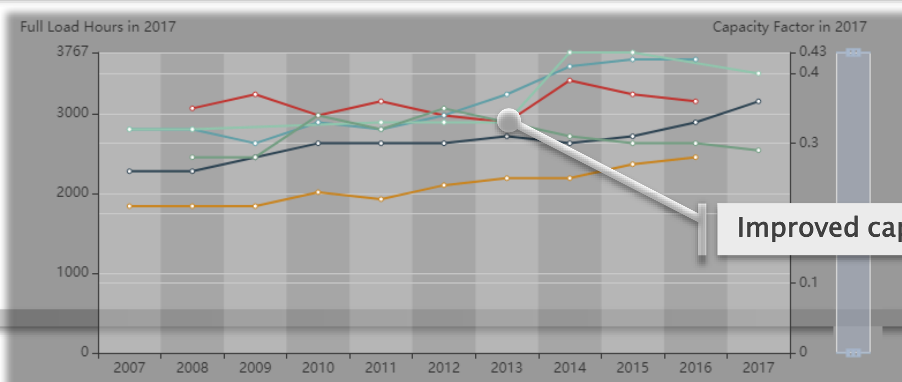


Design Trends



(Source: IEA Wind TCP Task 26)

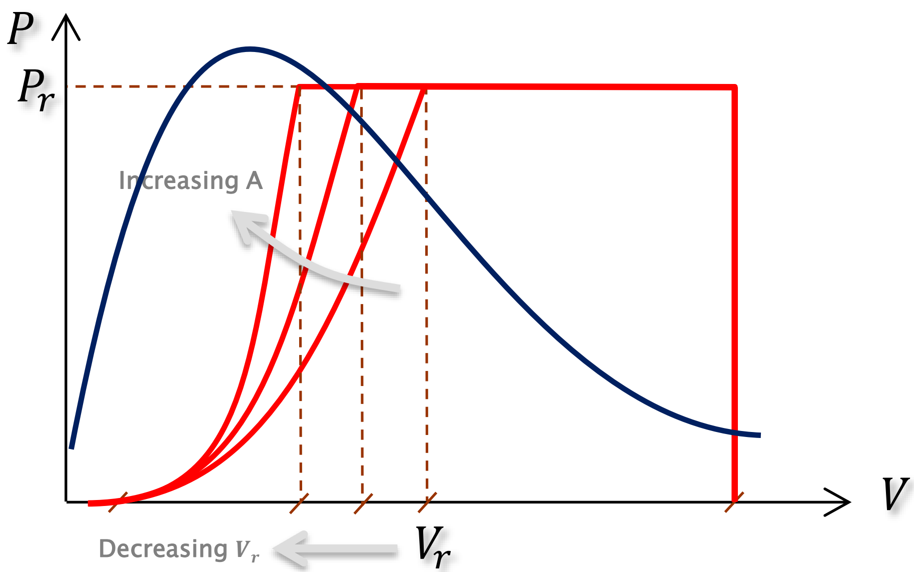
Data for onshore turbines ≥ 1MW



Why?

Rated power: $P_r = \frac{1}{2}\varrho A V_r^3 C_{P_{\max}}$ Rated wind speed $V_r = \sqrt[3]{\frac{P_r/_A}{\frac{1}{2}\varrho\, C_{P_{\max}}}}$

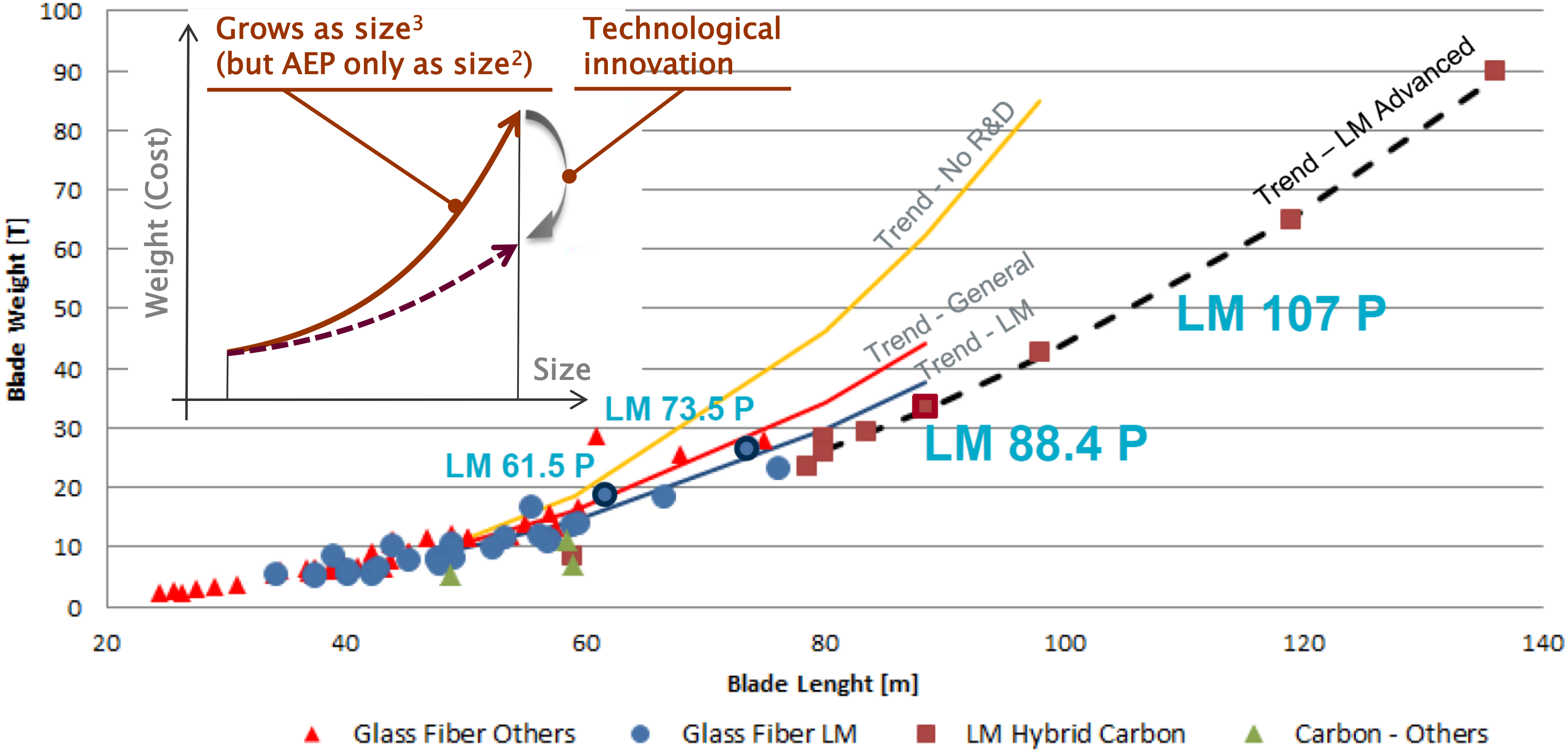
Since $C_{P_{\max}}$ can not be drastically increased, the most effective way to **decrease V_r** is to reduce **specific power (or power loading) $P_r/_A$**



More time spent in region III at full power, **increased capacity factor**

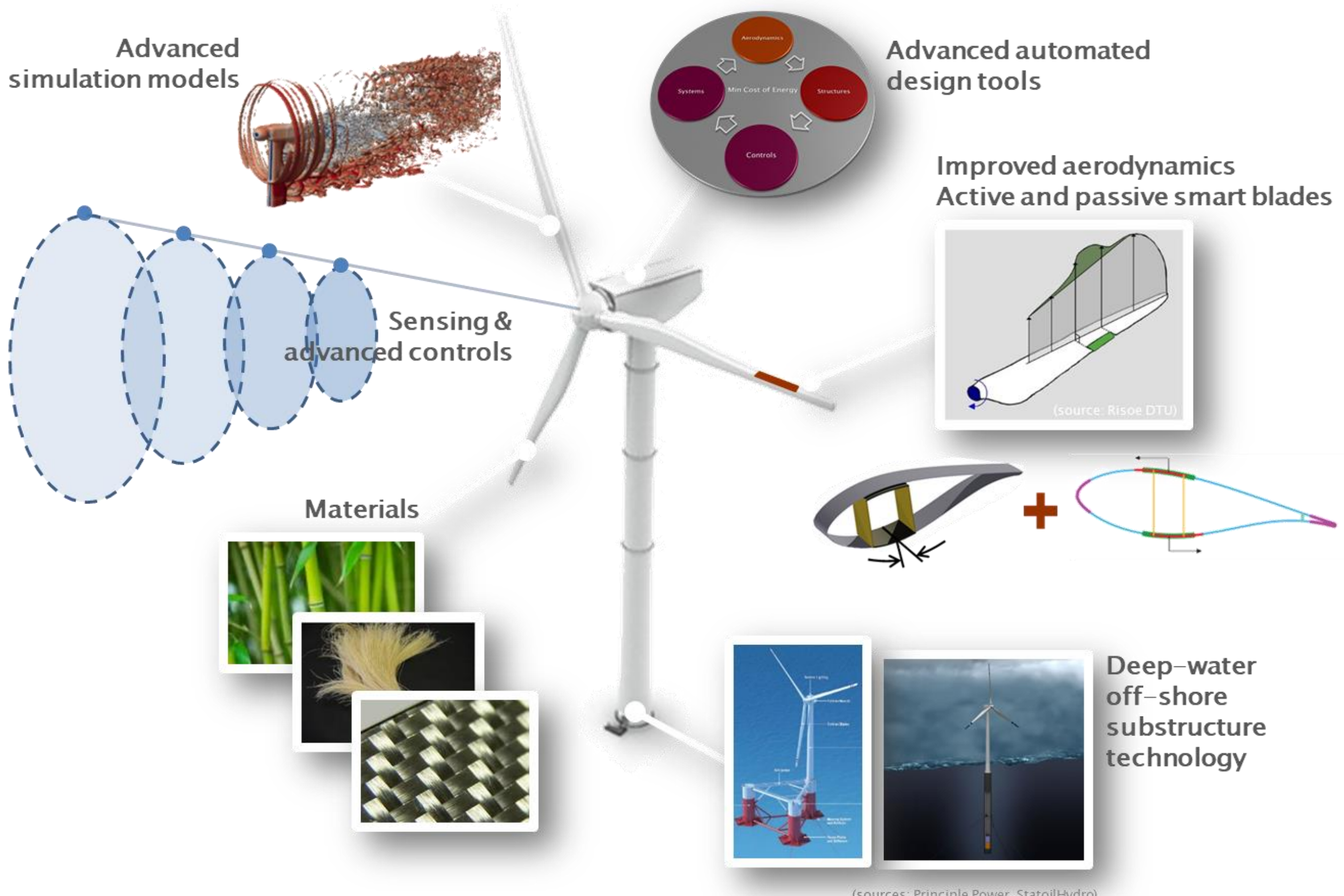
Design Trends & Challenges

Larger machines can not be designed by **simple upscaling** of smaller ones, to avoid cubic law of growth: need for R&D and technological innovation



(source: LM Wind Power)

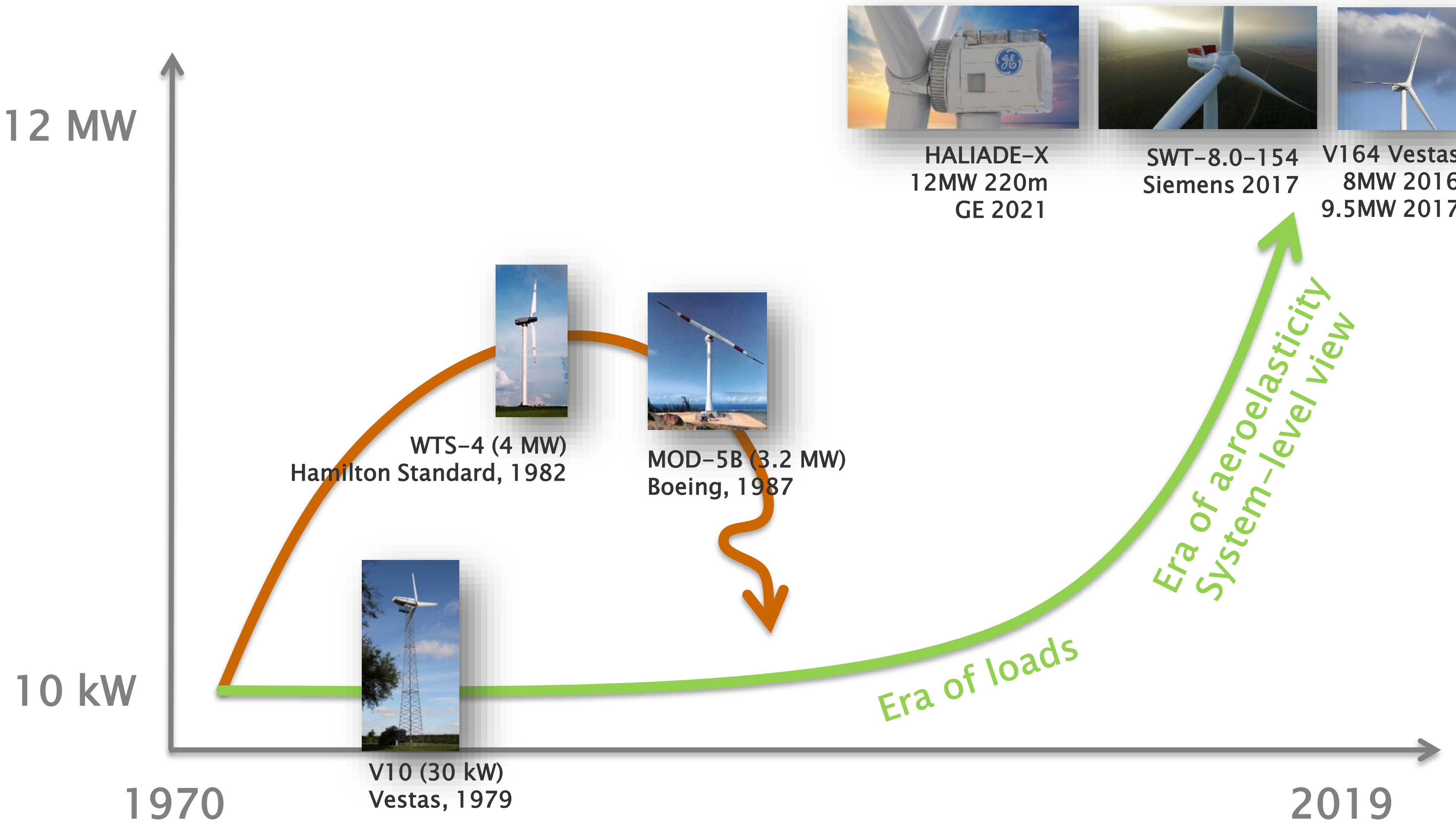
Some Present and Future Technological Innovations that Enable Upscaling



Each innovation will come with **pros** and **cons**

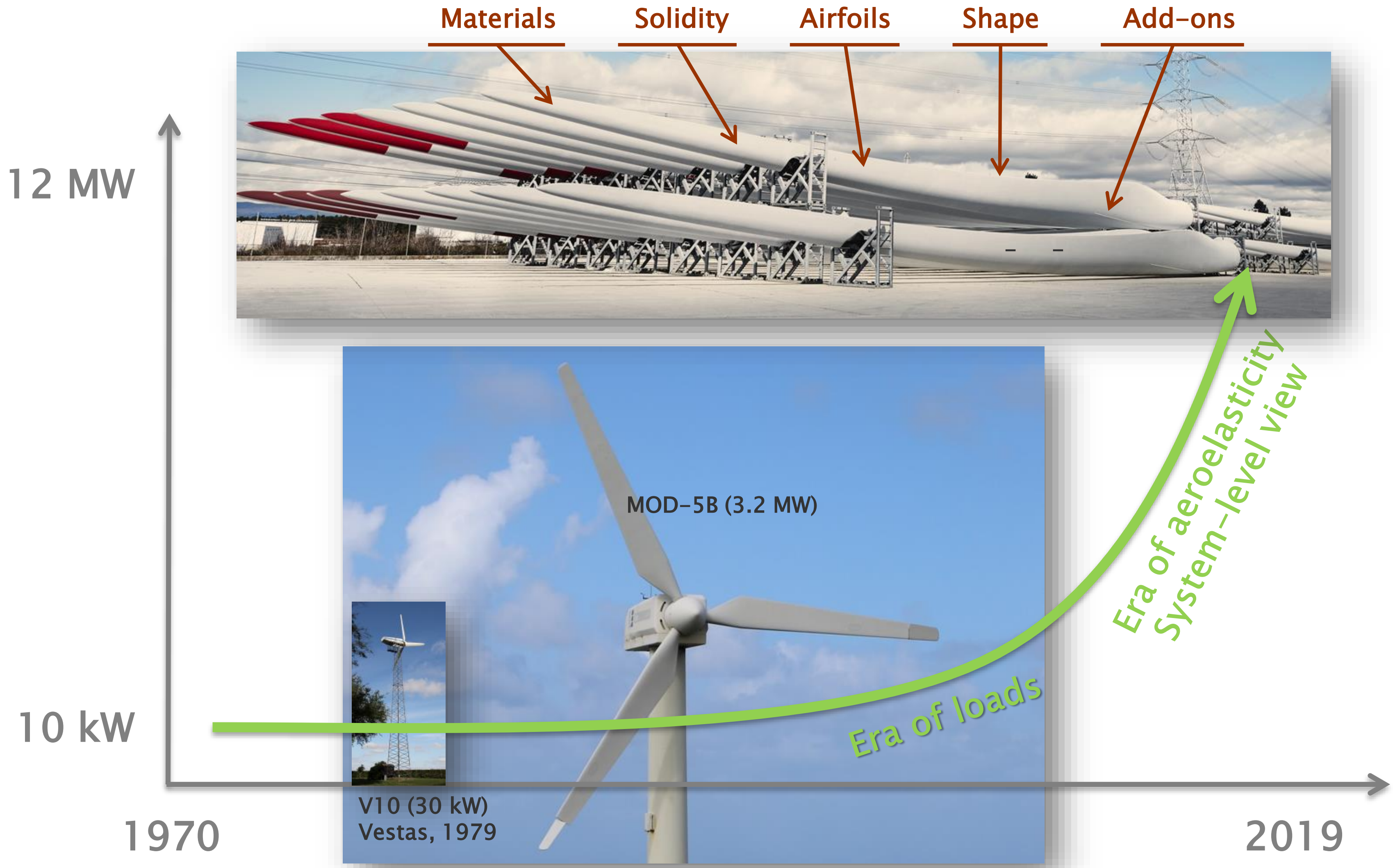
Systems engineering -the final judge-: *"Nice idea, but does it reduce CoE?"*

How Did We Get Here?



(in part from G. van Kuik, TUDelft)

Just Compare the Blades!



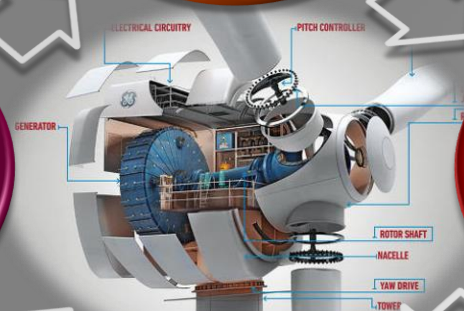
Multidisciplinarity & Couplings and the Need for MDAO

Aerodynamics

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

Systems

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



GE wind turbine (from inhabitat.com)

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
- …

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

Aerodynamics

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

Warning:

- Strong couplings
- Potentially expensive

(one load assessment: $10^7 \div 10^8$ time steps)

- **Loads**: **envelope** from large Design Load Cs, IEC-61400)
- (25 year life), Equivalent (DELs)
- m blade tip **s**
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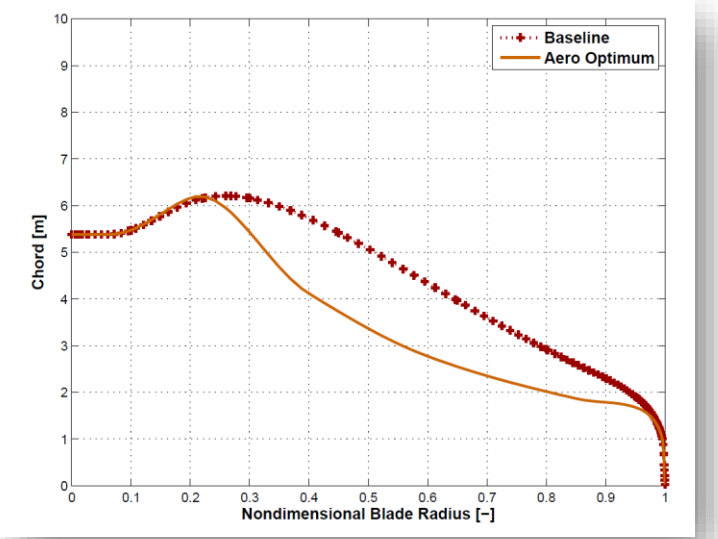
A Simple Example: Aero Optimum ≠ Structural Optimum

Example: INNWIND.EU 10 MW (class 1A, D=178.3, H=119m)

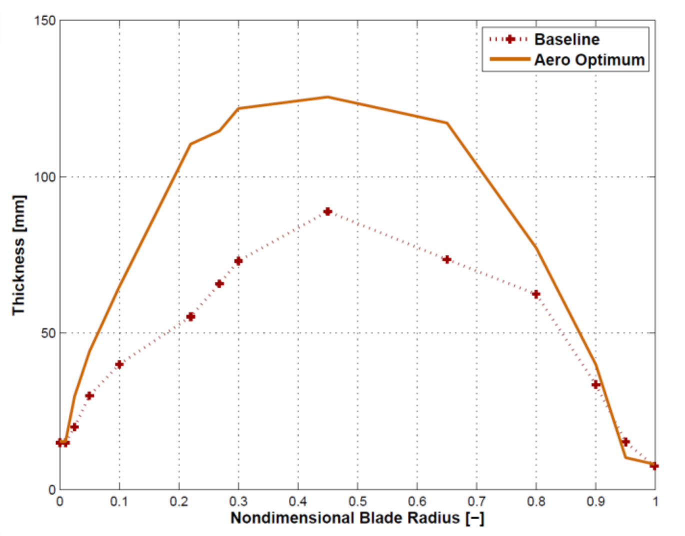
Baseline design by INNWIND.EU consortium

1. Perform purely aerodynamic optimization for max(AEP)
2. Follow with structural optimization for minimum weight

Chord ▼



Spar cap ▼

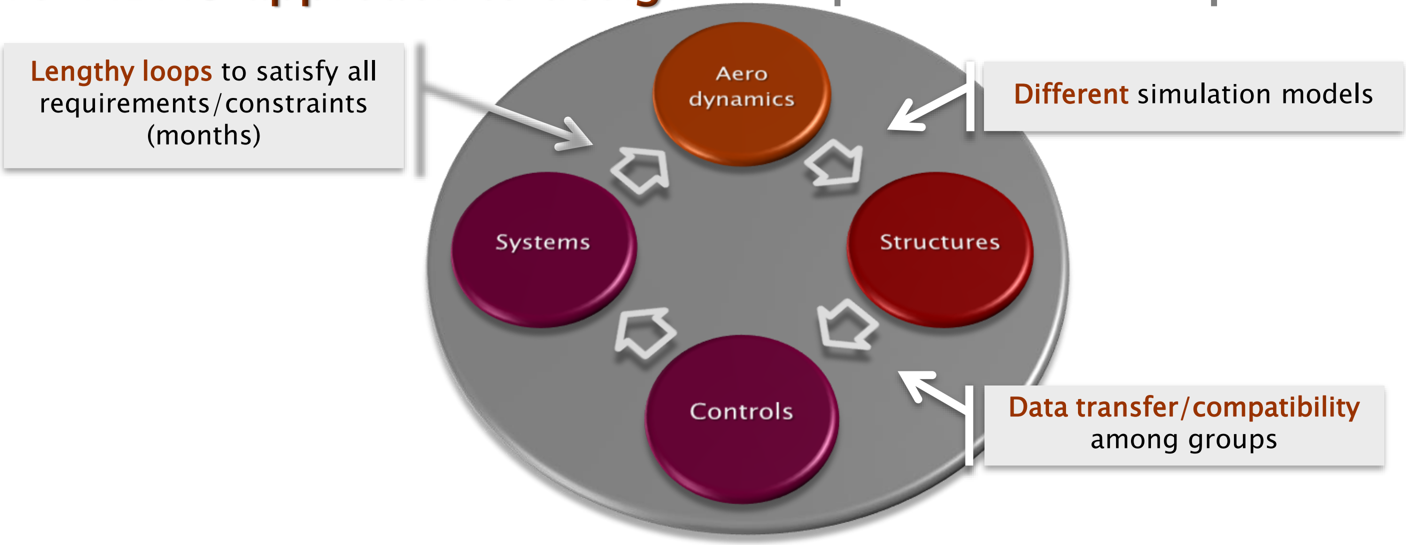


Dramatic **reduction in solidity** to improve AEP leads to **large increase in weight**

⇨ **CoE increases** (+2.6%)

Optimization-Based Design of WTGs

Pre-MDAO approach to design: discipline-oriented specialist groups



Requirements for multi-disciplinary optimization tools:

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

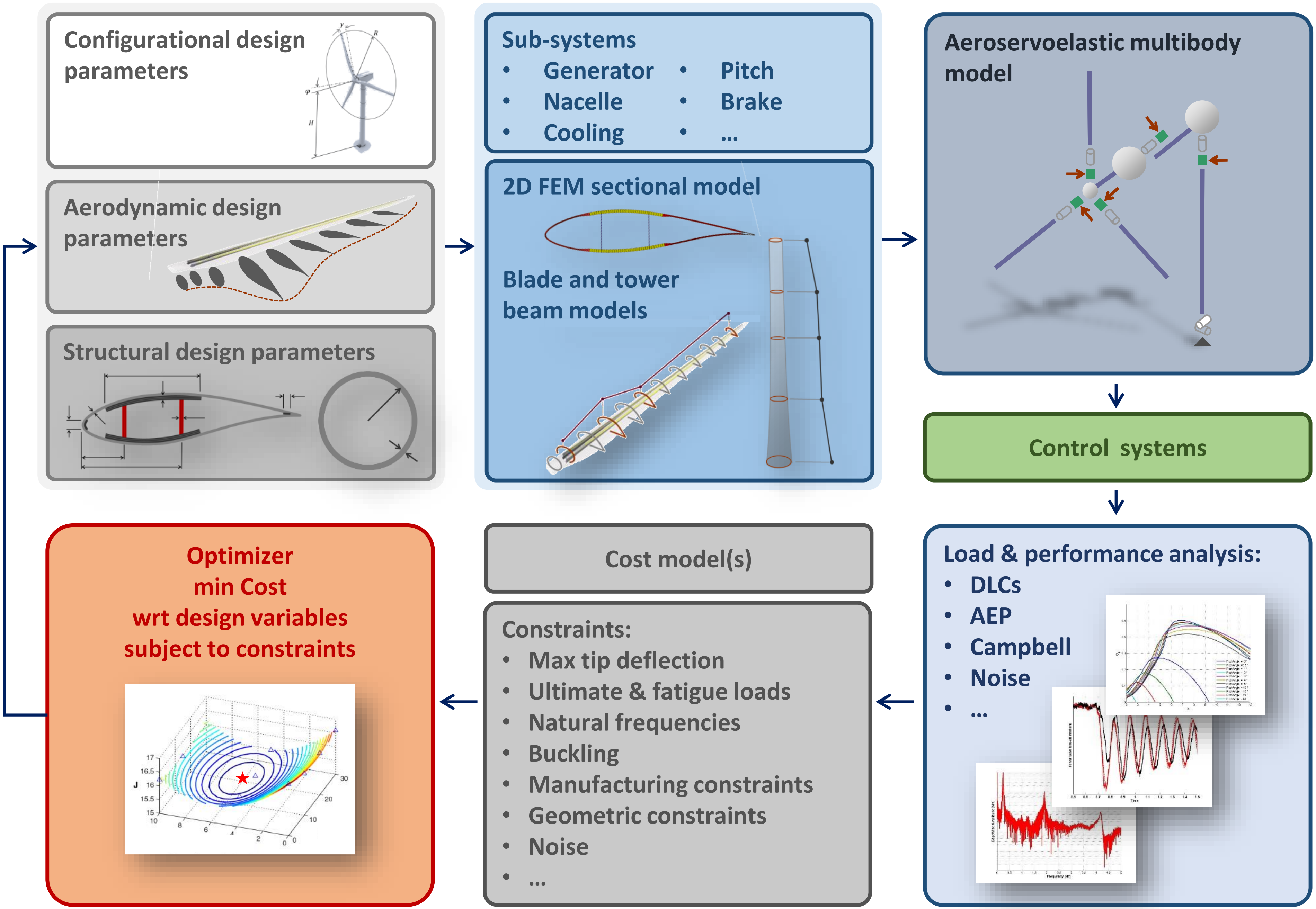
MDAO will **never replace** the experienced designer! … but greatly speeds up design, improves exploration/knowledge of design space

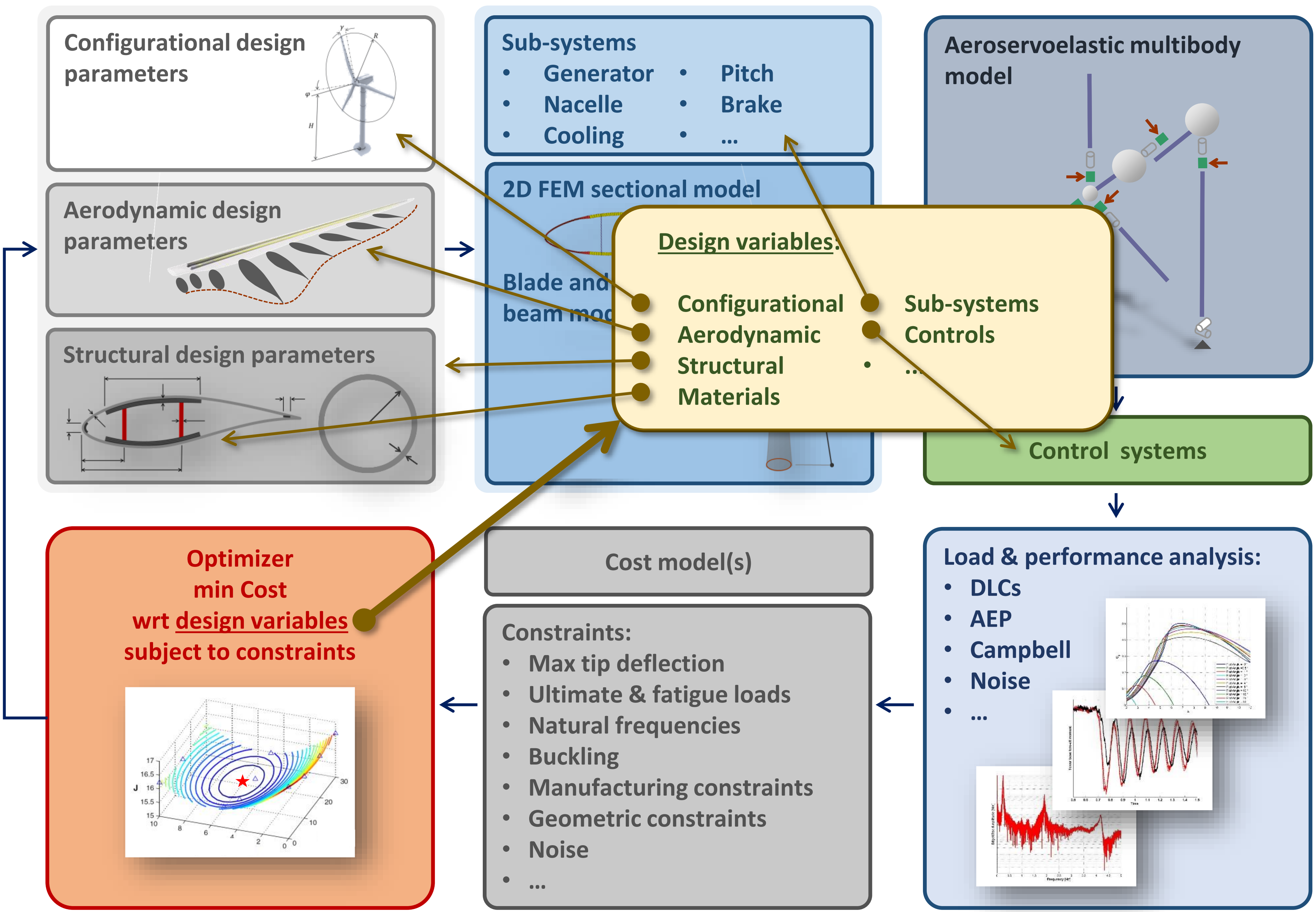
Literature

Integrated tools:
- ECN: FOCUS (Duineveld, 2008)
- DTU:
  - HAWTOPT (Døssing, 2011)
  - New design framework by M. McWilliam
- NREL & Sandia: WISDEM (Dykes et al., 2014)
- POLIMI & TUM: Cp-Max (with A. Croce, P. Bortolotti & many others)
  - Begin in 2007 thanks to grant from TREVI Energy Spa
  - First presentations to industry from 2008 onwards
  - First conference presentations from 2009 onwards (EACWE 2009)
  - Papers: Bottasso et al., 2012-2015; Croce et al. 2016, Sartori et al. 2016, Bortolotti et al. 2016-19

- Several proprietary tools at various companies

What Does a Typical MDAO Tool Look Like?


Configurational design parameters
Aerodynamic design parameters
Structural design parameters
Sub-systems
Generator
Pitch
Nacelle
Brake
Cooling
…
2D FEM sectional model
Blade and tower beam models
Aeroservoelastic multibody model
Control systems
Load & performance analysis:
DLCs
AEP
Campbell
Noise
…
Cost model(s)
Constraints:
Max tip deflection
Ultimate & fatigue loads
Natural frequencies
Buckling
Manufacturing constraints
Geometric constraints
Noise
…
Optimizer
min Cost
wrt design variables
subject to constraints


Configurational design parameters
Aerodynamic design parameters
Structural design parameters
Sub-systems
• Generator • Pitch
• Nacelle • Brake
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2D FEM sectional model
Blade and
beam mod
Aeroservoelastic multibody model
Design variables:
Configurational
Aerodynamic
Structural
Materials
Sub-systems
Controls
• ...
Control systems
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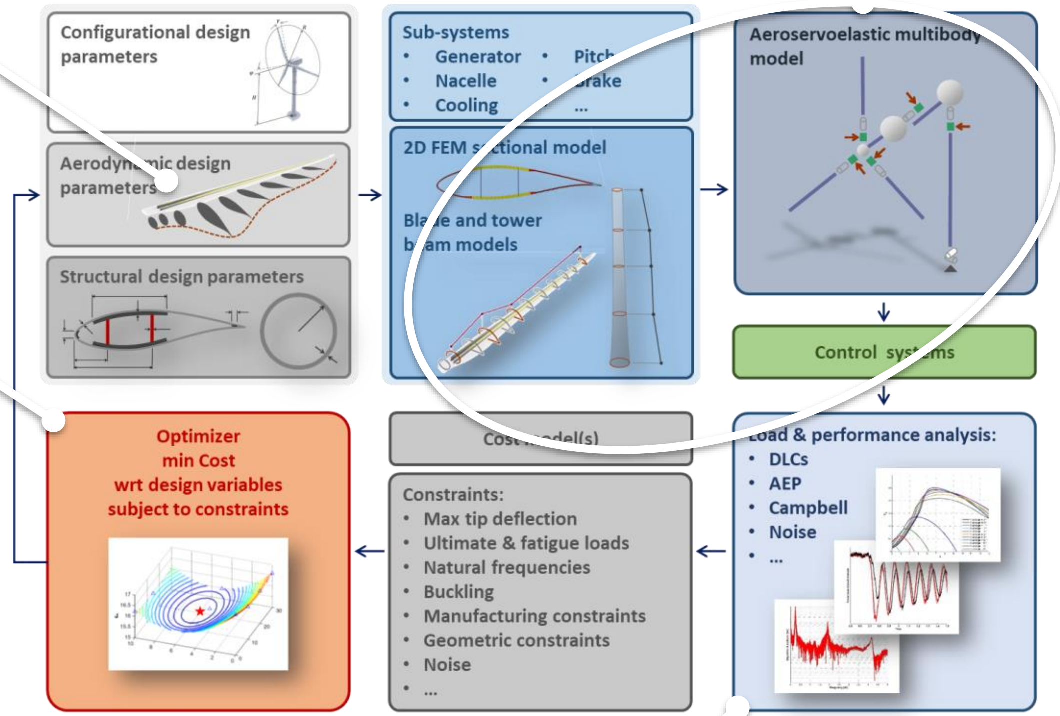
Cost model(s)
Constraints:
• Max tip deflection
• Ultimate & fatigue loads
• Natural frequencies
• Buckling
• Manufacturing constraints
• Geometric constraints
• Noise
• ...
Load & performance analysis:
• DLCs
• AEP
• Campbell
• Noise
• ...

Some design parameters have very minor effects on CoE
Problem may be **ill-posed**

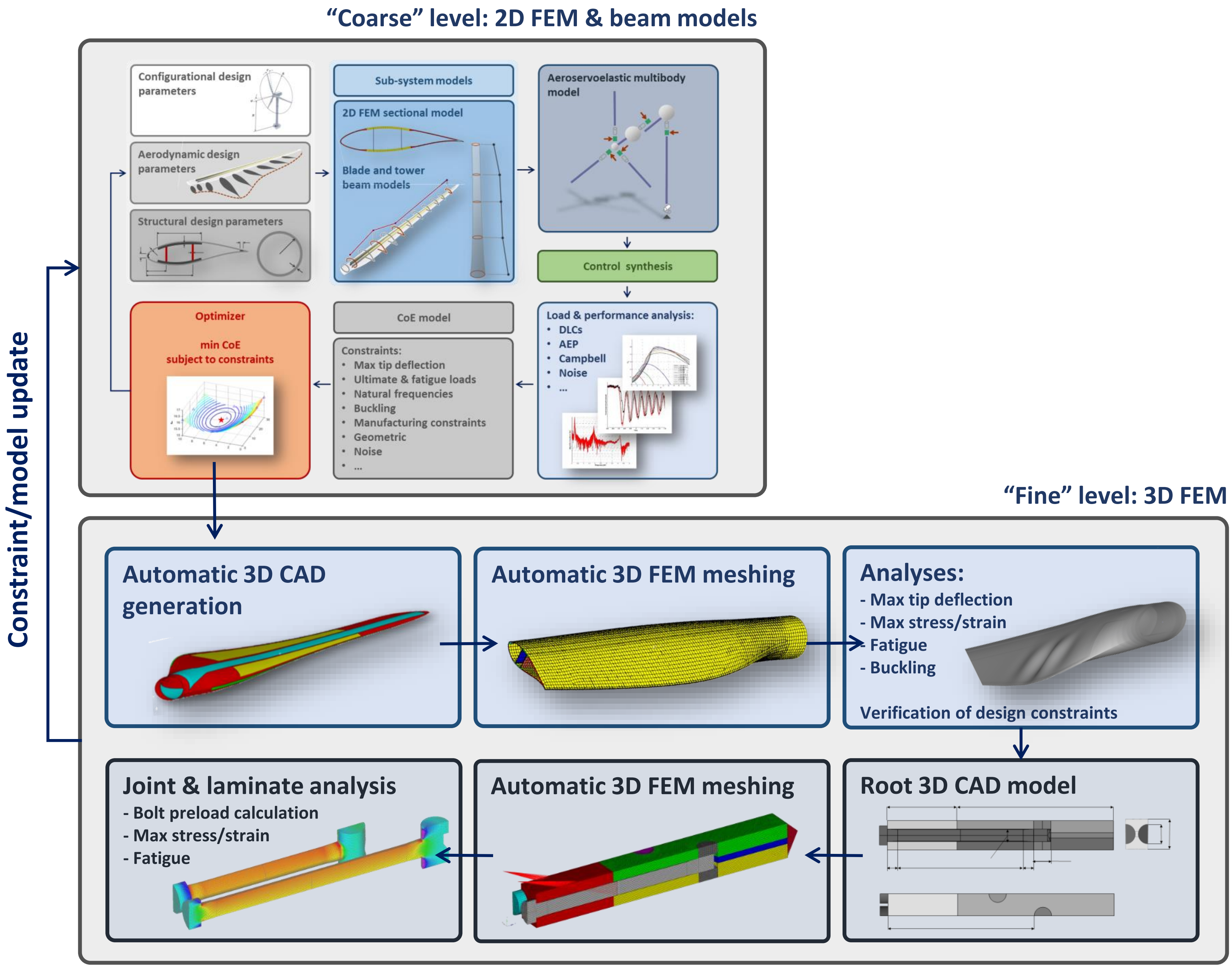
2D + beam models unable to capture **local 3D effects**

Various possible algorithmic flavors:

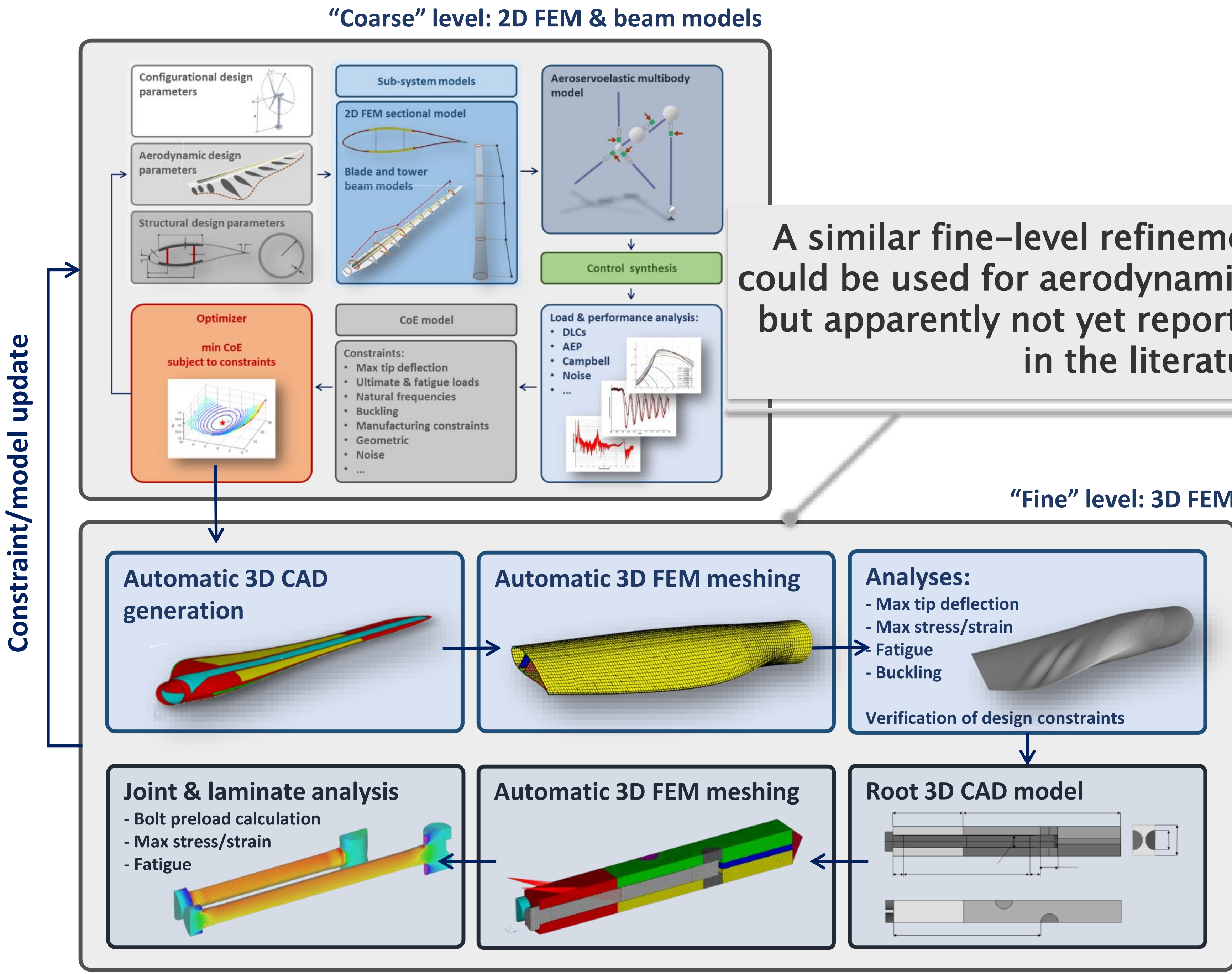
- Monolithic
- Iterative
- Partitioning of vars
- Surrogate models
- Global/local opt
- …



Expensive performance analysis has to be repeated for each change in each design variable
Possibly **non-smooth** load behavior (DLC jump)



(Ref.: C.L. Bottasso et al., Multibody System Dynamics, 2014)



A similar fine-level refinement could be used for aerodynamics, but apparently not yet reported in the literature

(Ref.: C.L. Bottasso et al., Multibody System Dynamics, 2014)

Composite Co-Design

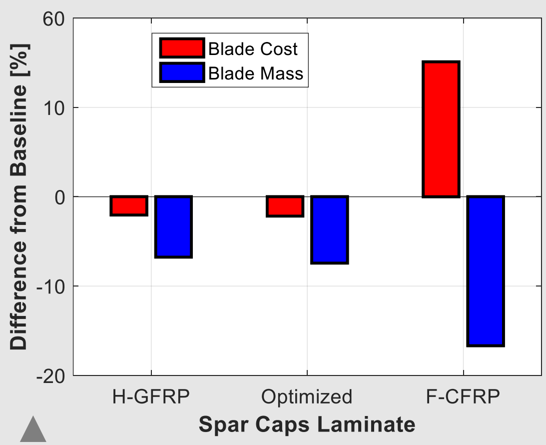
Idea:

- Define a parametric composite material model (mechanical properties vs. cost)
- Identify the best material for each component within the model

Result:

- Wind turbine designer: pick closest existing material within market products
- Material designer: design new material with optimal properties

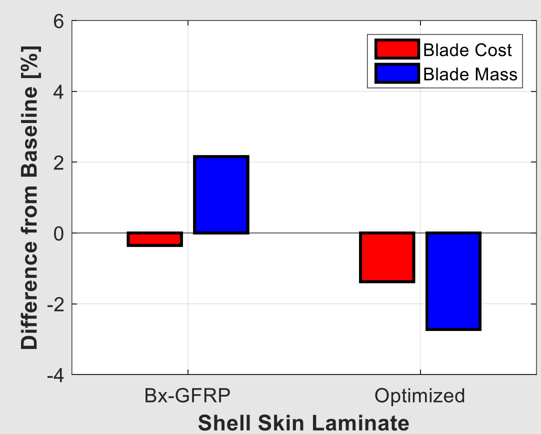
Example: INNWIND.EU 10 MW



▲

Redesign of **spar caps laminate**
Optimum is between H–GFRP and CFRP

Redesign of the **shell skin laminate**
Optimum is between Bx–GFRP and Tx–GFRP ▼

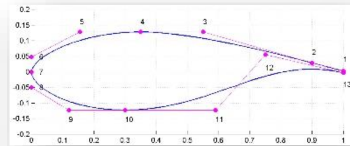


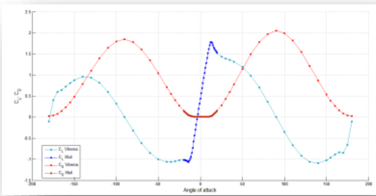
Combined optimum: Blade mass –9.3%, blade cost –2.9%

Airfoil Free-Form Co-Design

Design **airfoils together with blade**:

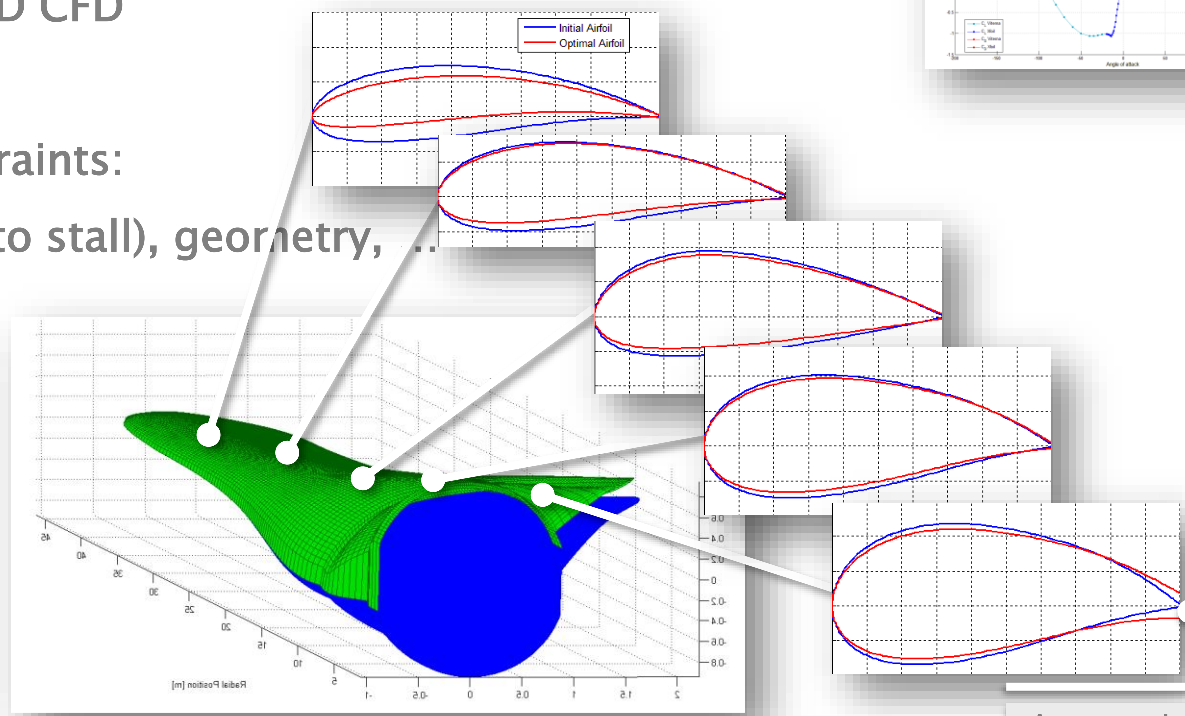
- Bezier airfoil parameterization
- Airfoil aerodynamics by Xfoil + Viterna extrapolation and/or 2D CFD





Additional constraints:

C_L max (margin to stall), geometry, …



Automatic appearance of **flatback** airfoil!

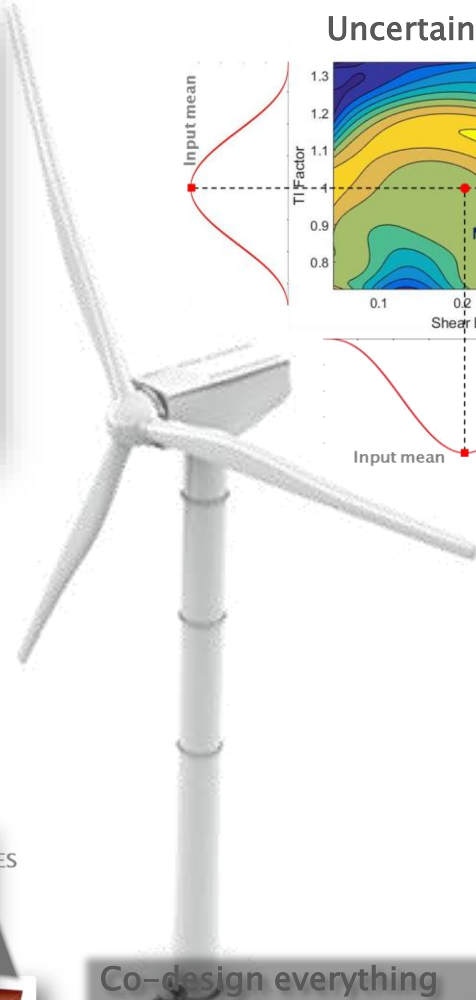
Appealing for noise-aware design

(Ref. Bottasso et al., J. Phys: Conf. Series, 524, 2014, SciTech 2015)

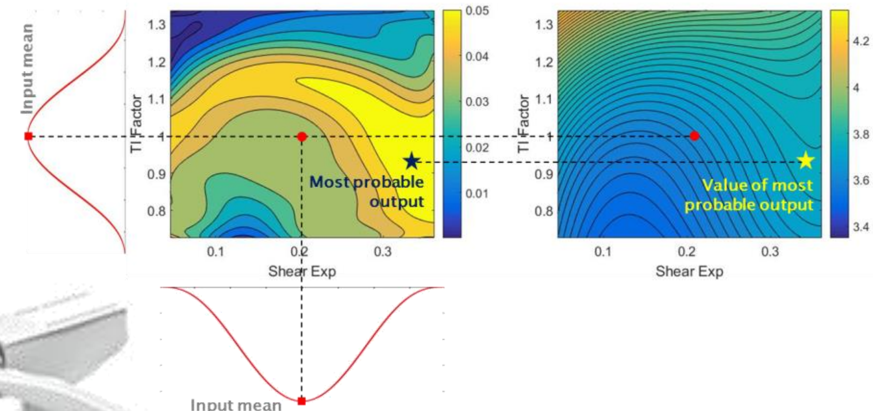
Some Open Issues: a Personal View

Understanding and measuring the inflow

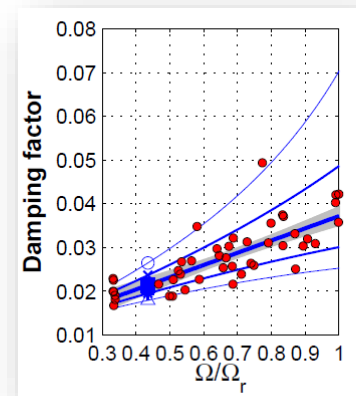
Beyond the turbine: plant design, wind farm control, grid integration



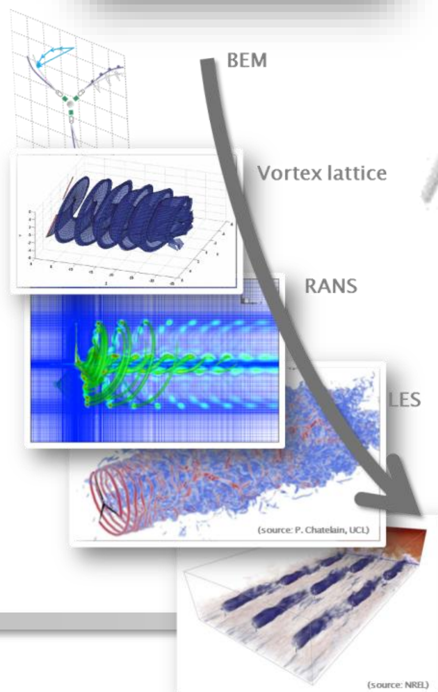
Uncertainty quantification



Stability analysis

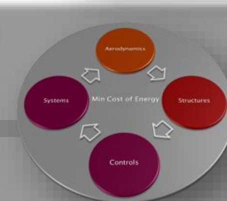


Design: beyond BEM



Co-design everything

- Control systems
- Materials
- Airfoils
- …



Conclusions

MDAO for WTGs: only about 10 years old, but growing strongly, gaining acceptance and delivering results

Work at TUM & POLIMI in collaboration with P. Bortolotti, H. Canet, F. Campagnolo, A. Croce, L. Sartori