Technische Universität München
Wind Energy Institute

Latest Advancements in the Integrated Design of Wind Turbines

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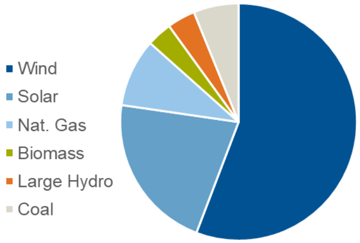
2018 Sandia Blade Workshop
Overton Hotel, Lubbock, Texas, 28-30 August 2018

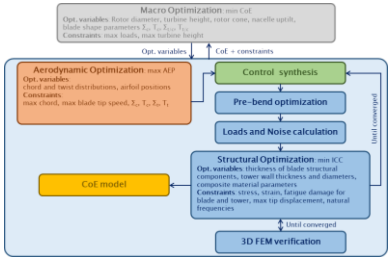
My Bio

- 2007 – 2010 B.Sc. Energy Engineering – **Politecnico di Milano**
- 2010 – 2012 M.Sc. Sustainable Energy Technology – Wind Energy Track
  TU Delft-WMC. Thesis: "Hybrid C-GFRP for WT blades"
- 2012 – 2013 Research employee at the Lightweight Structures Group – **DTU**
- 2013 – 2018 Ph.D. at the Wind Energy Chair – **TUM**
- 2018 – today Postdoctoral researcher at **NREL** – NWTC

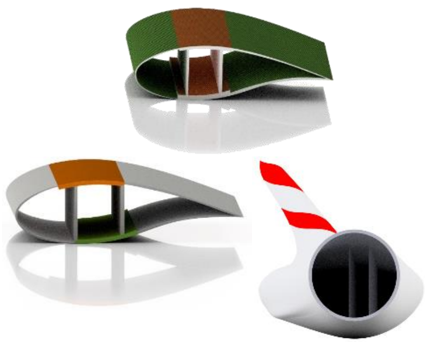
Agenda



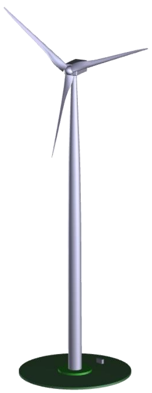
Background and motivation



Nested multi-level optimization framework



Applications



Other projects

2018:
Bortolotti P, Bottasso CL, Croce A, Sartori L.
Integration of multiple passive load mitigation technologies by automated design optimization — The case study of a medium-size onshore wind turbine.
Wind Energy, 2018. doi: 10.1002/we.2270

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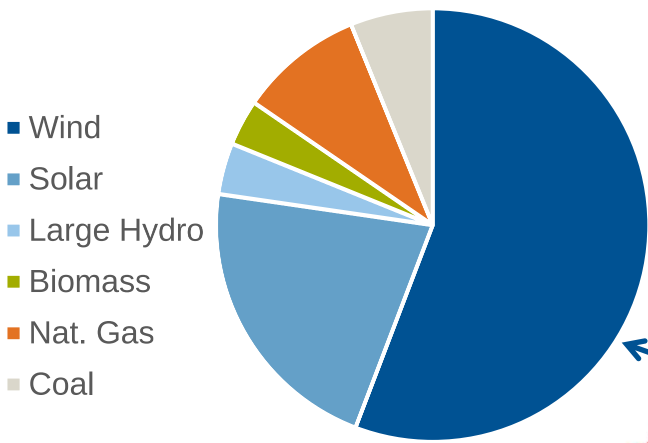
Multibody Syst. Dyn., 2016;38(4):317-344. doi: 10.1007/s11044-015-9488-1

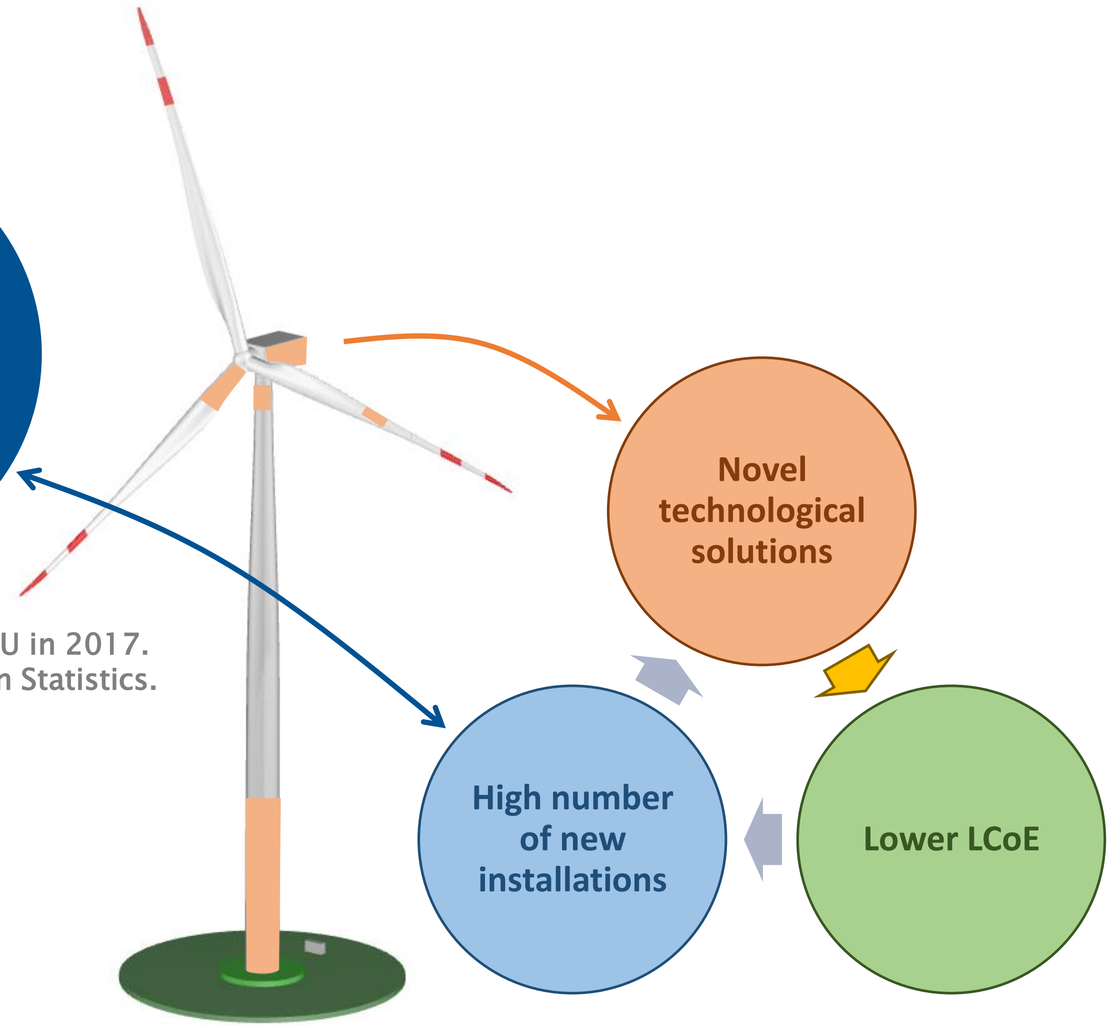
Bortolotti P, Adolphs G, Bottasso CL.
A methodology to guide the selection of composite materials in a wind turbine rotor blade design process.
J. Phys.: Conf. Ser., 2016;753. doi: 10.1088/1742-6596/753/6/062001

Conclusions and bibliography

Motivation



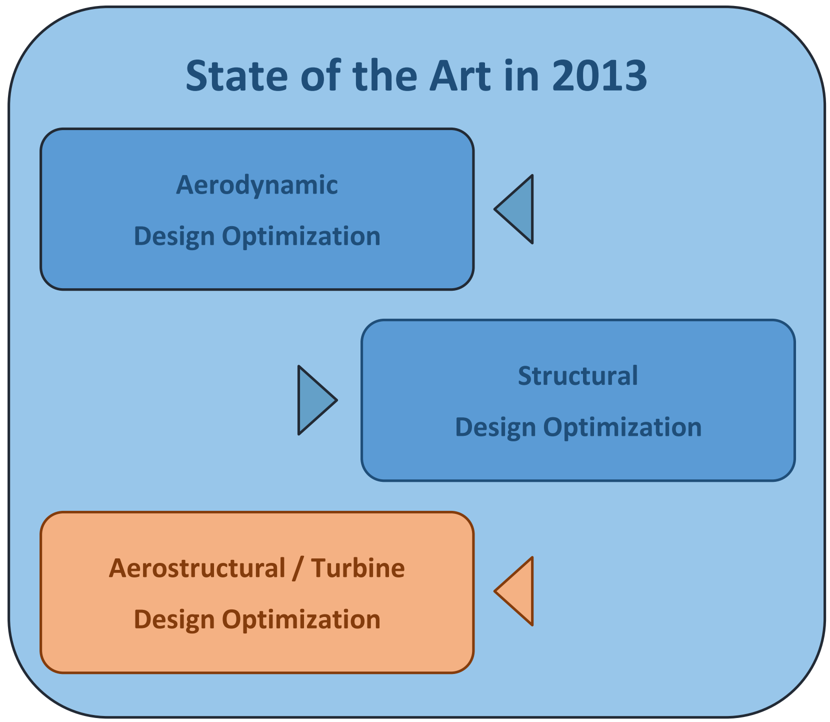
Shares of new installed capacity in EU in 2017.
Source: WindEurope – 2017 European Statistics.



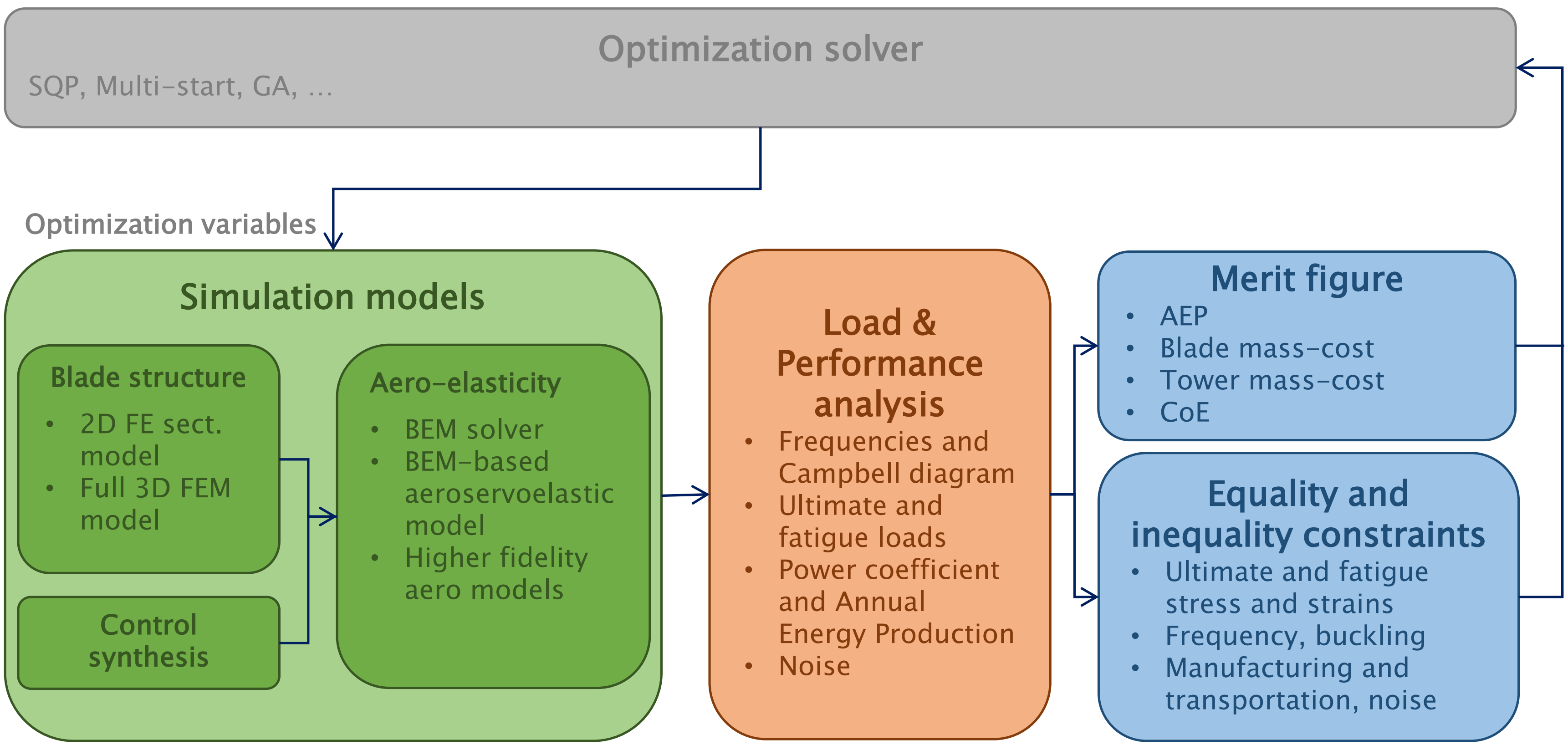
Importance of Integrated WT Design

Wind turbines are complex systems where **multiple disciplines** are **cross coupled**

There is a need for **holistic design tools** to assess the impact of each new technological solution



Algorithmic Approaches – Monolithic



Algorithmic Approaches – Monolithic

Accurate loads and performance estimation

- Ultimate loads, fatigue loads and displacements
- AEP under turbulent wind conditions
- Standards prescribe to run a **multitude of DLCs**

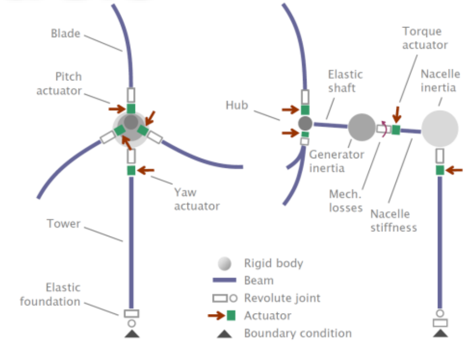
Adequate fidelity level of the simulation models

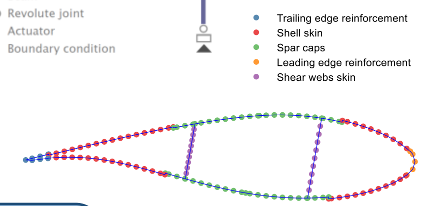
- **BEM-based aeroservoelastic** solvers to run DLCs
- **2D cross sectional** solvers for blade design
- **3D FEM** and **CFD** models to be integrated within a design procedure

Ill-posedness of the optimization problem

- **CoE** is often the merit figure to be minimized (maybe not in the next future?)
- CoE **response surface** is often **flat** wrt several design parameters

Simulation Models



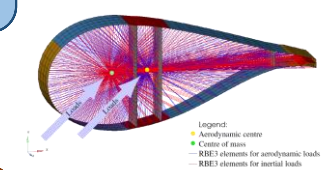


Aeroservoelastic solver
1. Cp-Lambda
2. LQR controller

Noise emission models
Airfoil self noise, adopting XFOIL, and turbulent inflow noise

Design and simulation framework implemented in MATLAB

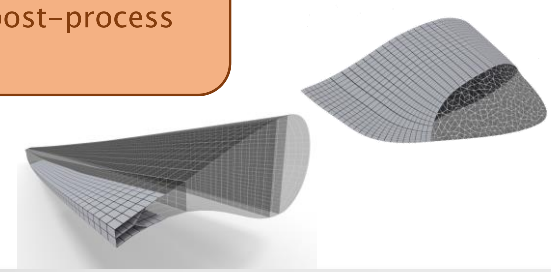
Cross sectional analysis
2D solver ANBA



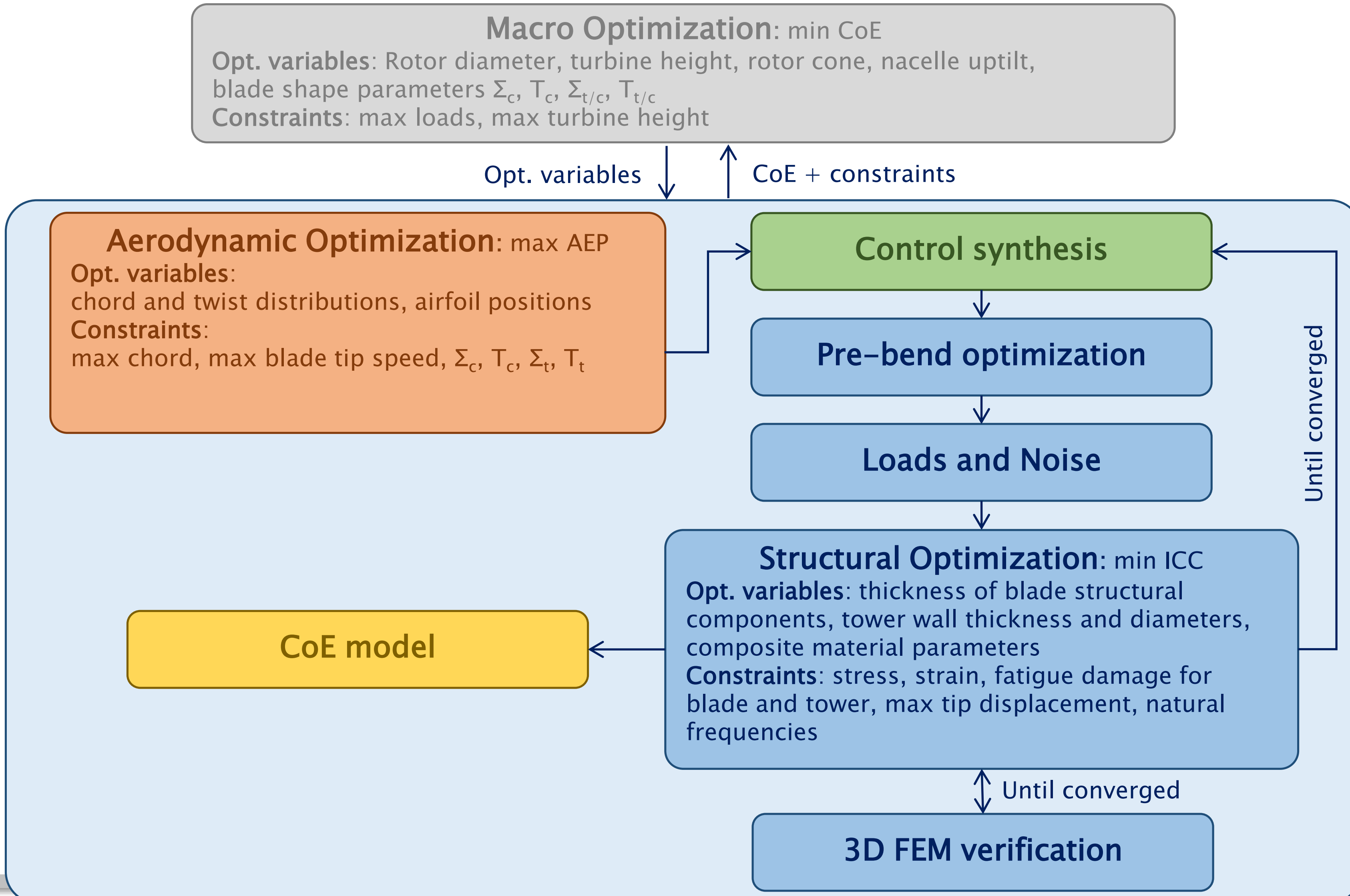
Cost models
1. NREL and INNWIND.EU CoE models
2. SANDIA blade cost model

3D FEM
Nastran, 3D CAD and FEM pre/post-process software

Inflow generation
TurbSim



A Nested Multi-Level Architecture



Publication: Bortolotti et al., 2016

Applications

Industrial project

2 MW onshore wind turbine

1. Macro re-optimization
2. Investigation of low-induction rotor

Upscale and redesign

3.35 MW wind turbine

1. Reference developed within IEA Wind Task 37
2. Studies on passive load alleviating technologies and macro re-optimization with swept-soft rotor
3. Estimation and alleviation of noise emission

DTU 10 MW RWT

10 MW conceptual wind turbine

1. Rotor structural redesign
2. Optimization of blade composites
3. Macro re-optimization
4. Investigation of low-induction rotor
5. Comparison with downwind configurations

Industrial Project

3.X WTs

Applications I – 2.0 MW

2.0 MW – 3A	Industry WT	Cp-Max Opt	Difference
Rated Power	2.0 MW	2.0 MW	--
Rotor Diameter	92.4 m	106.6 m	+15.4 %
Hub Height	80 m	97.6 m	+22.0 %
AEP	8.30 GWh	9.95 GWh	+19.9 %
TCC	1.41 M$	1.69 M$	+19.9 %
CoE	**41.98 $/MWh**	**40.56 $/MWh**	**-3.1 %**

→ WT upscale

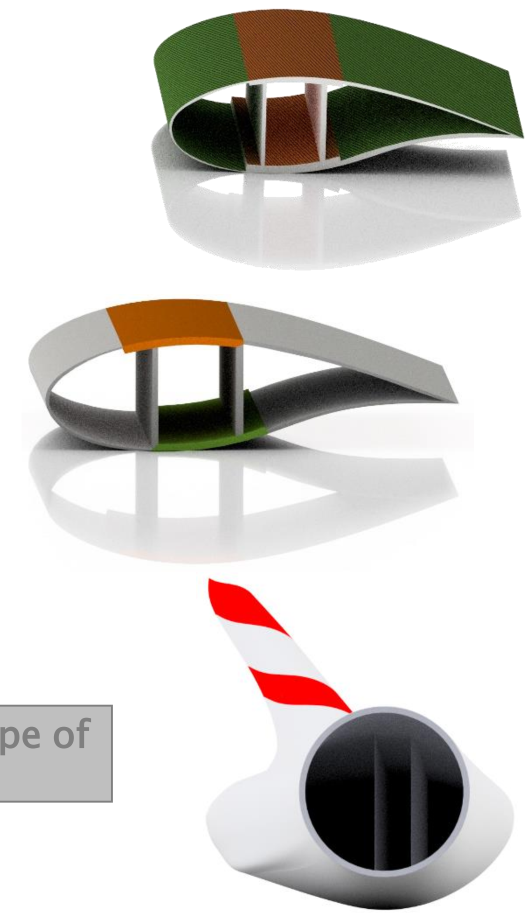
Low induction rotor also investigated, but higher CoE

Applications II – 3.4 MW

iea wind

3.35 MW – 3A	Standard	BTC-Soft	Difference
Rated Power	3.35 MW	3.35 MW	--
Rotor Diameter	130 m	136 m	+4.6 %
Hub Height	110 m	110 m	--
Rotor Cone	3 deg	8 deg	+166.7 %
Nacelle Uptilt	5 deg	6 deg	+20 %
Blade Cost	127.9 k$	126.2 k$	-1.3 %
Tower Cost	548.5 k$	438.2 k$	-20.1 %
AEP	13.96 GWh	14.32 GWh	+2.6 %
ICC	3,885.2 k$	3,850.9 k$	-0.9 %
CoE	**41.98 $/MWh**	**40.82 $/MWh**	**-2.8 %**

Same load envelope of the baseline

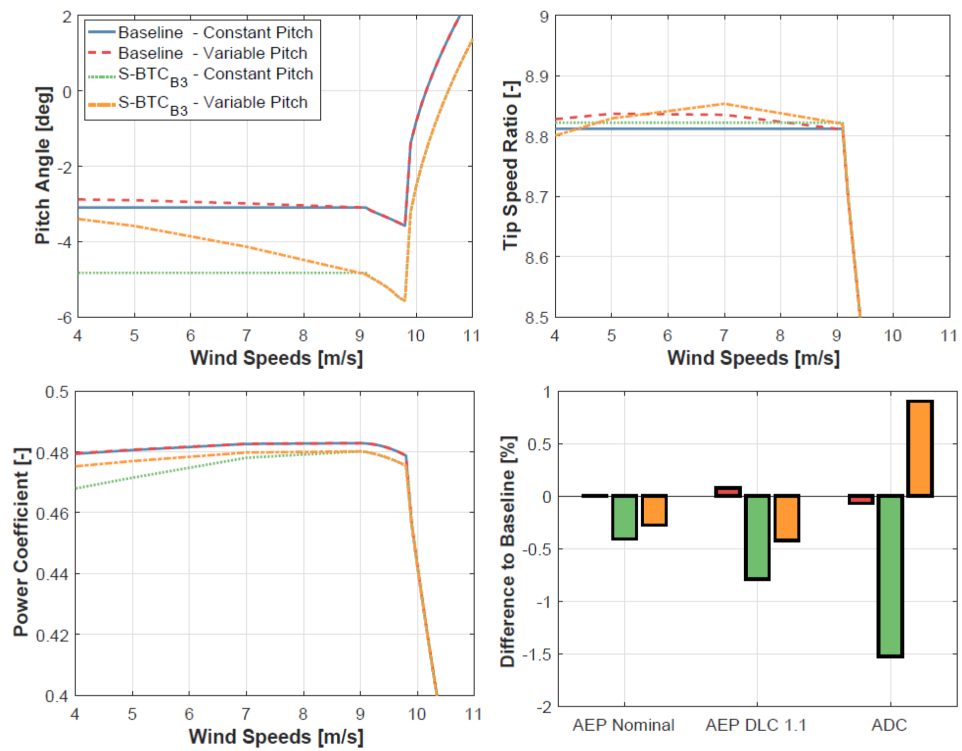


Publication: Bortolotti et al., 2018

Applications II – 3.4 MW

Novel **regulation trajectory** to minimize AEP losses

Variable pitch and TSR in region II to compensate the BTC of the blade

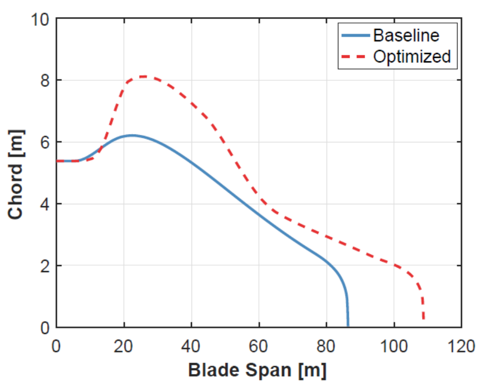


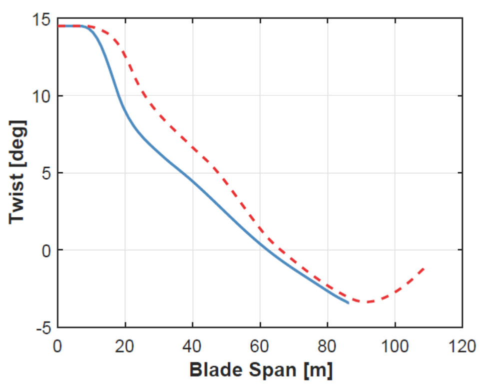
Applications III – 10.0 MW

Rotor **aerostructural** optimization of the DTU 10 MW

10.0 MW – 1A	Baseline	Cp-Max Opt	Difference
Rated Power	10.0 MW	10.0 MW	--
Rotor Diameter	178.3 m	223.2 m	+25.2 %
Hub Height	119.0 m	138.3 m	+16.2 %

ΔCoE (INNWIND.EU) = – 7.0%





Publication: Bortolotti et al., 2016

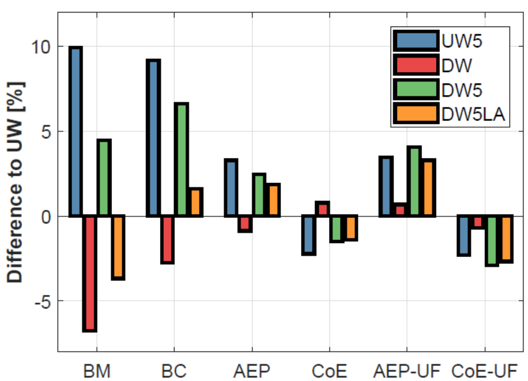
Applications III – 10.0 MW

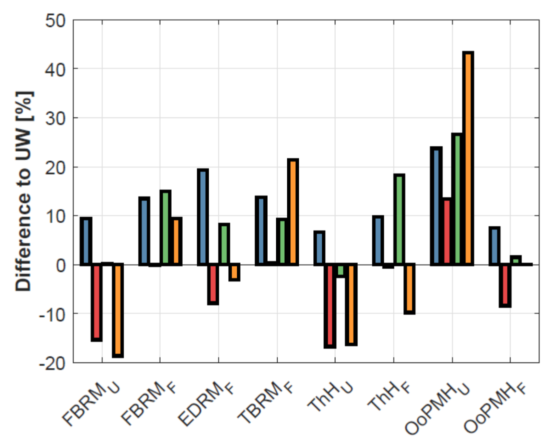
Preliminary study on various alternative configurations:

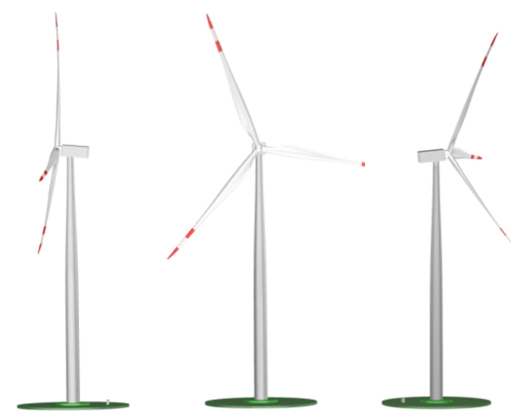
UW	INNWIND 10 MW upwind configuration
DW	**downwind** rotor
UW5	upwind redesign with 5% larger rotor
DW5	downwind rotor with 5% larger rotor
DW5LA	downwind rotor with **variable coning actively controlled** and 5% larger rotor

Conclusions:

- Hard to obtain **effective load alignment** during **turbulent wind**
- DW5LA has a relevant **added complexity**
- **Standard downwind looks more promising**





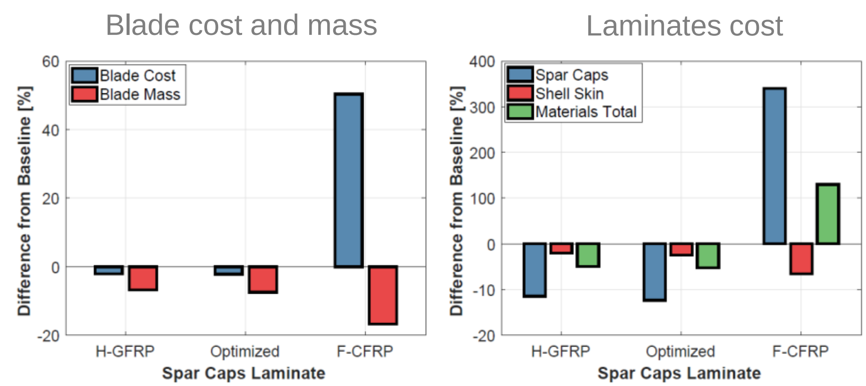


Composite Optimization

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

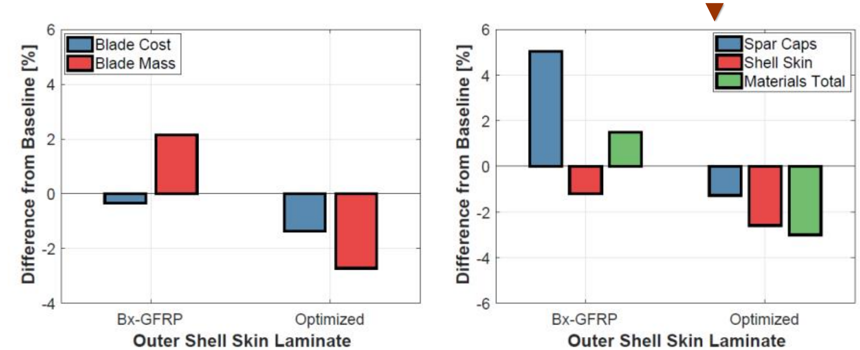
Result:
- Wind turbine designer: pick closest existing material within market products
- Material designer: design new material with optimal properties

Combined optimum:
Blade mass −9.3%
Blade cost −2.9%



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



Publication: Bortolotti et al., TORQUE 2016

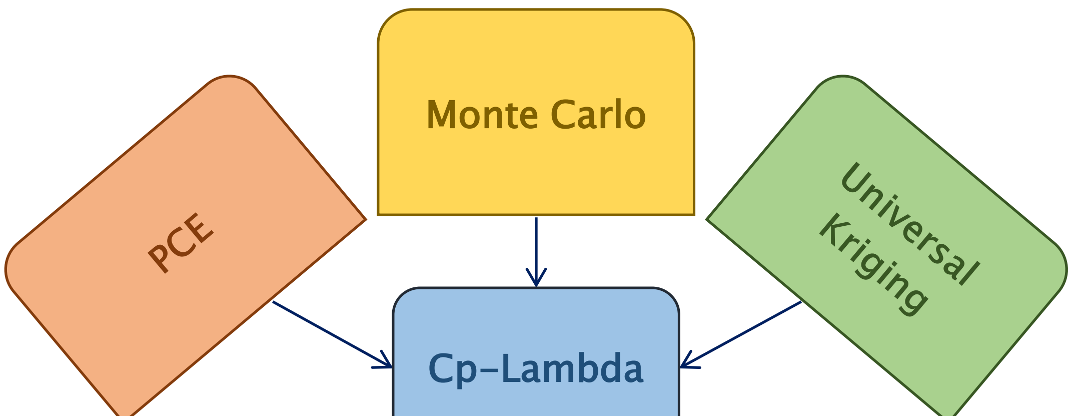
Uncertainty Quantification

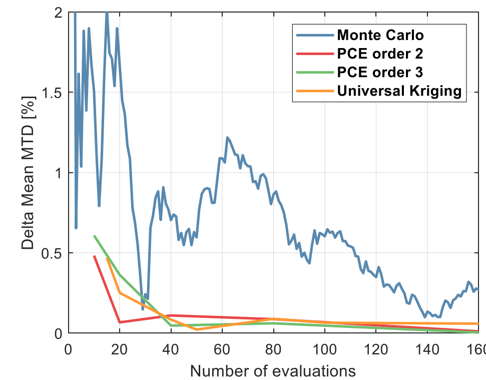
Aleatory **uncertainties** in wind and airfoil characteristics

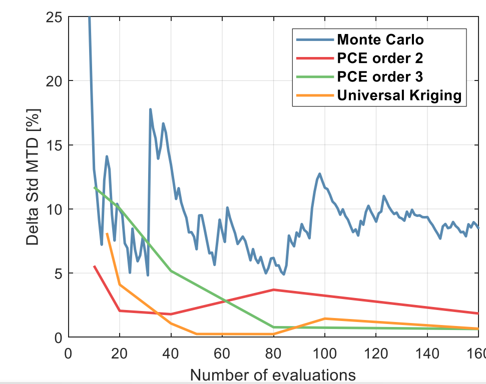
Propagation through the aeroelastic models of the 2 MW and the 10 MW AVATAR WTs

Reconstruction of the statistics of outputs of interest:

- Ultimate and fatigue loads
- AEP



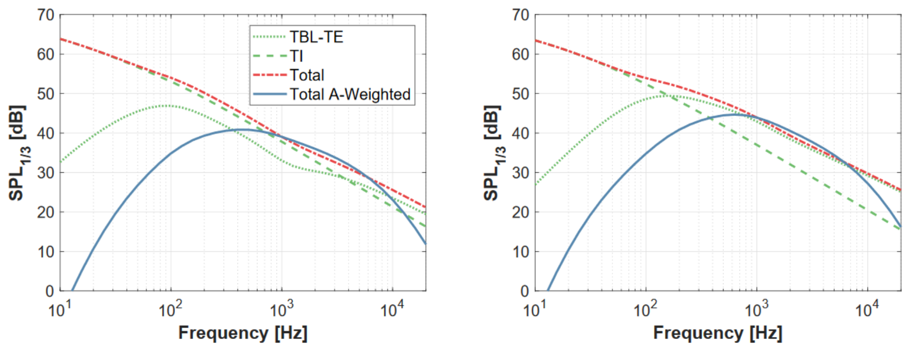




Publication: Matthäus et al., AIAA 2017

Noise within Design

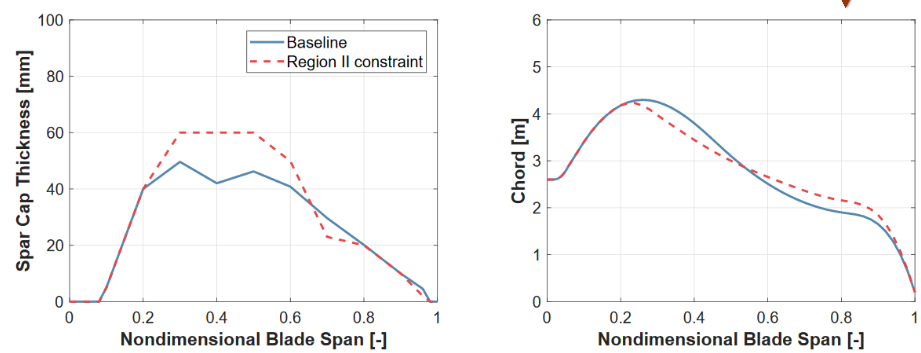
Multi- and single-objective optimization including **noise**



(a) Wind speed = 7 m/s (b) Wind speed = 13 m/s

▲ Noise computation adopting TI Amiet and TBL-TE Moriarty models

Optimization under noise constraint in region II increases the chord outboard. This induces a **lower TSR** and lower rpm at **constant CoE** ▼

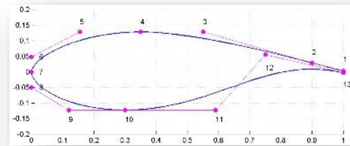


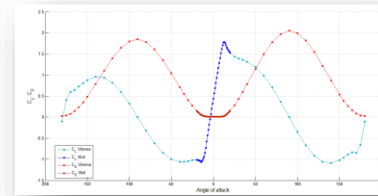
Publication: Bortolotti et al., TORQUE 2018

Free-Form Optimization

Design **airfoils together with blade**:

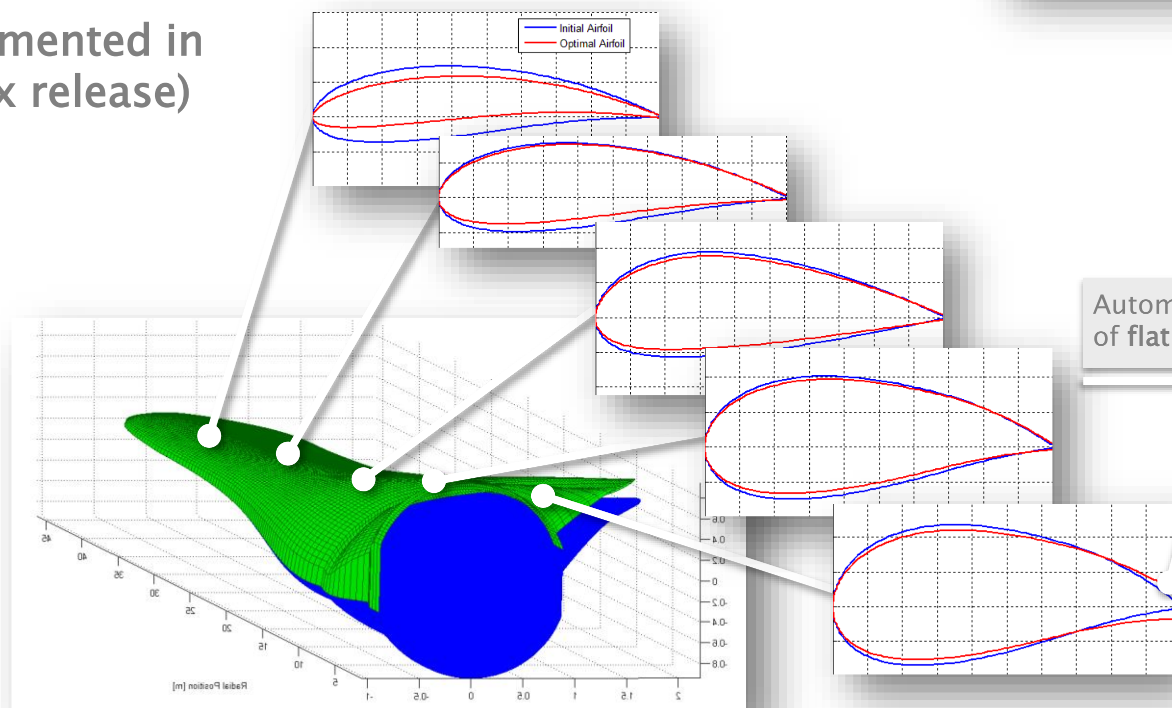
- Bezier airfoil parameterization
- Airfoil aerodynamics by Xfoil + Viterna extrapolation





Additional constraints: C_L max (margin to stall), geometry

(not yet implemented in latest Cp-Max release)



Automatic appearance of **flatback** airfoil!

Publications: Bottasso et al., TORQUE 2014
Bottasso et al., SciTech 2015

Ongoing Projects – WINSENT

German national project for a new test field with two small-size wind turbines located close to Stuttgart

TUM activities:

- Development of the BEM-based wind turbine numerical models
- Definition with Uni Stuttgart of an openly available controller
- Calculation of the various design margins to guarantee safe operation in future research activities
- **Design of gravo-elastically scaled wind turbine blades**

WINSENT
Wind Science & Engineering
Test Site in Complex Terrain

WindForS
Windenergie
Forschungscluster

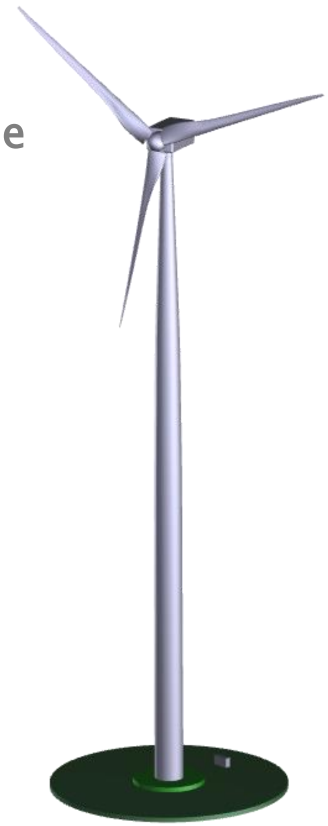
Publication: Canet et al., TORQUE 2018

Ongoing Projects – TremAc

German national project to characterize the vibrations and the noise emission of onshore wind turbines

TUM activities:

- Implementation of an aeroacoustic emission tool for both audible and infrasound spectra coupled to Cp-Lambda
- **Design** of a **generic wind turbine** model resembling the ENERCON E82
- **Validation** of the noise emission models



WindForS Windenergie Forschungscluster

Publication: Sucameli et al., TORQUE 2018

IEA Wind Task 37

International cooperation coordinate by Katherine Dykes (NREL), Frederik Zahle (DTU), Pierre-Elouan Réthoré (DTU) and Karl Merz (Sintef)

TUM contributions:

- **WP1**: Definition of turbine ontology and data exchange formats
- **WP2**: Active participation in the development of the reference onshore wind turbine and contribution to the development of the offshore one
- **WP3**: Contribution to the aerodynamic only optimization case and definition and analysis of the structural only optimization case

iea wind

Conclusions

Main conclusions:

- **Multi-level approach** to marry high fidelity and computational effort
- **Nested iterated sub-optimizations** of original monolithic problem to improve well-posedness, efficiency and robustness

Open issues/outlook:

- CoE: solutions are **highly sensitive to cost model**, need detailed reliable models that truly account for all significant effects, problem partially alleviated by Pareto solutions
- Include/improve physics-based **sub-system models**
- **Uncertainties everywhere** (aero, structure, wind, …), move towards robust design

Some Recent References

2018:

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