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Lightweight design of the INNWIND.EU and AVATAR rotors through multi-disciplinary optimization algorithms

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EERA DeepWind 2018, 17 January 2018, Trondheim

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Outline

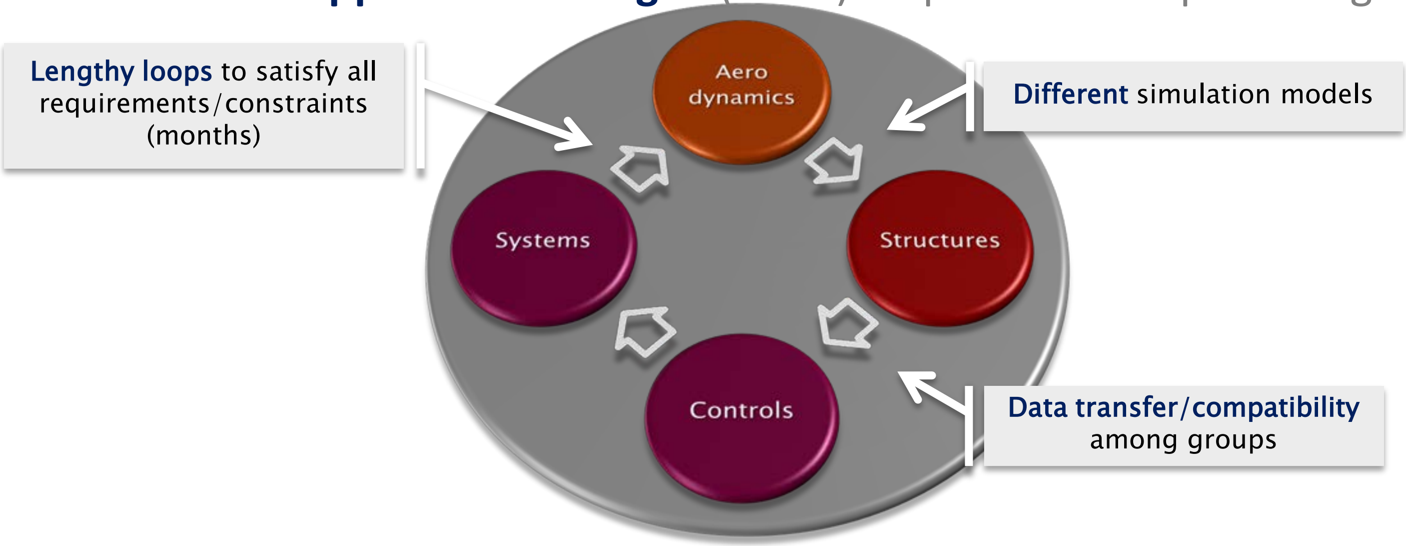
- Background
- Multi-disciplinary design algorithms for wind turbines
  - **Cp-Max:** a modular design framework
- Passive load-alleviation techniques
- Applications
  - Lightweight redesign of the INNWIND.EU rotor
  - Lightweight redesign of the AVATAR rotor
- Conclusions

Background

- Large rotors for 10+ MW wind turbines:
  - Strong aero-servo-elastic couplings
  - High mass and loads due to slender and flexible components
- Load-mitigation:
  - Passive and active techniques
  - Reduced loads on blades and fixed infrastructure
  - Impact on the AEP
- **MDAOs** help the design process:
  - High-fidelity models *plus* dedicated optimization methods
  - Automatic management of preliminary/detailed design of WTs
  - Trade-offs and cost-oriented studies

Holistic Design of Wind Turbines

Classical approach to design: (weak) loops between specialist groups

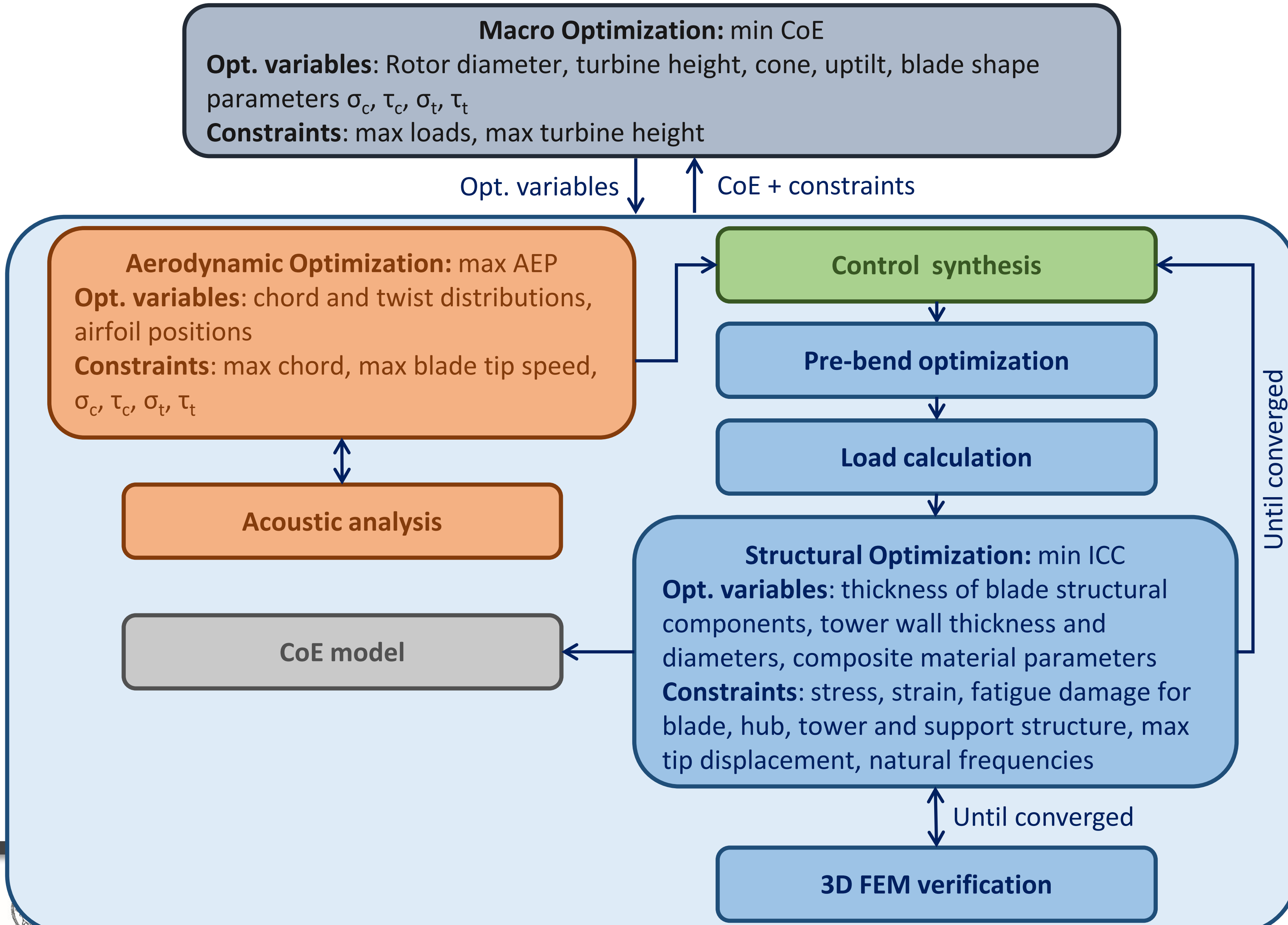


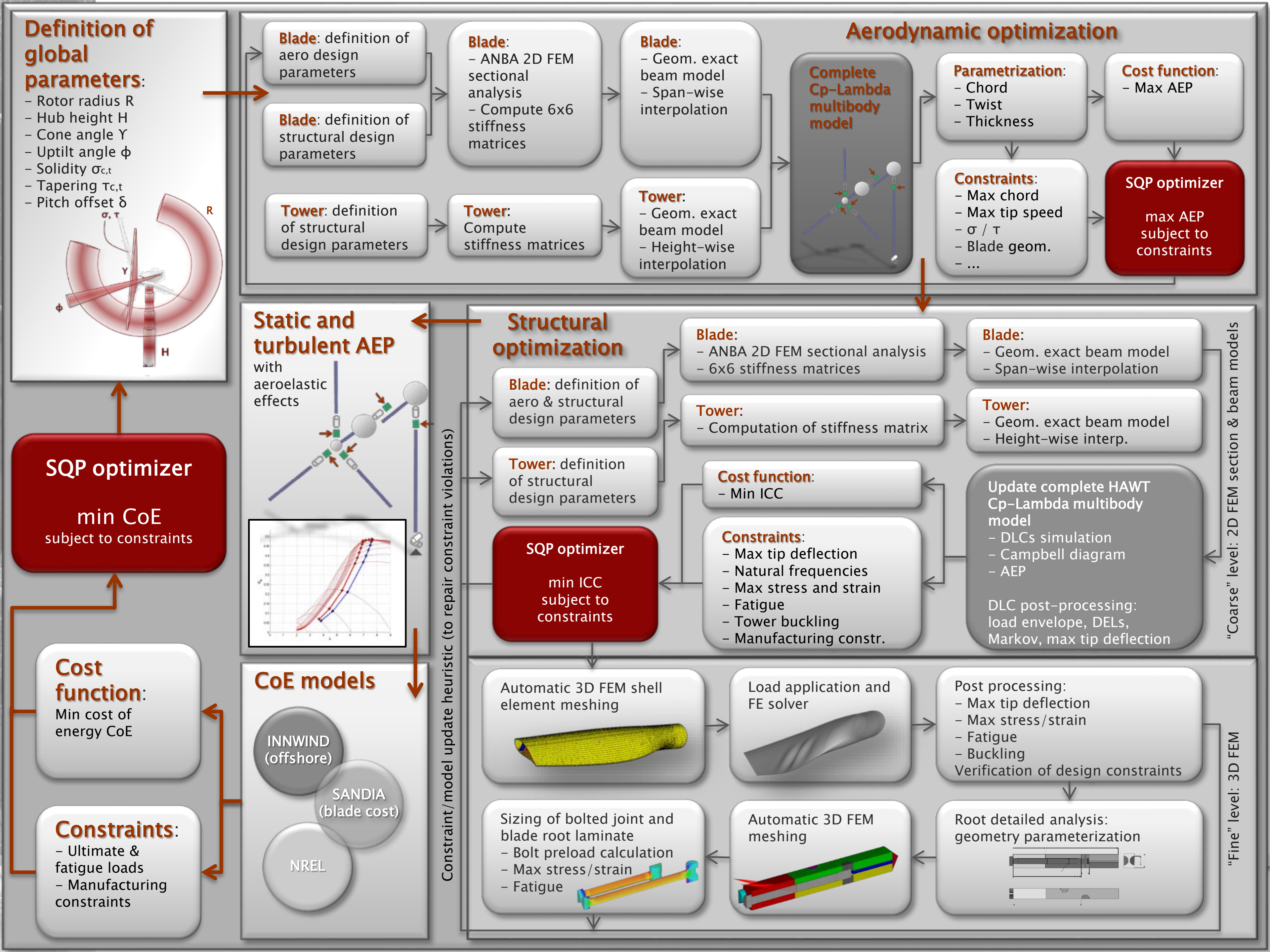
There is a need **for multi-disciplinary optimization tools**, which must:

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

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

Cp-Max: a modular design framework



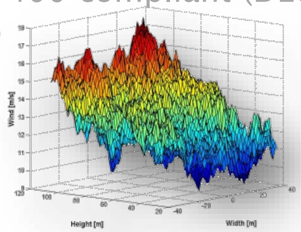


Definition of global parameters:
– Rotor radius R
– Hub height H
– Cone angle Υ
– Uptilt angle ϕ
– Solidity σc,t
– Tapering τc,t
– Pitch offset δ
R
σ, τ
Υ
ϕ
H
Blade: definition of aero design parameters
Blade: definition of structural design parameters
Tower: definition of structural design parameters
Blade:
– ANBA 2D FEM sectional analysis
– Compute 6x6 stiffness matrices
Tower: Compute stiffness matrices
Blade:
– Geom. exact beam model
– Span-wise interpolation
Tower:
– Geom. exact beam model
– Height-wise interpolation
Aerodynamic optimization
Complete Cp-Lambda multibody model
Parametrization:
– Chord
– Twist
– Thickness
Cost function:
– Max AEP
Constraints:
– Max chord
– Max tip speed
– σ / τ
– Blade geom.
– ...
SQP optimizer
max AEP subject to constraints
Static and turbulent AEP with aeroelastic effects
Structural optimization
Blade:
– ANBA 2D FEM sectional analysis
– 6x6 stiffness matrices
Blade:
– Geom. exact beam model
– Span-wise interpolation
Blade: definition of aero & structural design parameters
Tower:
– Computation of stiffness matrix
Tower:
– Geom. exact beam model
– Height-wise interp.
Tower: definition of structural design parameters
Cost function:
– Min ICC
Constraints:
– Max tip deflection
– Natural frequencies
– Max stress and strain
– Fatigue
– Tower buckling
– Manufacturing constr.
SQP optimizer
min ICC 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
"Coarse" level: 2D FEM section & beam models
SQP optimizer
min CoE
subject to constraints
Cost function:
Min cost of energy CoE
Constraints:
– Ultimate & fatigue loads
– Manufacturing constraints
CoE models
INNWIND (offshore)
SANDIA (blade cost)
NREL
Constraint/model update heuristic (to repair constraint violations)
Automatic 3D FEM shell element meshing
Load application and FE solver
Post processing:
– Max tip deflection
– Max stress/strain
– Fatigue
– Buckling
Verification of design constraints
Sizing of bolted joint and blade root laminate
– Bolt preload calculation
– Max stress/strain
– Fatigue
Automatic 3D FEM meshing
Root detailed analysis: geometry parameterization
"Fine" level: 3D FEM

Multibody Dynamics Technology

Cp-Lambda highlights:

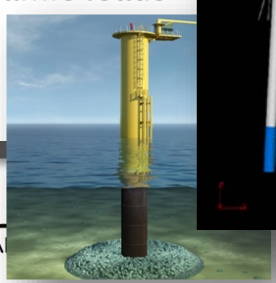
- IEC 61400 compliant (DLCs, wind models)

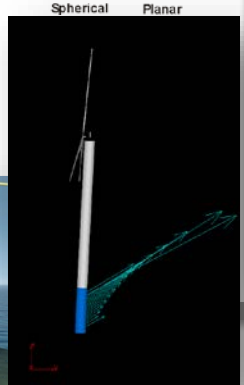


- **Geometrically exact composite-ready beam models**
- **Fully populated 6x6 stiffness (aeroelastic couplings)**

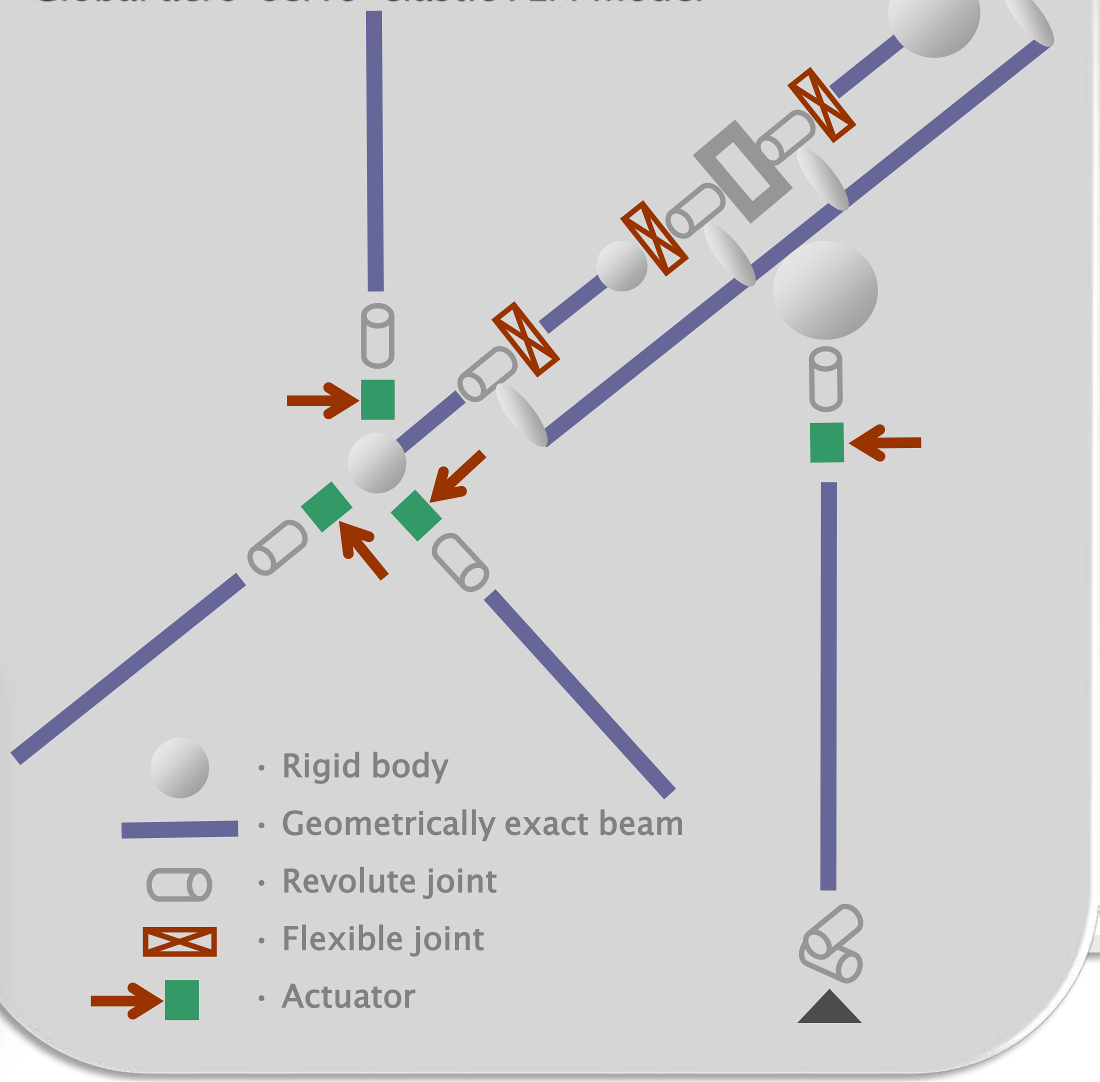
- Generic topology (Cartesian coordinates+Lagrange multipliers)

- Joints enforced by Lagrange multipliers
- Hydrodynamic loads





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



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Multibody Dynamics Technology

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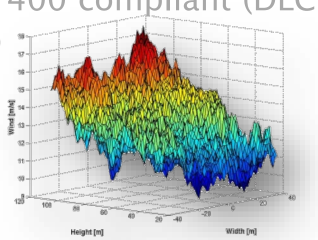

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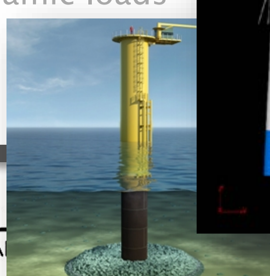
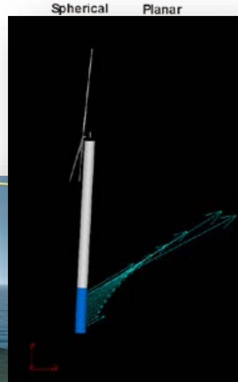
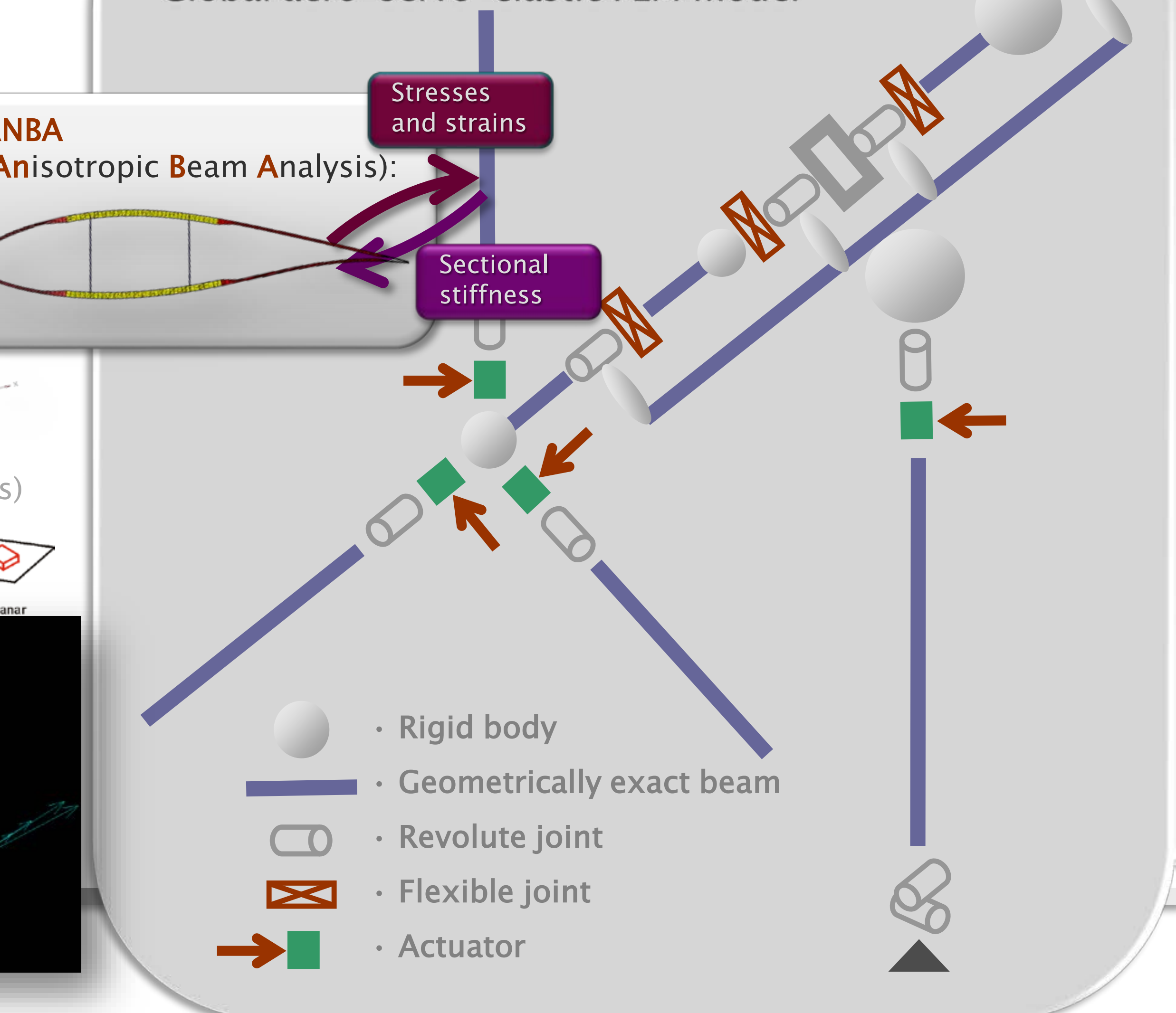


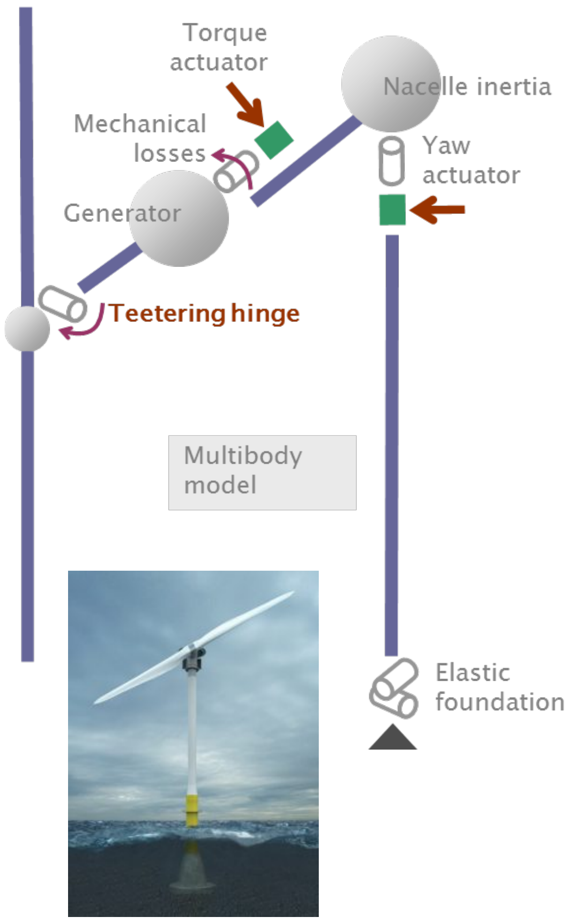


Cp-Lambda (Code for Performance, Loads, Aero-elasticity by Multi-Body Dynamic Analysis): Global aero-servo-elastic FEM model

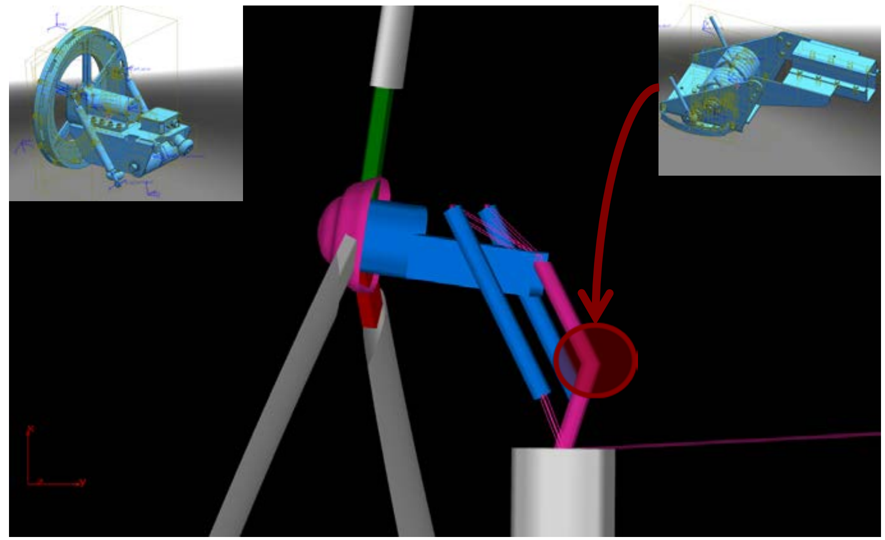


Multibody Dynamics Technology

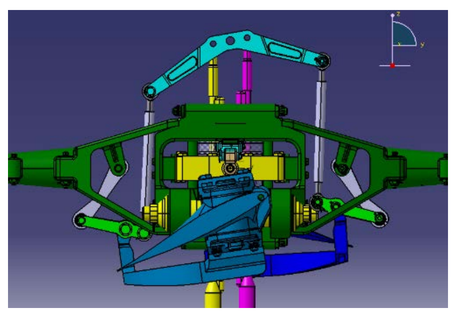
Different (complex) topologies

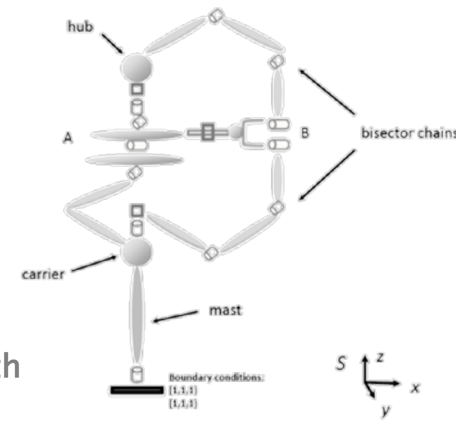


▲ 2-bladed yaw-controlled with teeter hinge offshore wind turbine



▲ 3-bladed rotor tilt-controlled

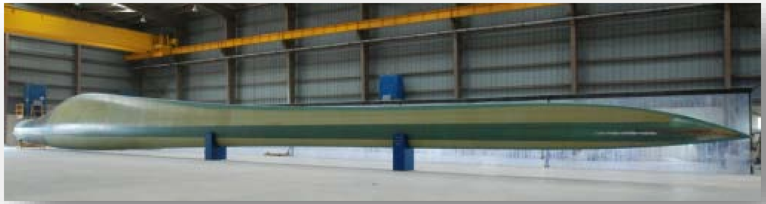




▲ 2-bladed helicopter rotor with gimbal joint and flybar

Manufactured Blades

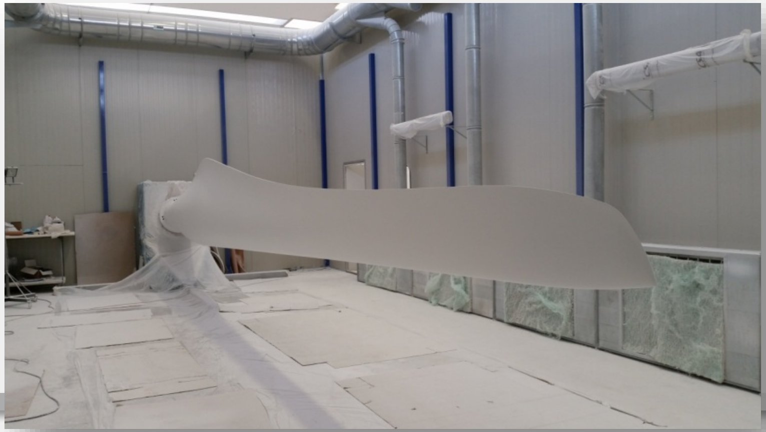
2MW – 45m (MAIT-Gurit) ▼



300kW – 16m (Italtech-Gurit-Euros) ▼

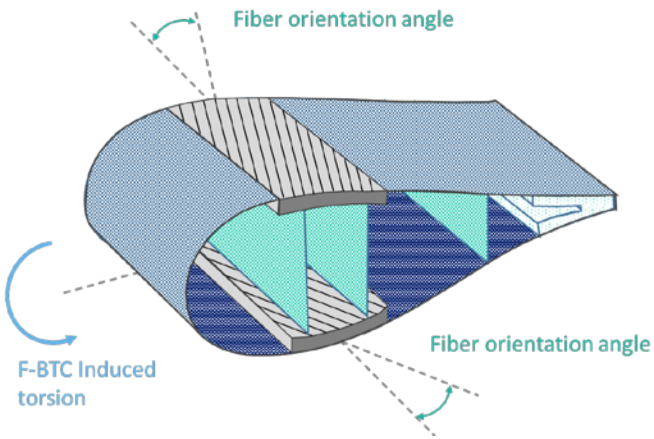
700kW – 24m (ETA-Gurit-ECN) ▼

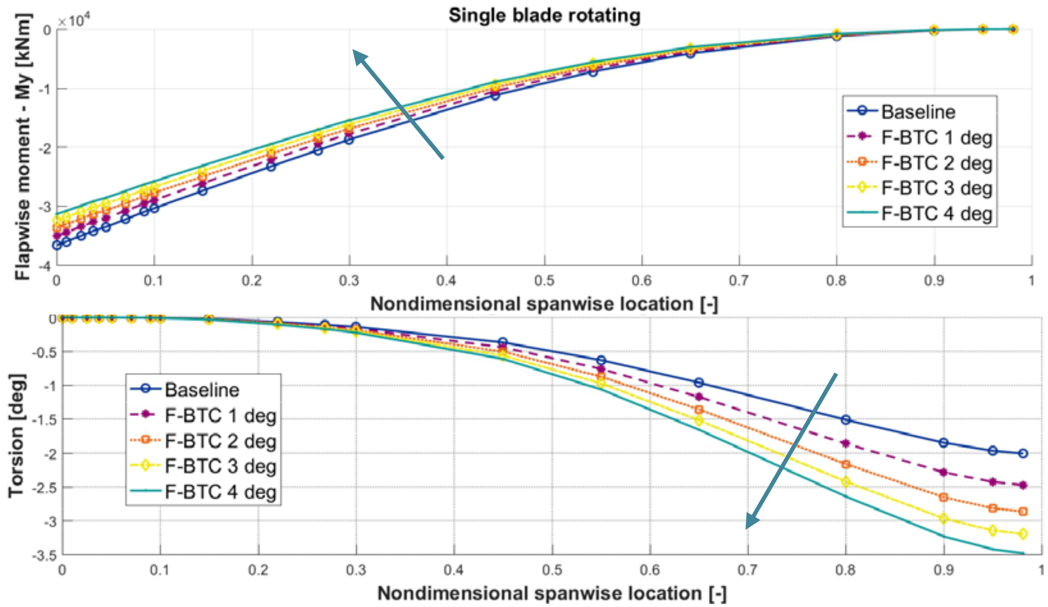
100kW – 10m (ETA) ▼

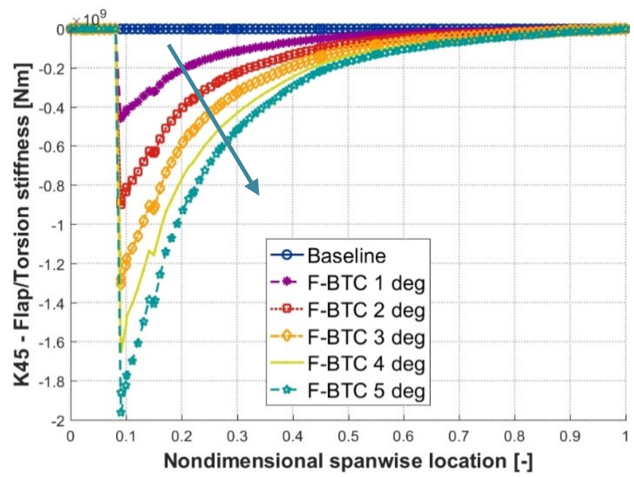


Passive load-alleviation techniques (i)

- **Fiber-induced Bend/Twist Coupling (F-BTC)**
  - Rotation of the laminae of composite fabrics
  - Increased extra-diagonal stiffness $K_{FLAP/TORS}$
  - Load mitigation due to induced torsion

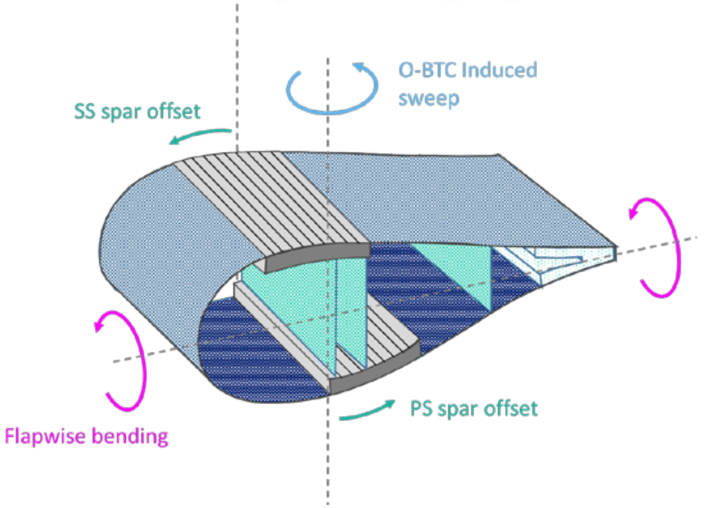


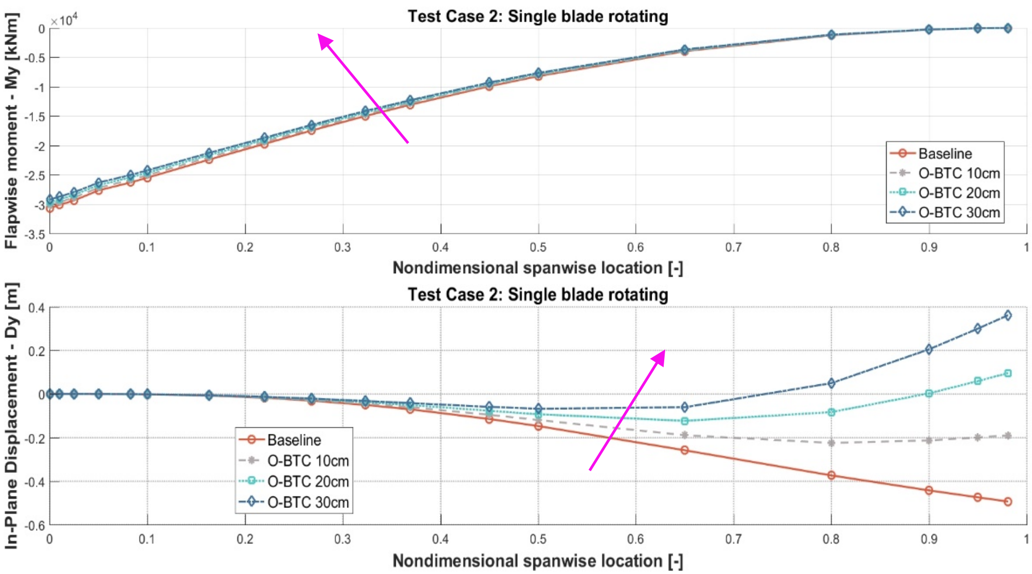


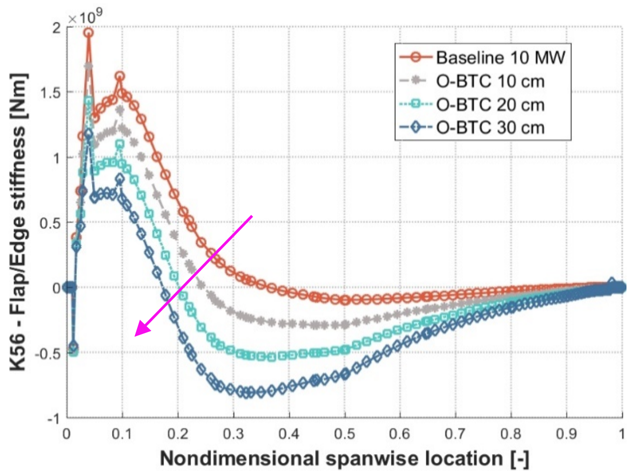


Passive load-alleviation techniques (ii)

- **Offset-induced Bend/Twist Coupling (O-BTC)**
  - Geometric offset between spar caps
  - Increased extra-diagonal stiffness $K_{FLAP/EDGE}$
  - Load mitigation due to induced sweep







Reference wind turbines

	INNWIND.EU	AVATAR
Design philosophy	Classic, max(Cp)	Low Induction
Rated power [MW]	10	10
IEC Class [–]	1A	1A
Blade length [m]	86.35	100.08
Rotor diameter [m]	178.3	205.76
Hub height [m]	119	132.5
Nacelle up-tilt [deg]	5	5
Rotor pre-cone [deg]	2.5	2.5
Rotor speed [RPM]	9.6	9.6
Blade mass [kg]	42481	50126
Tower mass [kg]	628441	628441

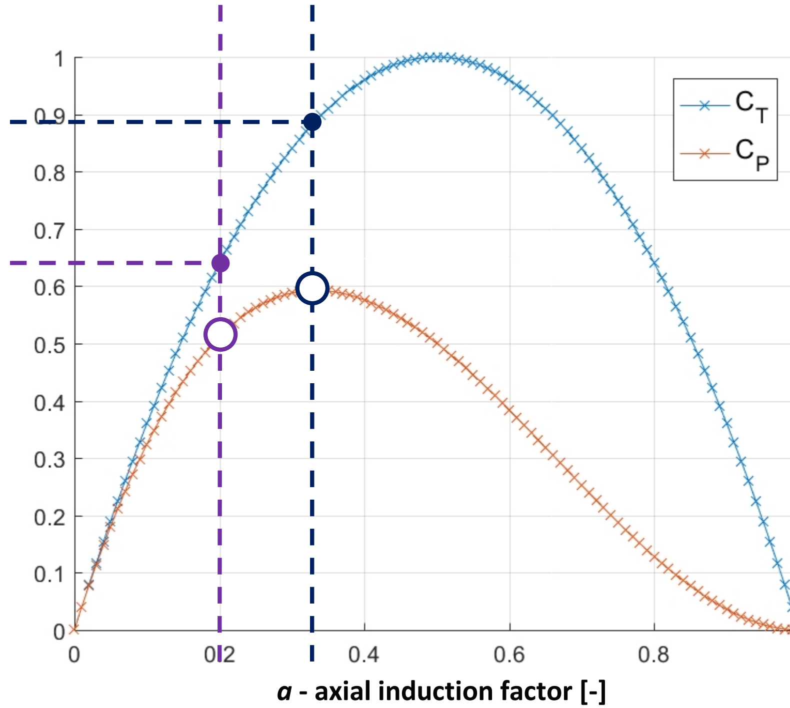
INNWIND.EU

AdVanced Aerodynamic Tools for lArge Rotors

Lightweight redesign of the AVATAR rotor

Low-Induction Rotors

- Classic WTs operate at Optimal C_P ($a \approx 1/3$)
- By operating at Lower Induction, one could trade some efficiency to achieve lower loads[1]
- Impact on COE and support structure is still not very well studied



Reference:

[1] Chaviaropoulos, P. K., Beurskens, H. J. M. and Voutsinas, S. G., " Moving towards large(r) rotors - is that a good idea?" Proceedings of EWEA 2013, Vienna, Austria.

Lightweight redesign of the AVATAR rotor

Setup

Goals:

- Apply F-BTC to mitigate loads
- Redesign rotor to minimize the ICC
- Optimize collective pitch to increase AEP

Cp-Max modules:

- Structural Design Submodule (SDS)
- Finite Element Model
- Stability analysis tool

Design constraints:

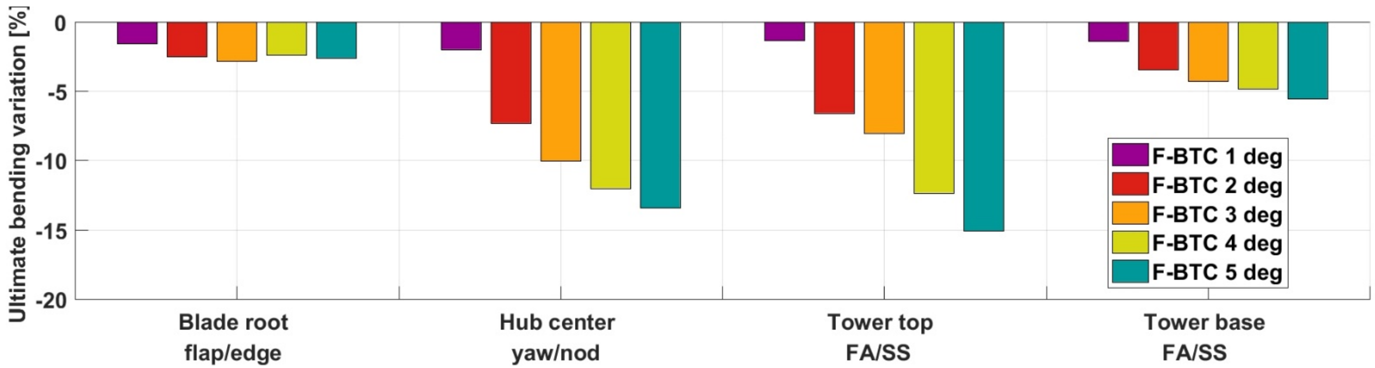
- Same radius of the Baseline
- Same planform of the Baseline

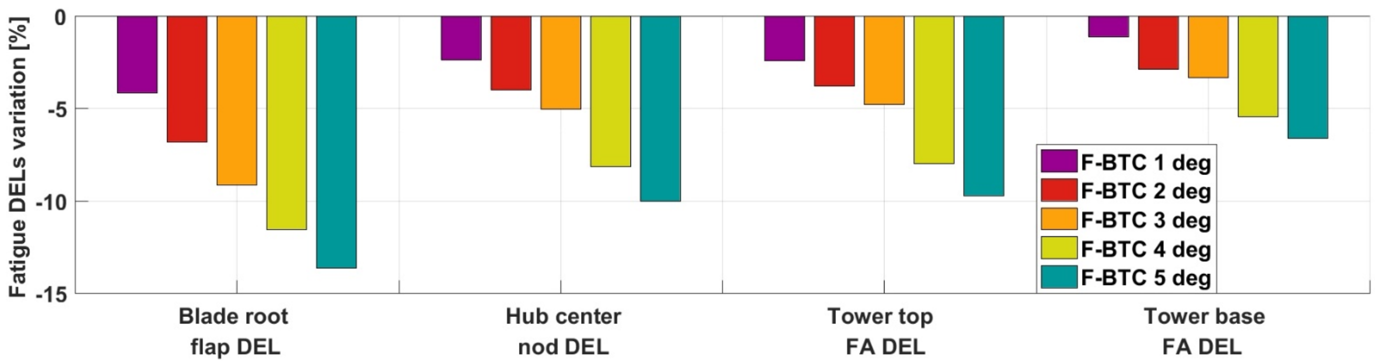
Note: all rotors satisty the same design constraints!

Lightweight redesign of the AVATAR rotor

Parametric lightweight redesign

- Parametric F-BTC (carbon spar caps) + pitch re-scheduling



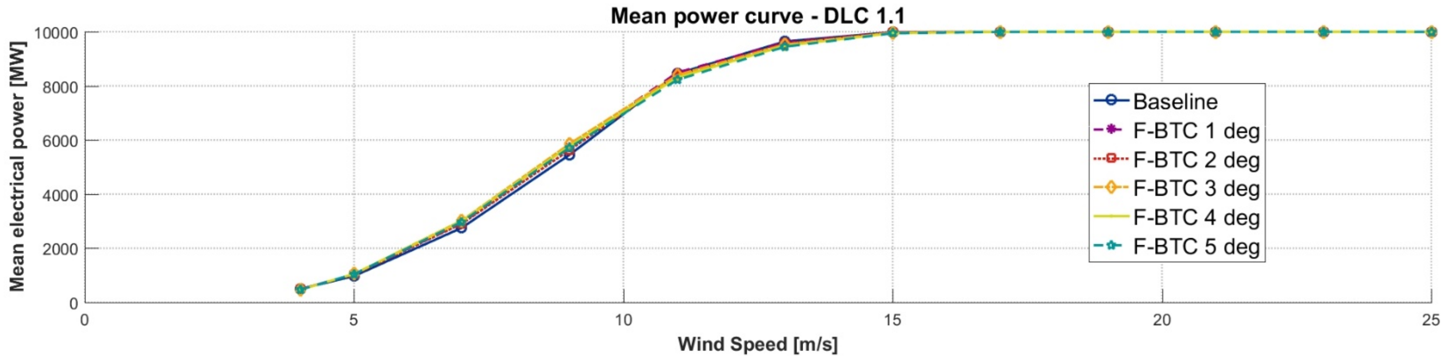


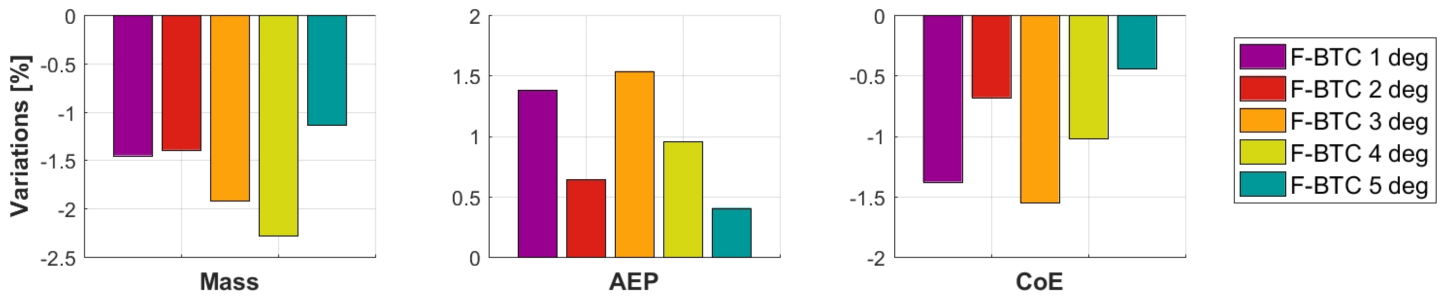
Comparisons against the Baseline 10 MW – 206m

Lightweight redesign of the AVATAR rotor

Parametric lightweight redesign

- Parametric F-BTC (carbon spar caps) + pitch re-scheduling





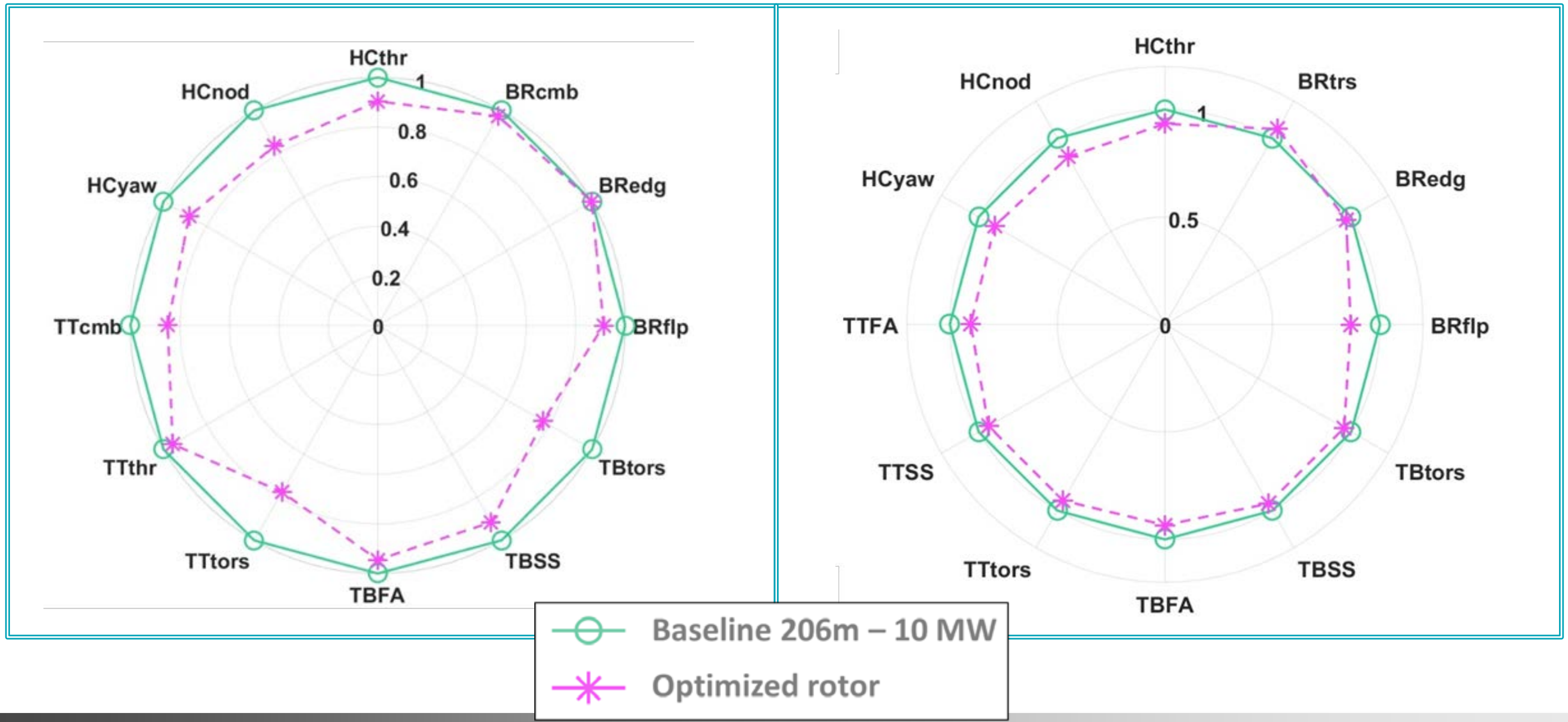
Lightweight redesign of the AVATAR rotor

Final comparison

Results:

- All loads reduced. Best reduction for F-BTC of 5°
- AEP restored by optimal pitch scheduling
- COE reduction for all the parametric solutions

BR – Blade root	
HC – Hub center	
TT – Tower top	
TB - Tower base	



Lightweight redesign of the INNWIND.EU rotor

Setup

Goals:

- Apply F-BTC, O-BTC and IPC to mitigate loads
- Redesign rotor to optimize COE

Cp-Max modules:

- Aerodynamic Design Submodule (ADS)
- Structural Design Submodule (SDS)

Design constraints:

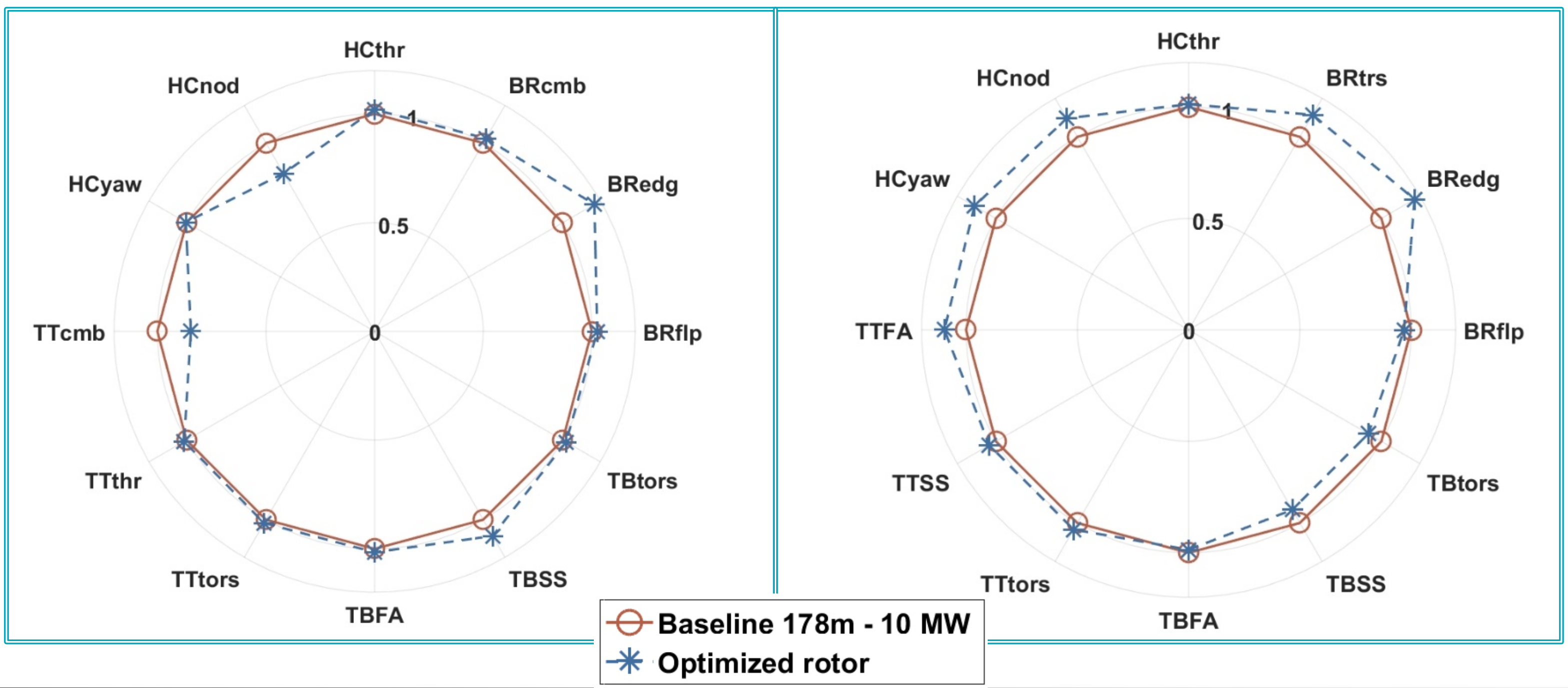
- Same hub thrust of the Baseline
- All loads at Hub, Tower Base < 1.10 than the Baseline
- Same rotor solidity of the Baseline

Lightweight redesign of the INNWIND.EU rotor

Results:

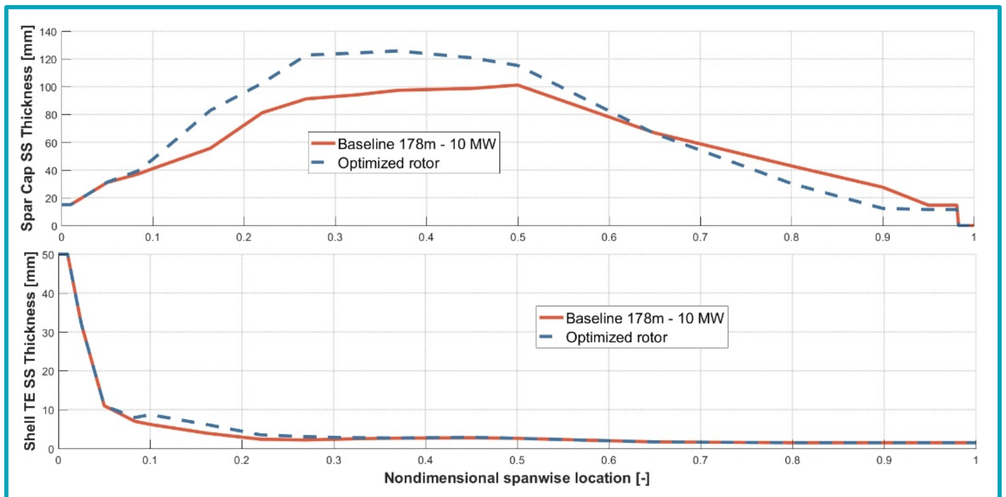
- Longer blade
- Larger AEP
- Same thrust
- Loads at HC, TB do not exceed 10% more than Baseline

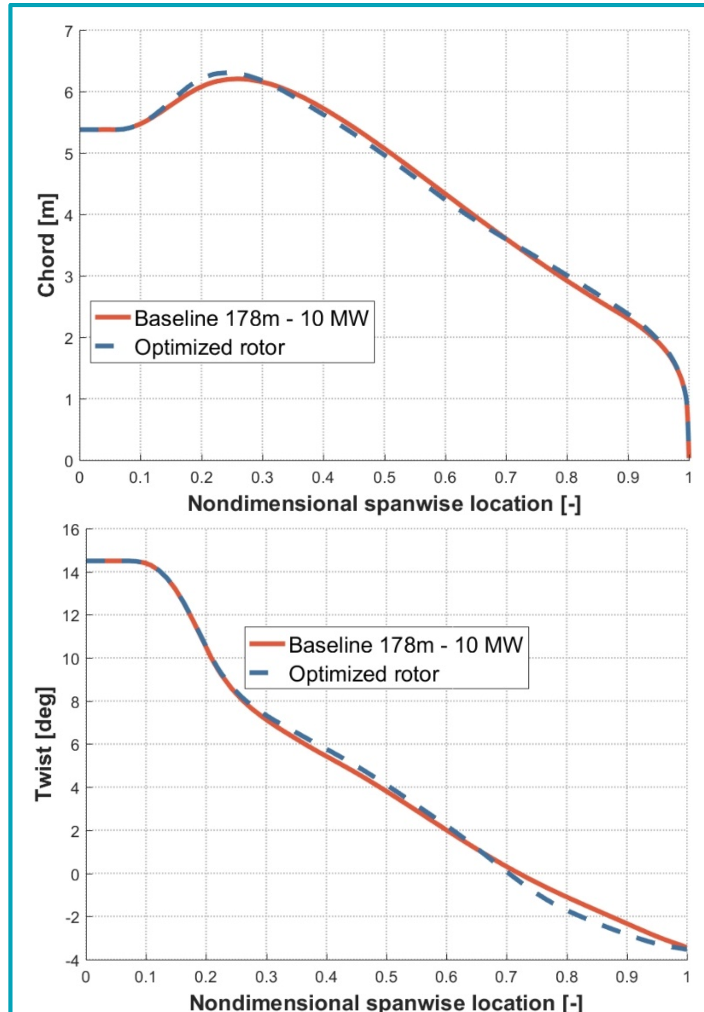
BR	Blade root
HC	Hub center
TT	Tower top
TB	Tower base



Lightweight redesign of the INNWIND.EU rotor

	Baseline 178m - 10 MW	Optimized rotor	Variation %
Diameter [m]	178	188	+ 5 %
SC fiber angle [deg]	0	5	-
SC offset [cm]	0	20	
Max chord [m]	6.2	6.3	+ 1.6 %
Blade mass [ton]	42.4	48.9	+ 15.5 %
AEP [GWh]	46.4	48.3	+ 4.15 %
COE [€/MWh]	74.9	72.8	- 2.8 %





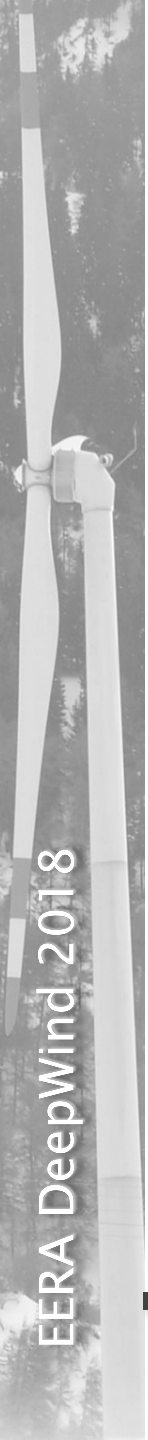
Conclusions

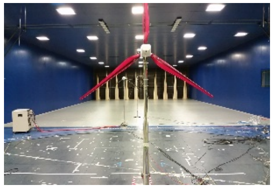
Remarks

- Several completed and ongoing activities about aero-structural rotor **tailoring**
- Application of **load mitigation** techniques to 10 MW concepts
- Important **loads reduction** (on hub and tower base)
- AEP losses could be limited by:
  - Elongating the blade (*Optimal-Cp* design)
  - Optimizing the collective pitch (*Low-Induction* design)
- Automated design procedures can help in identifying the **best trade-offs**

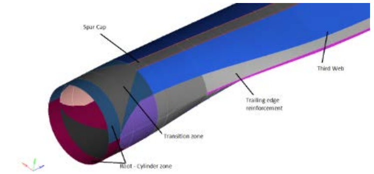
Outlook

- Application of additional load mitigation techniques (flap, VGs)
- Assessment of the effect of load alleviation techniques on the rotor stability
- Include airfoil shapes in the optimization loop
- **Add** module to analyze and **design the support structure**





POLI-Wind Research Lab



in collaboration with

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TORQUE 2018

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20-22 June 2018

DON'T FORGET!

The seventh edition of the conference «*The Science of Making Torque from Wind* (TORQUE 2018)» will take place in June 20-22, 2018 at Politecnico di Milano, Campus Bovisa, Milano, Italy

Topics, call for papers and important dates available at the conference web site:

www.torque2018.org

Alessandro Croce
Chairman of TORQUE 2018