Technische Universität München
Wind Energy Institute

An Algorithmic Framework for the Multi-Disciplinary Design Optimization of Wind Turbines

Carlo L. Bottasso [†,*], Pietro Bortolotti [†], Alessandro Croce [*]
[†] Technische Universität München, Germany
[*] Politecnico di Milano, Italy

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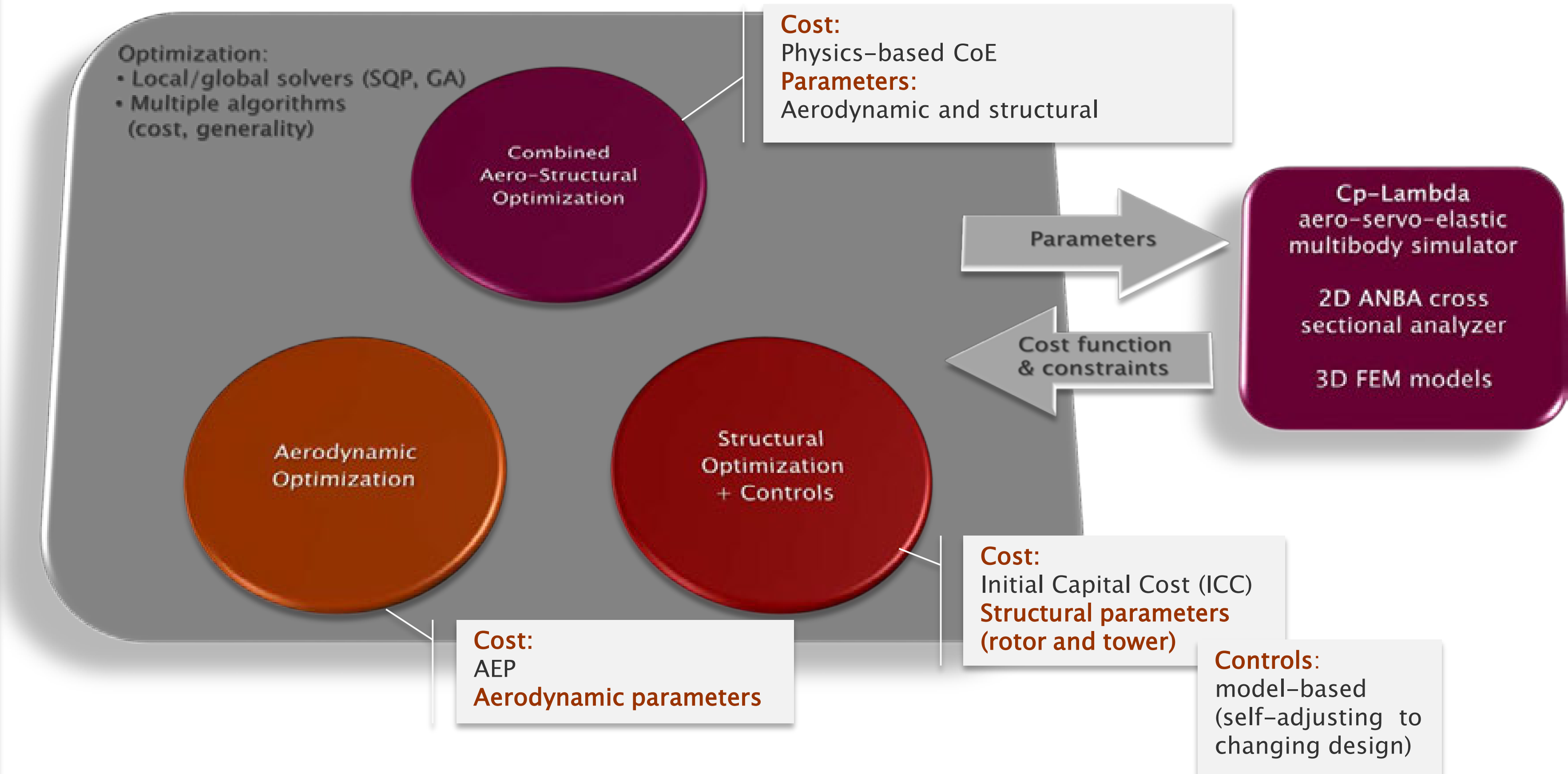
Cp-Max Design Environment

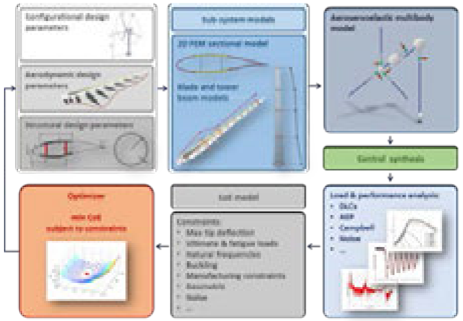


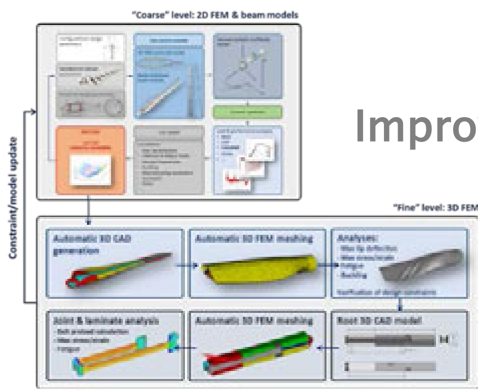
First release: 2007, improved and expanded since then

Applications: academic research and industrial blade design

Algorithmic Approach

Monolithic one-shot formulation of the constrained design problem

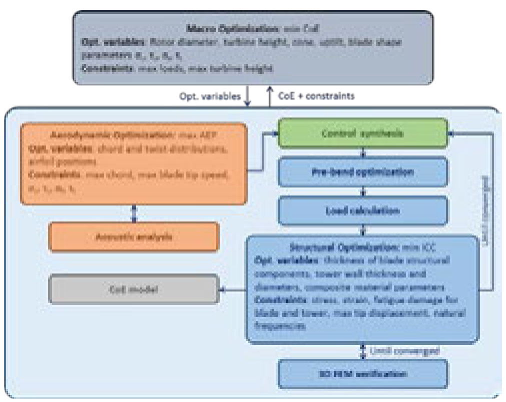


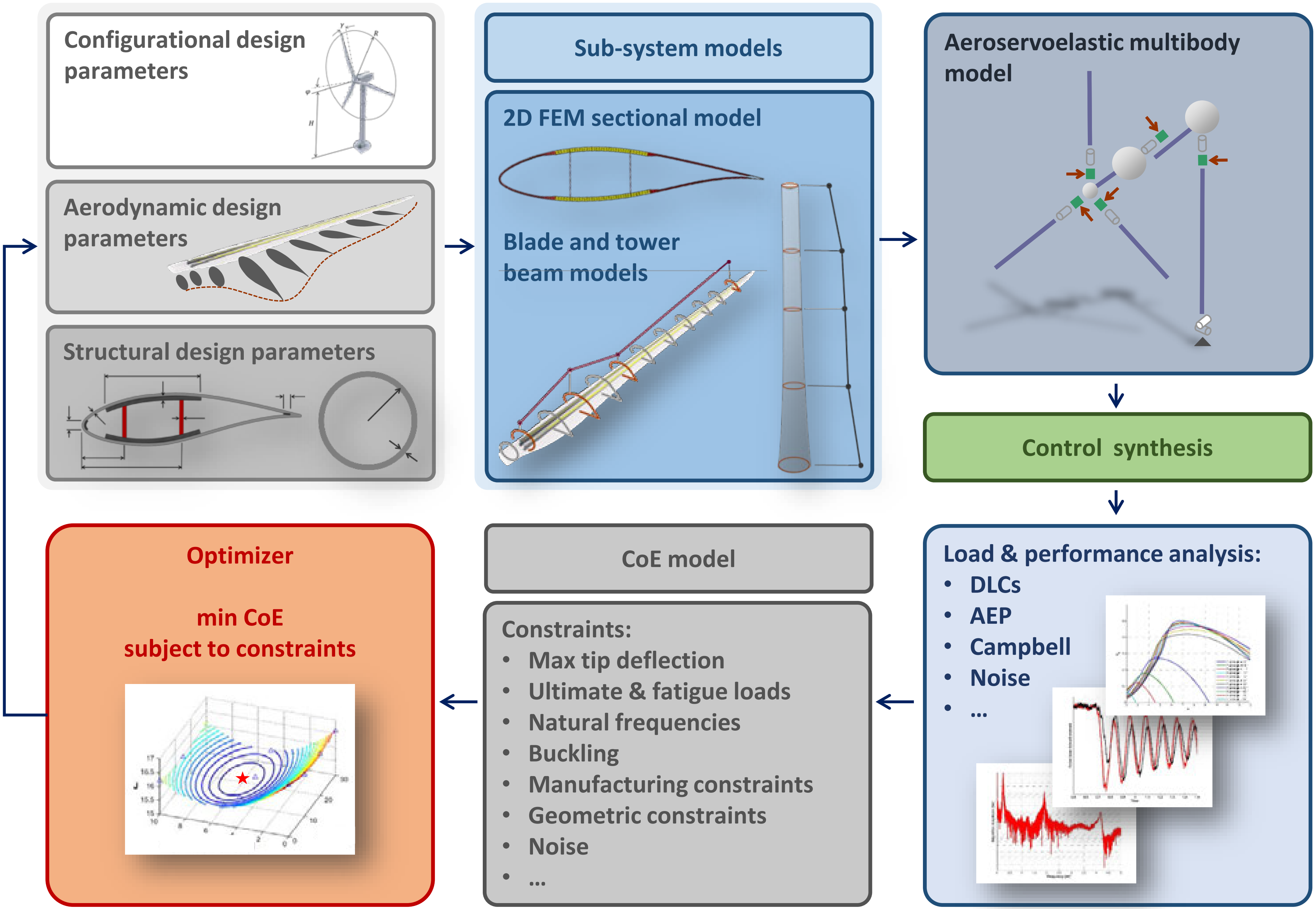


Improving accuracy by multi-level analysis

Issues with the monolithic approach:

- Improving well-posedness
- Improving computational efficiency



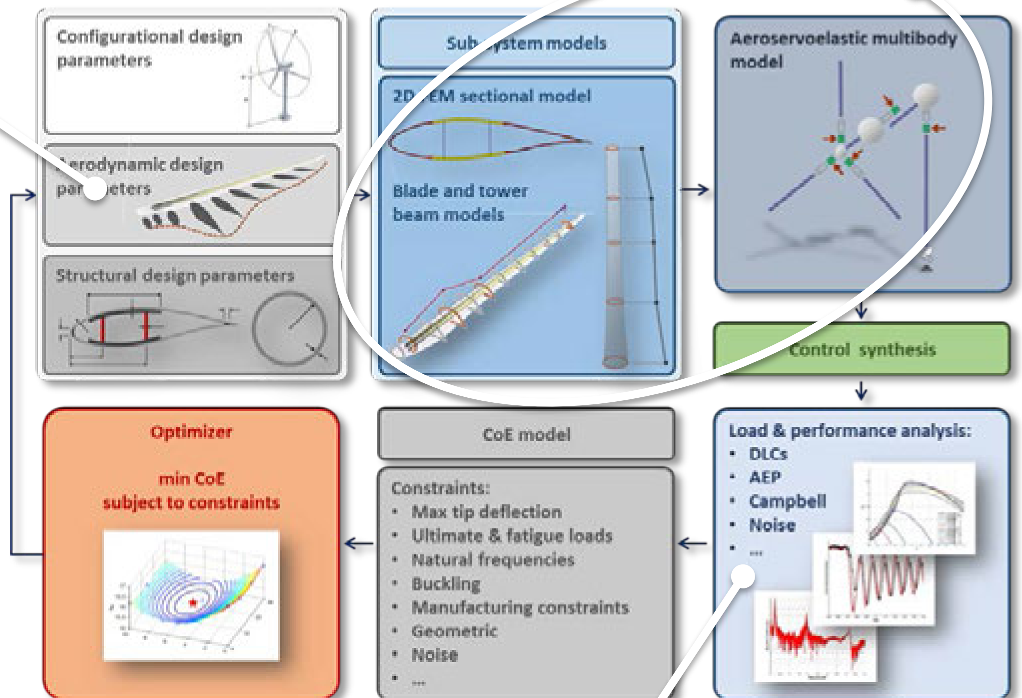


Configurational design parameters
Aerodynamic design parameters
Structural design parameters
Sub-system models
2D FEM sectional model
Blade and tower beam models
Aeroservoelastic multibody model
Control synthesis
Load & performance analysis:
DLCs
AEP
Campbell
Noise
…
CoE model
Constraints:
Max tip deflection
Ultimate & fatigue loads
Natural frequencies
Buckling
Manufacturing constraints
Geometric constraints
Noise
…
Optimizer
min CoE
subject to constraints

Issues with Monolithic Formulation

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

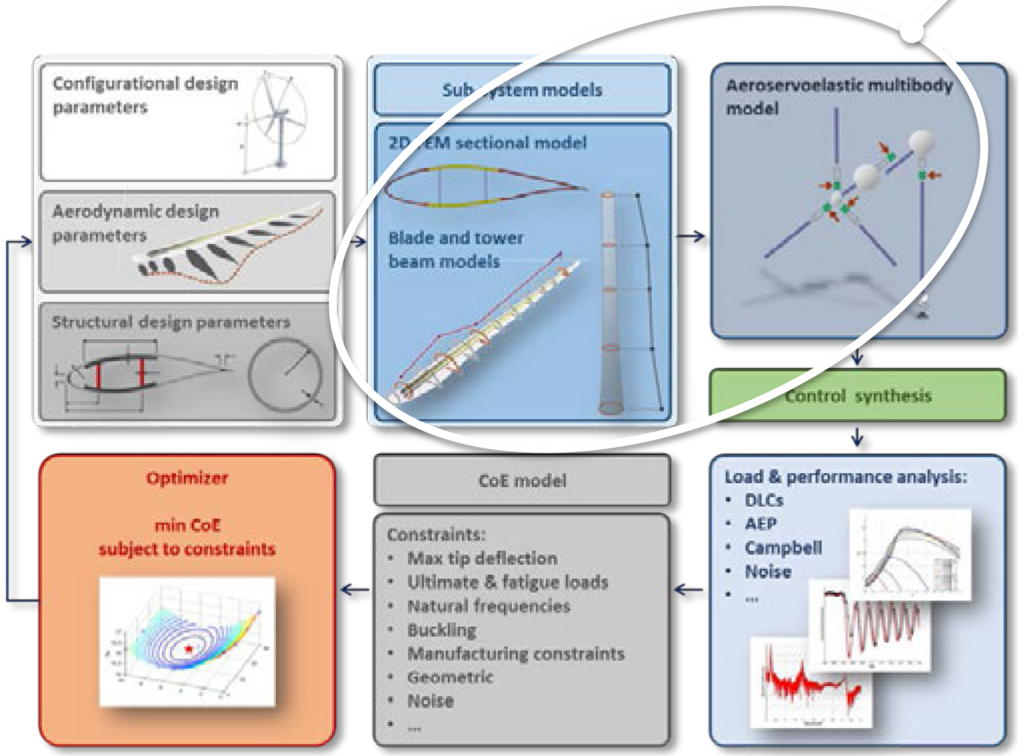
2D + beam models unable to capture **local 3D effects**

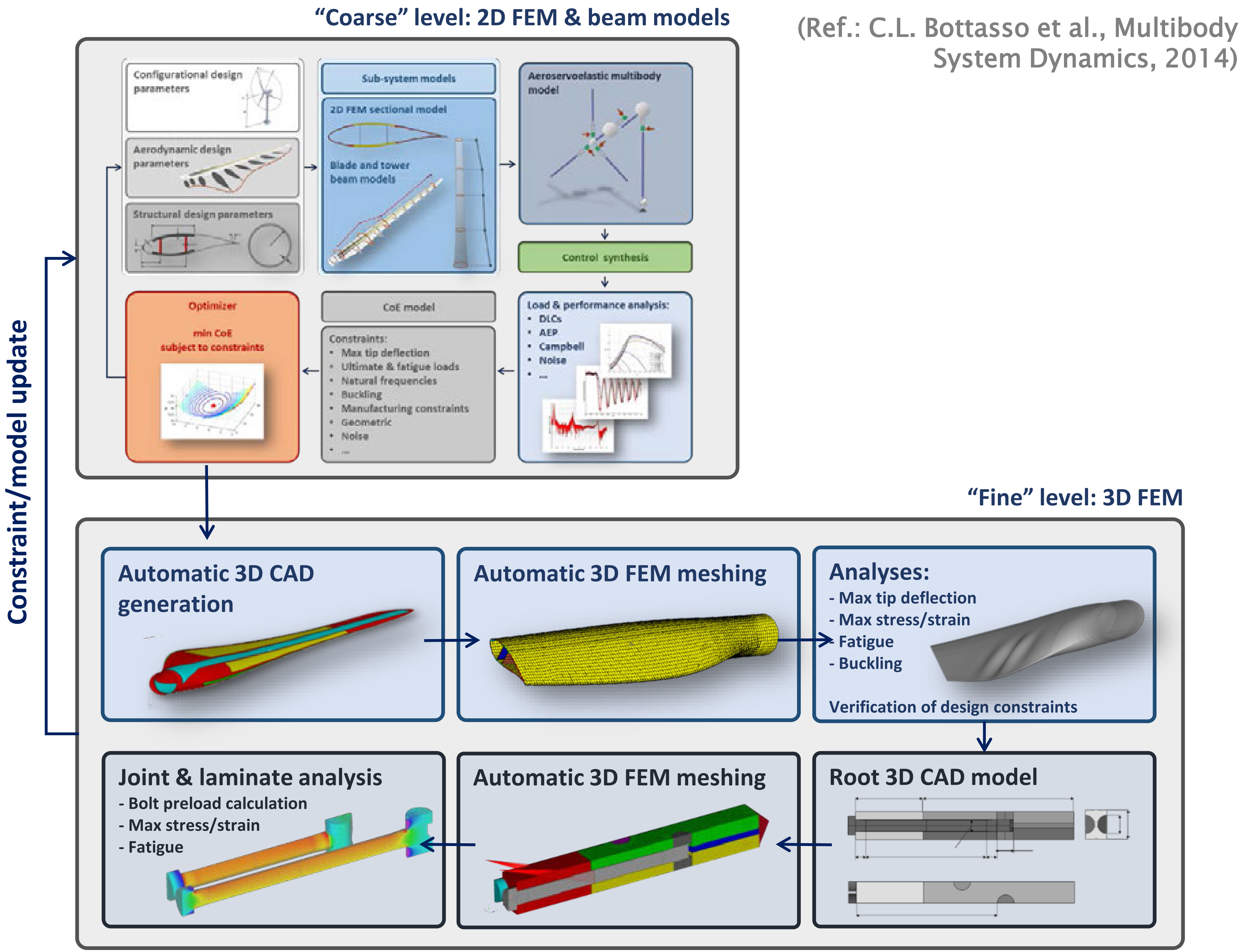


Expensive performance analysis has to be repeated for each change in each design variable
Possibly **non-smooth** load behavior (DLC jump)

Issues with Monolithic Formulation

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





"Coarse" level: 2D FEM & beam models
(Ref.: C.L. Bottasso et al., Multibody System Dynamics, 2014)
Configurational design parameters
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• DLCs
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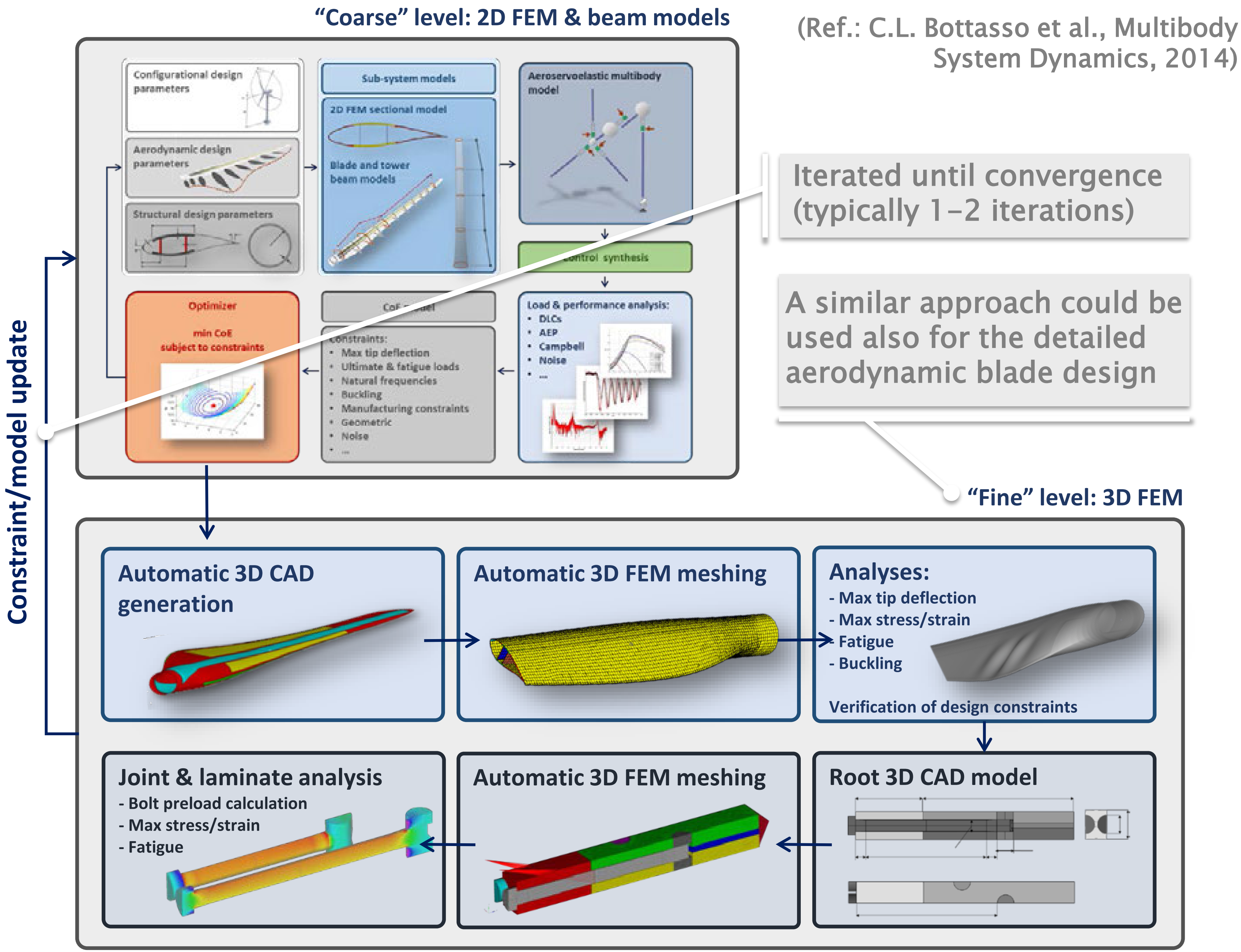
• ...
CoE model
Constraints:
• Max tip deflection
• Ultimate & fatigue loads
• Natural frequencies
• Buckling
• Manufacturing constraints
• Geometric
• Noise
• ...
Optimizer
min CoE
subject to constraints
Constraint/model update
"Fine" level: 3D FEM
Automatic 3D CAD generation
Automatic 3D FEM meshing
Analyses:
- Max tip deflection
- Max stress/strain
- Fatigue
- Buckling
Verification of design constraints
Joint & laminate analysis
- Bolt preload calculation
- Max stress/strain
- Fatigue
Automatic 3D FEM meshing
Root 3D CAD model



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Optimizer
min CoE
subject to constraints
CoE model
Constraints:
• Max tip deflection
• Ultimate & fatigue loads
• Natural frequencies
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• Manufacturing constraints
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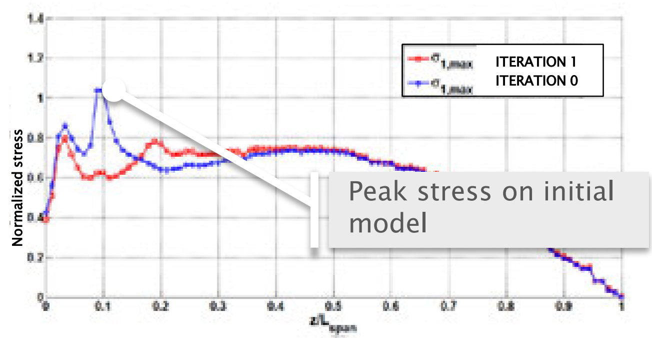
• ...
Iterated until convergence (typically 1–2 iterations)
A similar approach could be used also for the detailed aerodynamic blade design
Constraint/model update
"Fine" level: 3D FEM
Automatic 3D CAD generation
Automatic 3D FEM meshing
Analyses:
- Max tip deflection
- Max stress/strain
- Fatigue
- Buckling
Verification of design constraints
Joint & laminate analysis
- Bolt preload calculation
- Max stress/strain
- Fatigue
Automatic 3D FEM meshing
Root 3D CAD model

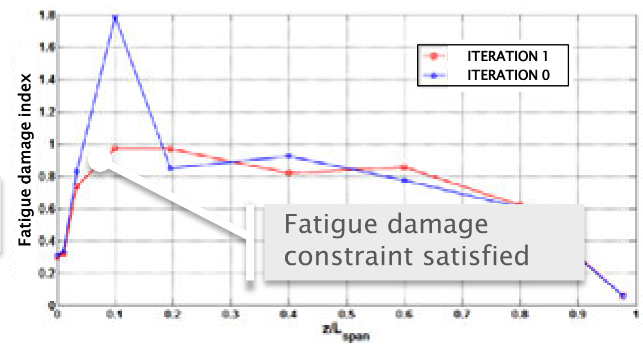
The Importance of Multi-Level Design

Fine-level verification of:

1) Stress/strain/fatigue/frequency/max tip deflection:

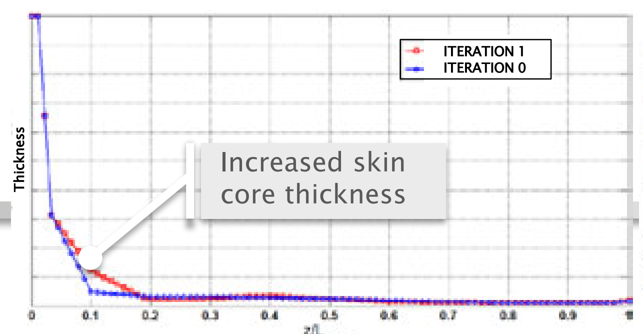
- Constraints violated at first iteration on 3D FEM model
- Modify constraints based on 3D FEM analysis
- Converged at 2nd iteration

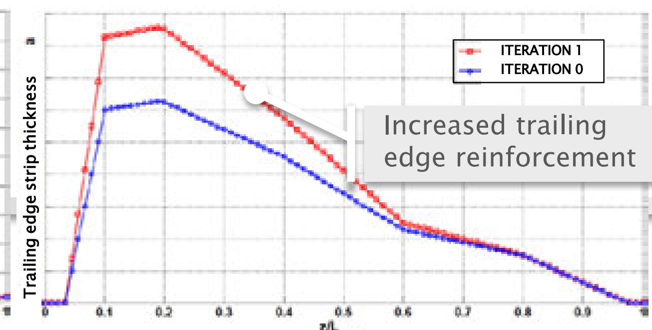




2) Buckling:

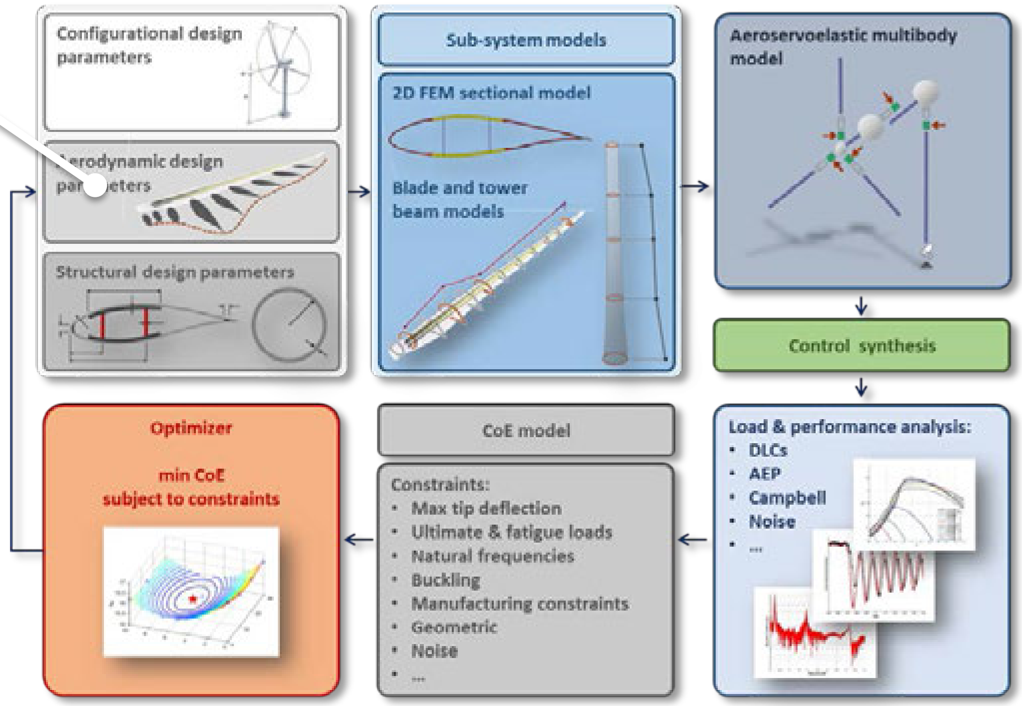
- Buckling constraint violated at first iteration
- Update skin core thickness
- Update trailing edge reinforcement strip
- Converged at 2nd iteration





Beyond a Monolithic Formulation

Some design parameters have very minor effects on CoE
Problem is ill-posed



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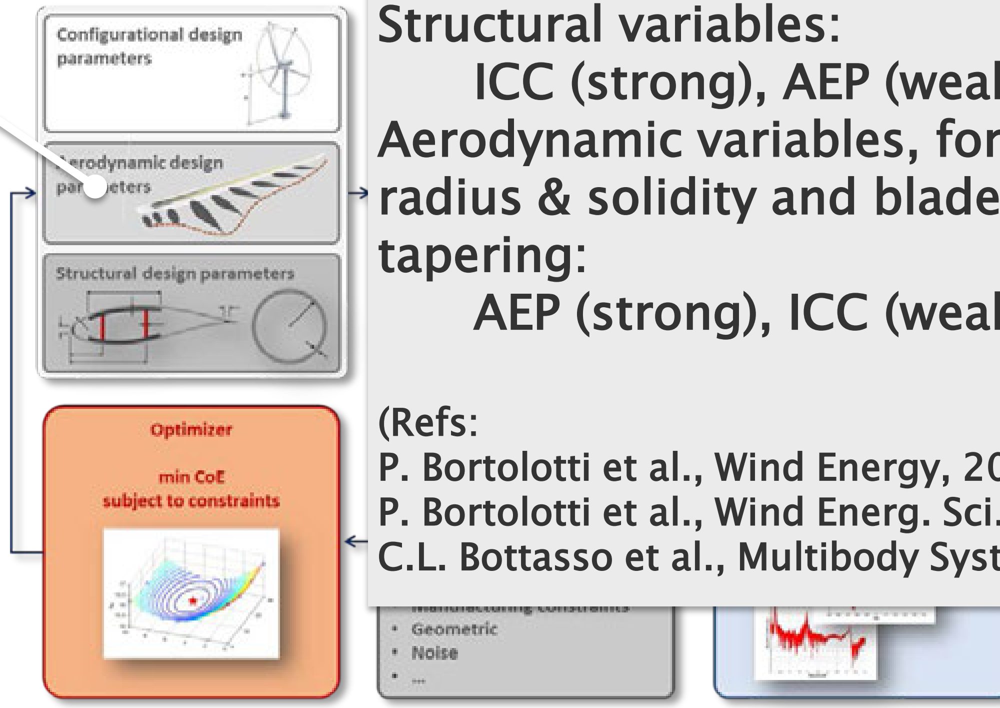
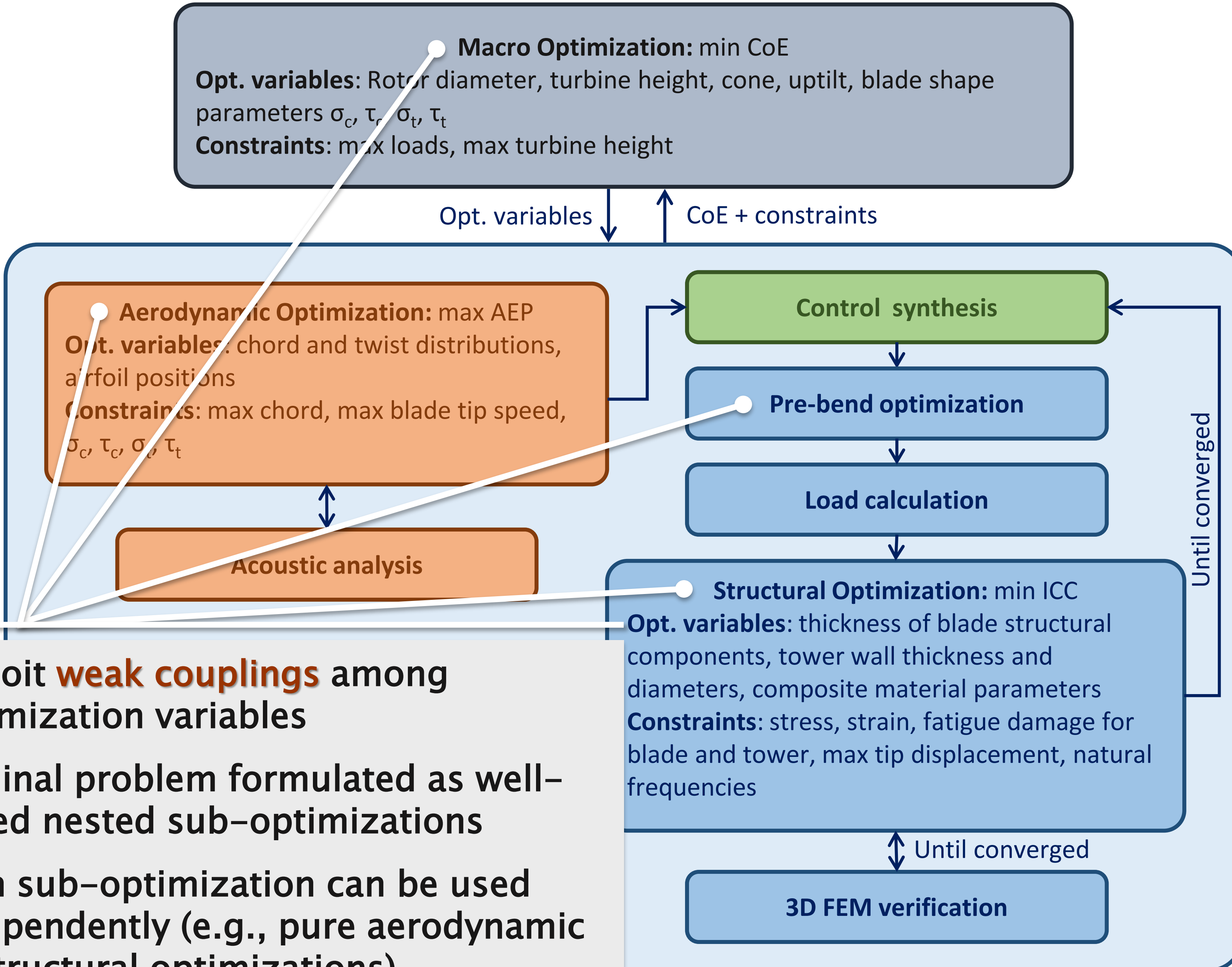


Solution: exploit **weak couplings** among optimization variables

Examples:
Structural variables:
ICC (strong), AEP (weak)
Aerodynamic variables, for given rotor radius & solidity and blade thickness & tapering:
AEP (strong), ICC (weak)

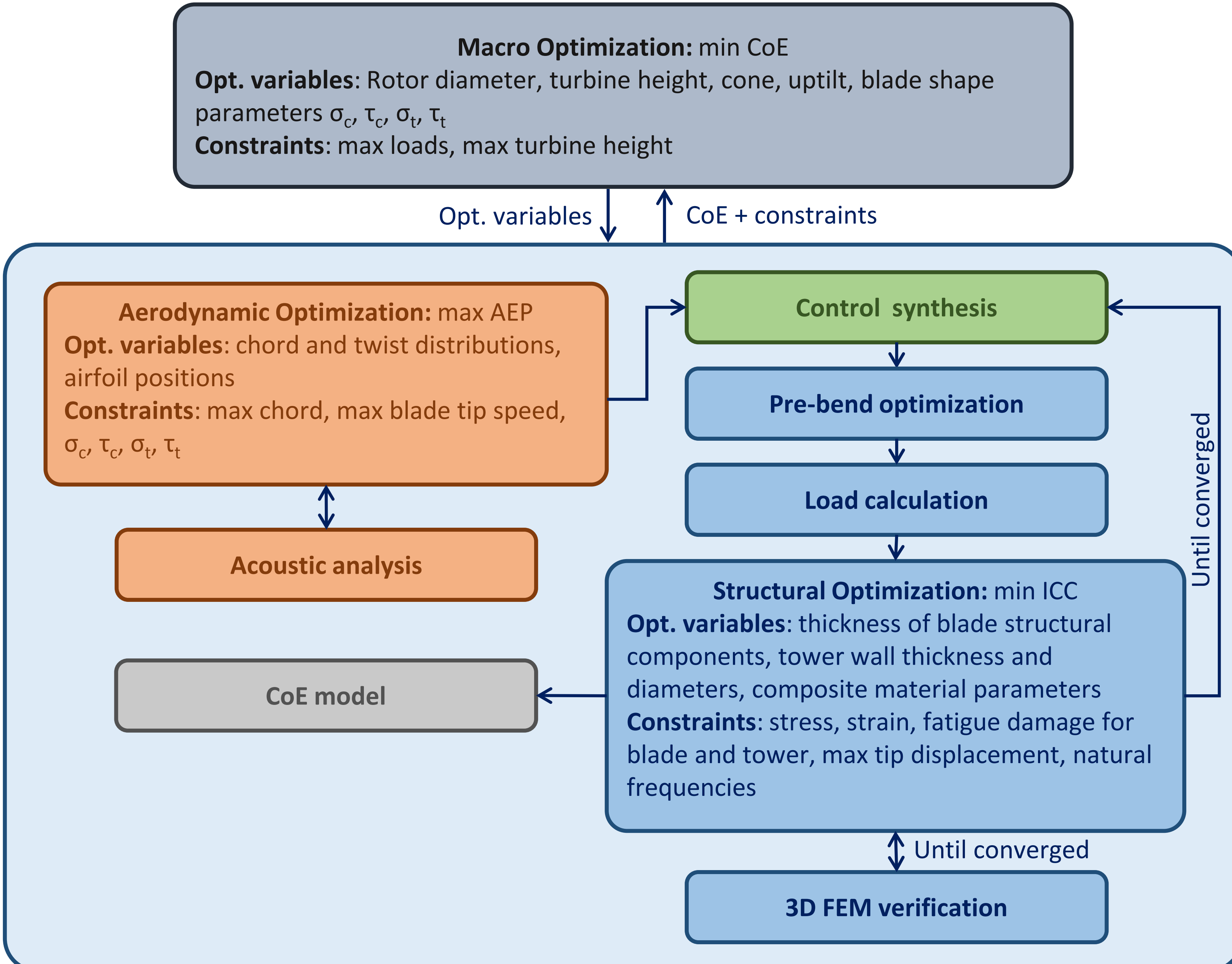
(Refs:
P. Bortolotti et al., Wind Energy, 2017;
P. Bortolotti et al., Wind Energ. Sci., 2016;
C.L. Bottasso et al., Multibody Syst. Dyn., 2015)

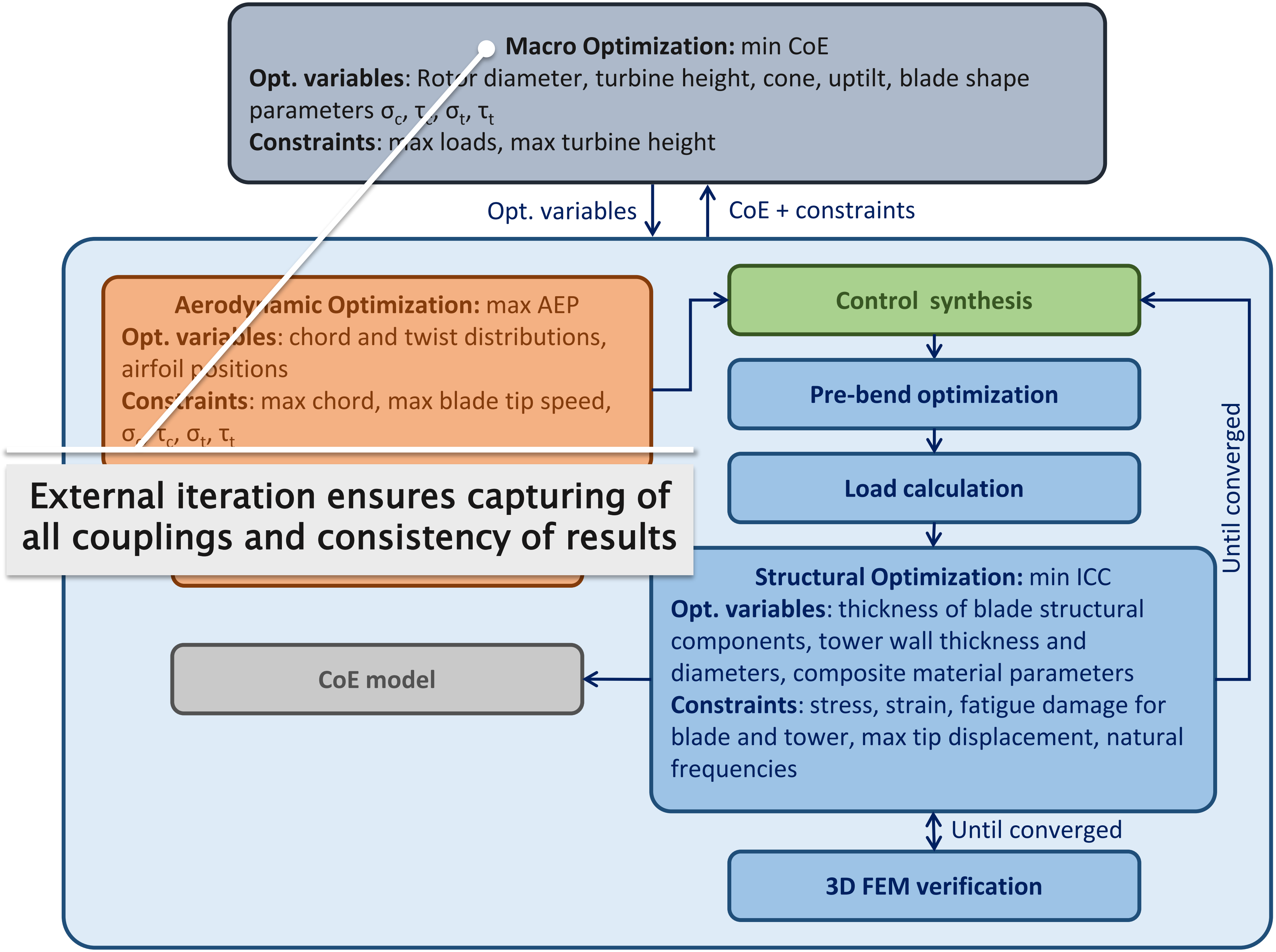


Exploit **weak couplings** among optimization variables

Original problem formulated as well-posed nested sub-optimizations

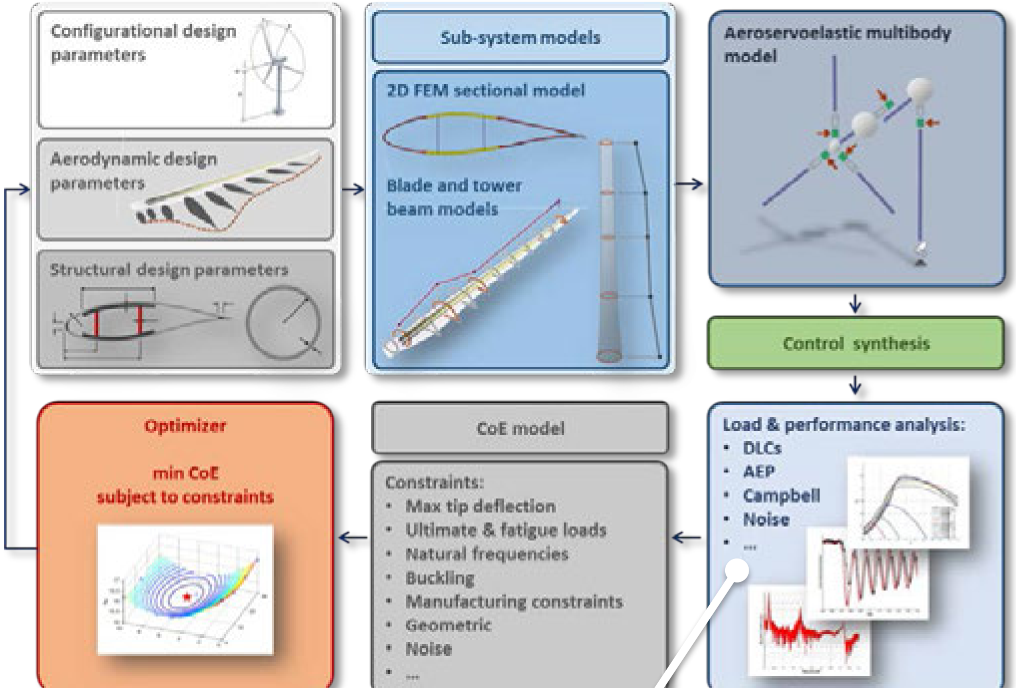
Each sub-optimization can be used independently (e.g., pure aerodynamic or structural optimization)


Macro Optimization: min CoE
Opt. variables: Rotor diameter, turbine height, cone, uptilt, blade shape parameters σ_c, τ_c, σ_t, τ_t
Constraints: max loads, max turbine height
Opt. variables
CoE + constraints
Aerodynamic Optimization: max AEP
Opt. variables: chord and twist distributions, airfoil positions
Constraints: max chord, max blade tip speed, σ_c, τ_c, σ_t, τ_t
Acoustic analysis
CoE model
Control synthesis
Pre-bend optimization
Load calculation
Until converged
Structural Optimization: min ICC
Opt. variables: thickness of blade structural components, tower wall thickness and diameters, composite material parameters
Constraints: stress, strain, fatigue damage for blade and tower, max tip displacement, natural frequencies
Until converged
3D FEM verification

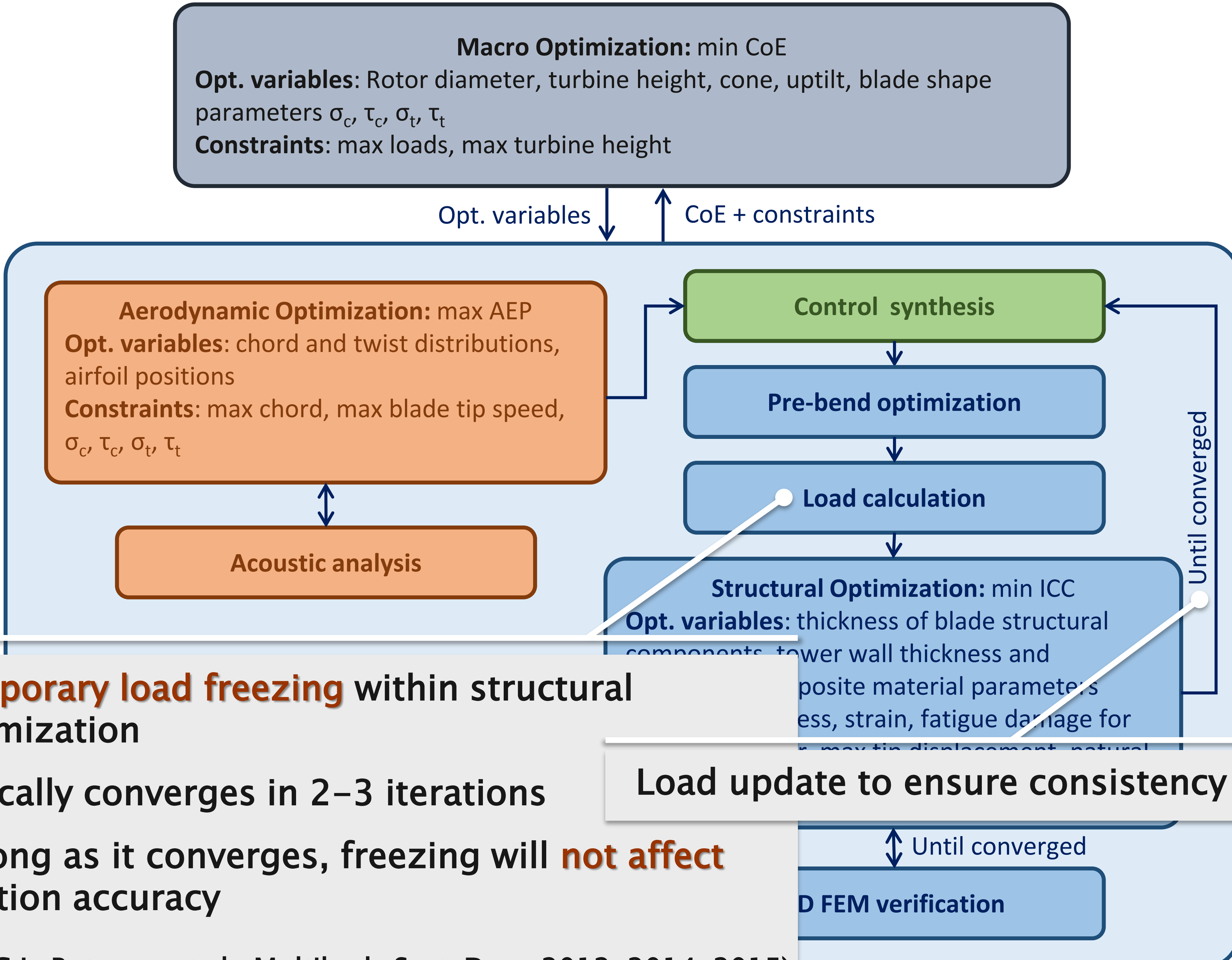


Macro Optimization: min CoE
Opt. variables: Rotor diameter, turbine height, cone, uptilt, blade shape parameters σ_c, τ_c, σ_t, τ_t
Constraints: max loads, max turbine height
Opt. variables
CoE + constraints
Aerodynamic Optimization: max AEP
Opt. variables: chord and twist distributions, airfoil positions
Constraints: max chord, max blade tip speed, σ_c, τ_c, σ_t, τ_t
External iteration ensures capturing of all couplings and consistency of results
Control synthesis
Pre-bend optimization
Load calculation
Until converged
Structural Optimization: min ICC
Opt. variables: thickness of blade structural components, tower wall thickness and diameters, composite material parameters
Constraints: stress, strain, fatigue damage for blade and tower, max tip displacement, natural frequencies
CoE model
Until converged
3D FEM verification

Improving Computational Efficiency



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



Temporary load freezing within structural optimization

Typically converges in 2–3 iterations

As long as it converges, freezing will not affect solution accuracy

(Ref: C.L. Bottasso et al., Multibody Syst. Dyn., 2012, 2014, 2015)

Load update to ensure consistency

Additional Features: Composite Optimization

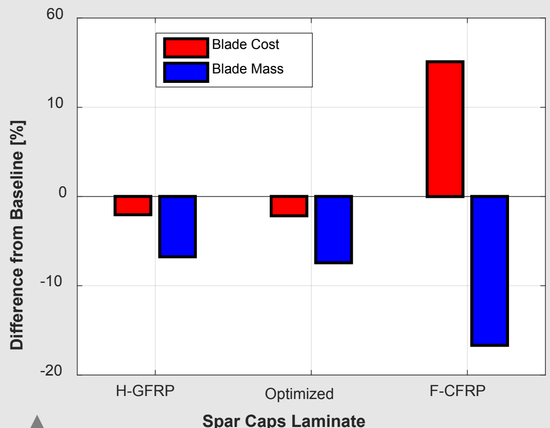
Idea:

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

Result:

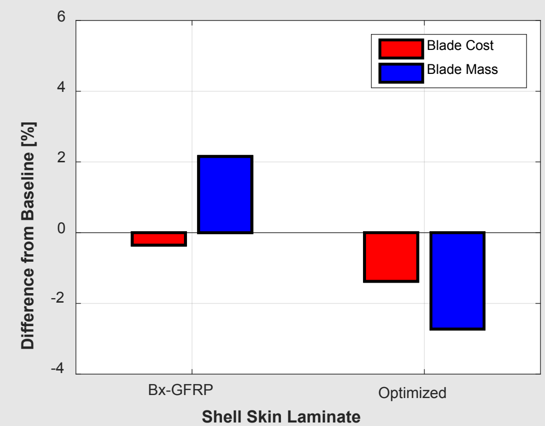
- Wind turbine designer: pick closest existing material within market products
- Material designer: design new material with optimal properties

Example: INNWIND.EU 10 MW



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

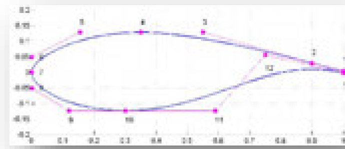
Redesign of the **shell skin laminate**
Optimum is between Bx-GFRP and Tx-GFRP ▼



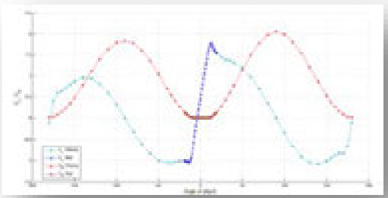
Combined optimum: Blade mass -9.3%, blade cost -2.9%

Additional Features: Free-Form Optimization

Design **airfoils together with blade**:

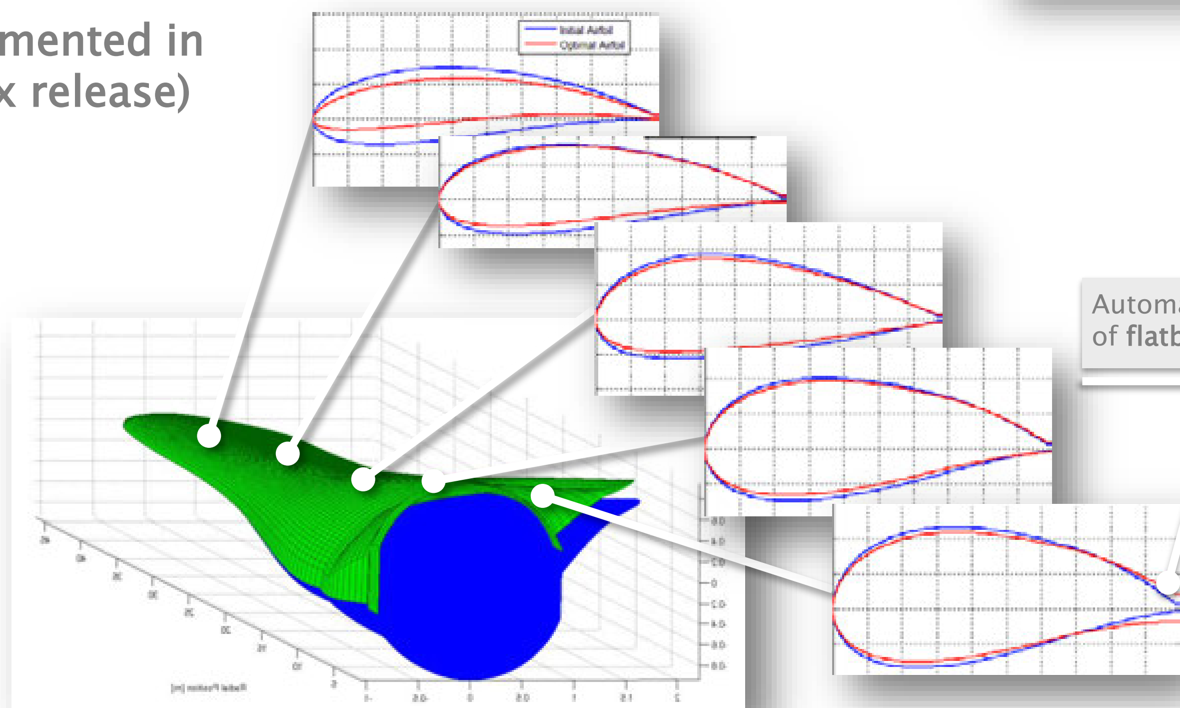


- Bezier airfoil parameterization
- Airfoil aerodynamics by Xfoil + Viterna extrapolation



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

(not yet implemented in latest Cp-Max release)

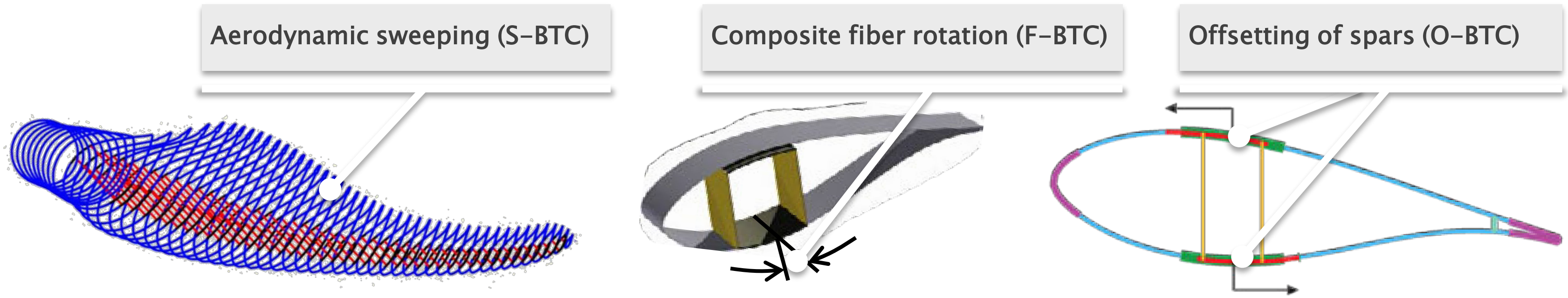


Automatic appearance of **flatback** airfoil!

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

Applications: Passive Load Alleviation

Full-span passive load mitigation:
Loaded structure deforms in order to self-reduce loading



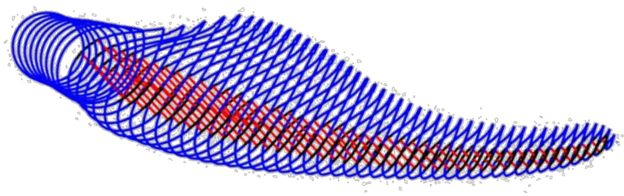
Potential advantages: no actuators, no moving parts, no sensors

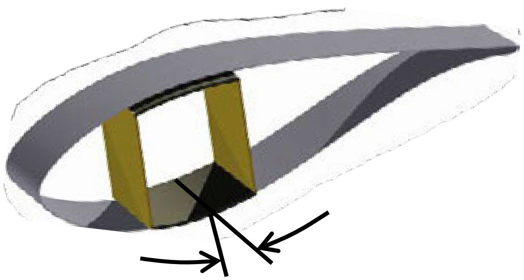
Application: IEA Task 37 3.35MW wind turbine

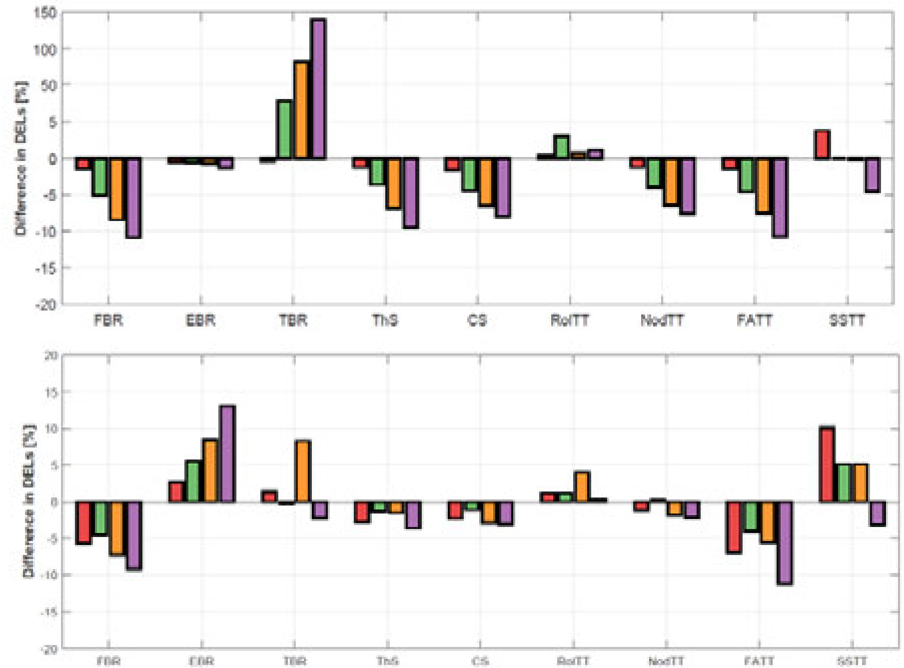
1. Each passive technology individually
2. Integrated passive technologies: larger rotor at similar loading

(Details in Bortolotti et al., Wind Energy, 2017)

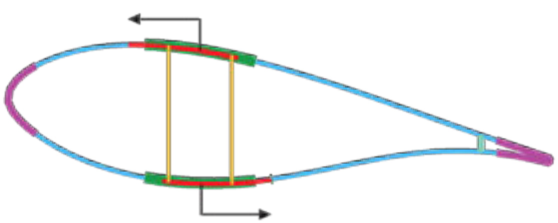
Applications: Passive Load Alleviation







S-BTC & F-BTC: significant DEL and ultimate load benefits

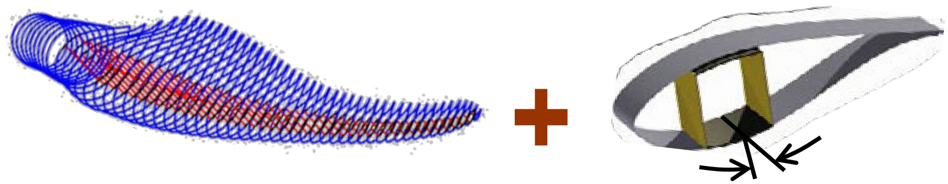


O-BTC: limited benefits due to large spar caps and pronounced blade slenderness

(Details in Bortolotti et al., Wind Energy, 2017)

Applications: Passive Load Alleviation

Optimal **combination of sweep and fiber rotation** (F-S-BTC):
larger rotor at similar loading



Constraints

Constraints on ultimate loads					
Load component	FBR	EBR	TBR	ThS	CS
Value	13.51 MNm	6.84 MNm	0.29 MNm	0.834 MN	8.81 MNm
Enforced	yes	yes	no	yes	yes
Load component	RolTT	NodTT	FATT	SSTT	
Value	4.69 MNm	7.42 MNm	0.75 MN	0.48 MN	
Enforced	yes	yes	yes	yes	

Constraint on fatigue DEL @ N=10^7, Wöhler exponent m=4					
Load component	FBR	EBR	TBR	ThS	CS
Value	6.61 MNm	13.34 MNm	0.08 MNm	0.26 MN	6.02 MNm
Enforced	yes	yes	no	yes	yes
Load component	RolTT	NodTT	FATT	SSTT	
Value	1.45 MNm	6.10 MNm	0.36 MN	0.27 MN	
Enforced	no	yes	yes	yes	

Results

Data	Baseline	F-S-BTC Optimum	Difference
Rotor diameter	130.0 m	136.0 m	+4.6%
Rotor cone angle	3.0 deg	8.0 deg	+166.7%
Nacelle uptilt angle	5.0 deg	6.0 deg	+20.0%
Blade mass	17,525 kg	14,560 kg	-16.9%
Blade cost	127.9 k$	126.2 k$	-1.3%
Tower mass	365 ton	292 ton	+20.0%
Tower cost	548.5 k$	438.2 k$	+20.1%
Aerodynamic AEP	15.01 GWh	15.40 GWh	+2.6%
Electrical AEP	13.96 GWh	14.32 GWh	+2.6%
ICC	3,885.2 k$	3,850.9 k$	-0.9%
CoE	42.00 $/MWh	40.82 $/MWh	-2.8%

New regulation in region II to limit AEP loss (**variable fine pitch setting**)

Some References

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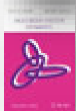

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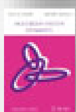

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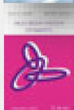

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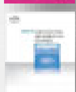

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- A. Croce, L. Sartori, M.S. Lunghini, L. Clozza, P. Bortolotti, C.L. Bottasso: Lightweight rotor design by optimal spar cap offset , J. Phys.: Conf. Ser. 753, 2016
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Conclusions

- **Strong couplings** between aero and structural design variables
- **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 (in progress)
- Include/improve physics-based **sub-system models**
- **Uncertainties everywhere** (aero, structure, wind, …), move away from deterministic design (but what about certification standards?), currently working on UQ and robust design