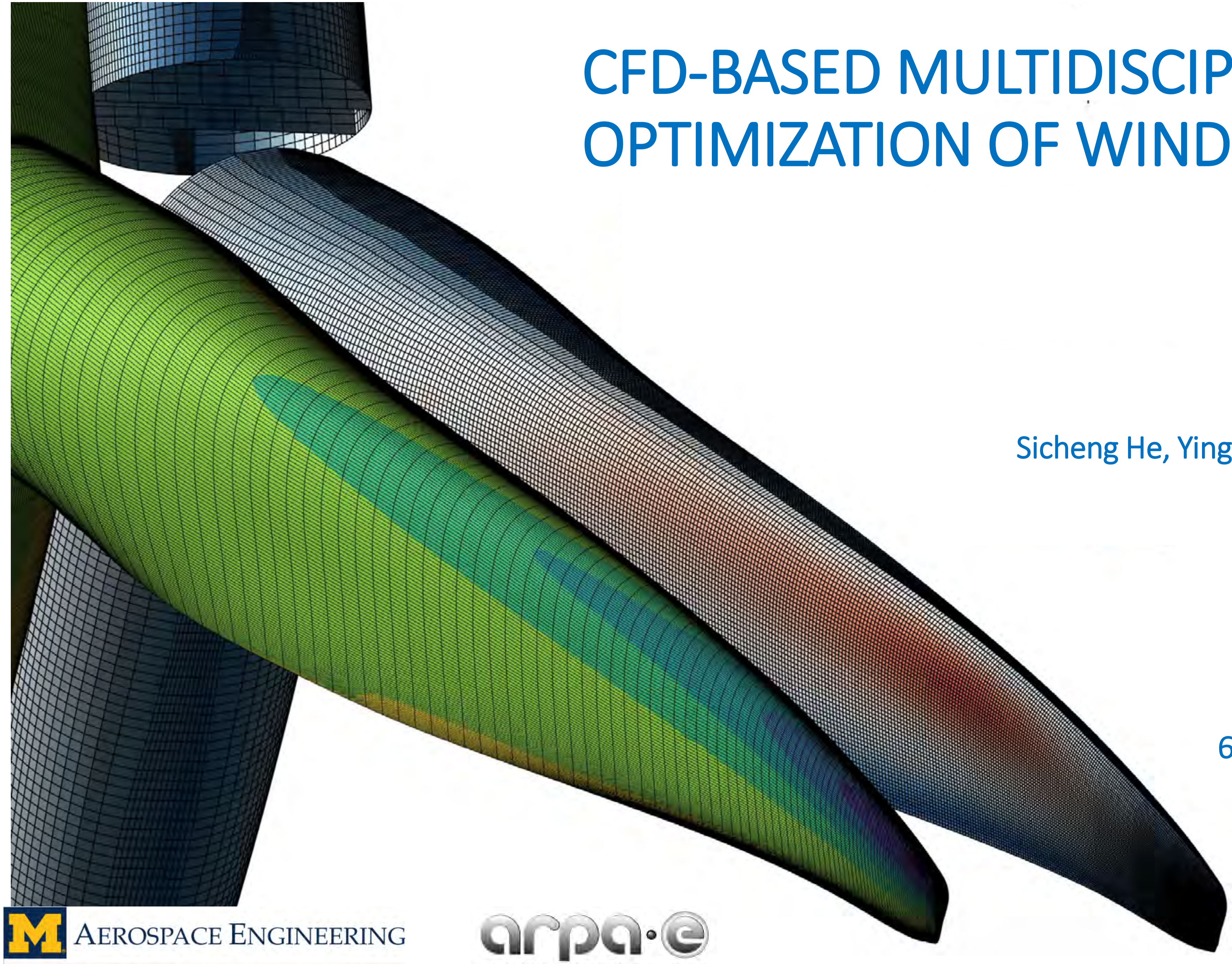

CFD-BASED MULTIDISCIPLINARY DESIGN OPTIMIZATION OF WIND TURBINE ROTORS

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With contributions from:
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6th WESE Workshop
August 31, 2022
Boulder, CO

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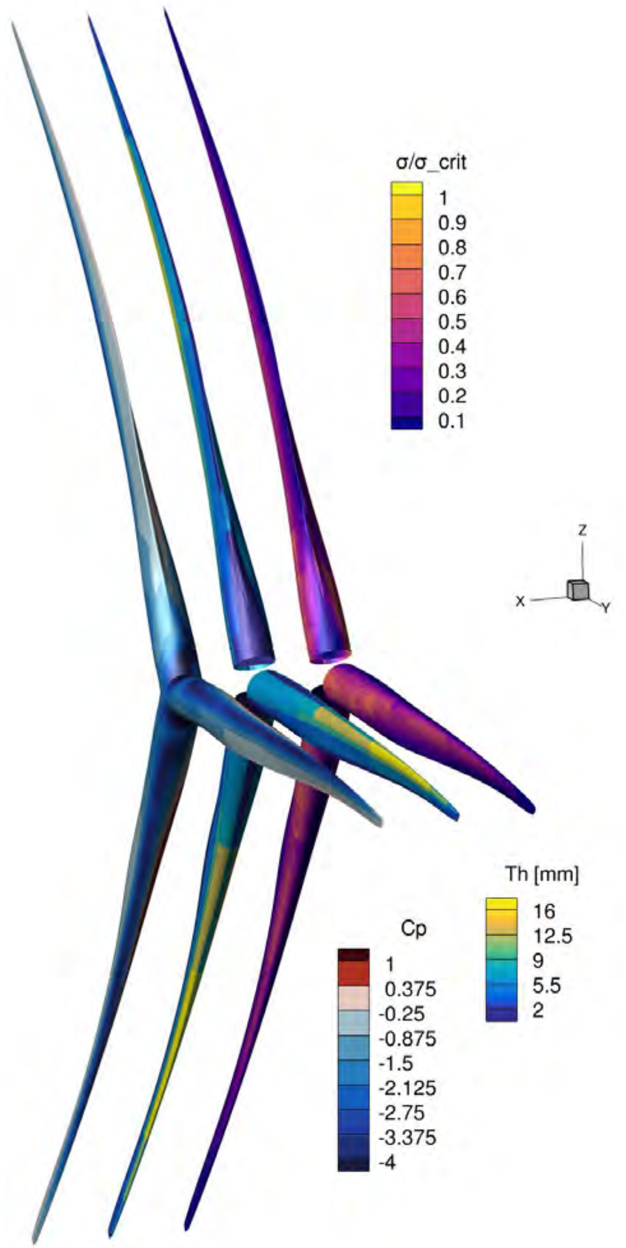
Today's takeaway: High-fidelity MDO is a feasible and effective approach to support wind turbine rotor design

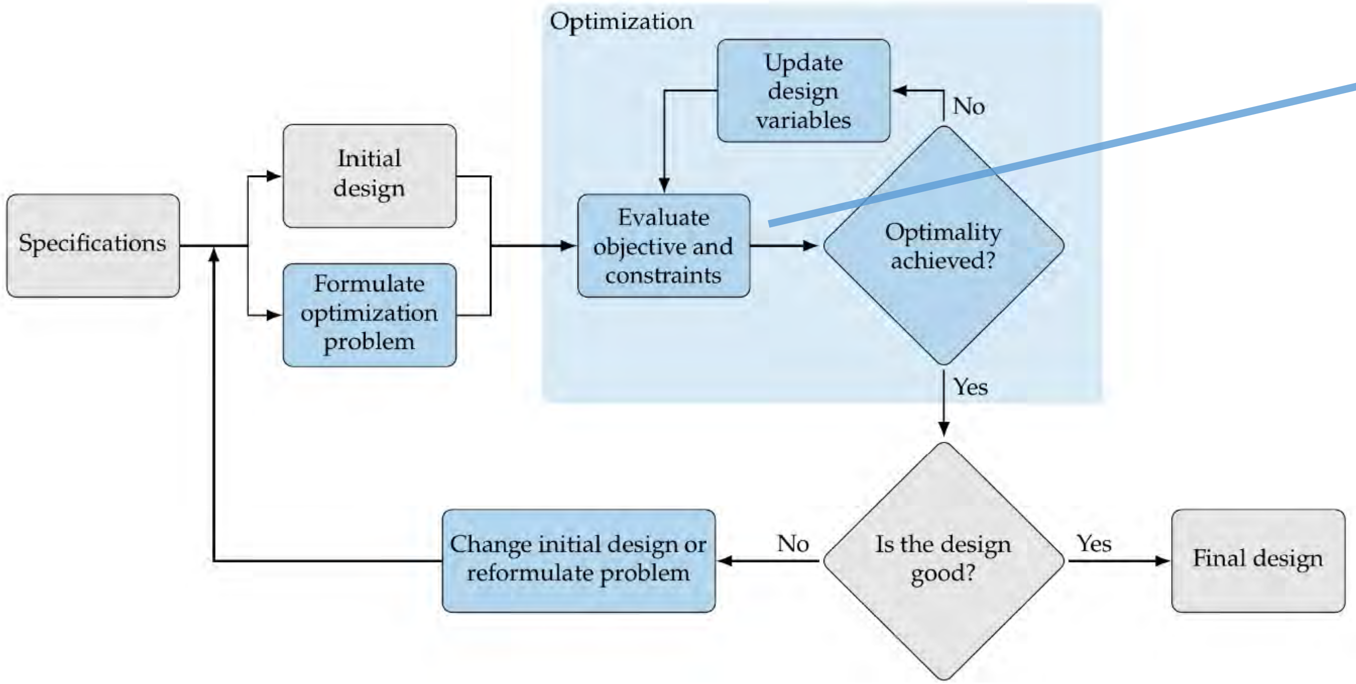
- **The next slides cover:**
  - High-fidelity Multidisciplinary Design Optimization (MDO) of a wind turbine rotor using MACH
  - A combined-fidelity approach that couples WEIS with MACH for life-cycle sizing constraints
  - The future of high-fidelity MDO: MPhys



How to make high-fidelity MDO computationally efficient?

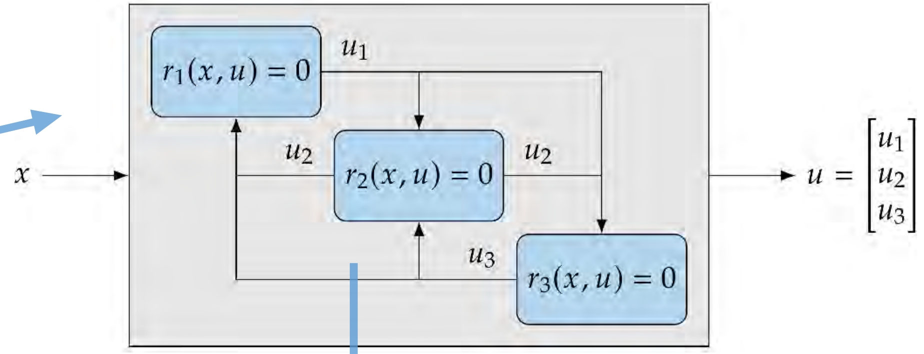
What is MDO?

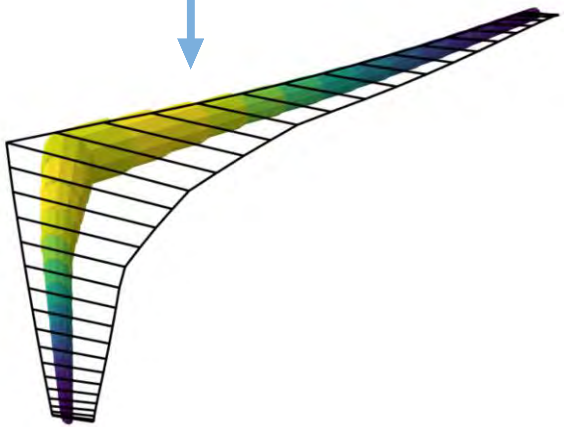
Design Optimization...



Martins, J. R. R. A., and Ning, A., **Engineering Design Optimization**, Cambridge University Press, 2021. doi:10.1017/9781108980647

..of complex Multidisciplinary systems

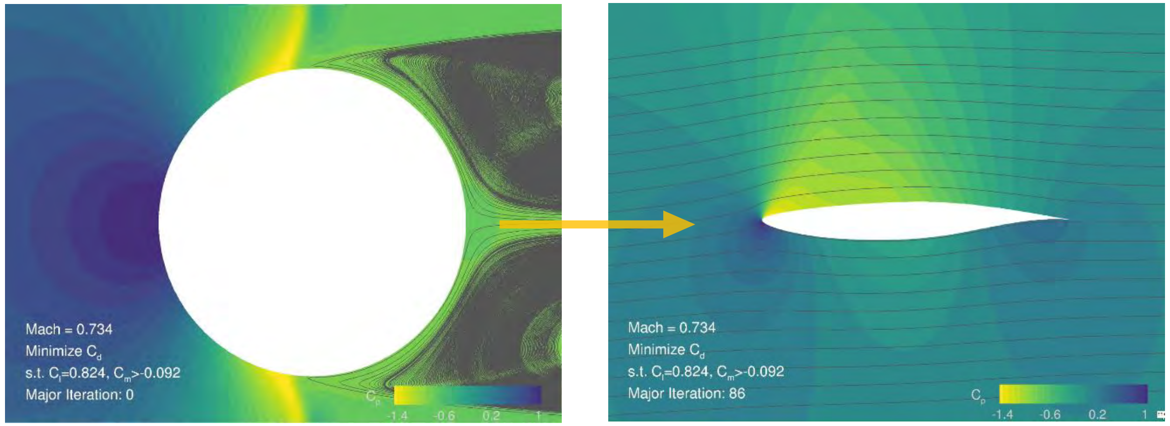




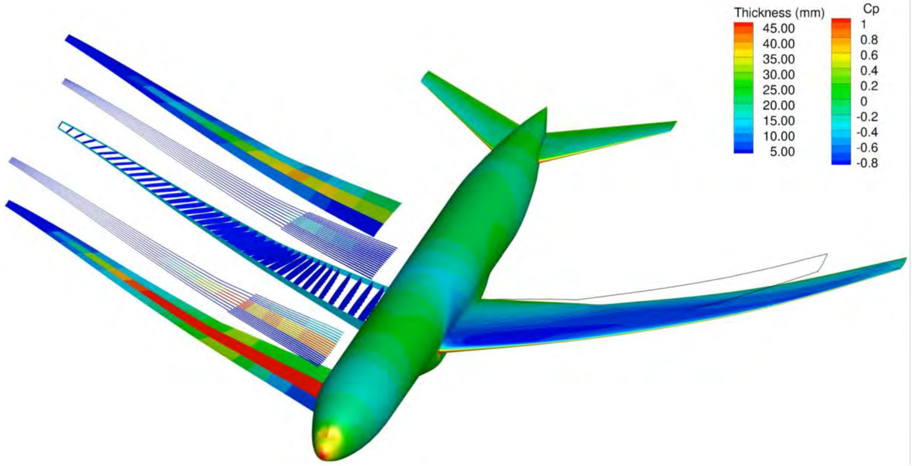
OpenAeroStruct, https://github.com/mdolab/OpenAeroStruct

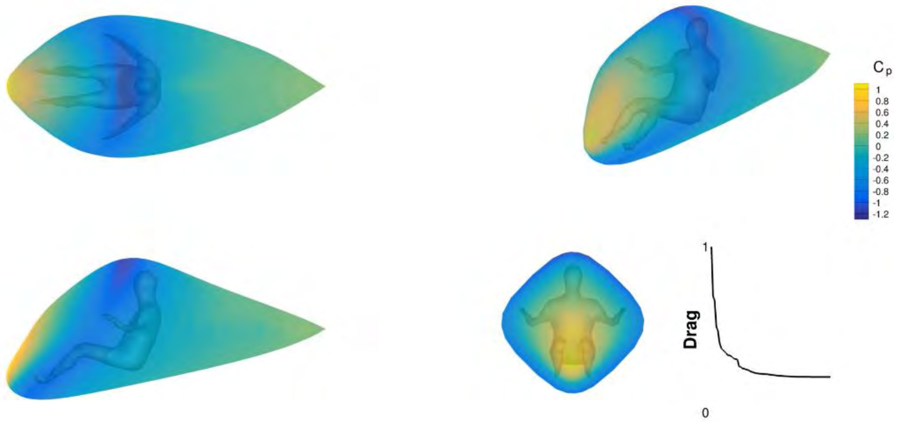
Our MDO tool has been extensively used for aerospace applications

https://github.com/mdolab/MACH-Aero

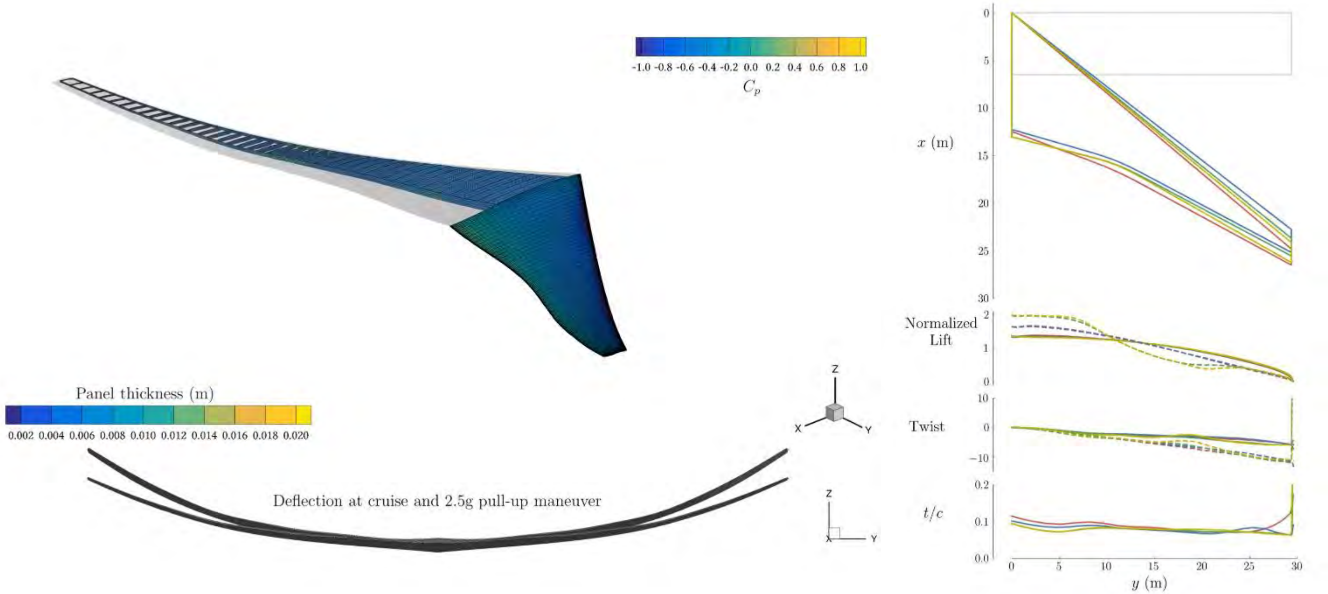


He, Li, Mader, Yildirim, Martins. **Robust aerodynamic shape optimization—from a circle to an airfoil**. *Aerospace Science and Technology*, 2019



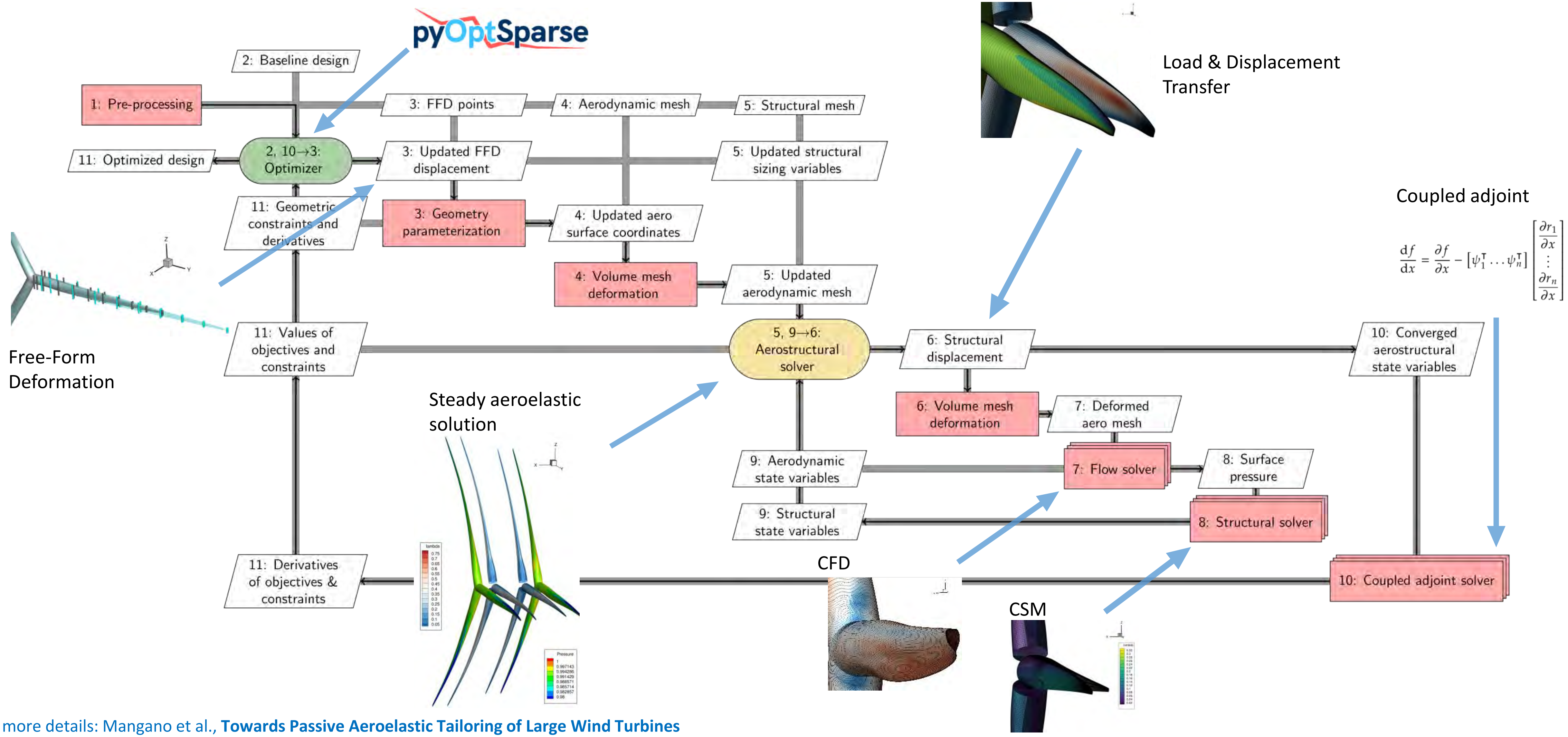


Brelje, Anibal, Yildirim, Mader, Martins. **Flexible formulation of spatial integration constraints in aerodynamic shape optimization**. *AIAA Journal, 2020*.



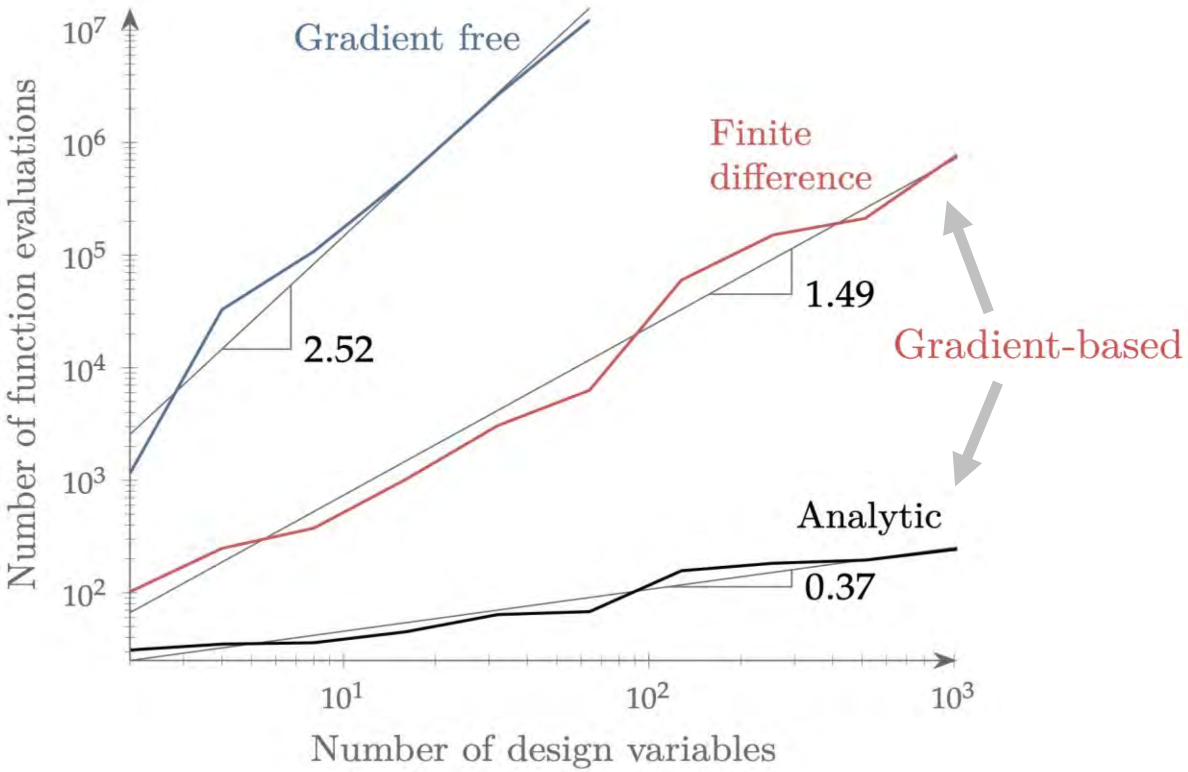
Bons and Martins. **Aerostructural design exploration of a wing in transonic flow**, *Aerospace,* 2020.

MACH framework enables gradient-based aerostructural optimization with high-fidelity analysis tools



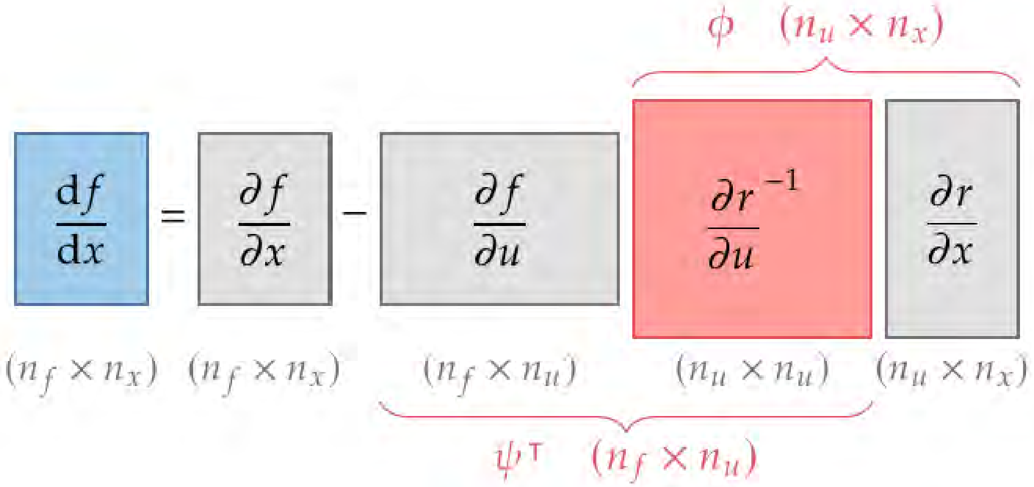
For more details: Mangano et al., **Towards Passive Aeroelastic Tailoring of Large Wind Turbines Using High-Fidelity Multidisciplinary Design Optimization**, 2022 AIAA Scitech conference, doi:10.2514/6.2022-1289

Why is the coupled adjoint method so effective?



Martins, J. R. R. A., and Ning, A., **Engineering Design Optimization**, Cambridge University Press, 2021. doi:10.1017/9781108980647

- Not subject to truncation errors
- Does NOT scale with the number of design variables
- Can leverage on code automatic differentiation and matrix-free solver formulation



How can we use high-fidelity MDO for wind turbine optimization?

We currently run optimizations for a combination of mass minimization and torque maximization

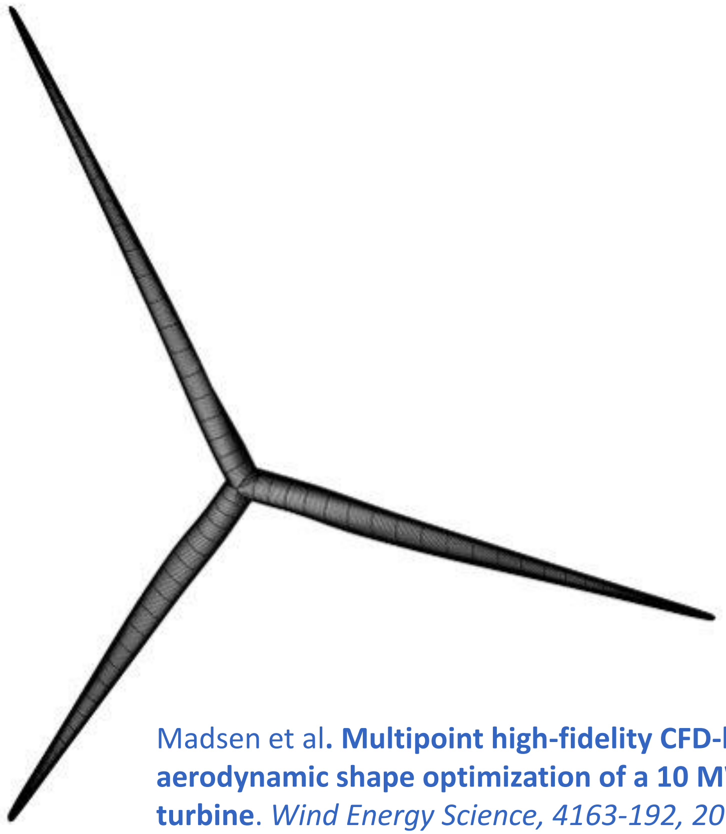
Aerostructural Optimization			
	Name	Symbol	Qty
Objectives	Torque	Q	1
	Mass	M	1
Design Variables	Panel thickness	x_{st}	100+
	Twist	x_{θ}	7
	Chord	x_{ch}	7
	Thickness	x_{tk}	7
	Airfoil shape	x_{sh}	+70
	...	...	...
Constraints	Max Stress	$\mathrm{KS}_{\sigma_{\max}} \leqslant 1$	3
	Thrust	$F_x \leqslant F_{x_{\mathrm{ref}}}$	1
	Tip Displacement	$\mathrm{KS}_{\mathrm{disp}} \leqslant 1$	1
	Torque†	$Q_x \geqslant Q_{x_{\mathrm{ref}}}$	1
	Adjacency constraints		318
	Buckling	$\mathrm{KS}_{\mathrm{buck}} \leqslant 1$	2

* KS: Aggregated Kreisselmeier—Steinhauser formulation

- The optimizer acts on the thickness distribution, blade twist, and planform
- Stress and thrust constraints are driving the design
  - Adjacency constraints added for manufacturability
  - Torque and displacement constraints for sizing-only problems
- Active development to include local airfoil shape modifications and buckling constraints

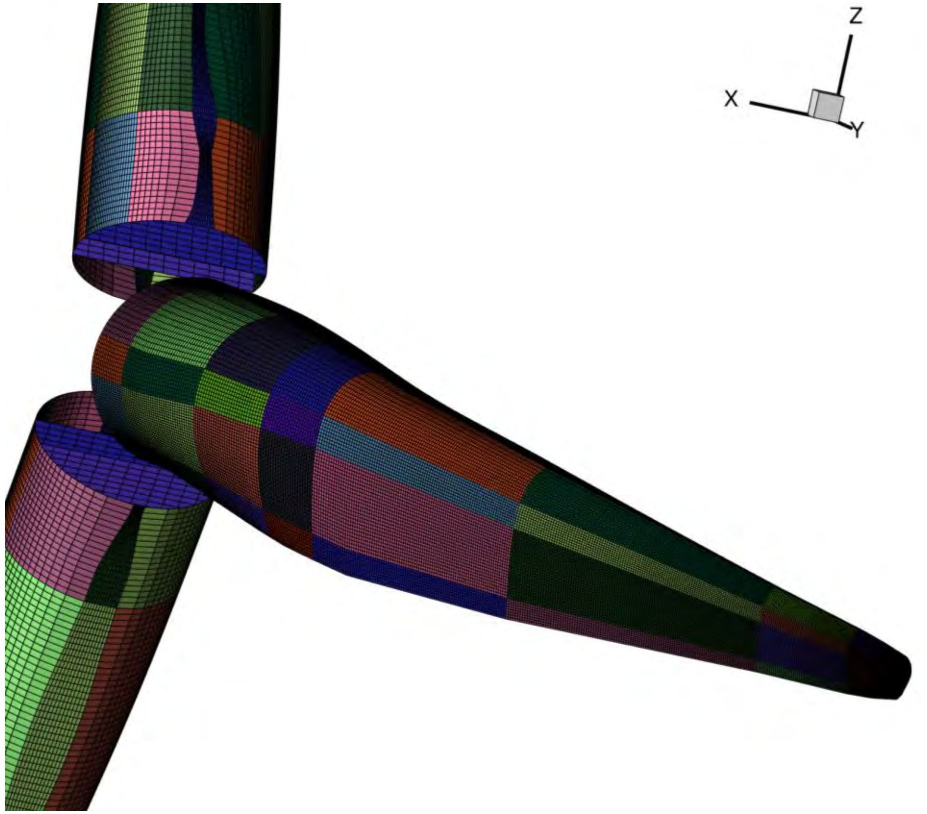
We use the DTU 10MW rotor as reference model

- Aerodynamic meshes from previous work on aerodynamic shape optimization (*Madsen et al. 2019*)
  - 7 spanwise control sections for parametrization
  - 1.7M cells (~40 CPU hrs) for the current CFD mesh



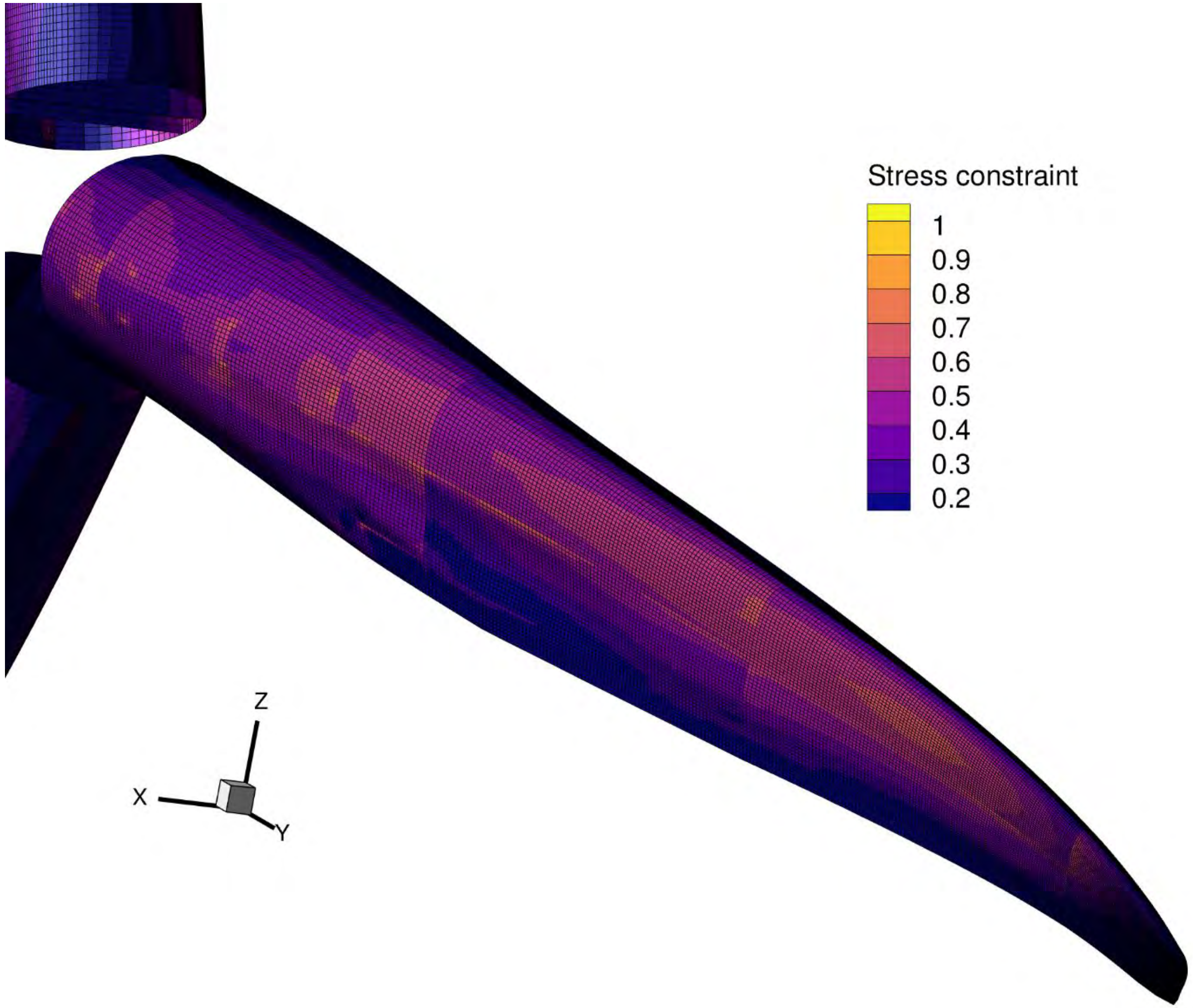
Madsen et al**. Multipoint high-fidelity CFD-based aerodynamic shape optimization of a 10 MW wind turbine**. *Wind Energy Science, 4163-192, 2019*.

- Structural mesh developed from scratch
  - Shear web + TE reinforcement spar
  - One DV for every colored patch
  - Verified conservativeness of load-displacement transfer

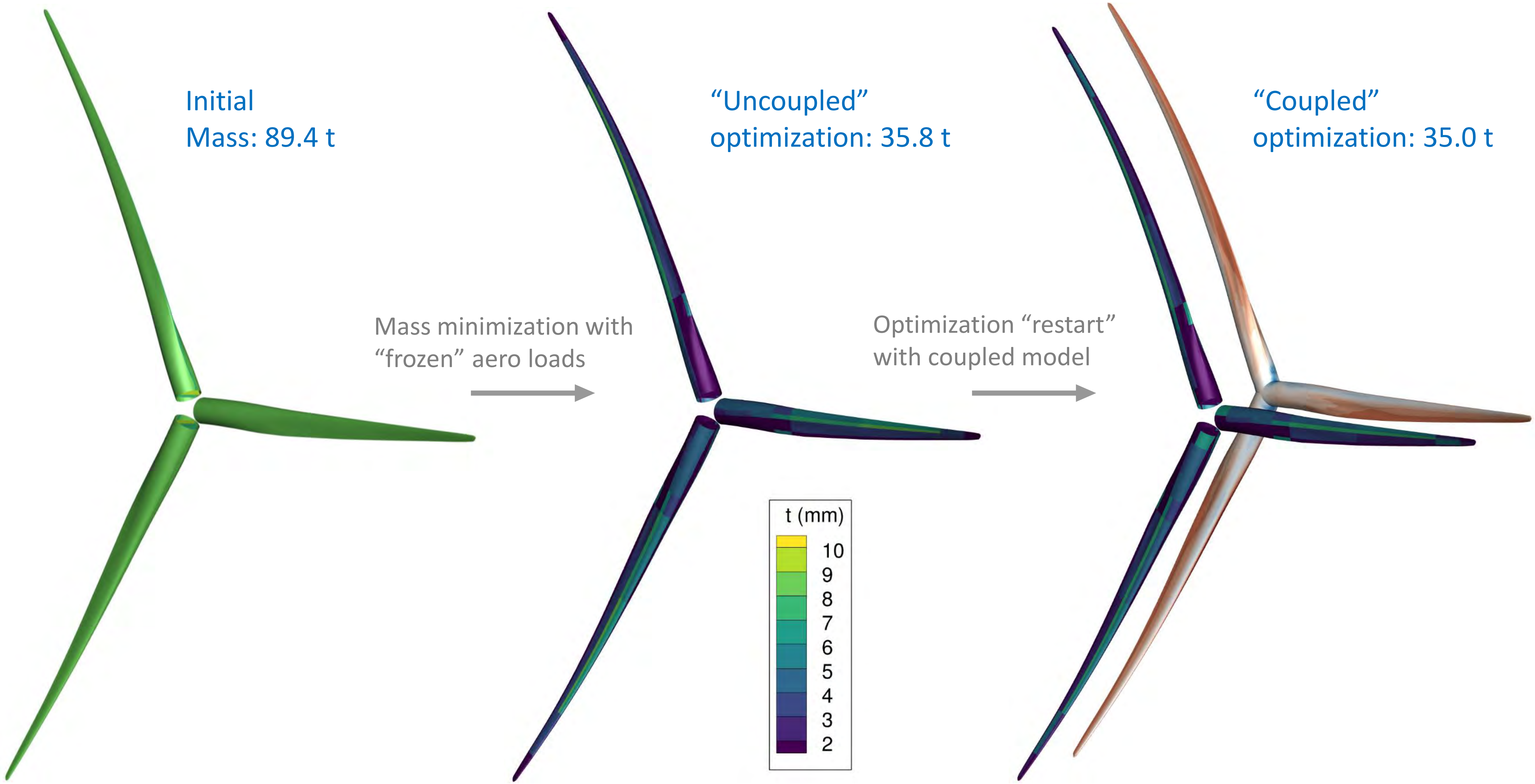


Our CFD/CSM model comes with certain modelling assumptions

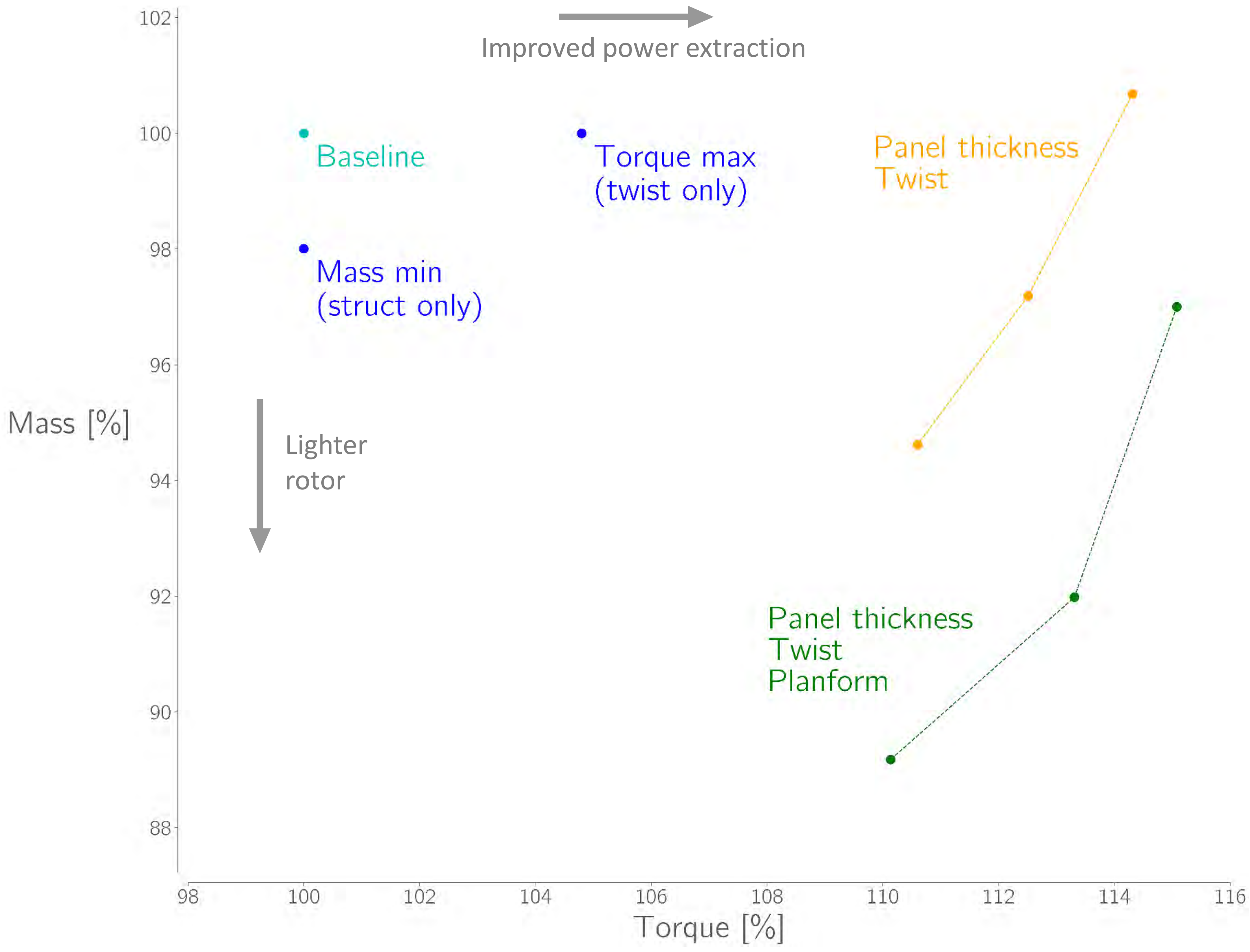
- Steady-state inflow condition and aeroelastic response
  - Unsteady RANS CFD has a much higher analysis and implementation cost
- Fully-turbulent flow
- Single design point considered
  - Representative of power output
  - Simplifies cost and efficiency metrics
  - Future extension to multipoint approach (Madsen 2019)
- Isotropic material properties (for now!)
  - Composite model under active development
  - More refined parametrization needed



Using the coupled model leads to more effective structural sizing...

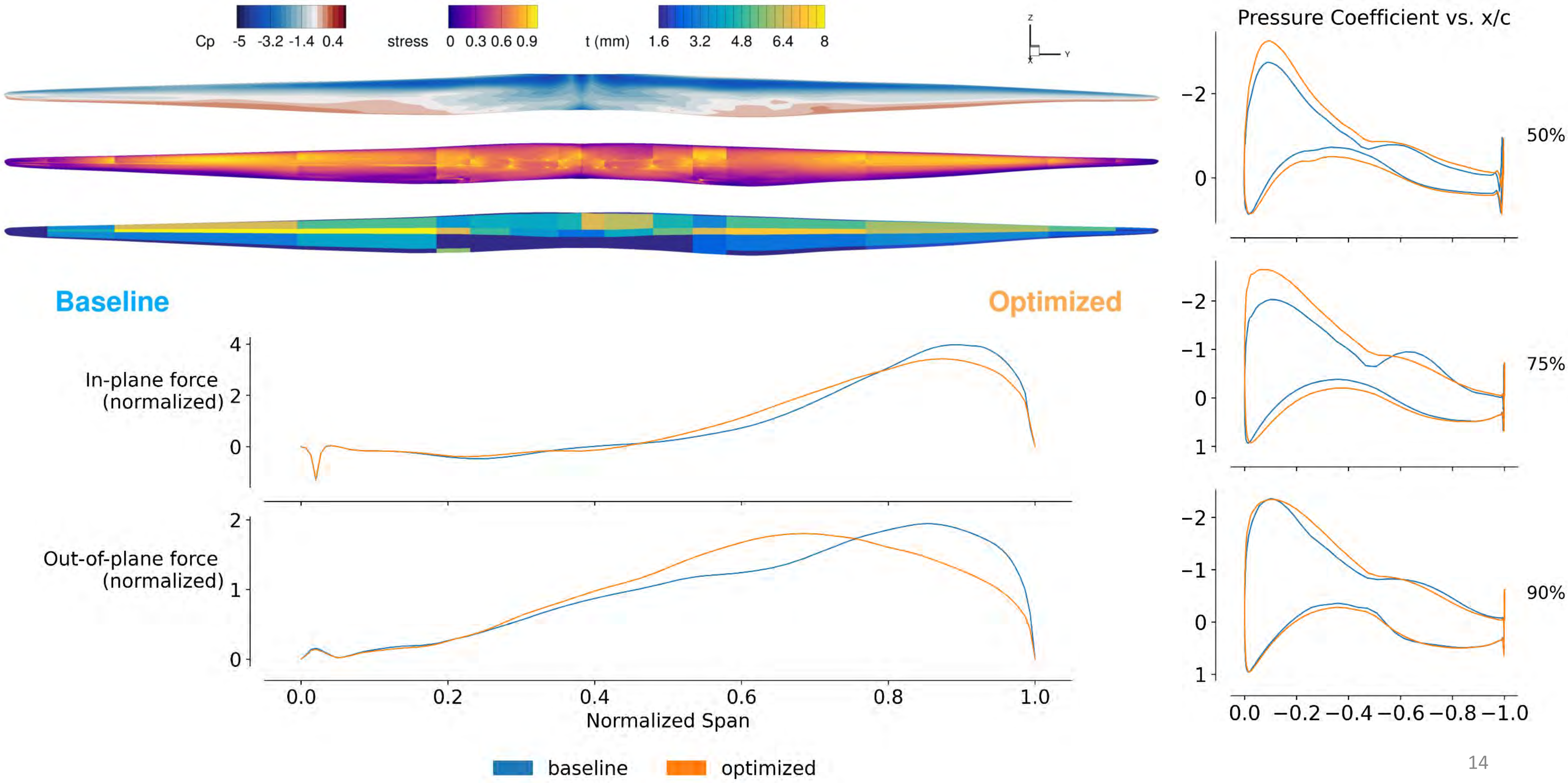


… and enables concurrent structure and shape optimization



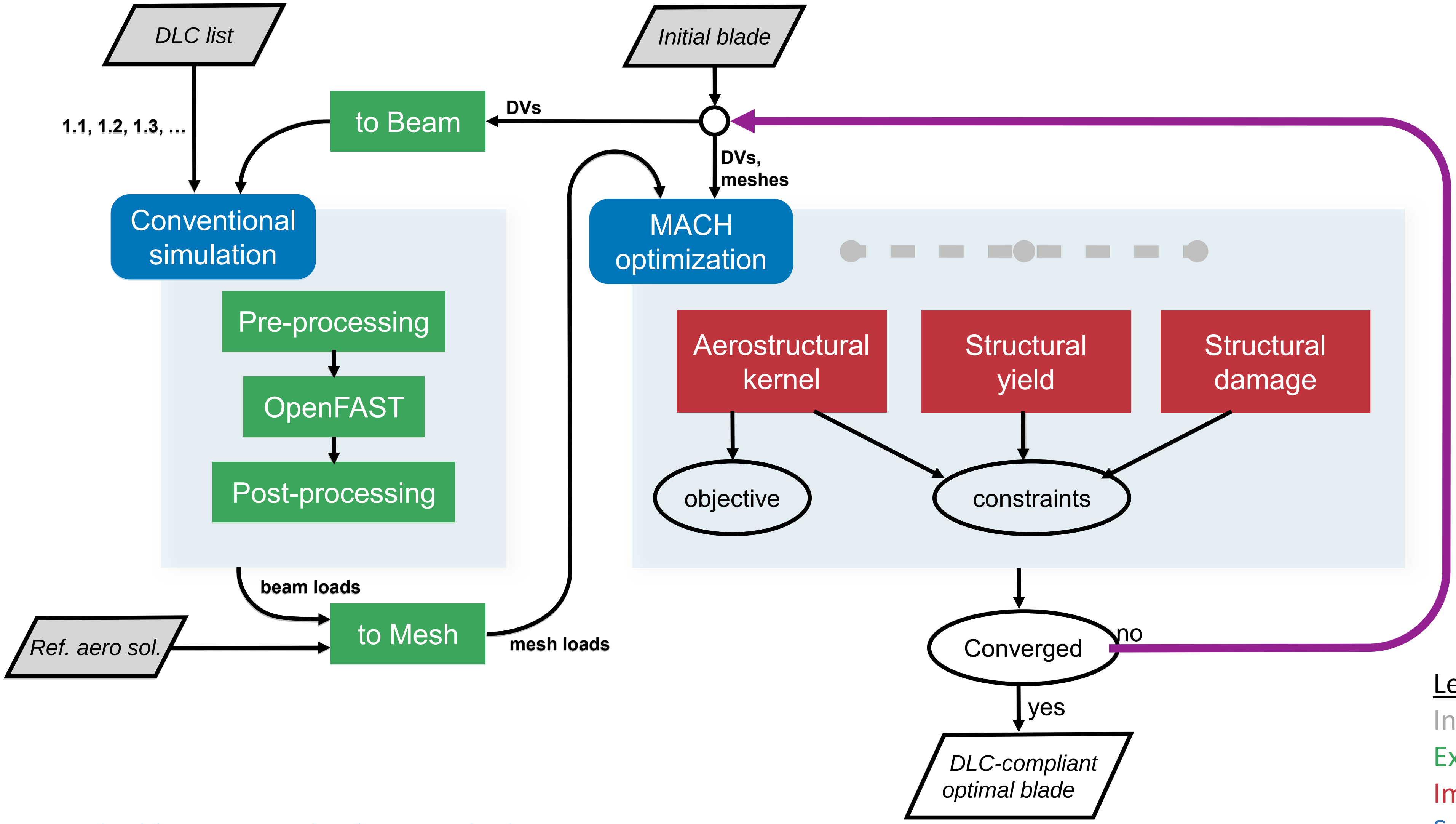
- The optimizer exploits the additional design freedom from shape variables
- Trade-offs between objective coefficients can be used for LCOE considerations

High-fidelity MDO offers deeper design insight than conventional tools



What about the rest of the turbine life cycle?

We combined WEIS and MACH into a mixed-fidelity framework

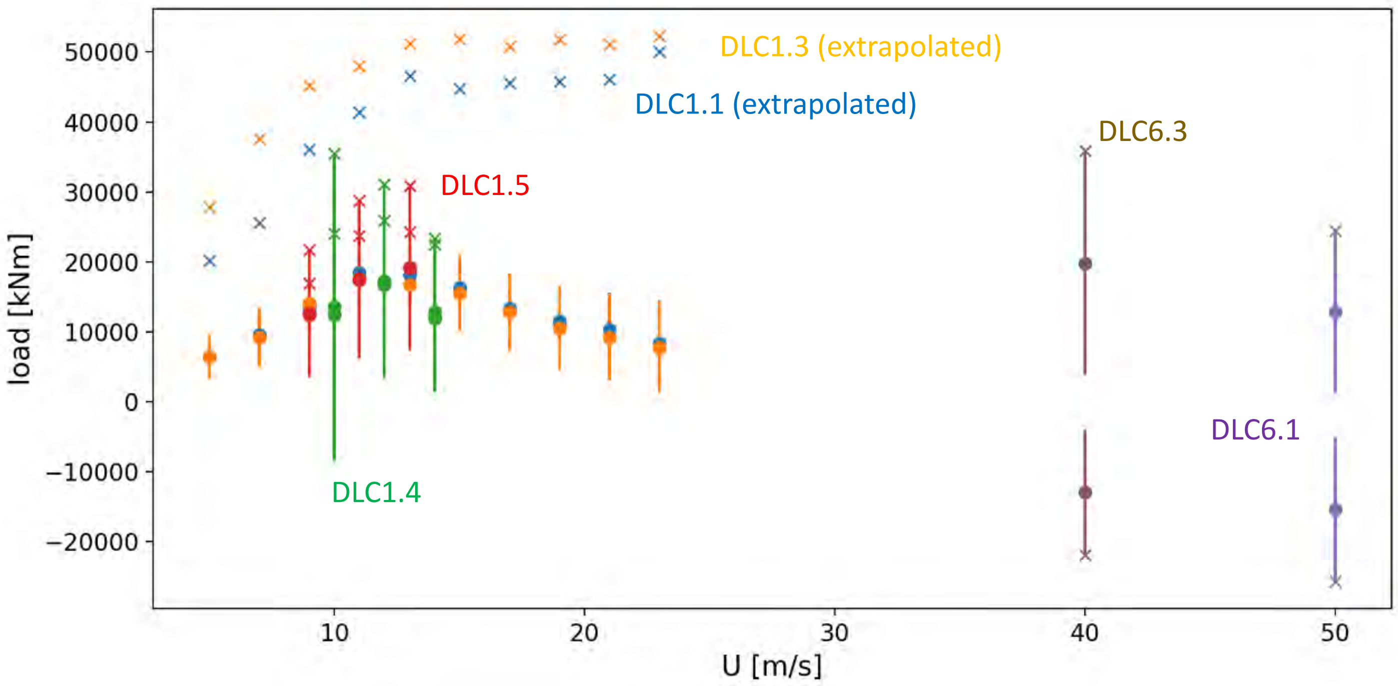


Legend:
Input
Explicit component
Implicit component
System

Caprace et al., **Incorporating High-Fidelity Aerostructural Analyses in Wind Turbine Rotor Optimization**, 2022 AIAA Scitech conference, doi:10.2514/6.2022-1290

Two approaches for incorporating fatigue and extreme loads into high-fidelity optimization

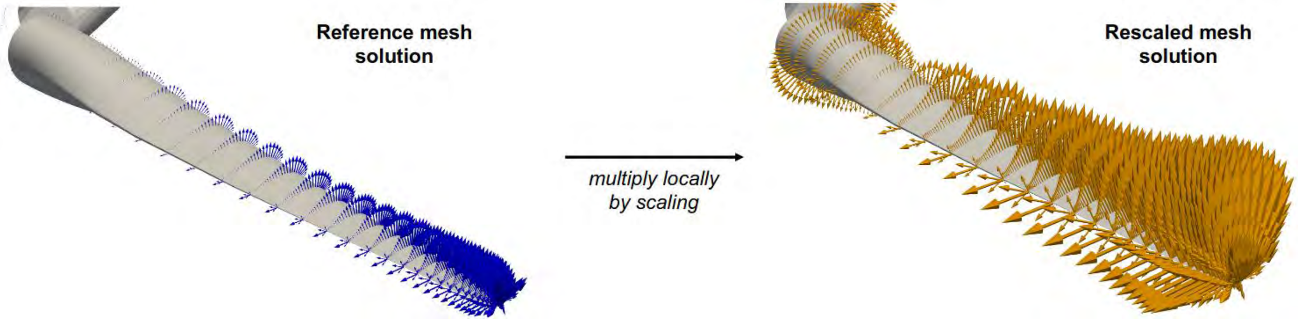
- Life cycle loads estimated through WEIS (OpenFAST) simulations



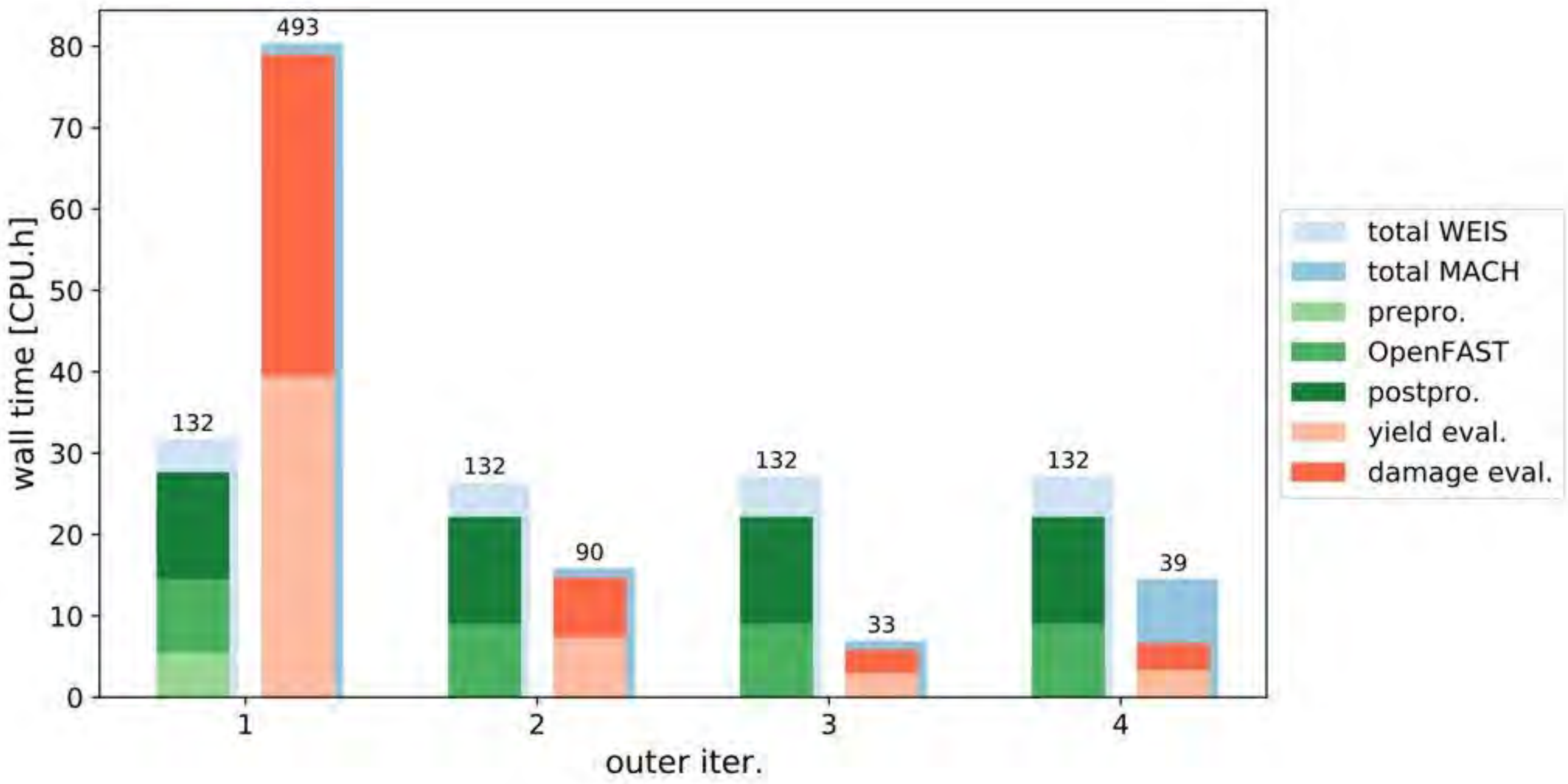
- Two approaches to transfer the loads from WEIS to MACH

  1. DEL-based load scaling on CFD/CSM models (current implementation)

  2. DEL loads from BEM model on Precomp-generated beam (future work)



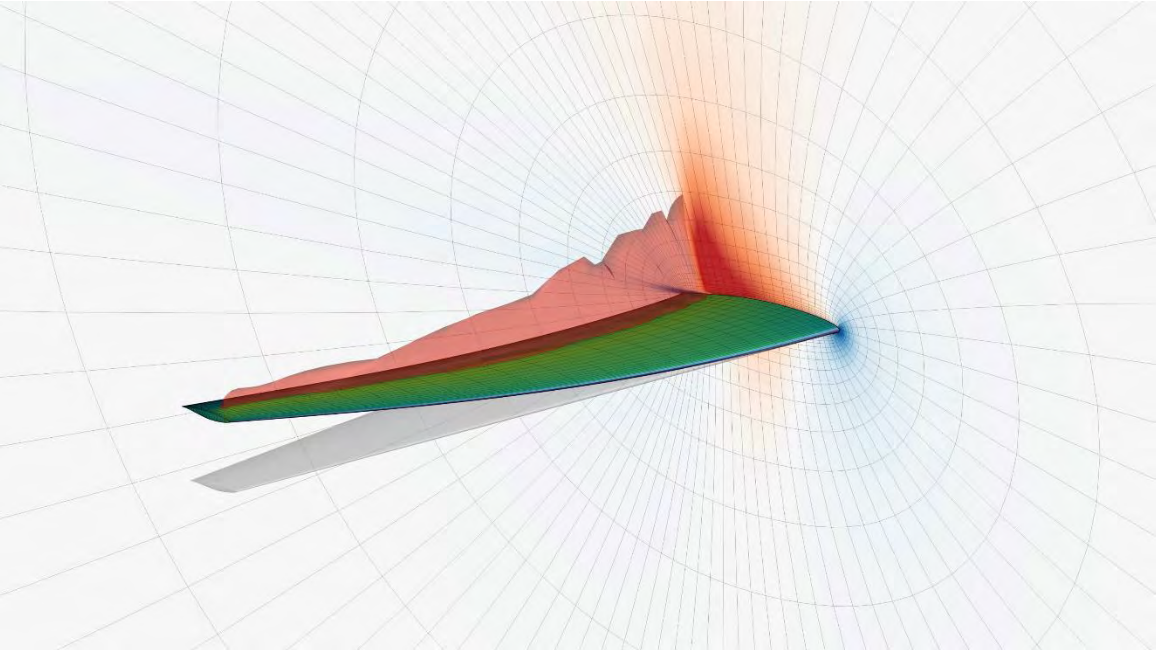
Mixed-fidelity optimizations converge in a few "outer"-iterations



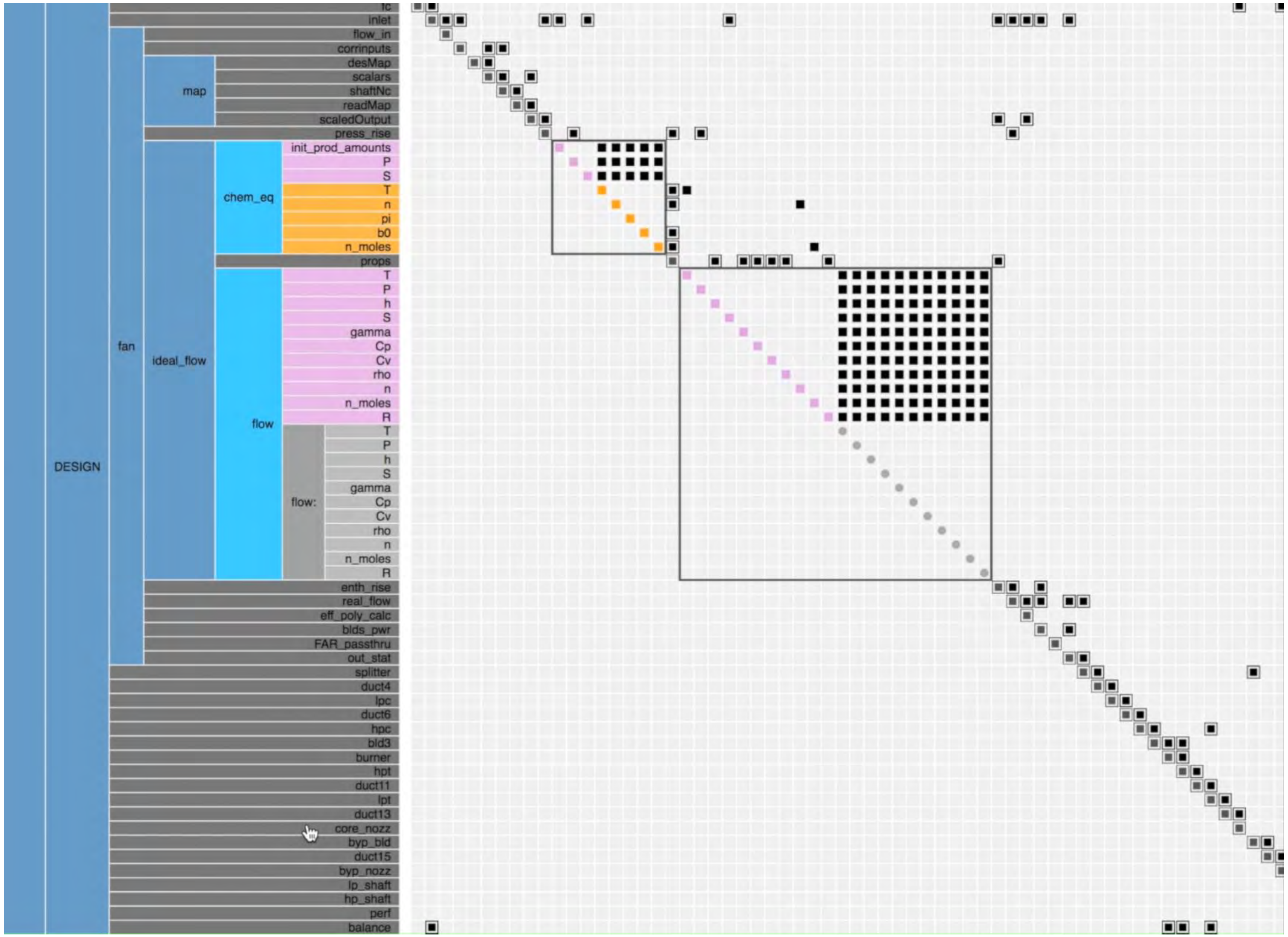
What is MPhys? And how can it shape the future of high-fidelity MDO?

MPhys: a “more flexible MACH” based on OpenMDAO

- Extends a MACH-like approach to a more general and modular formulation
- Takes care of the complex integration of multiple high-fidelity models and the assembly of the coupled adjoint for gradient-based optimization problems
- Emphasis on computational performance and parallelization
- Plug-and-play, interchangeable solvers
- https://github.com/OpenMDAO/mphys contains a Python-based API to connect solvers
- Users can add their own solver "wrapper" and drive the API development

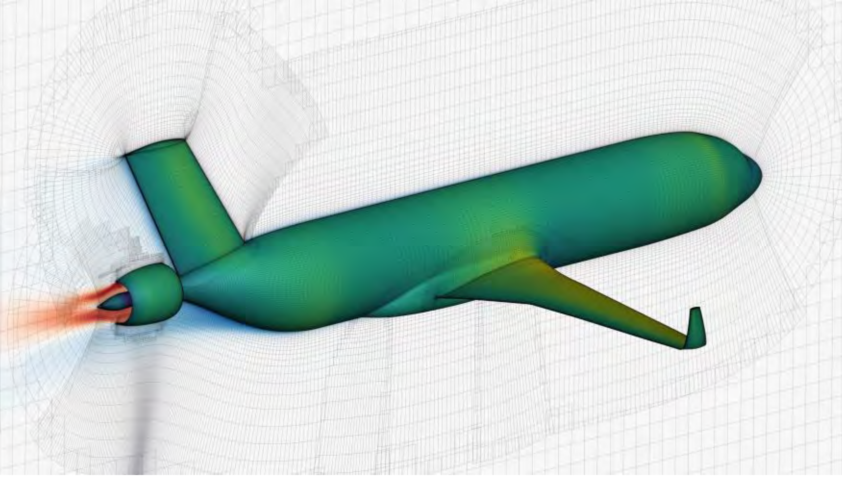


OpenMDAO facilitates model coupling and derivative calculation

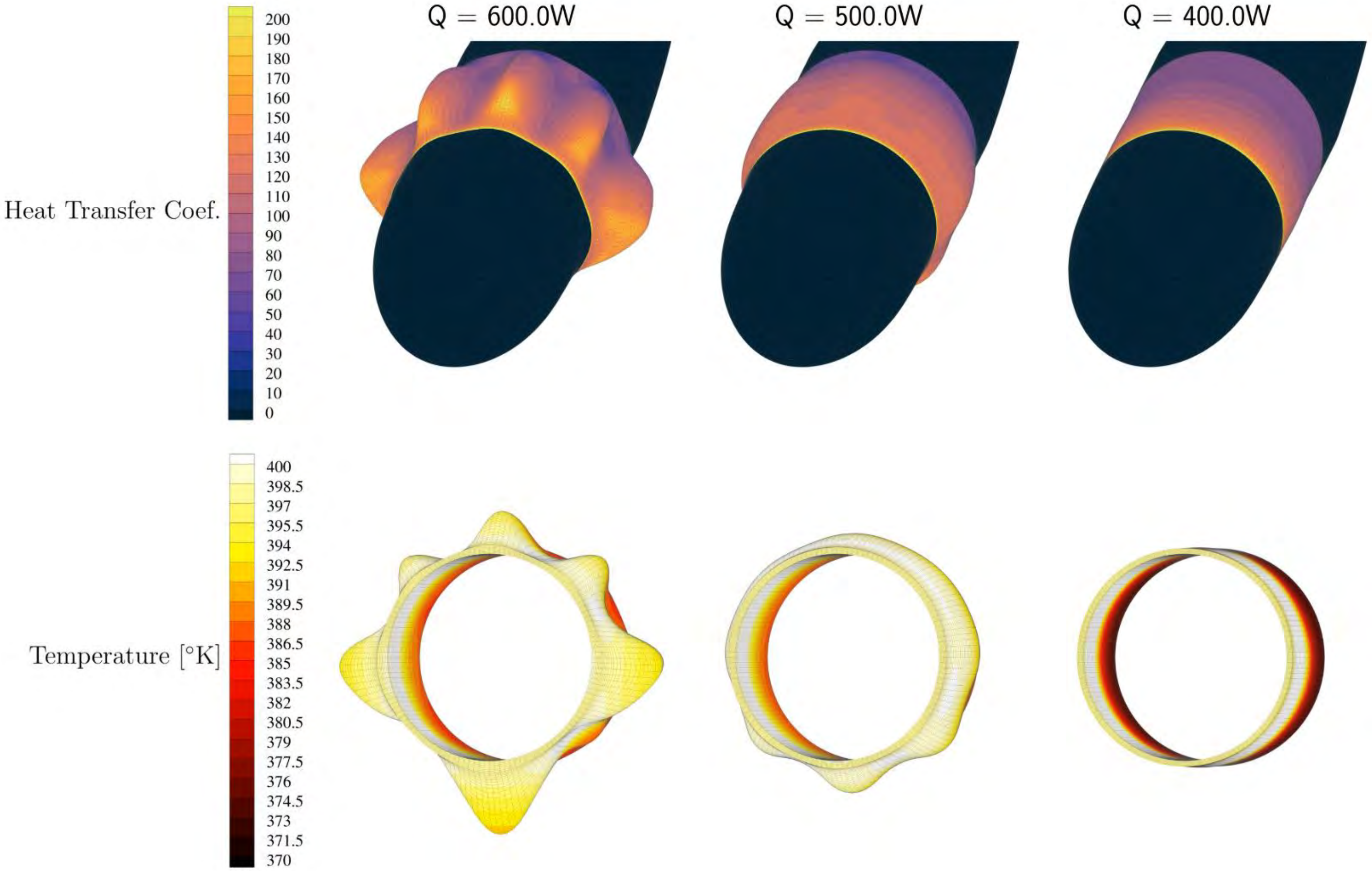


- Developers only need to provide partial derivatives for each component
- OpenMDAO efficiently assembles the total derivatives considering the problem sparsity
- Generalized interface for different types of solvers and sets of “scenarios” to build the optimization problem

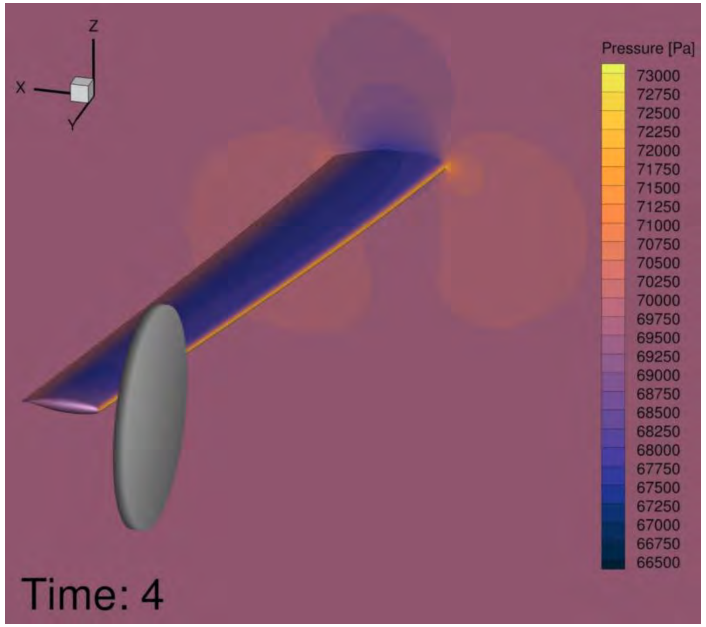
MPhys facilitates the effective integration of high-fidelity solvers



Yildirim et al., **Boundary Layer Ingestion Benefit for the STARC-ABL Concept**, *Journal of Aircraft*, doi:10.1514/1.C036103



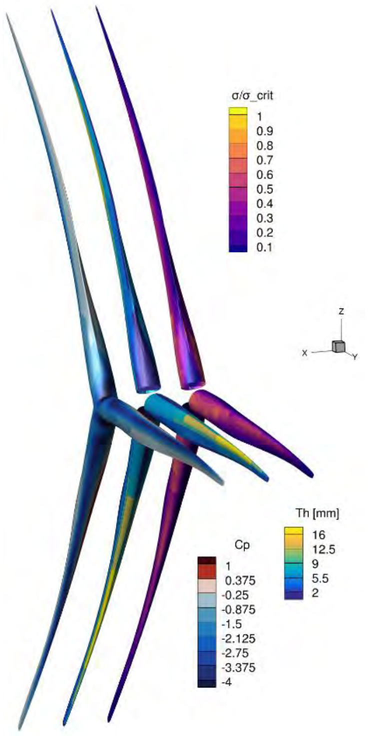
Anibal et al., **Aerodynamic shape optimization of an electric aircraft motor surface heat exchanger with conjugate heat transfer constraint**, *International Journal of Heat and Mass Transfer*, doi:10.1016/j.ijheatmasstransfer.2022.122689

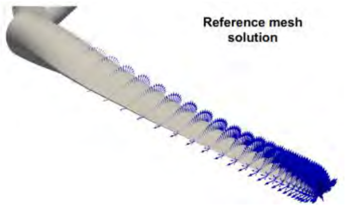


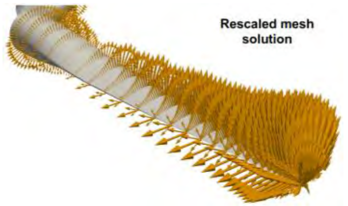
Pacini et al., **Multipoint Aerostructural Optimization for Urban Air Mobility Vehicle Design**, Scitech 2023

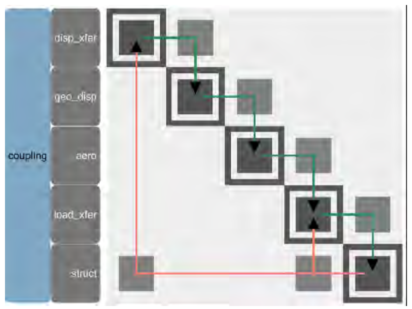
Conclusions

- Coupled aerostructural high-fidelity models enable detailed rotor optimization early in the design process
- “Expensive” high-fidelity models can be coupled with conventional design tools to include life-cycle considerations in the optimization process
- OpenMDAO and MPhys can be leveraged to extend the current high-fidelity MDO capabilities

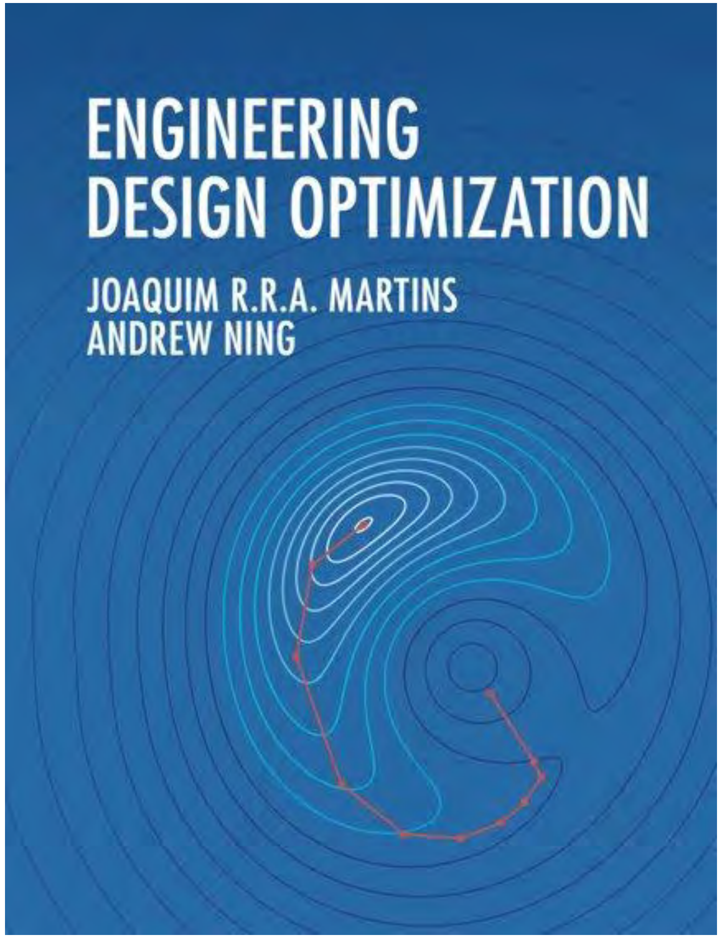






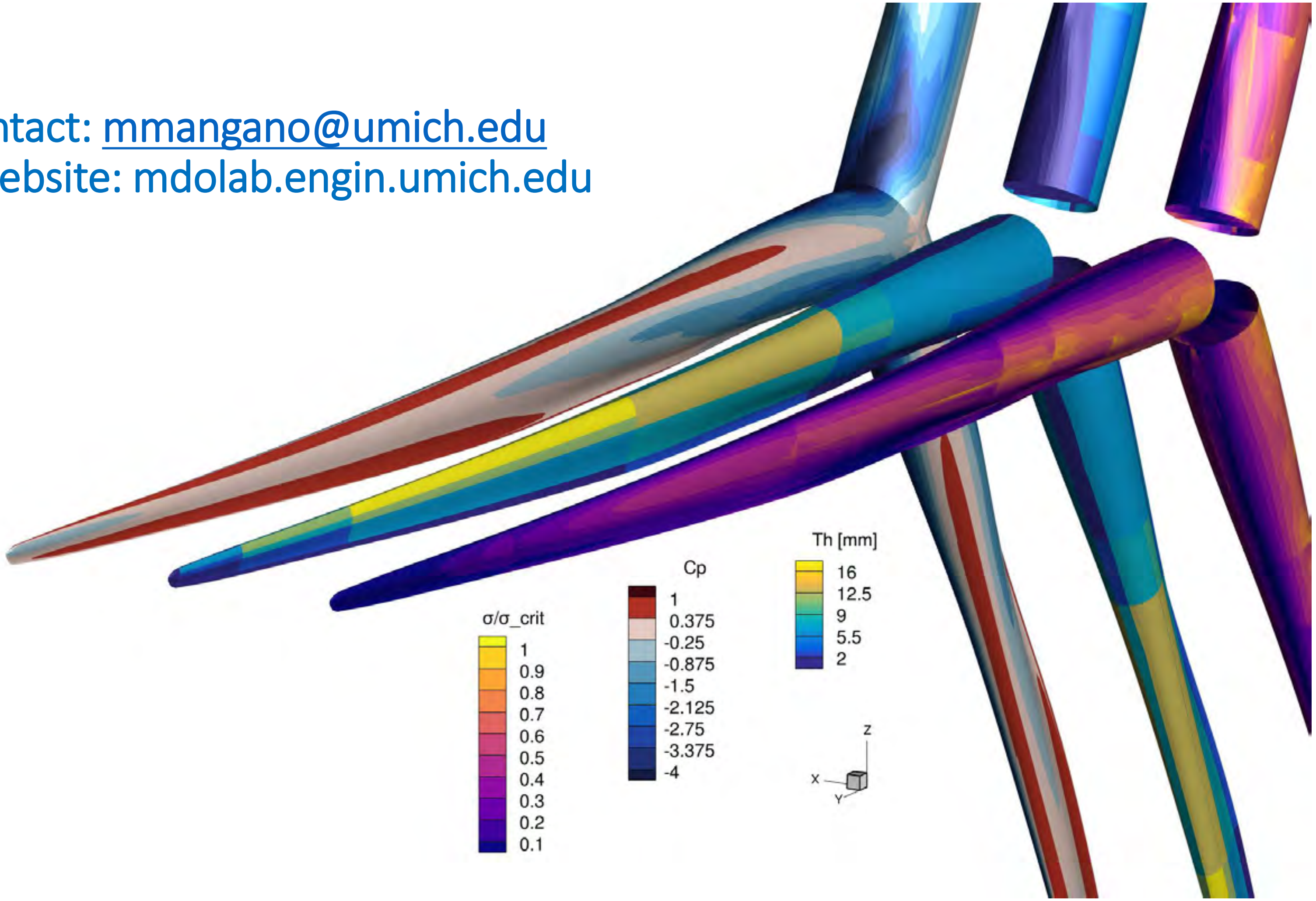


THANK YOU!



Free download at: https://mdobook.github.io

Contact: mmangano@umich.edu
Lab website: mdolab.engin.umich.edu



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Acknowledgements

- This research is supported by the Department of Energy (DOE) Advanced Research Projects Agency-Energy (ARPA-E) **Program award DE-AR0001186 entitled "Computationally Efficient Control Co-Design Optimization Framework with Mixed-Fidelity Fluid and Structure Analysis."** The authors thank DOE ARPA-E Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control (ATLANTIS) Program led by Dr. Mario Garcia-Sanz. Special thanks to the entire ATLANTIS Team for their support.

- This research was supported in part through computational resources and services provided by Advanced Research Computing at the University of Michigan, Ann Arbor. The authors also made extensive use of the Texas Advanced Computing Center (TACC) Stampede2 High Performance Computing system via the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by the National Science Foundation grant number ACI-1548562

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