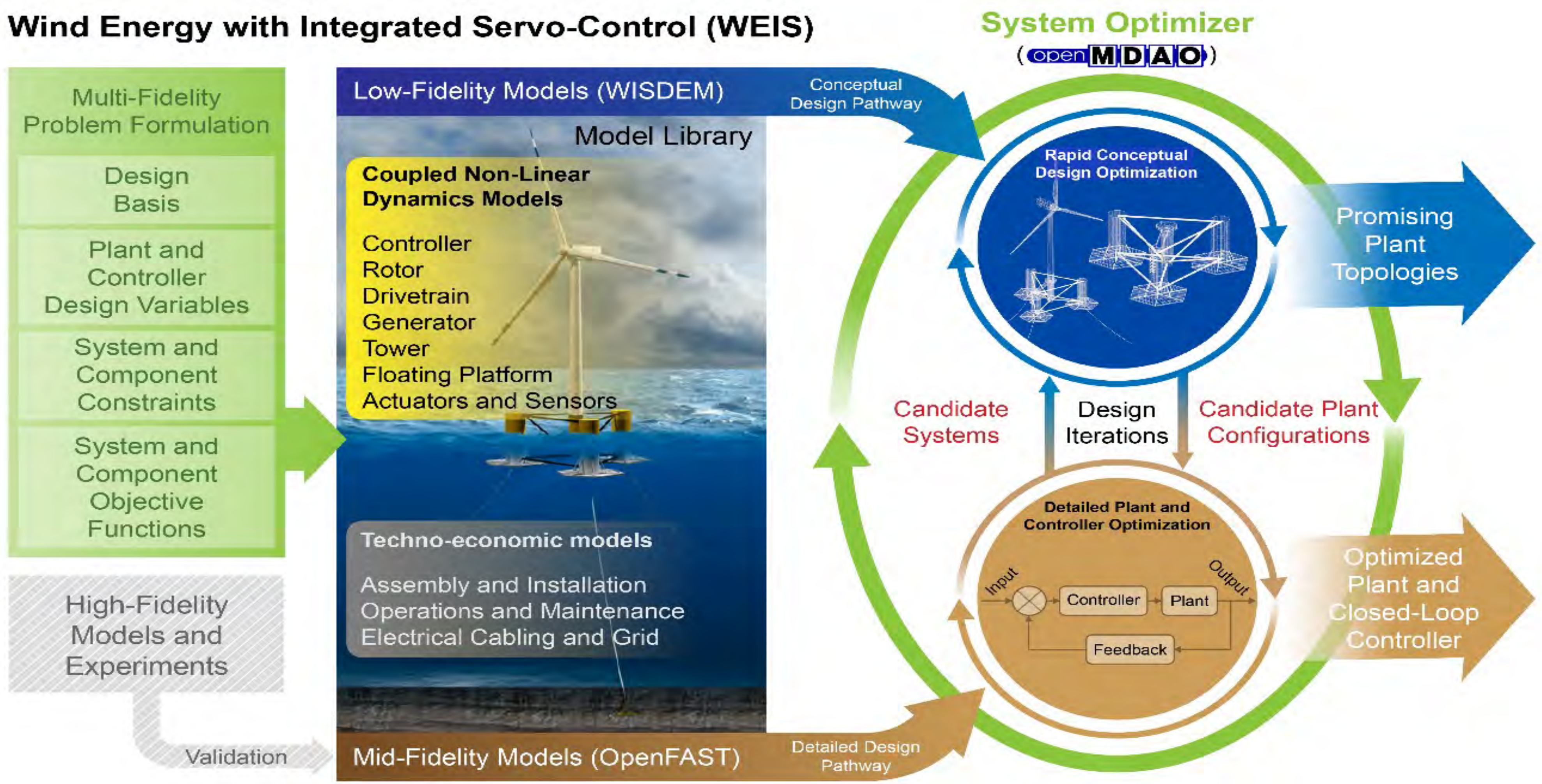
Control Co-design of Floating Wind Turbines Using WEIS

The Wind Energy with Integrated Servo-control (WEIS) Toolset

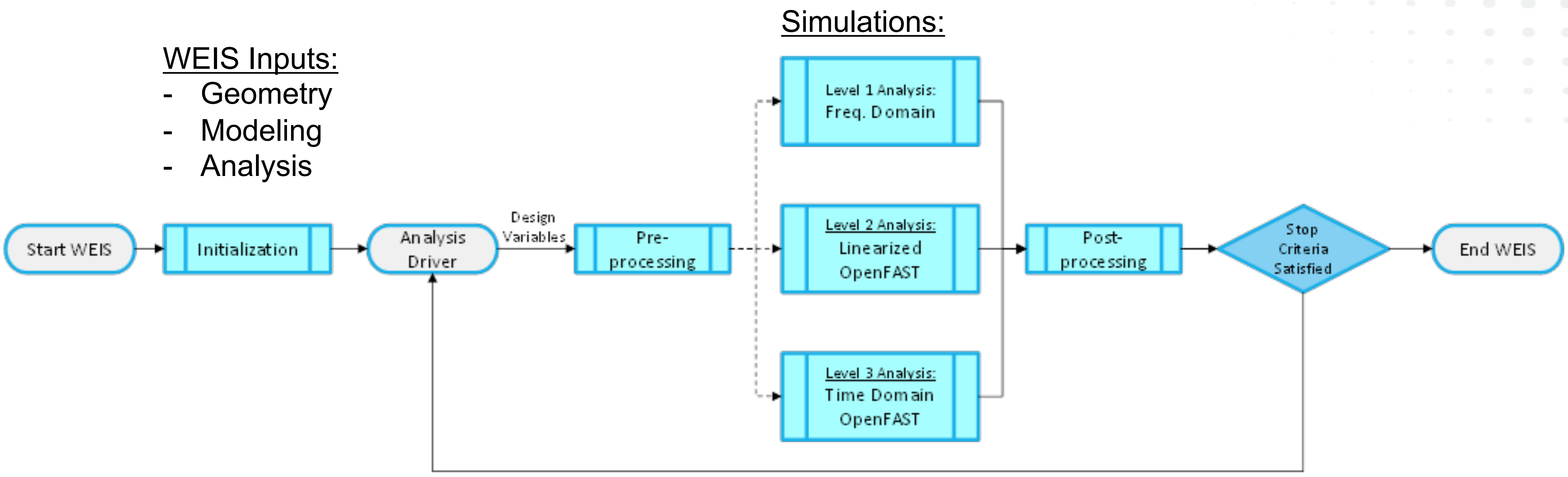
NREL Transforming ENERGY

Project Goals and Overview:



https://github.com/WISDEM/WEIS

WEIS Data Flow



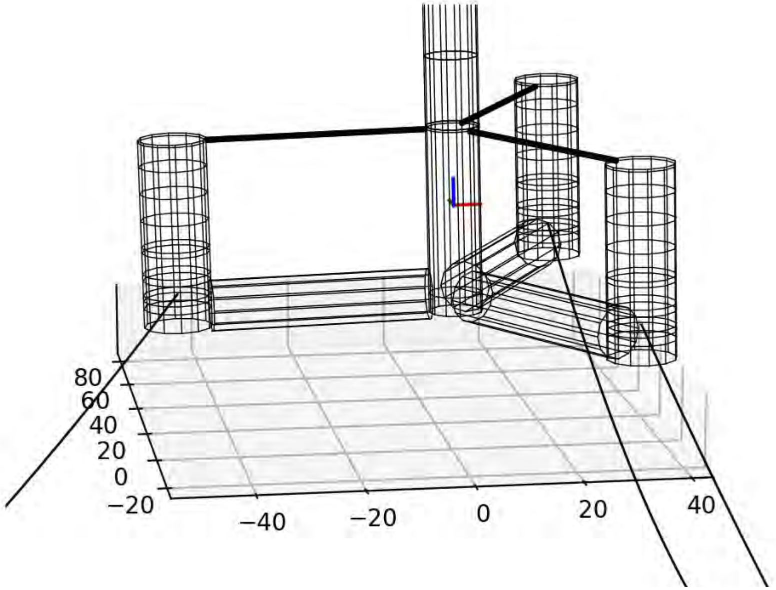
WEIS Stack

- [WindIO](#)
  - Parameterized turbine and floater geometry
  - Blade, tower
  - Platform: joints and members
  - Control system

- [WISDEM](#)
  - NREL's systems engineering toolset
  - Converts geometry into mass, cost estimates
  - Has other pre-processing tools for computing aerodynamic performance, blade/tower modes, load cases

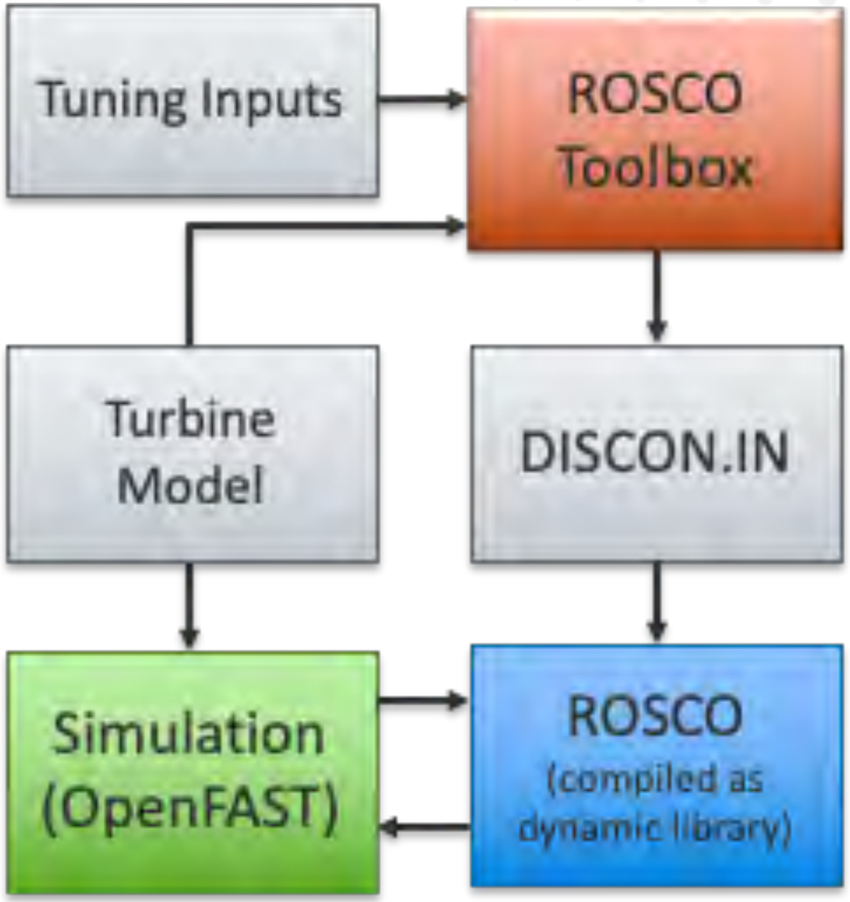
- [pyHAMS](#): potential flow solver

Structural postprocessing	**WISDEM***		**WEIS (glue code)***	**Co-Design Optimization***
Loads postprocessing	**pCrunch**			
Aero-servo-hydro-elastic modeling	**OpenFAST***	**RAFT***		
Hydrodynamic preprocessing	**pyHAMS***			
Controller tuning	**ROSCO* + ROSCO_Toolbox***			
Other preprocessing	(many NREL utilities)			
Geometry, mass, and cost	**WISDEM***			
Parameterized turbine + floater	**WindIO***			
	Level 3 / Level 2 / Level 1			



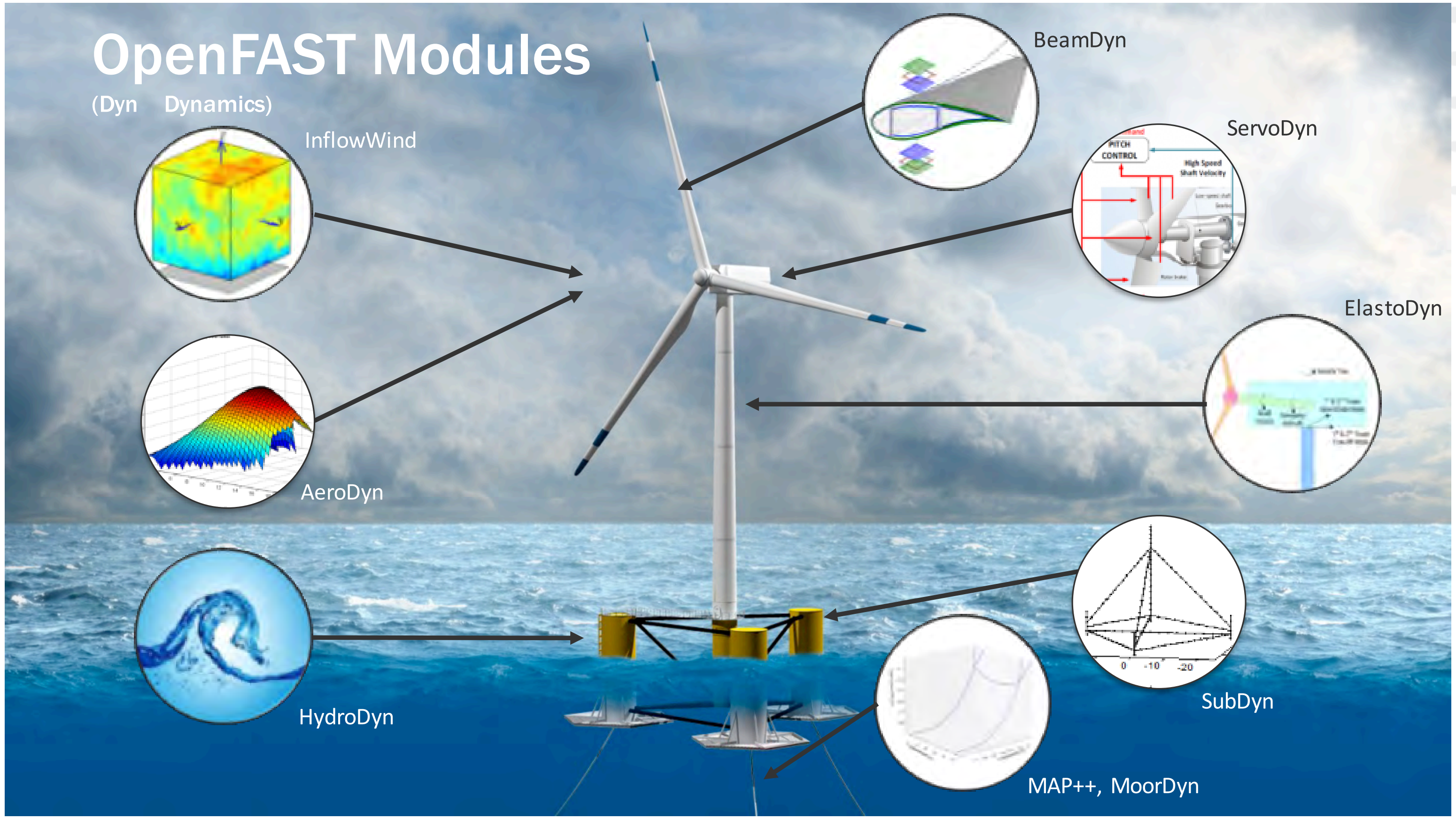
WEIS Stack – Reference Open-Source Controller

- ROSCO
  - a flexible, open-source reference controller to provide common functionalities to modern OEM controllers
- ROSCO Toolbox
  - A python-based tool for tuning controllers
- WEIS users can optimize turbine and controller parameters simultaneously



WEIS Modeling Levels

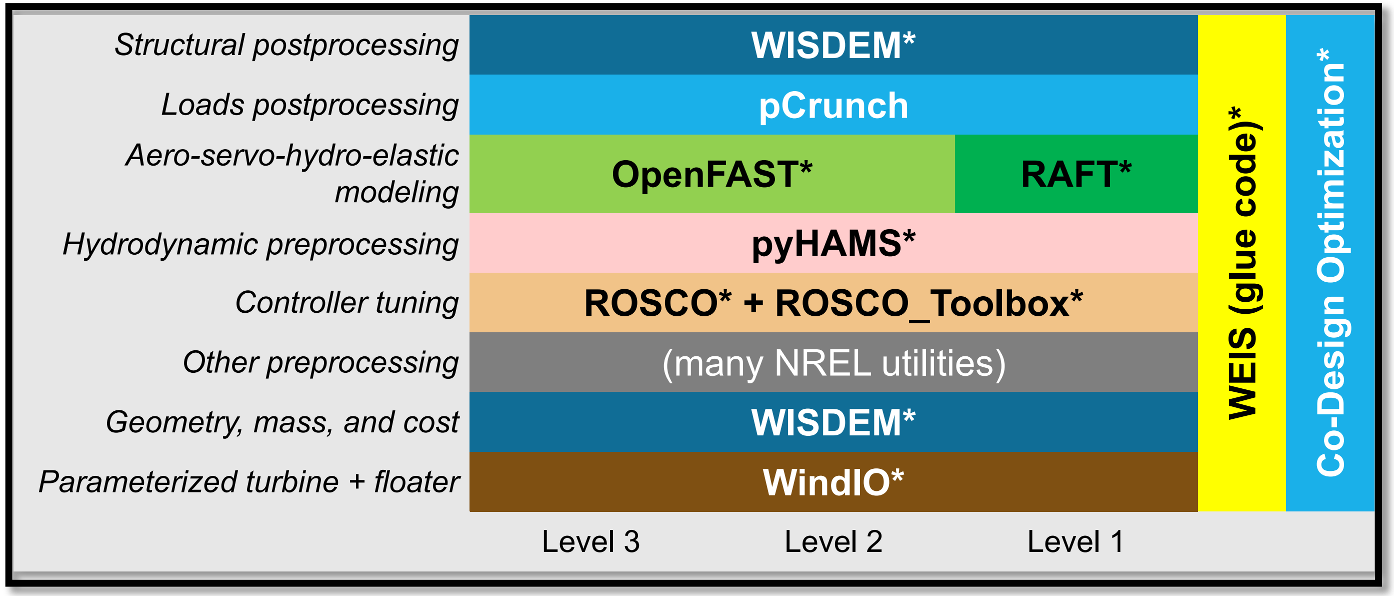
- Level 3: OpenFAST (3 – 30 min./sim.)
  - Nonlinear aero-hydro-servo-elastic solver
- Level 2: Linearized OpenFAST (20 sec./sim.)
  - Set of linearized models, simulated in time
- Level 1: RAFT (1 - 5 sec./sim.)
  - Linear, frequency domain model



WEIS Postprocessing and Glue Code

- Loads and structural postprocessing (pCrunch)
  - Simulation levels share common outputs

- Glue code: openMDAO components and groups
  - Organize design elements
  - Compute merit figures and constraints
  - Drive design variables
  - Interface with optimization drivers



WEIS Case Studies

Goal: Demonstrate control co-design of floating wind turbines across multiple fidelity levels by optimizing the IEA-15MW reference turbine with the UMaine Semisubmersible

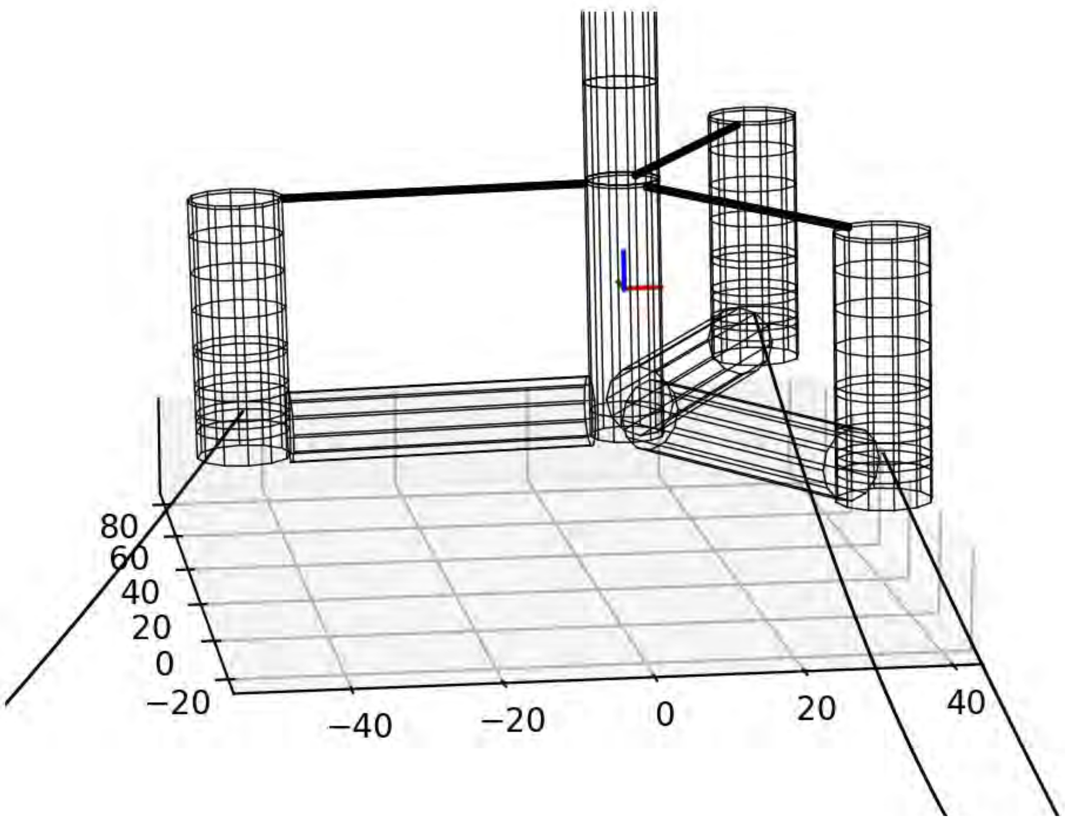
Model Type	Merit Figure	Design Variables (DVs)	Constraints

Level 1 (RAFT)	→	Level 2 (Linearized OpenFAST across wind speeds)	Level 3 (Nonlinear OpenFAST simulations)	→	Level 3 (Nonlinear OpenFAST simulations)
Platform Mass	Hydrodynamic model for OpenFAST	AEP	Error between open- and closed-loop control inputs	Initial closed-loop controller	LCOE
Platform DVs (column sizing and spacing)		DTQP: Open-loop control inputs (blade pitch, gen. torque)	Closed-loop control parameters		Tower DVs (thickness, diameter), ROSCO DVs
Platform motion, nacelle acceleration, generator overspeed		None	None		Platform motion, nacelle acceleration, generator overspeed

Initial Design – Platform Geometry

- Like VolturnUS platform but with all cylindrical columns
- LCOE of $97.30/MWh
- Maximum platform pitch of 6.2 deg. in DLC 1.6 and DLC 1.3

- Environment (modeling options of WEIS)
  - Wind and wave conditions
    - Class IIB
    - Sea states based on Gulf of Maine
  - Simulation Cases
    - DLC 1.1/1.2 for AEP and fatigue loading
    - DLC 1.3, 1.4, 1.5, 1.6 for extreme loading
    - DLC 6.1, 6.3 for parked cases



Initial Design – Design Load Cases (DLCs)

- Like VolturnUS platform but with all cylindrical columns
- LCOE of $97.30/MWh
- Maximum platform pitch of 6.2 deg. in DLC 1.6 and DLC 1.3

- Environment (modeling options of WEIS)
  - Wind and wave conditions
    - Class IIB
    - Sea states based on Gulf of Maine
  - Simulation Cases
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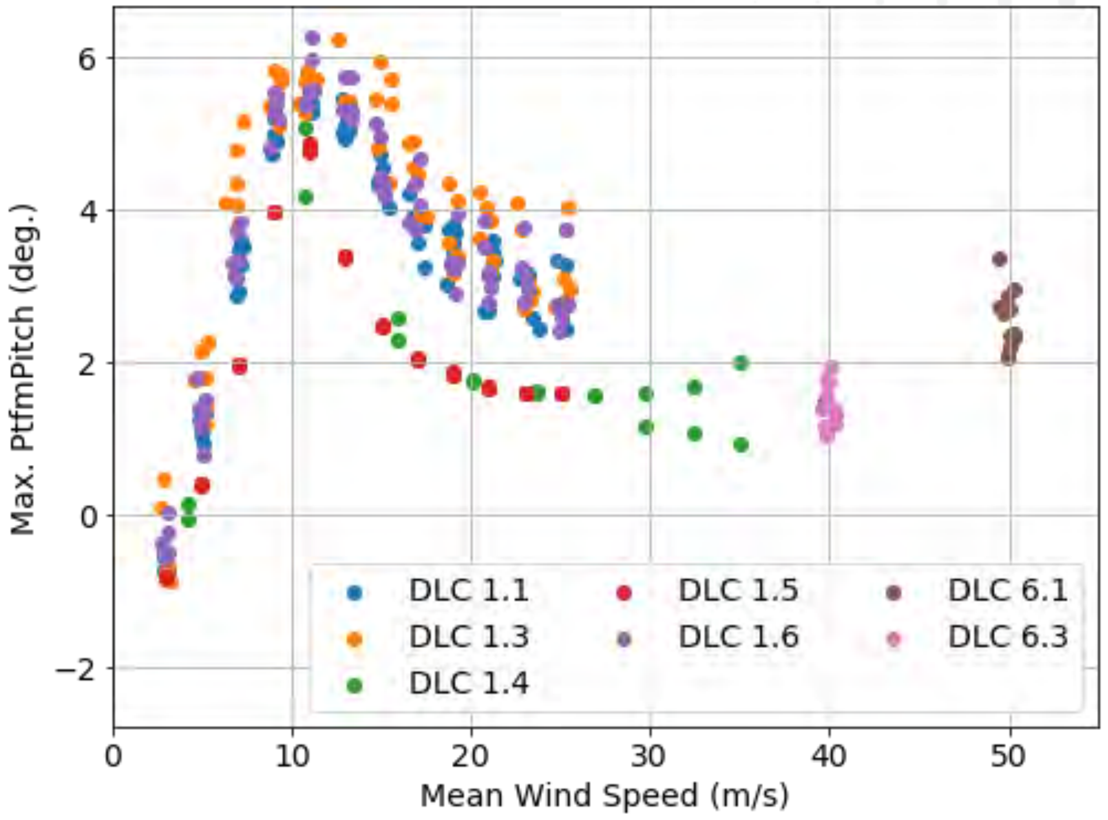

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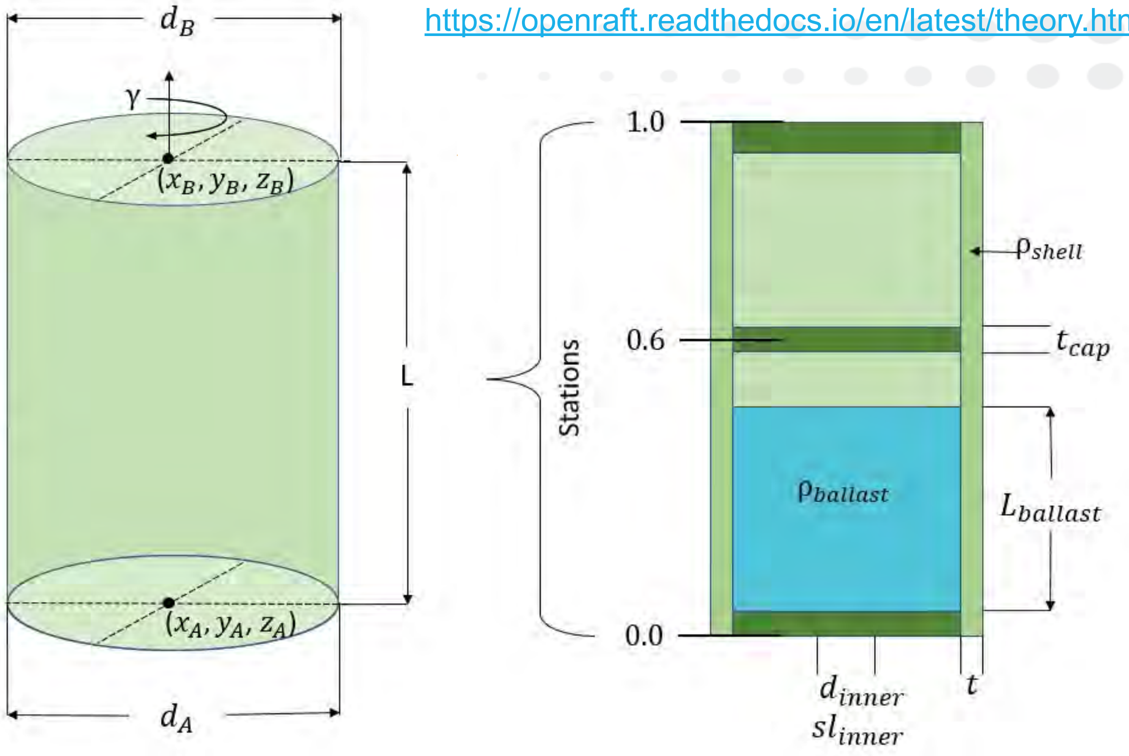
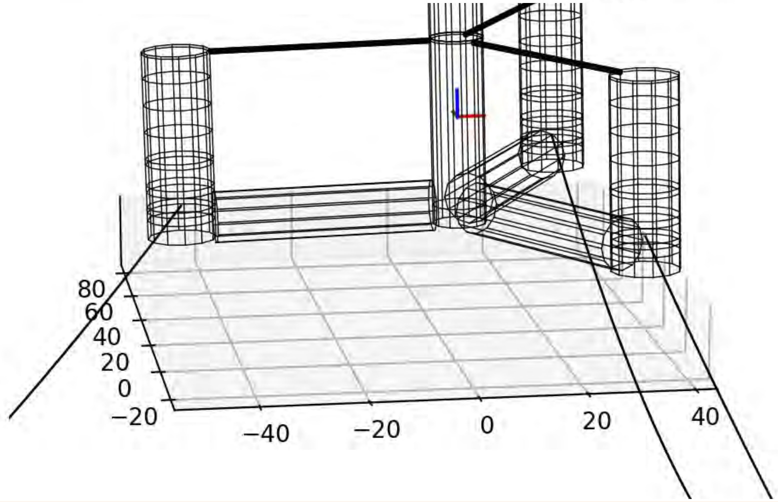
CHANGING WHAT'S POSSIBLE

RAFT Optimization Goal and Model Inputs

https://openraft.readthedocs.io/en/latest/theory.html

- Minimize platform mass by optimizing platform geometry
- Platform Geometry
  - Joints: (x, y, z) locations
    - This case examines draft and spacing
  - Members
    - Diameter and thickness
    - This case studies outer columns and lower pontoons

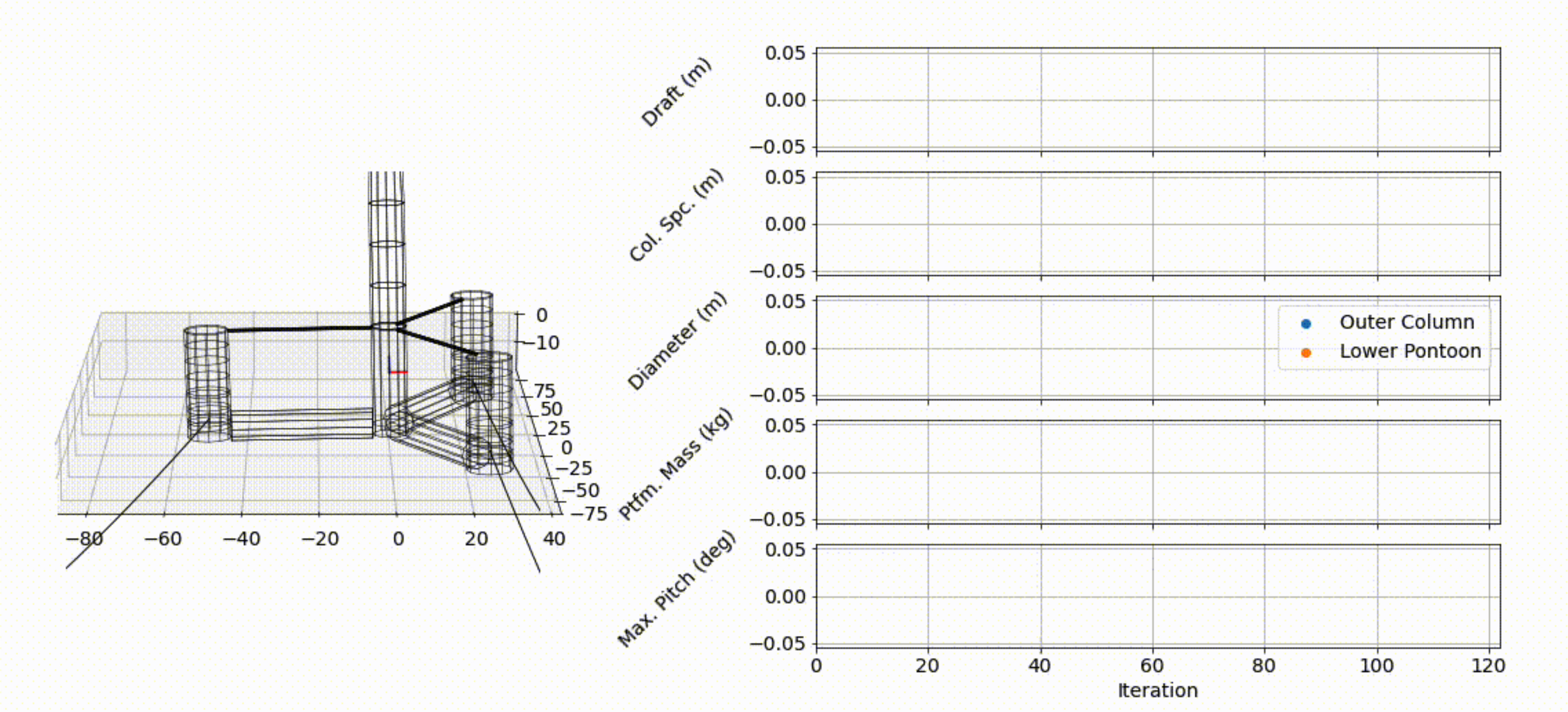




RAFT Optimization Setup in WEIS

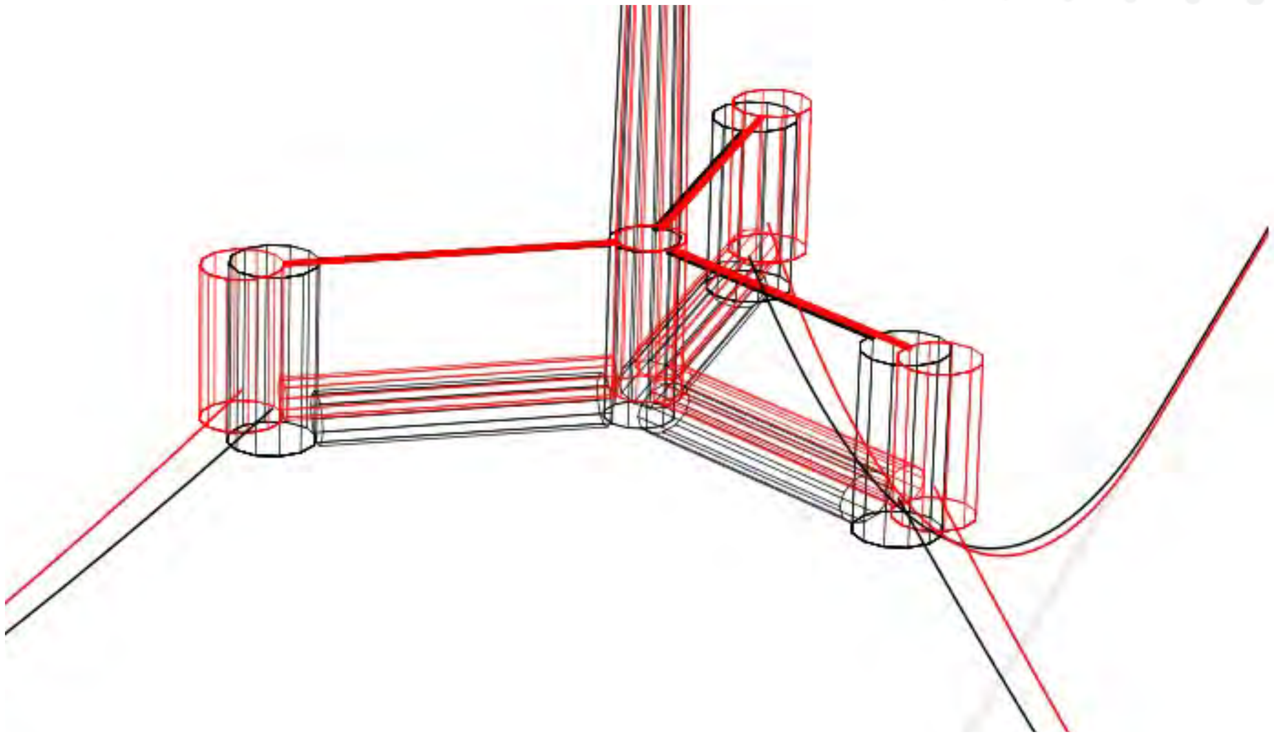
- Minimize platform mass by optimizing platform geometry
- Platform Geometry
  - Joints
    - Draft and spacing
  - Members
    - Diameter and thickness
    - Outer columns and lower pontoons
- RAFT Model
  - Steady-state hydrostatics and mooring reactions
  - Frequency-domain dynamics
    - Strip theory hydrodynamics
    - Blade element momentum (BEM) aerodynamics
    - Wind and waves: DLC 1.6 for this optimization
- Outputs
  - Steady-state offsets
    - Mean heave (ballasting)
    - Surge/sway offset (power cable constraints)
  - Dynamics
    - Power spectral densities (PSDs) -> standard deviations -> maxima across wind speeds
    - Rotor speed maxima based on nacelle motion, control
  - Structural constraints from WISDEM
    - Stress, buckling constraints
  - Updated model
    - Mass properties, ballast adjustments (0 mean heave)
    - Potential-flow hydrodynamics preprocessing for OpenFAST
- **WEIS Analysis Options: Merit figure, constraints, and DVs**
- **WEIS Modeling Options: Run RAFT or OpenFAST in DLC 1.6**

Animation of Platform Optimization



Final Platform Design Parameters

- Reduced platform draft
- Increased radial column spacing
- Decrease lower pontoon diameter by 2.1 m
- Maximum platform offset of 20 m
- Maximum rotor overspeed 25% above rated
- Platform mass reduction of 37%
- LCOE reduction of 1.7%



WEIS Benchmark Case Study

Goal: Demonstrate control co-design of floating wind turbines across multiple fidelity levels by optimizing the IEA-15MW reference turbine with the UMaine Semisubmersible

	Stage 1	→	Stage 2a	Stage 2b	→	Stage 3
Link between stages		Hydrodynamic model for OpenFAST			Initial closed-loop controller	
Model Type	Level 1 (RAFT)		Level 2 (Linearized OpenFAST across wind speeds)	Level 3 (Nonlinear OpenFAST simulations)		Level 3 (Nonlinear OpenFAST simulations)
Merit Figure	Platform Mass		AEP	Error between open- and closed-loop control inputs		LCOE
Design Variables (DVs)	Platform DVs (column sizing and spacing)		DTQP: Open-loop control inputs (blade pitch, gen. torque)	Closed-loop control parameters		Tower DVs (thickness, diameter), ROSCO DVs
Constraints	Platform motion, nacelle acceleration, generator overspeed		None	None		Platform motion, nacelle acceleration, generator overspeed

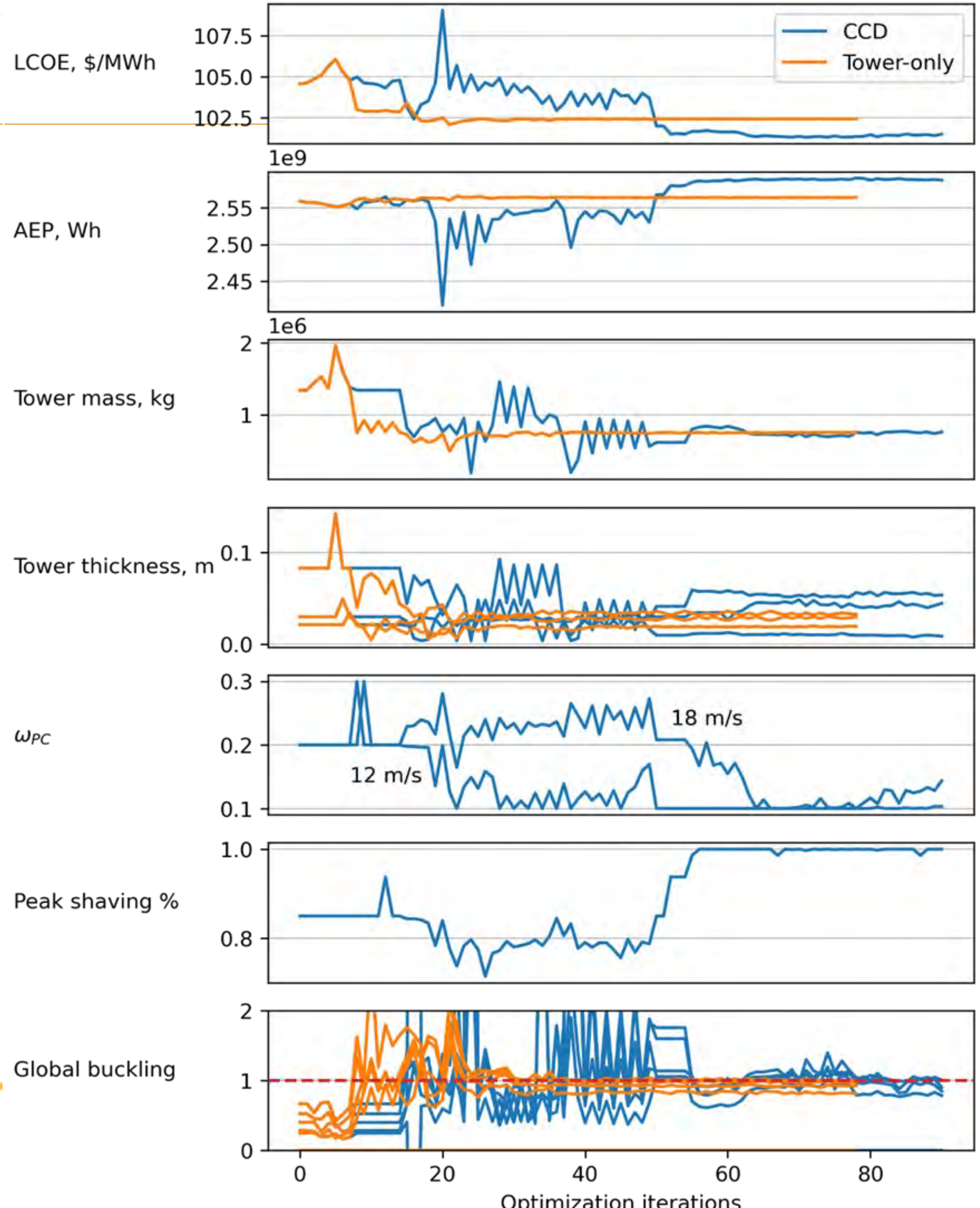
Level 3 Full CCD Design Studies

- Model:
  - IEA 15 MW with optimized platform, DLCs 1.1 and 1.6

- Design Variables:
  - Tower thicknesses and diameters at 3 control points along the tower (6 tower DVs)
  - ROSCO: pitch control parameterization (2 breakpoints per controller parameter), peak thrust shaving, floating feedback gain and phase (7 control DVs)
  - 13 total DVs

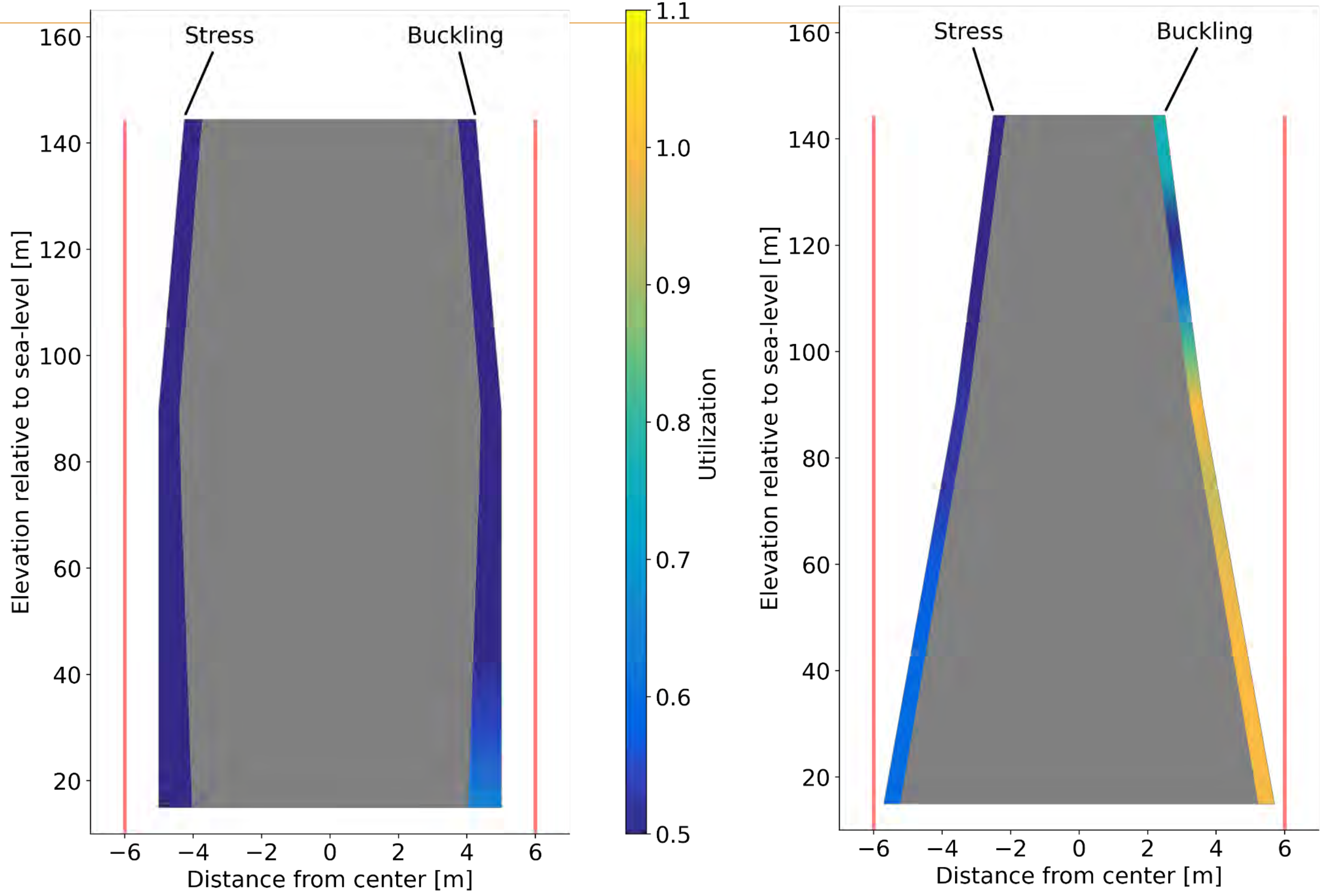
- Constraints and merit figure
  - Stress, local and global buckling, diameter-to-thickness ratio, taper ratio, tower slope constraints
  - Constrained rotor overspeed
  - Minimizing LCOE

- Example on right:
  - CCD results in blue compared with tower-only in orange
  - Initial controller design comes from optimized Level 2 outputs
  - The CCD method finds a 0.9% decrease in LCOE
  - The optimal tower designs slightly differ in the tower wall thickness
  - All constraints are satisfied at the optimal designs



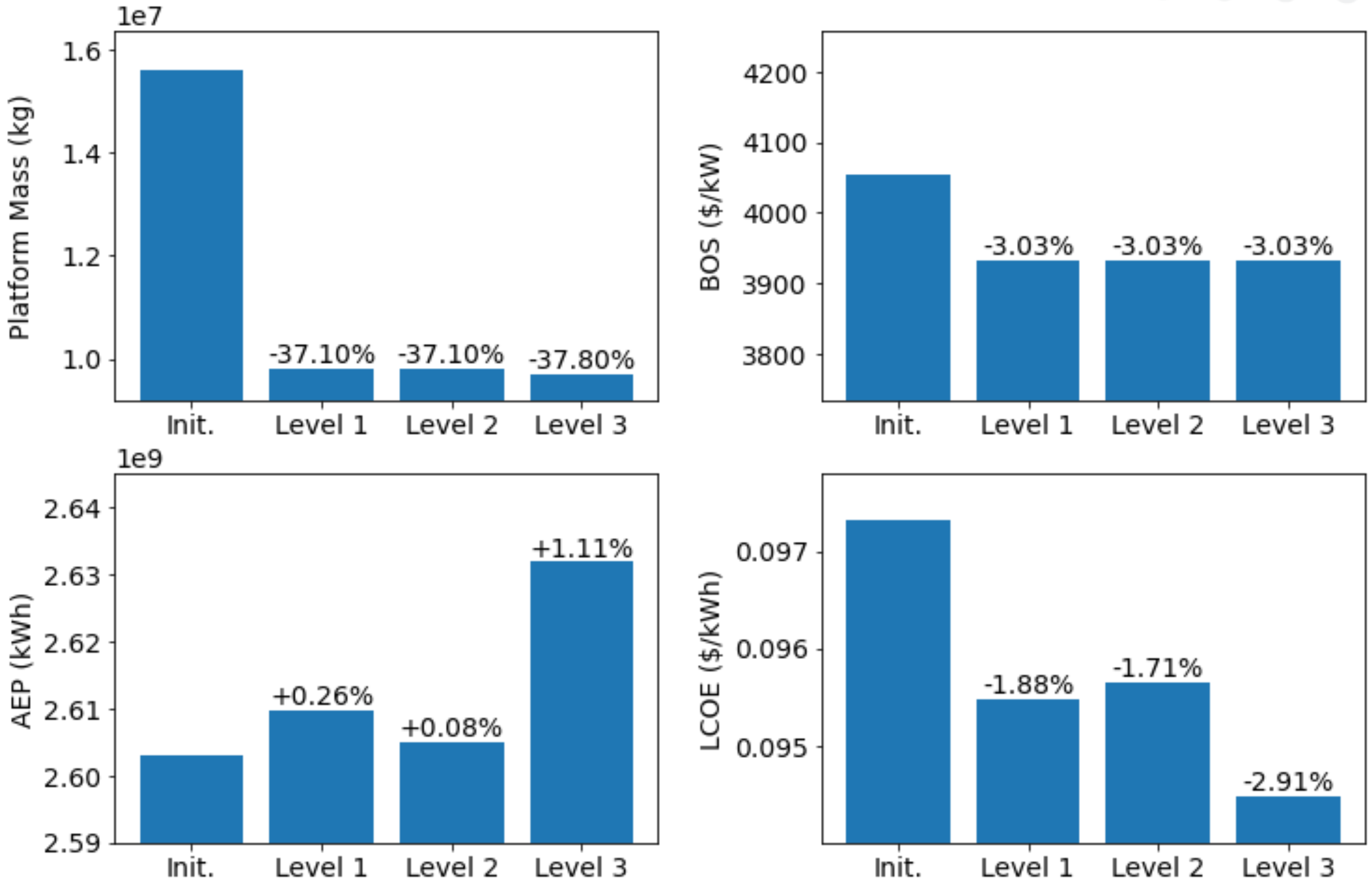
Level 3 Full CCD Design Studies

- The optimal tower design more aggressively tapers the outer diameter
- The tower wall thickness is reduced throughout the tower
- The optimal design is buckling constrained near the base
- The stress constraint is not active at the optimal design



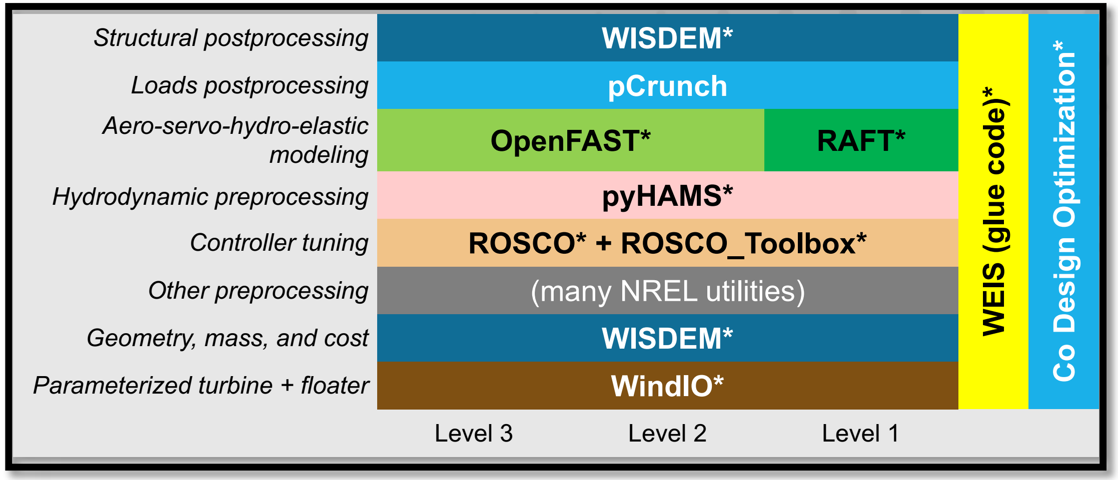
Final Benchmark Case Study 3 Results

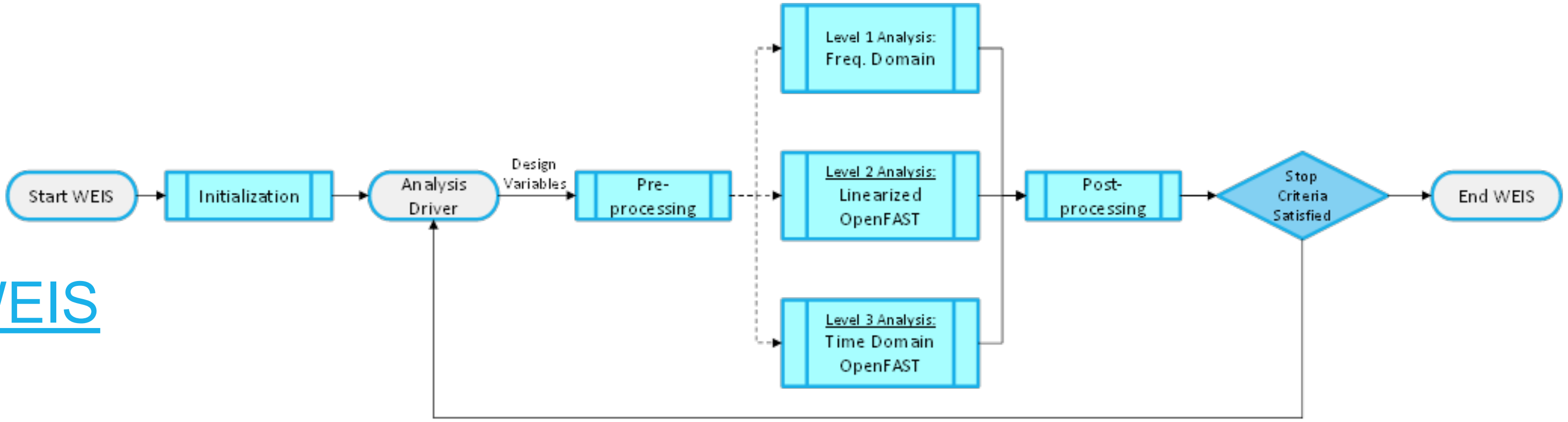
- Platform mass reduced in Level 1 optimization with a slight decrease in Level 3 due to ballasting
- Balance-of-station (BOS) decreases with platform mass
- Annual energy production (AEP) marginally affected, until Level 3 nonlinear control parameters optimized
- Levelized cost of energy (LCOE) is a combination of the BOS and AEP updates and demonstrates WEIS' ability to optimize *a given technology*



WEIS Overview and Future Work

- Collaboration for demonstration
  - Different platforms, turbines, components
  - Any optimization problem that uses simulation results in the loop
- WEIS is modularly built, so users can bring their own tools





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