Optimal tower and monopile designs for an IEAWind Task 37 Borssele reference wind farm

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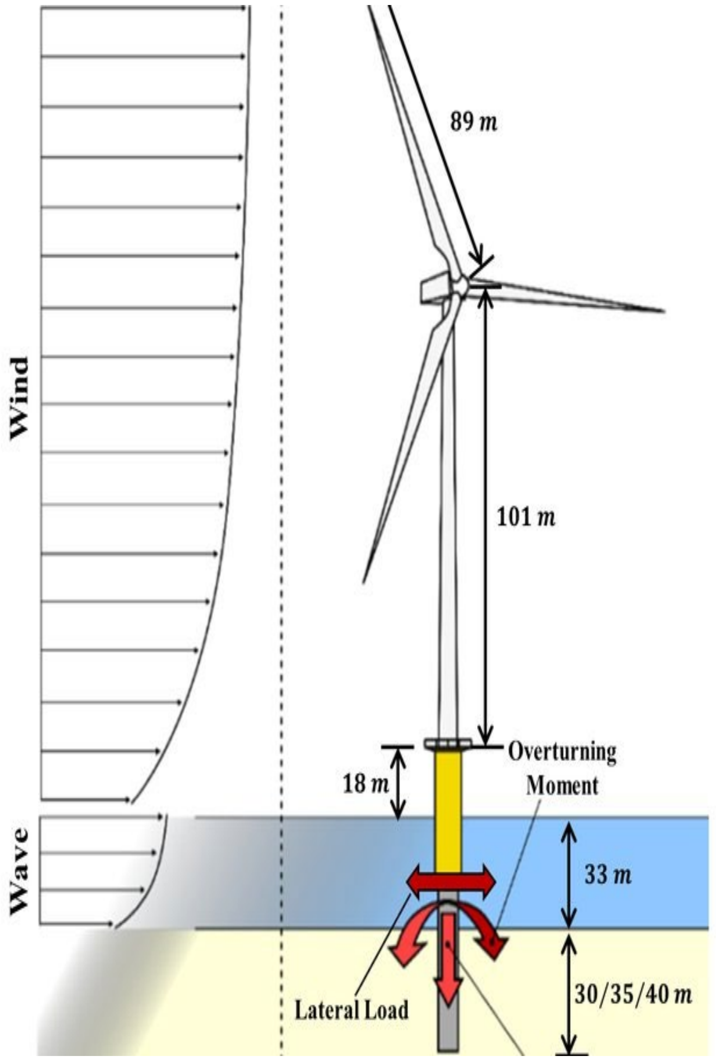
Wind Turbine Support structure Design Problem

1. Wind Turbines are highly flexible structures with a slowly rotating rotor.
2. As the rotor speed reduces with large diameters, more variations in the wind are sampled by the rotation of the rotor and transmitted to the support structure.
3. Monopile support structures can be easily mass manufactured, but can be very heavy compared to jackets at water depths more than 30m and for 10+MW wind turbines.

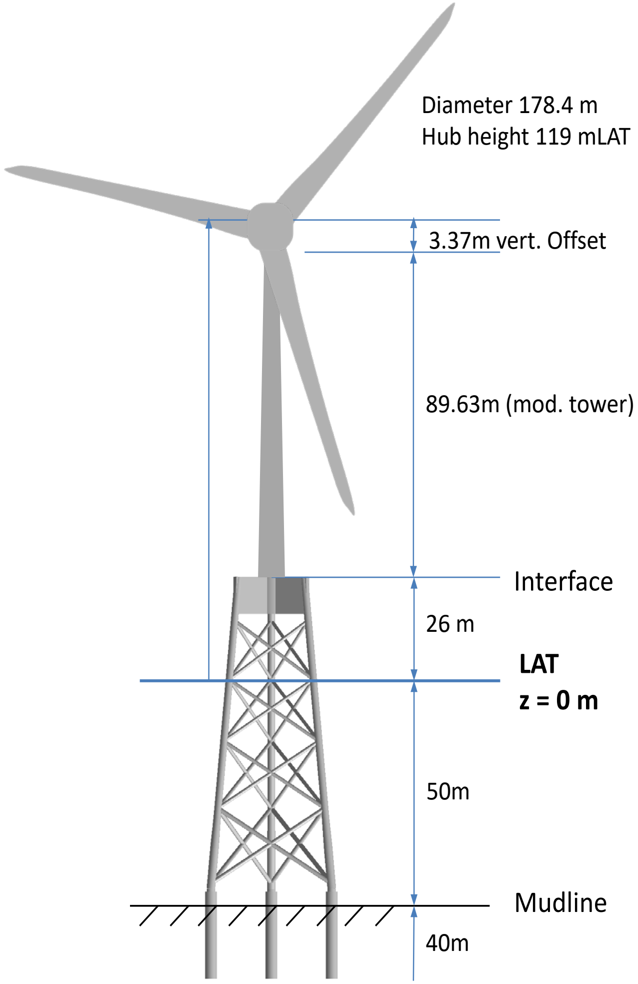
The support structure should be designed so as to have minimal structural excitation from external sources and still be cost effective across a wind farm.



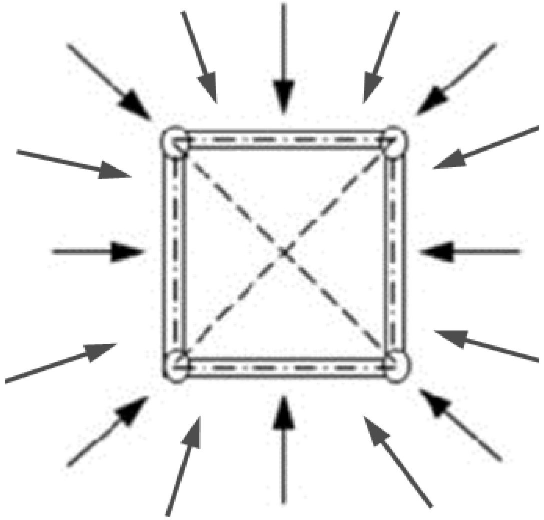
Problem description

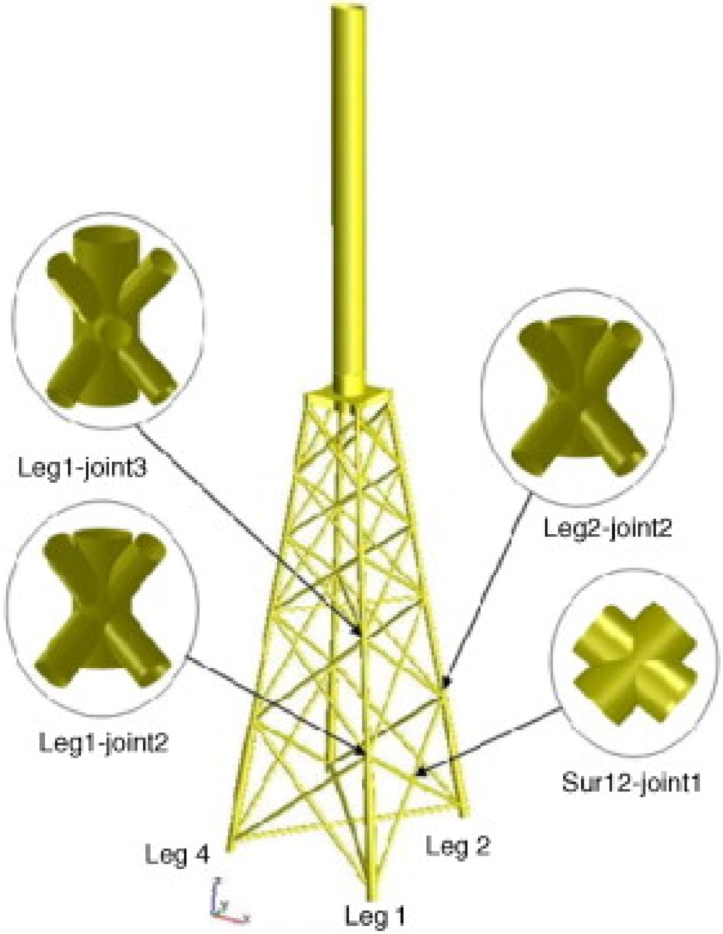
1. Develop an optimization scheme with minimal load evaluations to enable preliminary design of optimal monopiles at different turbine ratings, turbine system parameters and water depths.
   - Start from a feasible design at 10 MW for a fixed water depth
   - Use two different optimization tools:
     - WISDEM from NREL using simple load constraints, buckling constraints and frequency constraints
     - An excel based tool from DTU starting with a fully detailed monopile design, but only using scaling rules for different conditions to re-size the monopile and with only frequency and stiffness constraints.
2. Compare the resulting monopile geometries and weights from the two tools that used two different approaches to determine the sensitivity to the modeling approach and constraints.

Optimal Jackets for 10 MW wind turbines



360deg load cases for fatigue assessment



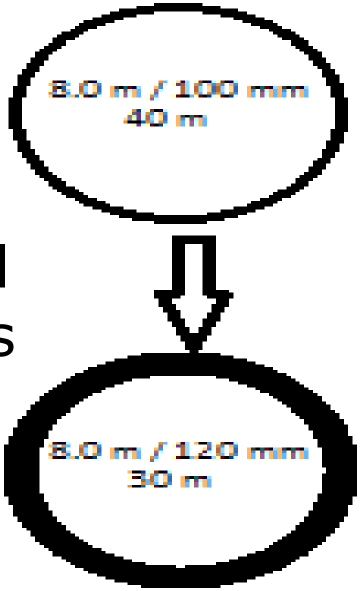


As a reference, at 50m water depth, an optimal 10 MW wind turbine jacket+tower+transition piece has a net weight of ~2000 tons

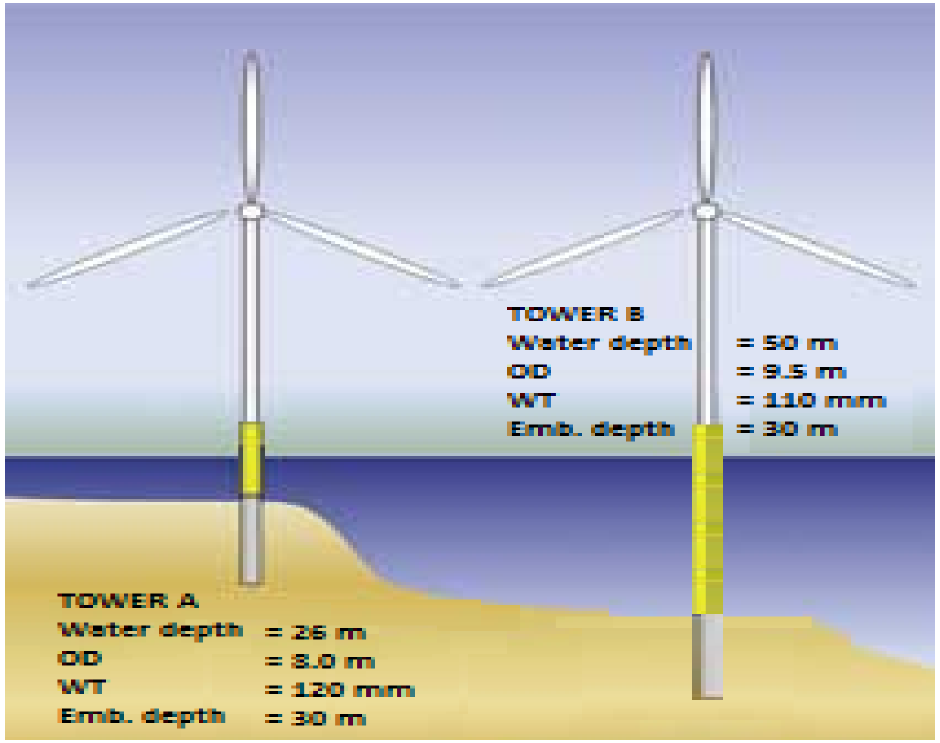
Monopiles at large water depths

MONOPILE for a 10 MW Reference turbine

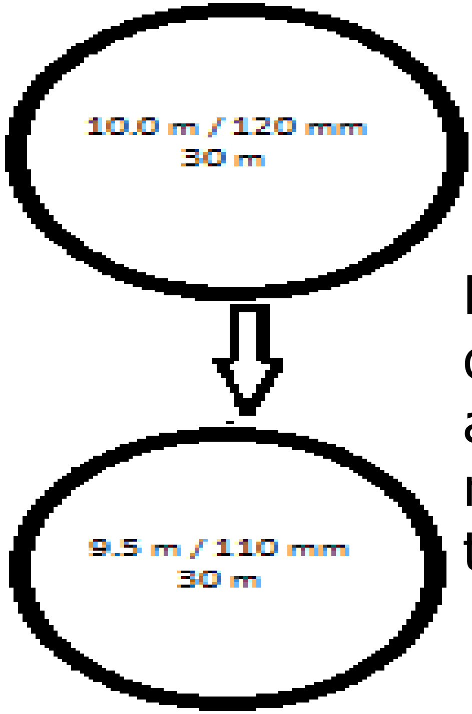
8.0 m diameter



High wall thickness



10.0 m diameter



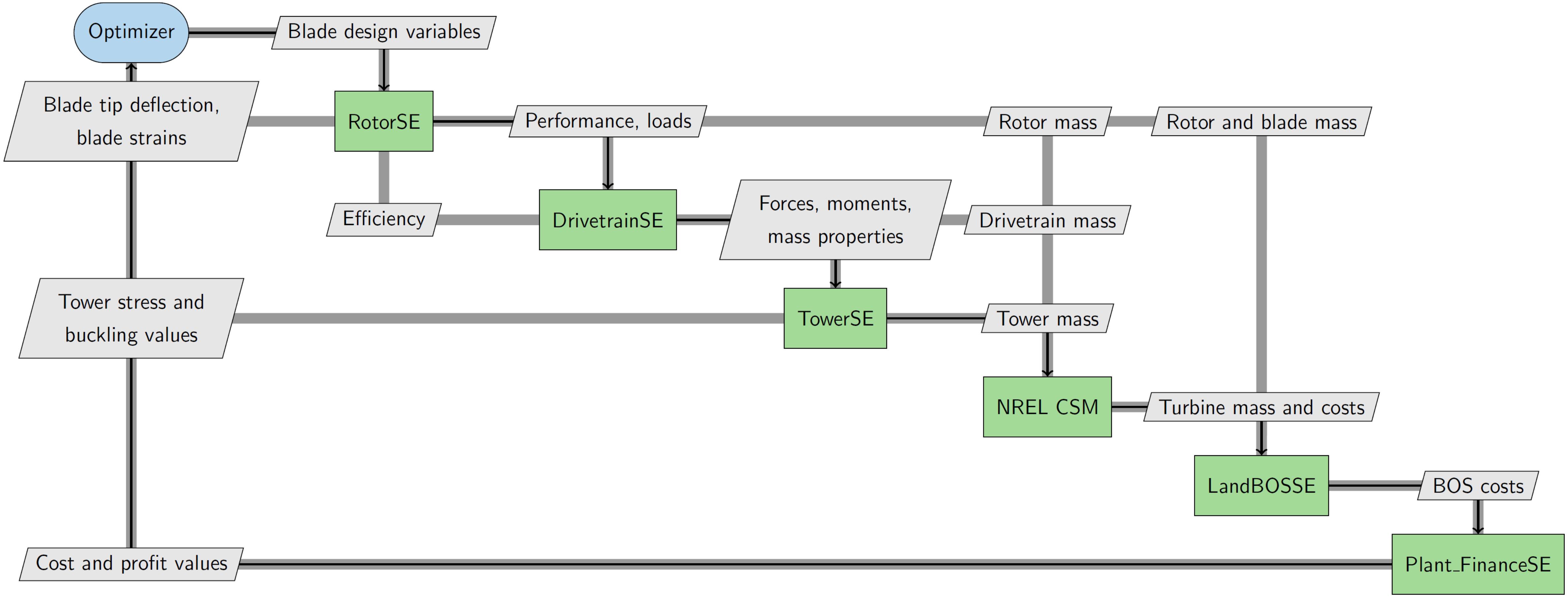
Larger diameter allows reducing wall thickness

~3000 tons in weight

Monopile support structures (tower, transition piece, pile) for 10 MW wind turbines can be heavier at 30+m water depths. Can their weight be reduced ?

WISDEM System Optimization Tool

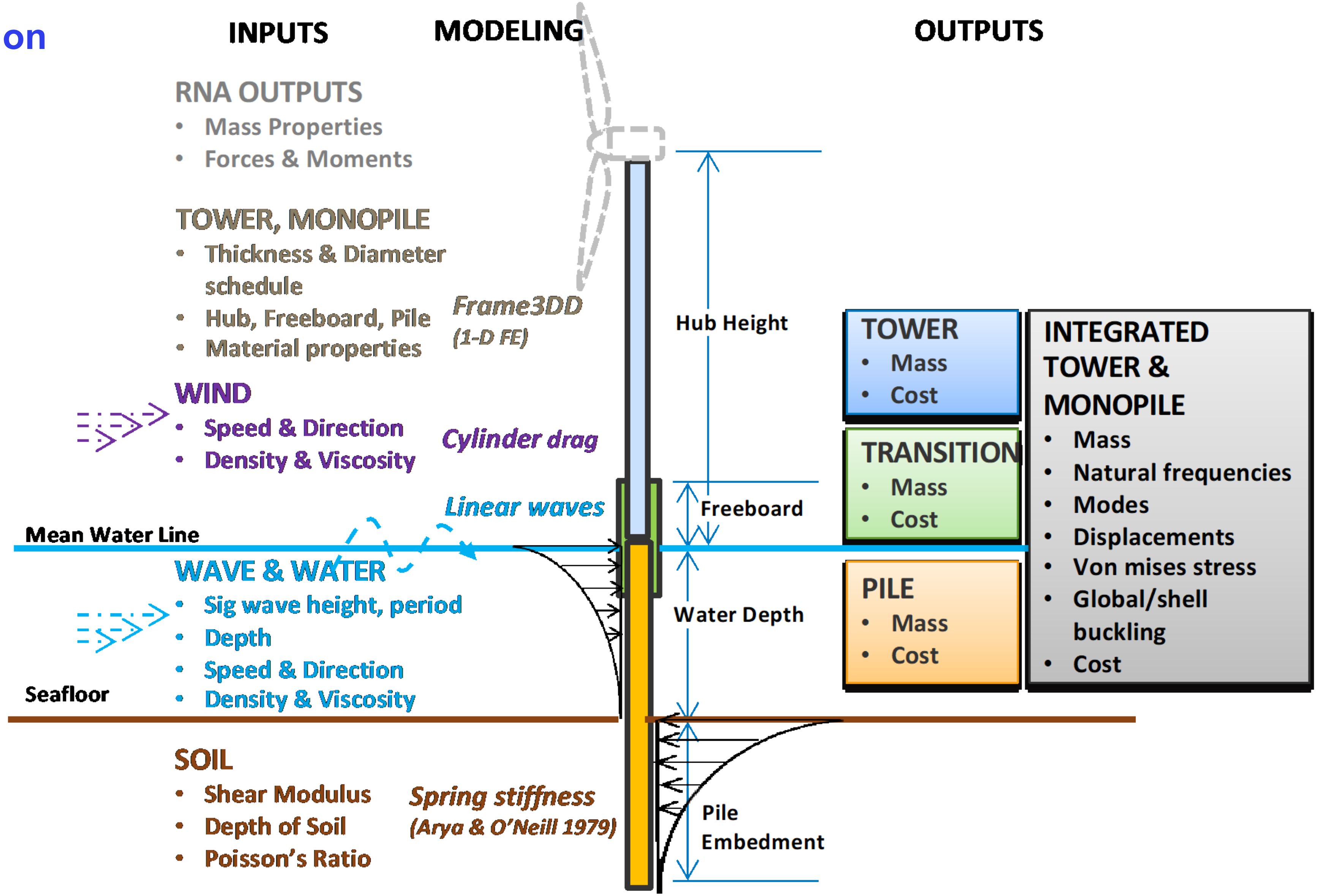
Apply multidisciplinary analysis and optimization (MDAO) to in an open framework to enable full wind turbine support structure design given wind farm conditions.



Monopile Optimization in WISDEM

WISDEM Design Optimization

- **Objective**
  - Tower + monopile mass
- **Design variables**
  - Diameter schedule
  - Thickness schedule
- **Constraints**
  - von Mises stress
  - Global buckling
  - Shell buckling
  - Manufacturing
    - D:t ratio
    - Taper ratio
  - 1st natural frequency
- **DLCs**
  - Max thrust
  - Survival wind speed
- **Algorithm**
  - IPOPT (commercial)

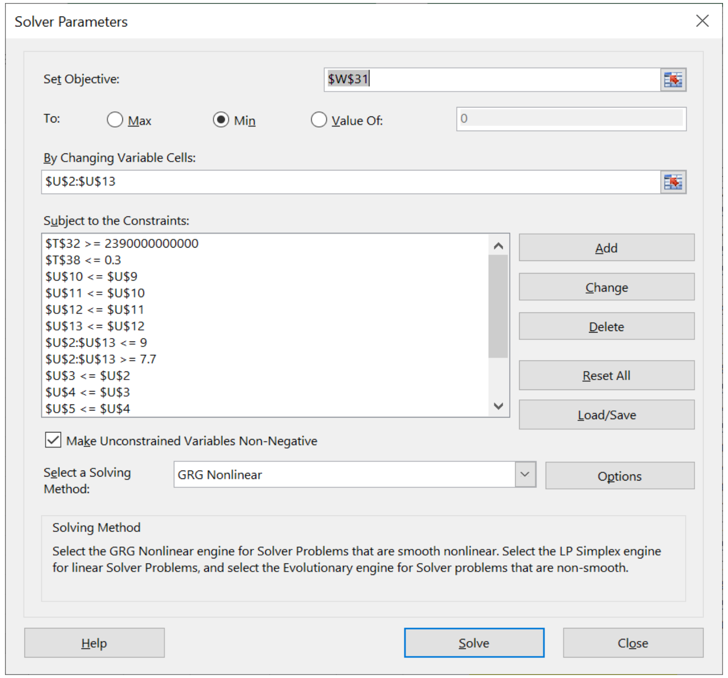


DTU Monopile Optimization Tool

Simple Excel based optimization tool based on scaling rules starting from a detailed reference design and considers the effect of

1. Turbine rating – Affects support structure diameter
2. Rotor diameter – Affects support structure wall thickness and blade tip-water clearance
3. Hub height, water depth – support structure mass, stiffness
4. Tower top mass – natural frequency
5. Soil penetration – extended beam model

Height (m)	EI	M/EI	Integrate M/EI	M	Integrate M	D	t
0.000	5.6456E+12	8.8564E-13	9.74203E-12	10.000	110	9	0.097
10.000	5.6456E+12	1.0628E-12	6.37713E-12	12.000	72.006	9	0.097
22.000	5.6456E+12	8.8564E-17	3.13753E-16	0.001	0.004	9	0.097
22.001	6.3746E+12	6.2742E-13	4.54846E-12	7.999	57.9887505	9	0.11
30.000	6.3746E+12	5.0984E-13	1.65723E-12	6.500	21.12825	9	0.11
36.500	6.3746E+12	7.8437E-17	8.63493E-16	0.001	0.00975	9	0.11
36.501	5.6456E+12	1.7269E-12	1.69228E-11	19.499	191.080451	9	0.097
56.000	5.6456E+12	8.8564E-15	5.75704E-14	0.100	0.455	9	0.097
56.100	3.9386E+12	1.1426E-12	1.0283E-11	9.000	81	8.5	0.08
65.100	3.9386E+12	1.1426E-12	9.7117E-12	9.000	76.5	8.5	0.08
74.100	3.9386E+12	1.0156E-12	4.11319E-12	8.000	32.4	8.5	0.08
82.100	3.9386E+12	1.2695E-14	1.66059E-13	0.100	0.43	8.5	0.08
82.200	1.28E+12	3.3085E-12	1.40629E-11	8.500	36.12925	7.743	0.034
90.700	1.15E+12	4.3464E-16	2.65347E-15	0.001	0.0057505	7.4646	0.034
90.701	1.08E+12	5.3065E-12	3.05154E-11	11.500	66.13075	7.4646	0.032
102.201	9.66E+11	5.1745E-16	3.03342E-15	0.001	0.0055005	7.1861	0.032
102.202	9.07E+11	6.0663E-12	3.33682E-11	11.000	60.5055	7.1861	0.03
113.202	8.05E+11	6.2123E-16	3.99044E-15	0.001	0.0060005	6.9076	0.03
113.203	7.52E+11	7.9803E-12	4.78861E-11	12.000	72.006	6.9076	0.028
125.203	6.64E+11	7.5276E-16	4.45499E-15	0.001	0.0055005	6.6292	0.028
125.204	6.17E+11	8.9092E-12	4.90058E-11	11.000	60.5055	6.6292	0.026
136.204	5.42E+11	9.217E-16	5.98586E-15	0.001	0.0060005	6.3507	0.026

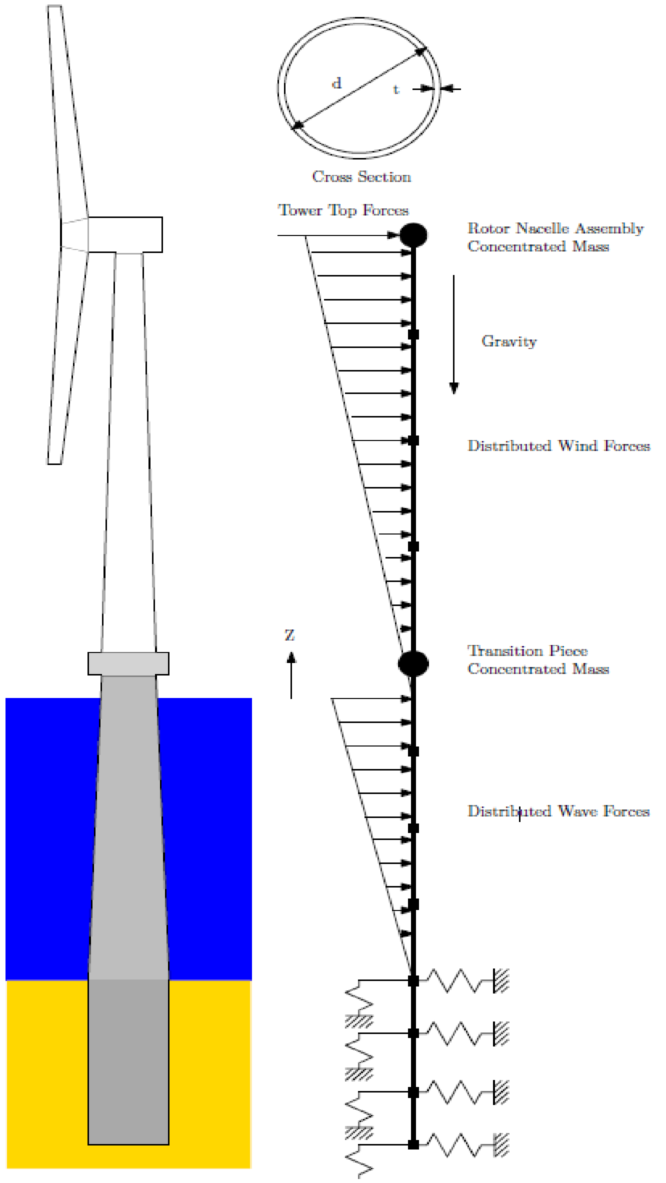


Monopile Optimization in DTU tool

- The reference 10 MW support structure design has been assessed for all limit states: buckling, ultimate and fatigue.
- Changes in water depth, rotor diameter and turbine rating cause a change in support structure diameter through scaling rules.
- Minimize mass subject to:
  - Keep the equivalent bending rigidity (EI) of the support structure within 2% of the original reference.
  - Diameter limits
  - Diameter monotonically increasing from monopile base to tower top.
- Monopile and transition piece diameters at each section are the only optimization variables.
- The optimization takes less than 3 seconds on a standard laptop.

Wind Turbine Models Used

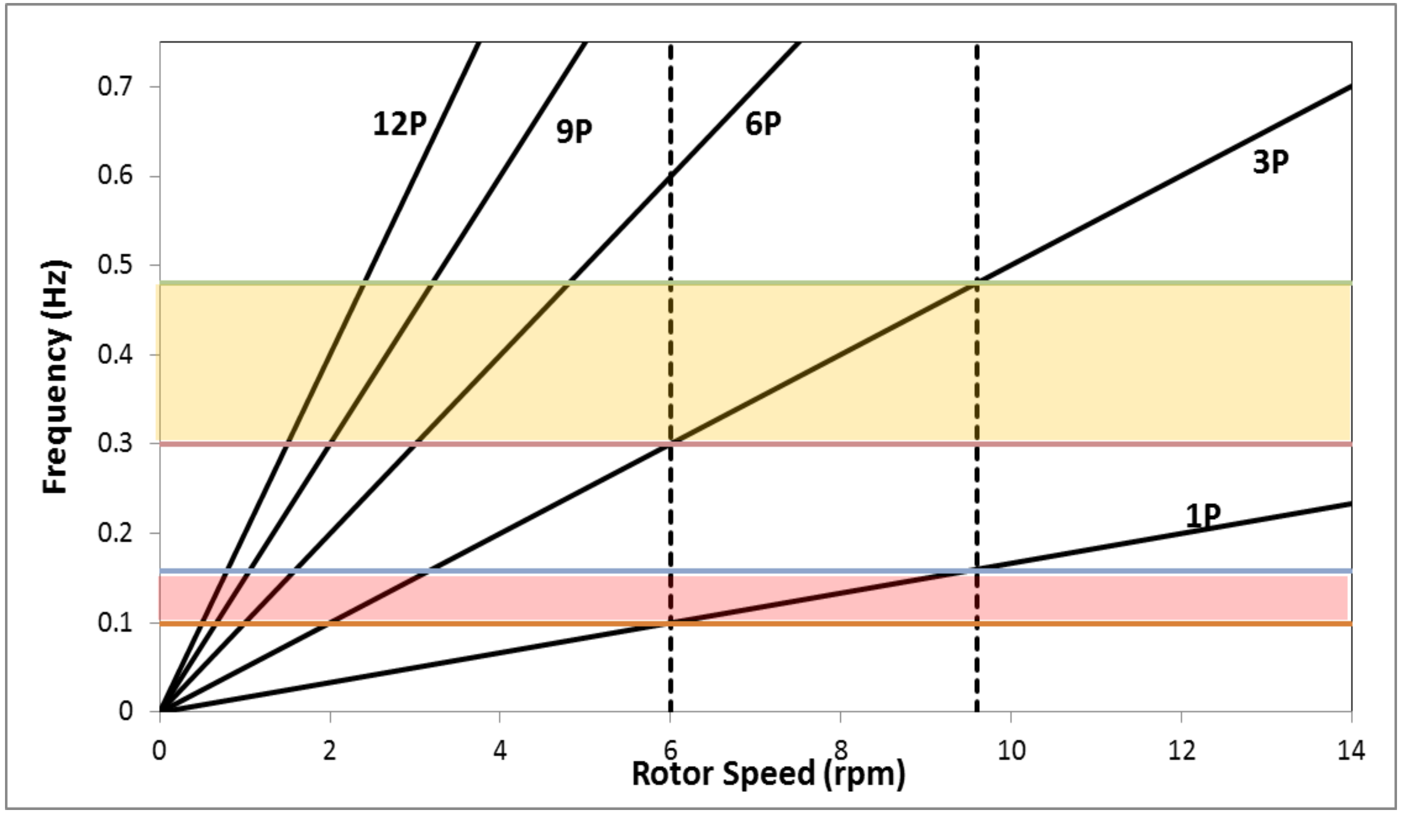
1. IEAWIND 10 MW wind turbine is used which has the same major characteristics as the DTU 10 MW, but with a larger rotor diameter of 198m. The hub height is 119 m.
2. The tower top mass of the IEAWIND 10 MW increased to 864 tons from the 660 tons for the DTU 10 MW.
3. The IEAWIND 15 MW wind turbine is also used that has a rotor diameter of 240m with a hub height of 150m and tower top mass of 1017 tons.
4. Both wind turbine are assumed to be mounted on monopile substructures and placed at varying water depths from 25m to 40m.



Campbell Diagram for the 10 MW wind turbine

The operation of the turbines should be such that multiples of the P frequency (nP) do not interact with the coupled structural frequencies.

This implies that the monopile support structure natural frequency must be less than 0.29 Hz. and greater than 0.15 Hz.

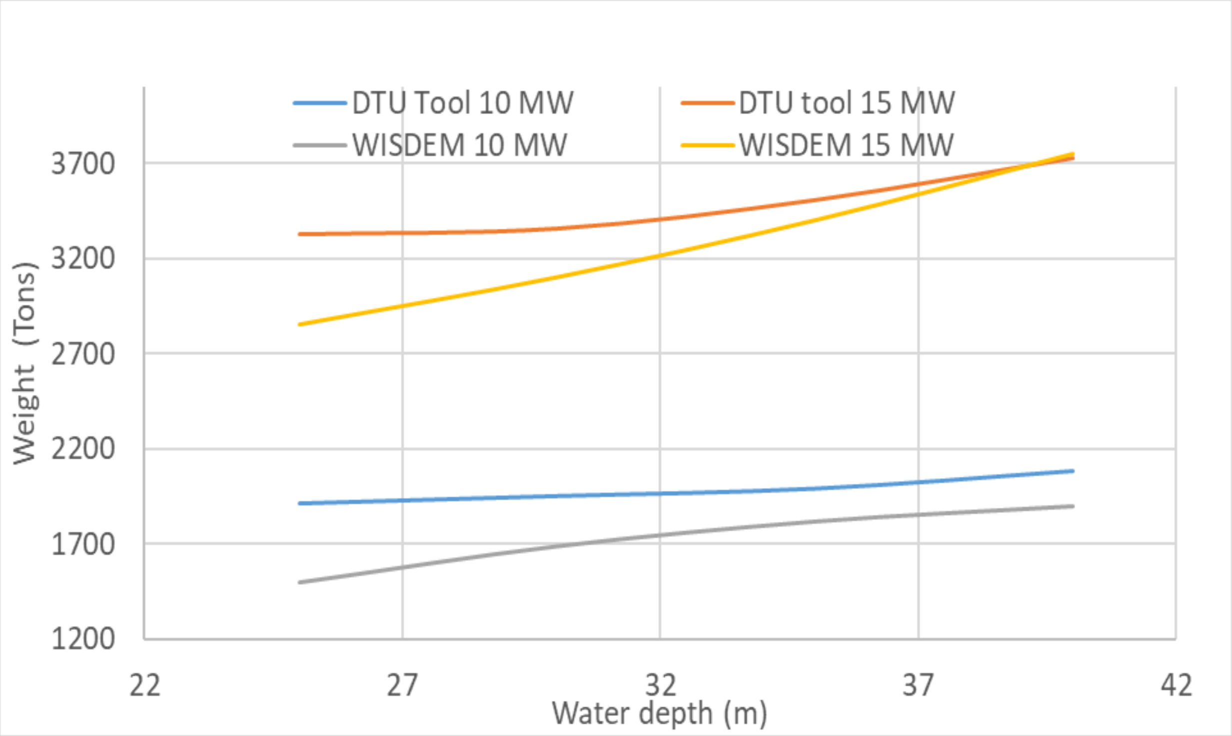


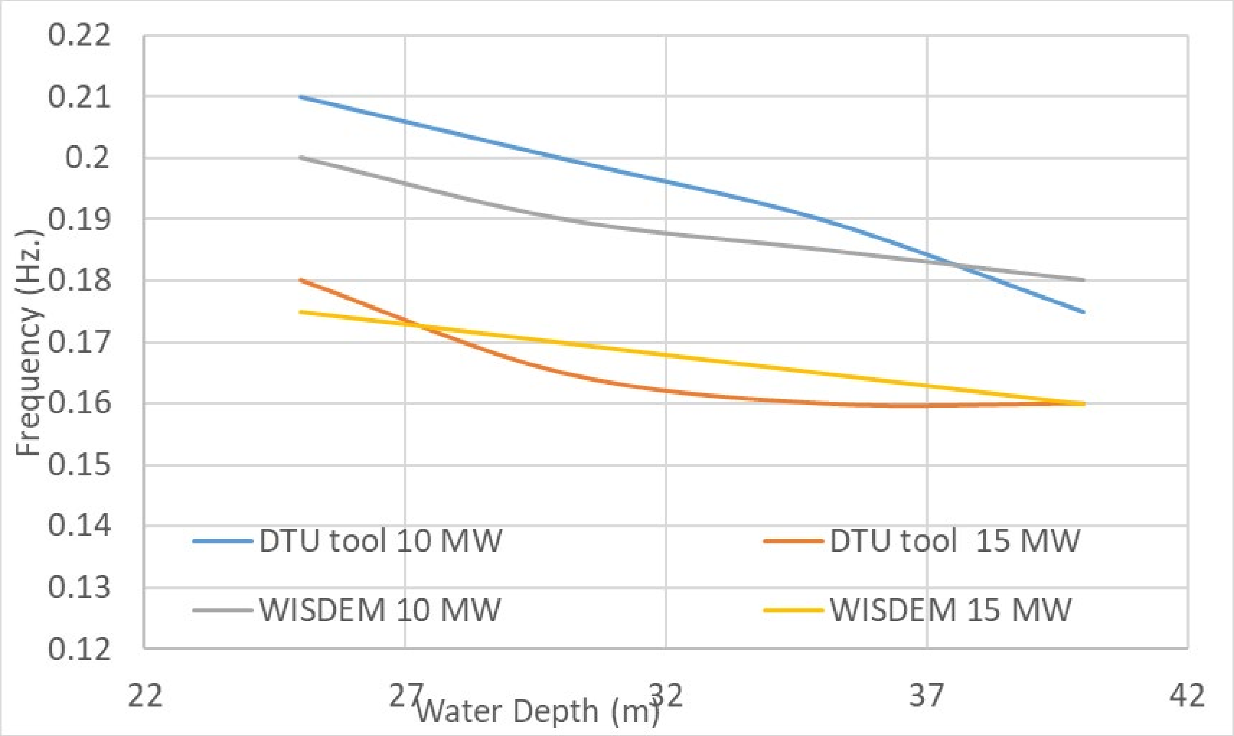
P – Rotor Speed

2P – Blade pass frequency for a 2-bladed turbine

3P – Blade pass frequency for a 3-bladed turbine

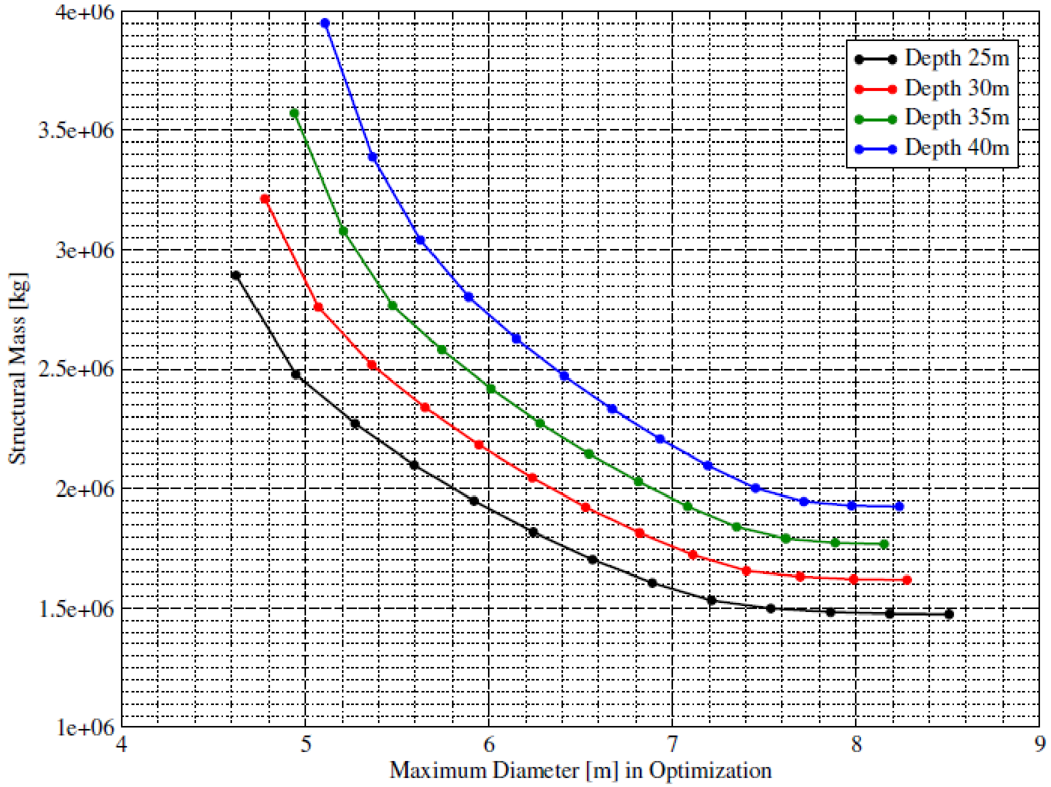
Preliminary Results from WISDEM and the DTU Opt Tool

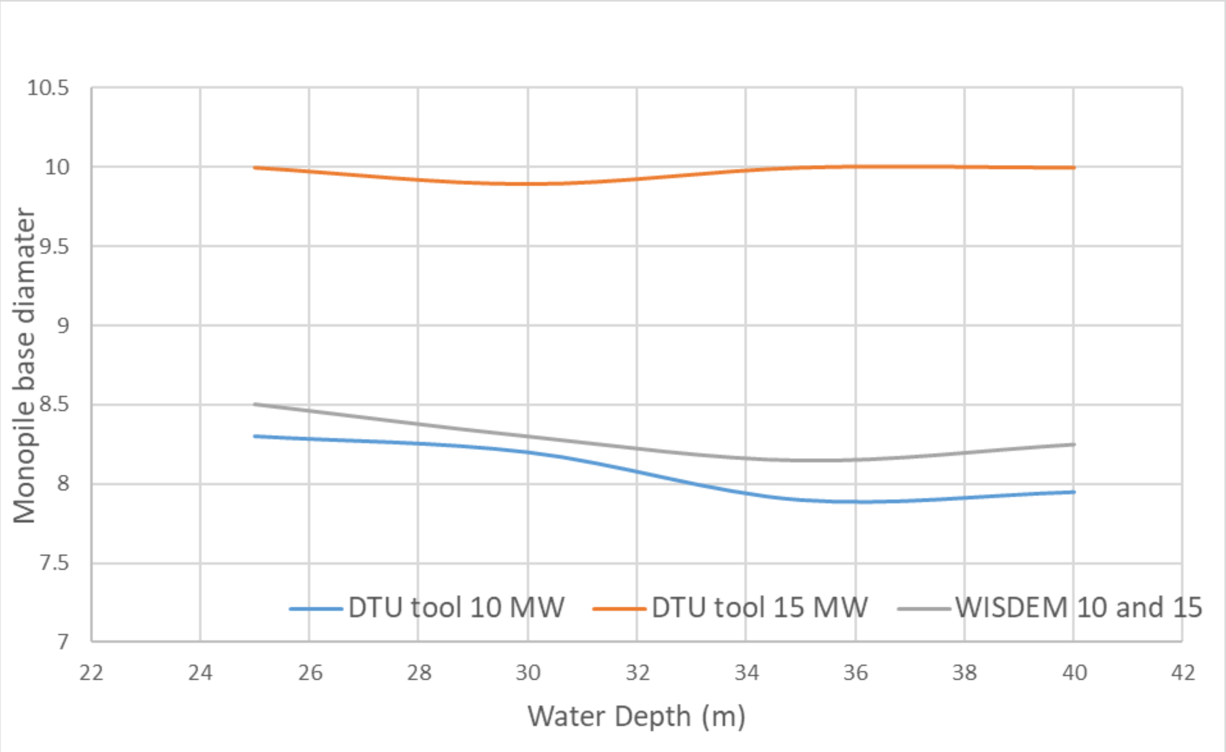




The optimization from both tools even though using different schemes and different constraints, still show very close behaviour.

Monopile mass versus base diameter





The optimization from both tools show similar trends of base diameter with water depth. While the WISDEM tool does not show change with turbine rating, the DTU tool tends to increase the monopile diameter with turbine rating, if allowed to do so.

Optimization Benefits

- Start with a valid detailed design as reference which has already been assessed to meet all limit states.
- New designs made with limited design constraints – such as natural frequency constraints, buckling limits.
- Results from two different tools with different methodologies and constraints show very similar trends on support structure mass, diameter and natural frequency.
- This implies that system level optimization (such as wind farm level substructure preliminary design) can be done with simple optimization tools.
- The resulting optimal design must be re-assessed and changed if necessary to check that all limit states are met.

Take Aways

1. The optimization enables the quick sizing of monopile diameter and reduces weight to meet wind farm manufacturing/installation requirements.

2. Can be integrated into a wider wind farm layout and cost optimization tool.

3. Two different optimization tools with different constraints and inputs converged to very similar optimal monopile designs.

4. This enables integrated design of considering the rotor nacelle assembly directly in the monopile design as opposed to de-coupled substructure design.

5. Does not require detailed aeroelastic information on the turbine that the turbine manufacturer does not wish to provide.