EERA DeepWind CONFERENCE 2024

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Mooring optimization for compliant FOWTs using an adaptive PSO with regrouping behavior

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Motivation & Goal

- Station-keeping vital for compliant FOWTs (excl. TLPs)
  - multiple lines
  - catenary, taut or semi-taut systems
  - ancillary equipment (clump weights, buoyancy elements, load-reduction devices)

  → large number of possible design variables → tedious task with large complexity

- Typical simplification:
  - limited number of variables considered + all lines restricted to one topology

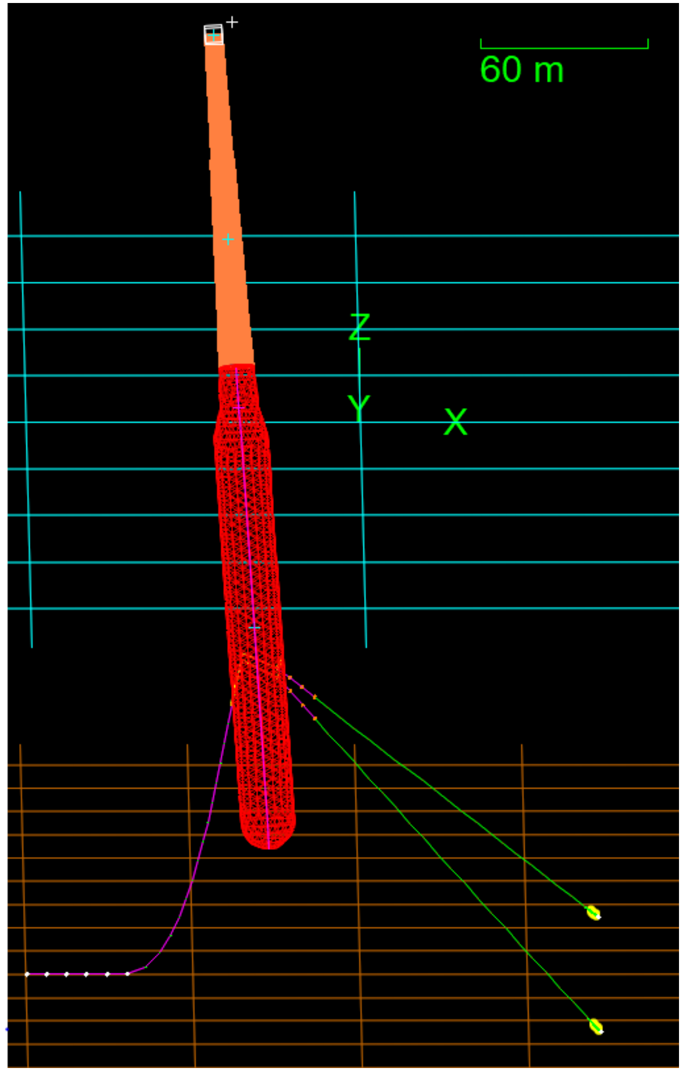
- Goals:
  - development of a fast and automatic optimization method for CAPEX minimization, using:
    - a metaheuristic to allow for high-quality and fast solutions,
    - Python for data pre- and postprocessing, and
    - OrcaFlex for the technical assessment
  - explore
    - different topologies in a single mooring system
    - semi-submersible vs SPAR structure for a 15 MW wind turbine
    - differences for different water depths
      - shallow 200m
      - deep 800m

Assumptions & Conditions

- mooring lines divided into groups
    - line in groups identical → allows allocation to different topologies

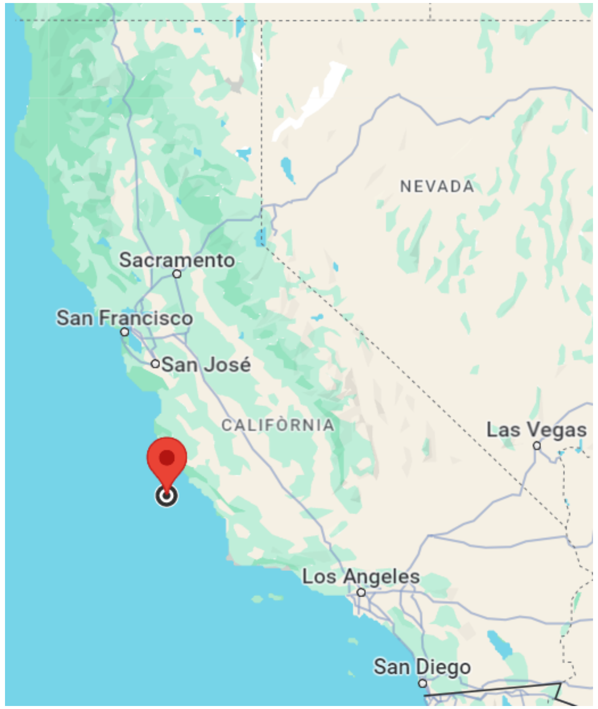
- frequency-domain assumed good enough for preliminary optimization
    - requires constant rated thrust application
    - fast computation

- most important DLCs incl. full- and half-way corrosion (4mm/year for 25 years)
    - 1.6 (ULS)
        - consequence class I (ST-0119)
        - safety factor for frequency to time-domain (derived from OS-E301)
    - 1.2 (FLS)

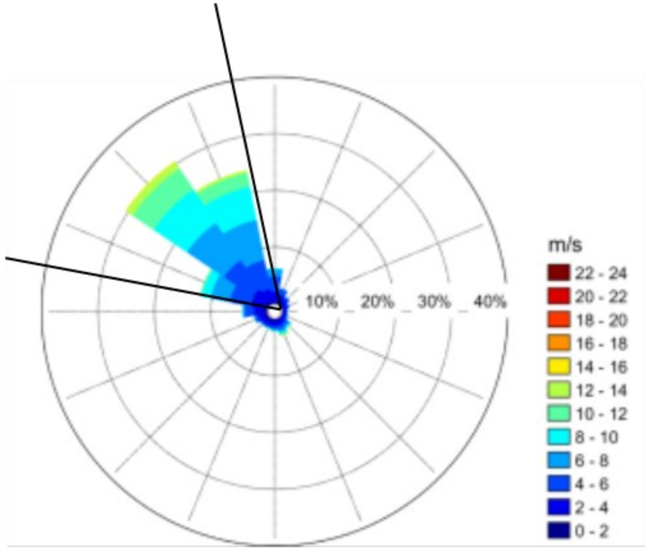


Assumptions & Conditions

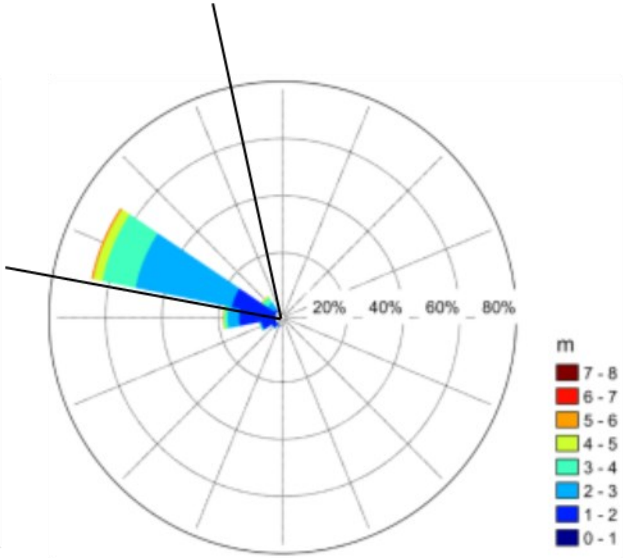
- Environmental conditions
  - irregular sea state via JONSWAP spectrum
  - co-alignment of wind, wave and current applied at 0º & 30º
    - symmetry → assessment valid for a 60º span



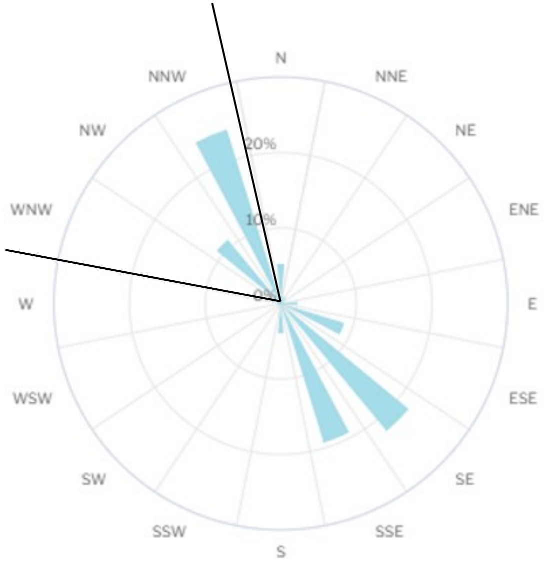
Morro Bay Wind Area



Wind rose



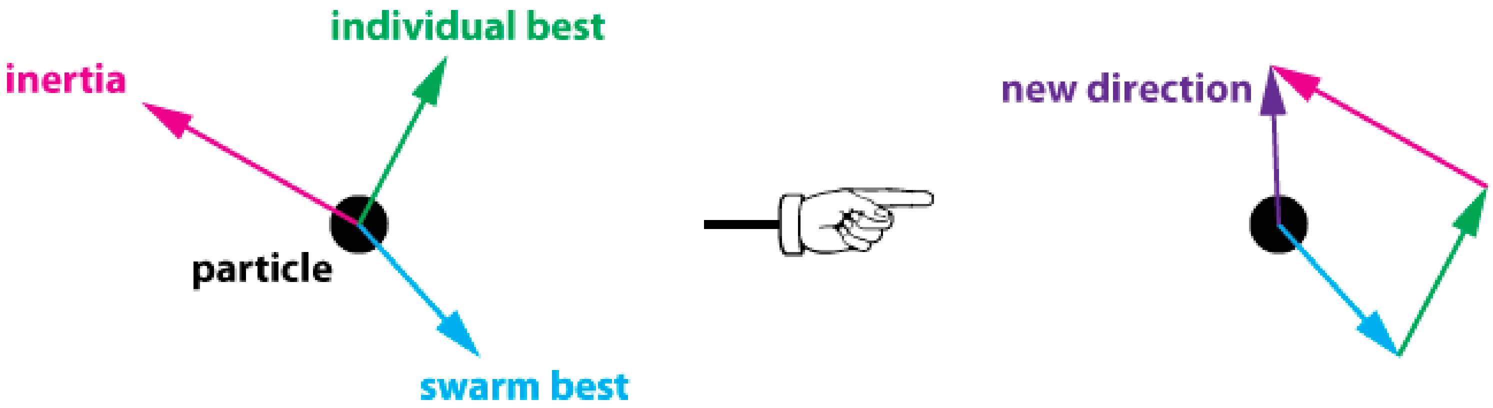
Wave rose



Current rose

Implementation

- adaptive PSO with regrouping behavior
  - adaptive: PSO characteristics are adapted to lead to convergence and exploitation

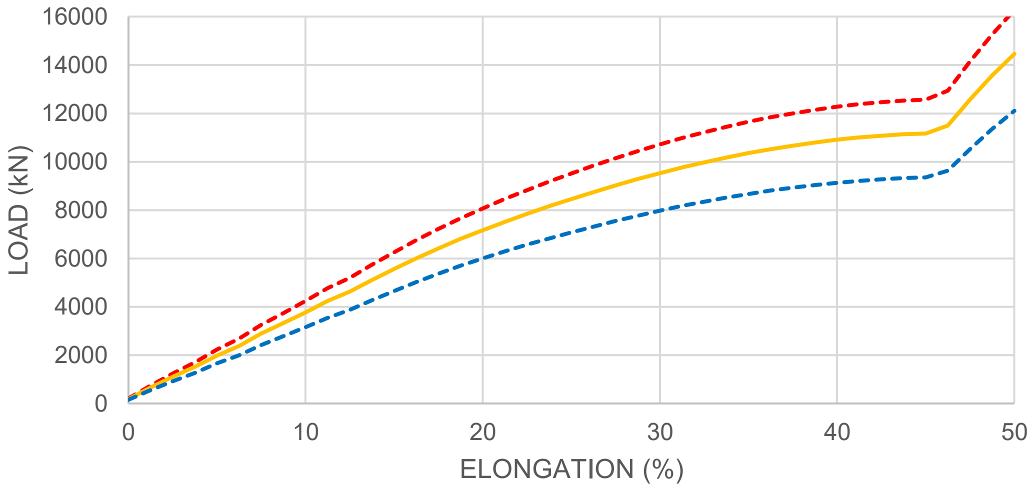


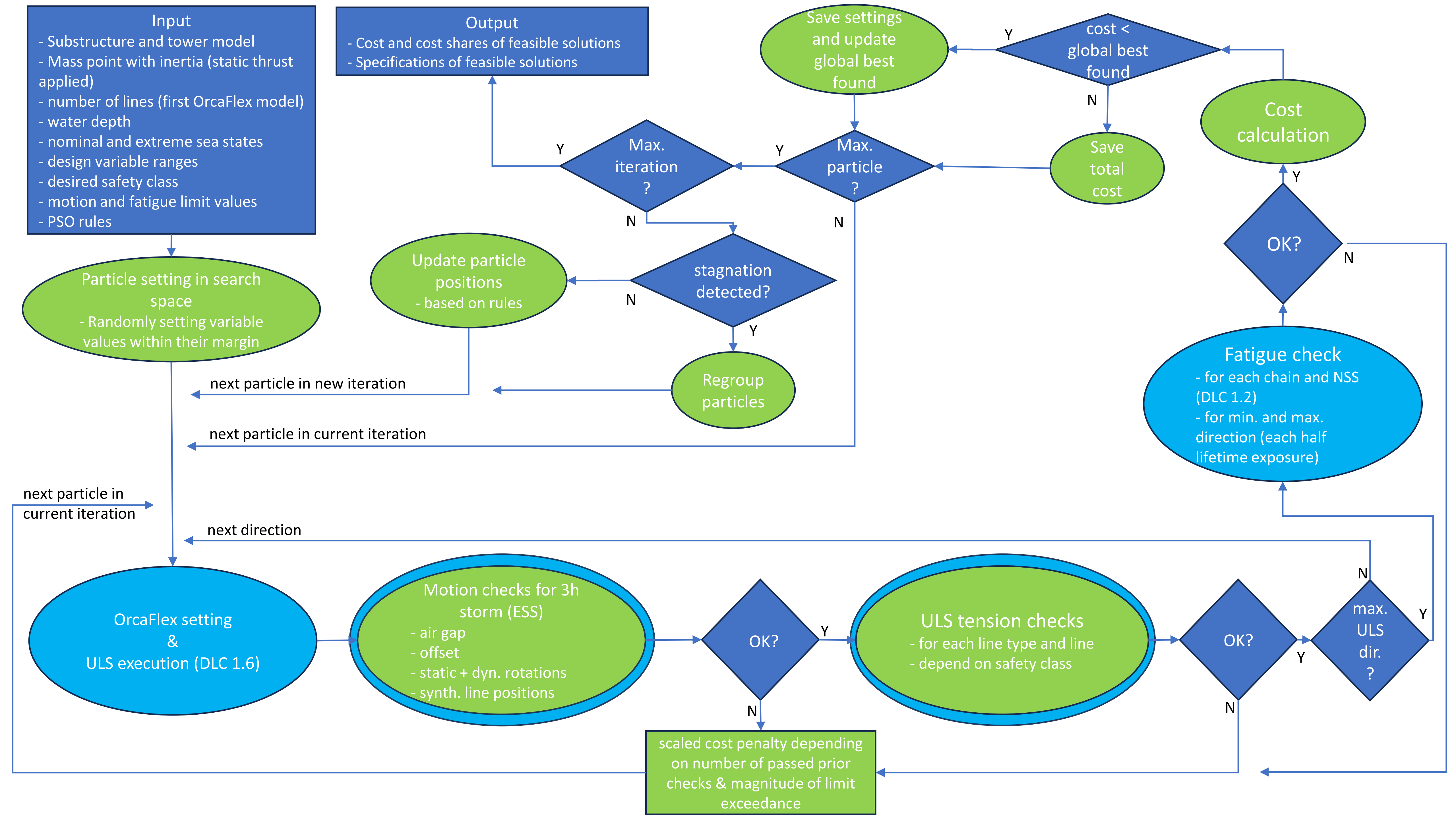
  - regrouping of particles (solutions) in case no new best solution is found over iteration threshold

- applied to
  - VolturnUS semi: Orcina example
  - WindCrete SPAR: self-built model validated with OpenFAST

Implementation

- Design variables per line group
  - anchor radius
  - spread angles
  - total line length
  - line section lengths and diameters
    - bottom chain (studless)
    - fiber rope/wire
    - forerunner chain (studless)
  - fiber/wire rope material
    - polyester, nylon, steel spiral wire
  - number, class and position of
    - buoyancy elements
    - clump weights
    - load-reduction devices (LRDs)
      - variable axial stiffness
      - shock absorber
      - can be helpful for mitigating fatigue and extreme loads




Input
- Substructure and tower model
- Mass point with inertia (static thrust applied)
- number of lines (first OrcaFlex model)
- water depth
- nominal and extreme sea states
- design variable ranges
- desired safety class
- motion and fatigue limit values
- PSO rules
Output
- Cost and cost shares of feasible solutions
- Specifications of feasible solutions
Save settings and update global best found
cost < global best found
Y
N
Cost calculation
Save total cost
Max. particle ?
Max. iteration ?
Y
N
Particle setting in search space
- Randomly setting variable values within their margin
Update particle positions
- based on rules
stagnation detected?
Regroup particles
OK?
Fatigue check
- for each chain and NSS (DLC 1.2)
- for min. and max. direction (each half lifetime exposure)
next particle in new iteration
next particle in current iteration
next particle in current iteration
next direction
OrcaFlex setting & ULS execution (DLC 1.6)
Motion checks for 3h storm (ESS)
- air gap
- offset
- static + dyn. rotations
- synth. line positions
ULS tension checks
- for each line type and line
- depend on safety class
max. ULS dir. ?
scaled cost penalty depending on number of passed prior checks & magnitude of limit exceedance

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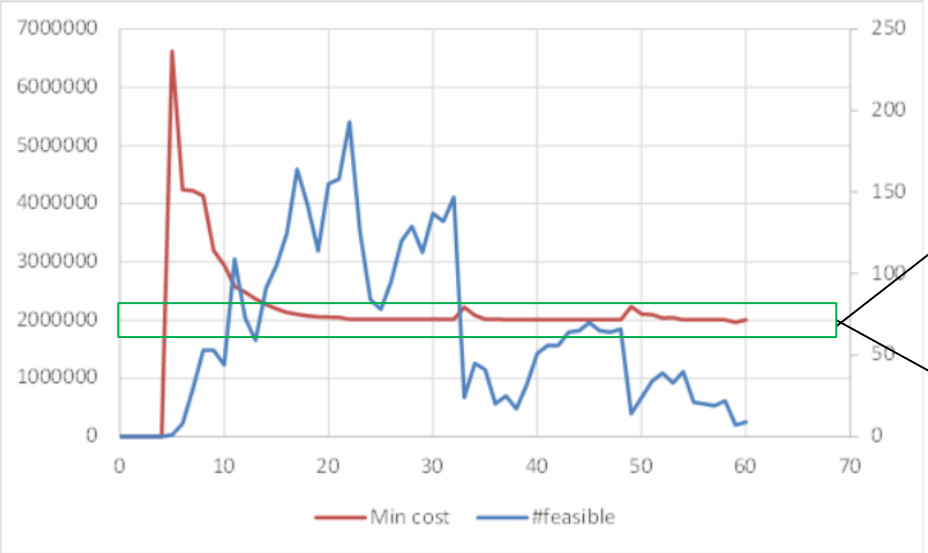
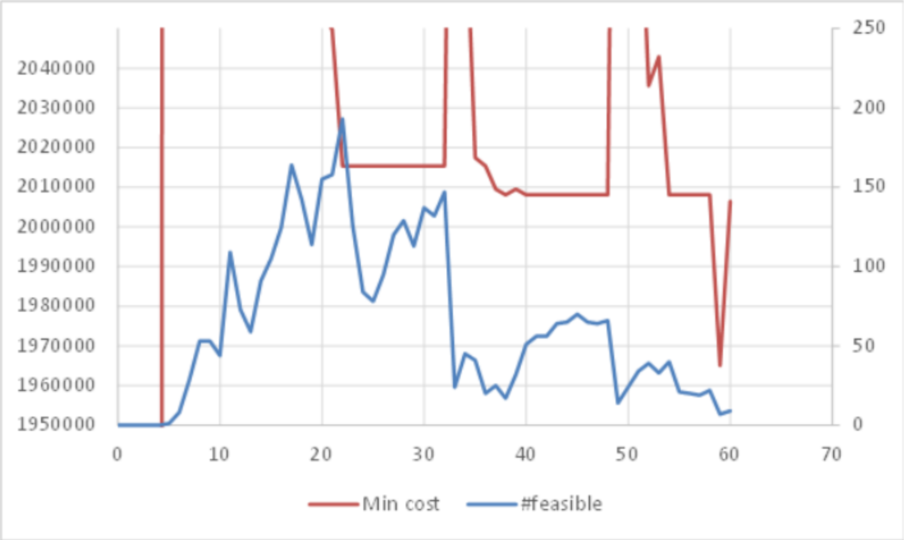
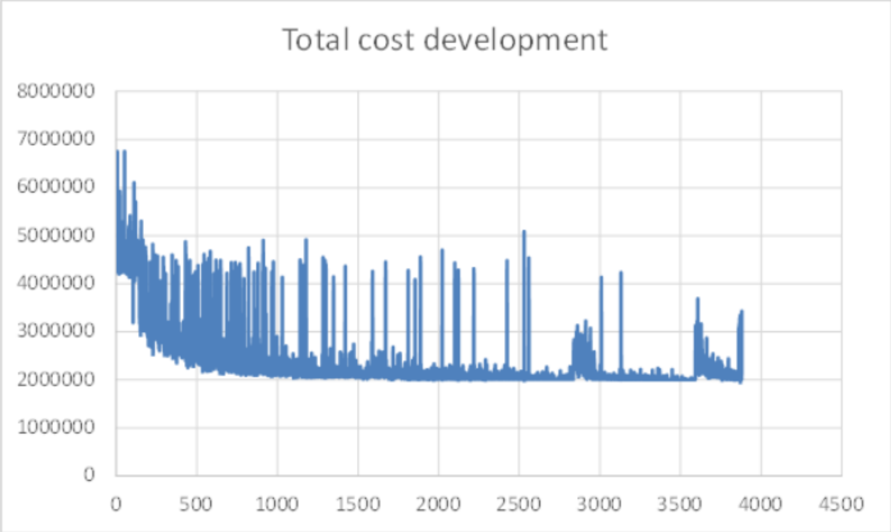
Performance of optimizer (example)

- VolturnUS: 3 lines 2 upwind (800m) (400p, 60 it., 10 regr.)





2x Regrouping!



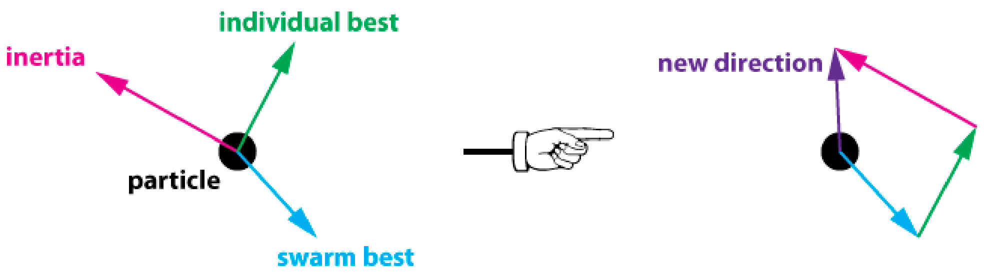
Typical behavior observed:

- Ultimate solution found is often similar to solution found around 1/3 of progress

Performance of optimizer (solution approach)

- include initial valid solution to guide the optimization

- set PSO characteristics to allow for more search space exploration
  - ↑ inertia (how strictly does particle follow its own path)
    - 0.95 → 0.99 (< 1; avoids explosion)
  - ↑ cognitive (how much influence does personal best have)
    - 1.4 → 1.7
  - ↓ social (how much influence does global best have)
    - 1.5 → 1.0



Benchmark vs. obtained results

- 2022 Corewind Project D2.3 – "Exploration of innovations and breakthroughs of station keeping systems for FOWT"
  - optimized mooring system incl. LRDs
  - main differences to PSO
    - among others used DLC 6.1 & 6.2 in time domain
    - used materials are fixed
    - deterministic optimization
    - similar cost functions and constraints

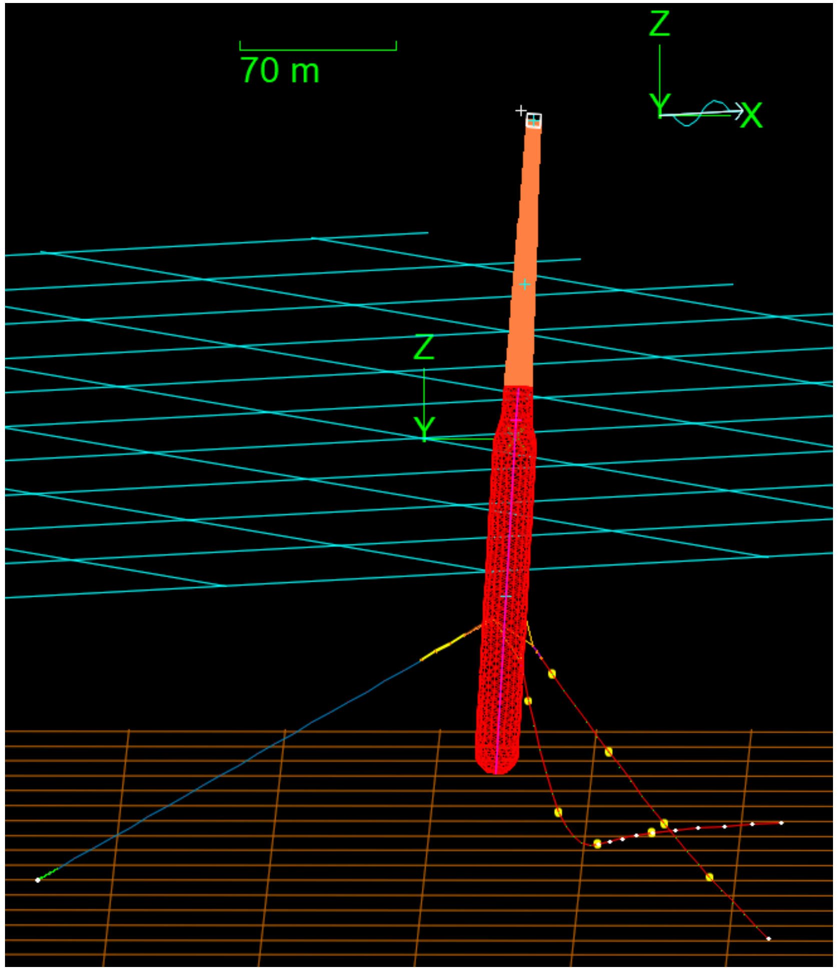
Structure	200m (Gran Canaria)	870m (Morro Bay)
"ActiveFloat" SEMI	713k € 864k €	2 220k € 1 494k €
"WindCrete" SPAR	814k € 634k €	1 529k € 1 153k €

results in same order of magnitude (and even lower)

Preliminary results – SPAR – 200m – 634k €

- 1 upwind mooring line
  - taut
    - top chain 9565kN MBL (~ x2)
    - LRD 1000kN x 3 / x2 → no static convergence
    - Nylon 12062kN MBL @ 240mm
    - bottom chain 10753kN MBL
    - suction anchors

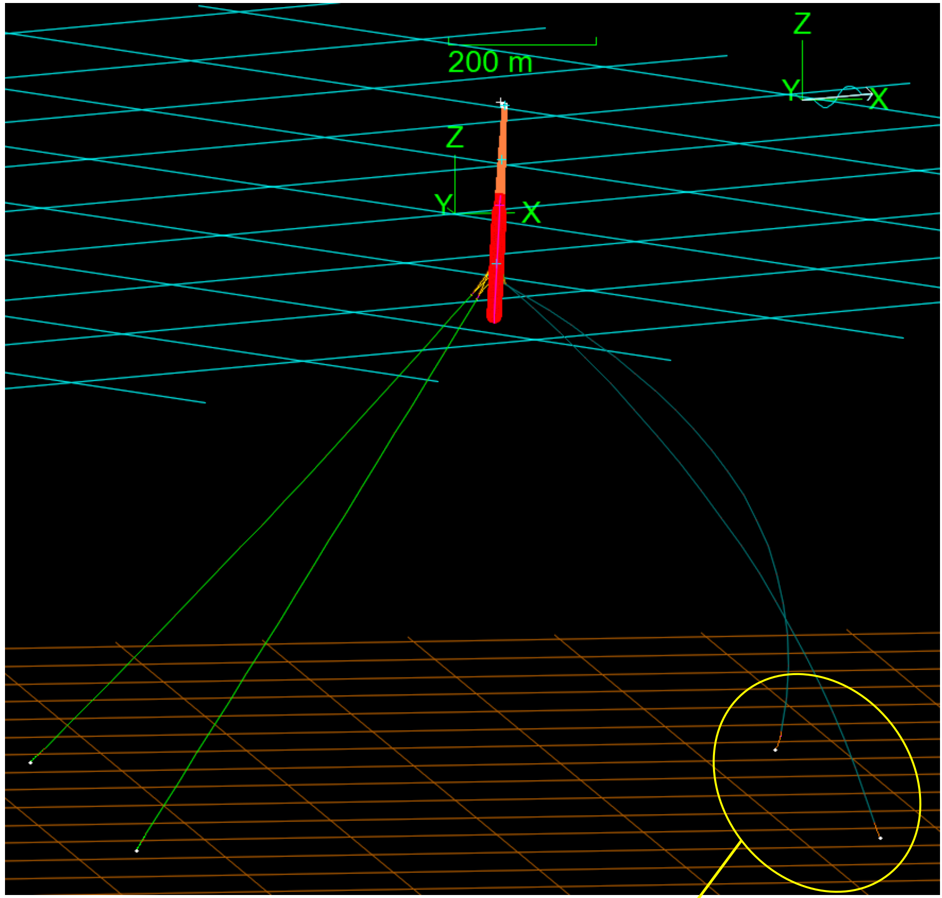
- 2 downwind mooring lines
  - “catenary” taut
    - top chain 4621kN MBL (~x2)
    - LRD 1000kN x 2 / x1 → yaw violation
    - bottom chain 4621kN MBL
      - clump weights 4 x 3t / x3 → fatigue issue
    - suction anchors



Preliminary results – SPAR – 800m – 1 153k €

- 2 upwind mooring lines
  - taut
    - top chain 6745kN MBL (~ x2)
    - LRD 1000kN x 1 / x0 → higher BC grade → + 23k €
    - Polyester 13514kN MBL @ 216mm / 214mm → offset violation!
    - bottom chain 10574kN MBL
    - suction anchors

- 2 downwind mooring lines
  - "light" taut
    - top chain 18876kN MBL (~x2) @ 172mm / 167mm → fatigue issue!
    - Nylon 2461kN MBL
    - bottom chain 4621kN MBL
    - suction anchors



extremely large uplift angle

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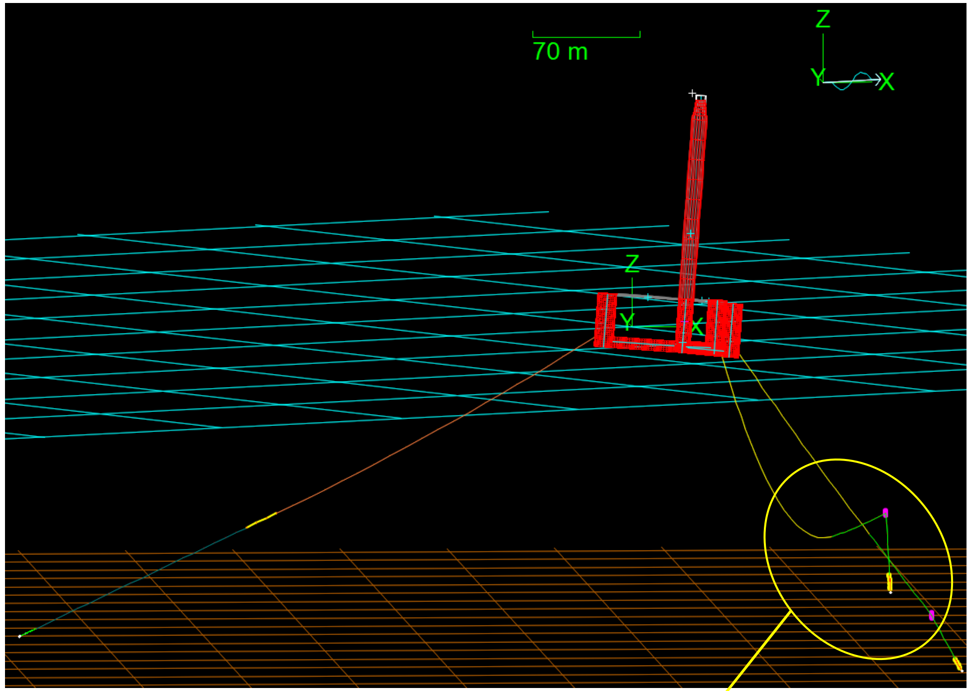
Preliminary results – Semi – 200m – 864k €

- 1 upwind mooring line
  - taut
    - top chain 13085kN MBL
    - LRD 1000kN x 3
    - Nylon 12062kN MBL
    - bottom chain 13085kN MBL @ 137mm / 132mm → fatigue
    - suction anchors

- 2 downwind mooring lines
  - semi-taut
    - top chain 5454kN MBL
    - Nylon 9807kN MBL @ 216mm / 192mm → pitch vio.
      - Buoys 9t x 1 / 6t → works well / 3t → fatigue of BC
    - bottom chain 5490kN MBL
      - clump weights 3t x 4 / 3t x 1 → fatigue of BC
    - suction anchors



large line bending

- Together
  - THICKER BC, 3t x 1 buoy, no weights → works well (835k €) + thinner Nylon → offset violation

→ tedious task of mooring optimization

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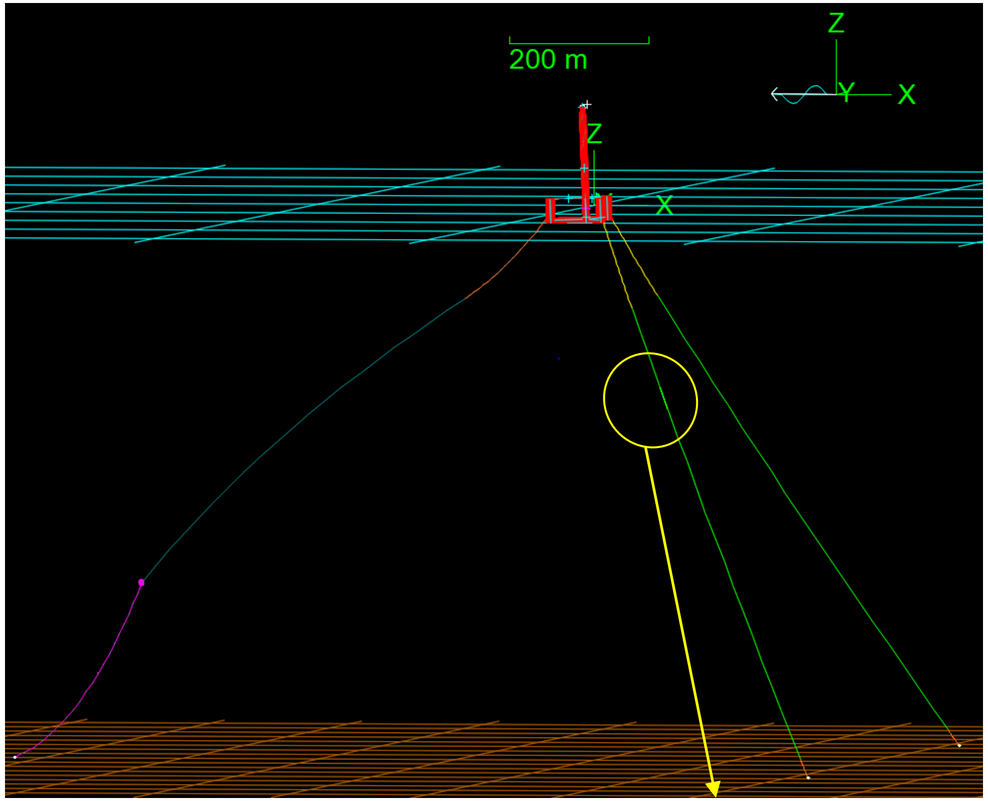
Preliminary results – Semi – 800m – 1 494k €

- 2 upwind mooring lines
  - taut
    - top chain 13887kN MBL
    - Polyester 19777kN MBL @ 258mm / 252mm → offset violation
    - bottom chain 13085kN MBL
    - suction anchors

- 1 downwind mooring line
  - semi-taut
    - top chain 4621kN MBL
    - Nylon 12062kN MBL @ 240mm / 192mm→ works
      - Buoys 3t x 1 / no buoy → offset violation
    - bottom chain 4621kN MBL
    - suction anchors



Line foldback
→ adjustable with larger system damping parameters
→ offset violation
→ longer upwind BC

Critics

- frequency-domain
  - known ULS load underestimation
  - inaccuracy of fatigue loads due to static thrust application
  - bigger WTs more wind-driven
- computational time
  - running 7 scripts in parallel on older PC
    - 64bit, i5 Processor, Windows 10, 3.3GHz, 8GB RAM

    → 1 week/water depth
- limited directionality & co-alignment of environmental forces
- missing considerations & constraints:
  - marine growth
  - line bending, uplift angles
  - false positive static convergence
  - RNA accelerations
  - resonances
  - …

Conclusion & Outlook

- developed tool good for preliminary design
- explored potential of having different line topologies in one mooring system
- Next steps:
  - verification of results via coupled time-domain simulations
  - exploration of PSO parameters to achieve better/faster performance
  - working with fully-coupled time-domain simulations → AI training
  - extension to shared mooring systems

Takk!

Questions and comments?

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