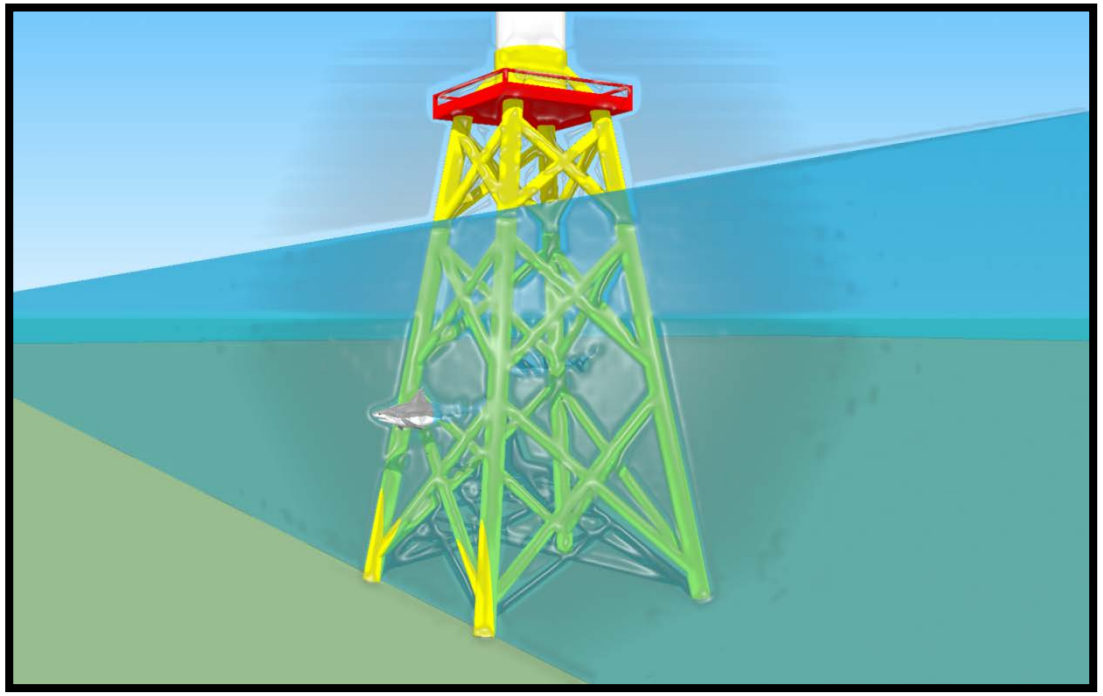
Integrated design optimization of jackets and foundations for offshore wind turbines



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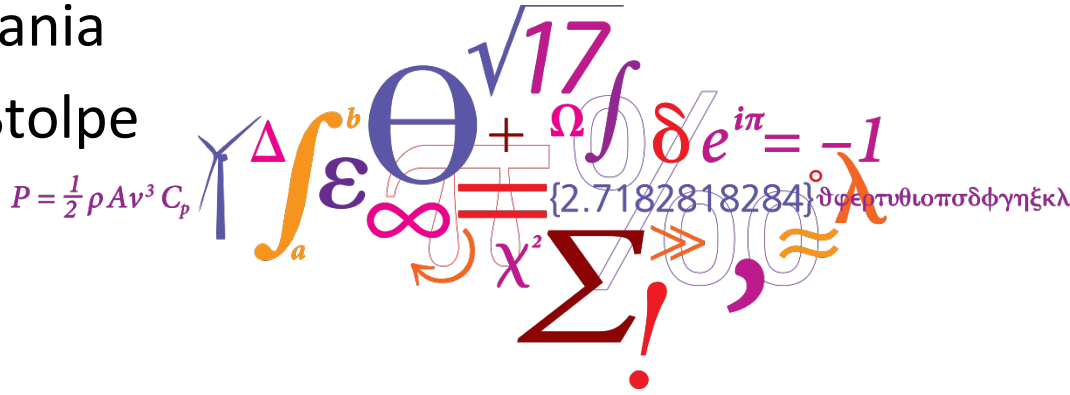
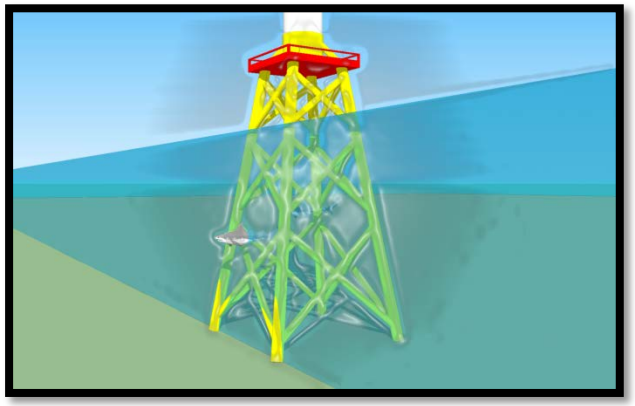


ABYSS – *Advancing BeYond Shallow waterS*
funded by Innovation Fund Denmark

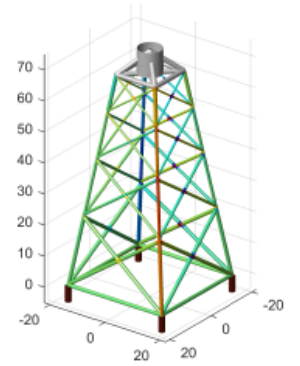
DTU Wind Energy
Department of Wind Energy

This is how optimization can become a valuable tool for structural engineers in offshore wind

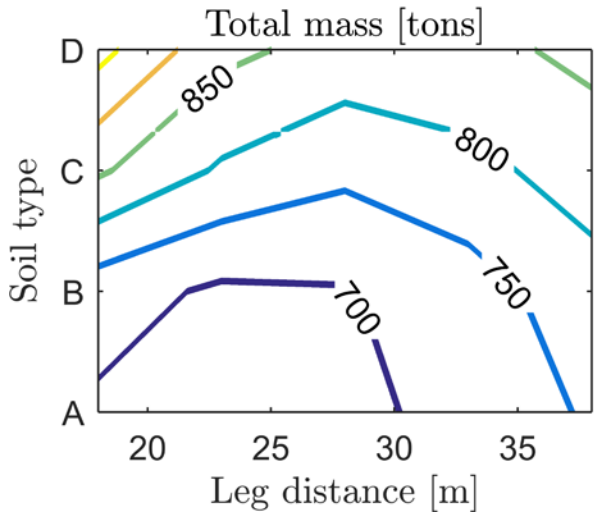


Design considerations

$$\begin{aligned} \text{minimize} \quad & f(\boldsymbol{x}) \\ \text{subject to} \quad & \boldsymbol{A}\boldsymbol{x} - \boldsymbol{b} \leq \boldsymbol{0} \\ & \underline{\boldsymbol{\sigma}} \leq \boldsymbol{\sigma}(\boldsymbol{x}) \leq \overline{\boldsymbol{\sigma}} \\ & \underline{\boldsymbol{\omega}} \leq \boldsymbol{\omega}(\boldsymbol{x}) \leq \overline{\boldsymbol{\omega}} \end{aligned}$$



Optimal design problem



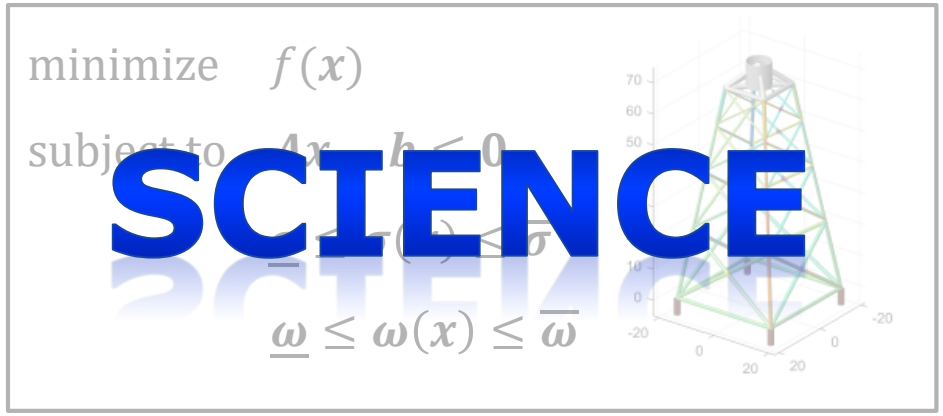
Design trends

This is how optimization can become a valuable tool for structural engineers in offshore wind

ENGINEERING

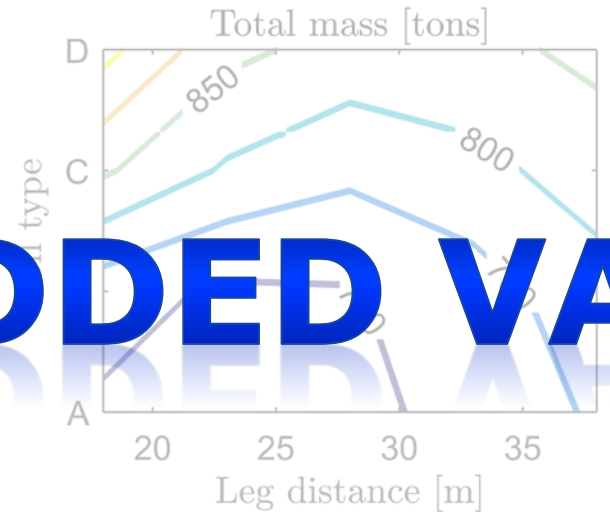
Design considerations

SCIENCE



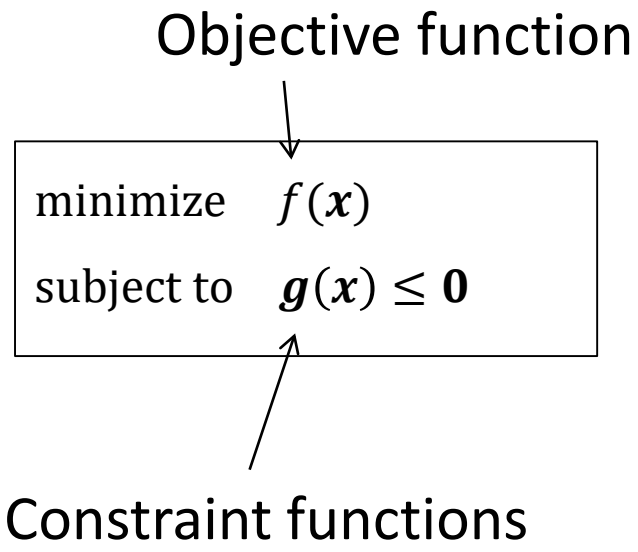
Optimal design problem

ADDED VALUE



Design trends

How to formulate a numerical optimization problem:
Let *x* be a vector of variables, where we want to minimize *f*(*x*)



How to design a jacket and its foundation with optimization: Let *x* describe the design, *f*(*x*) the cost, and *g*(*x*) the engineering limits

Cost ≈ Jacket + foundation mass

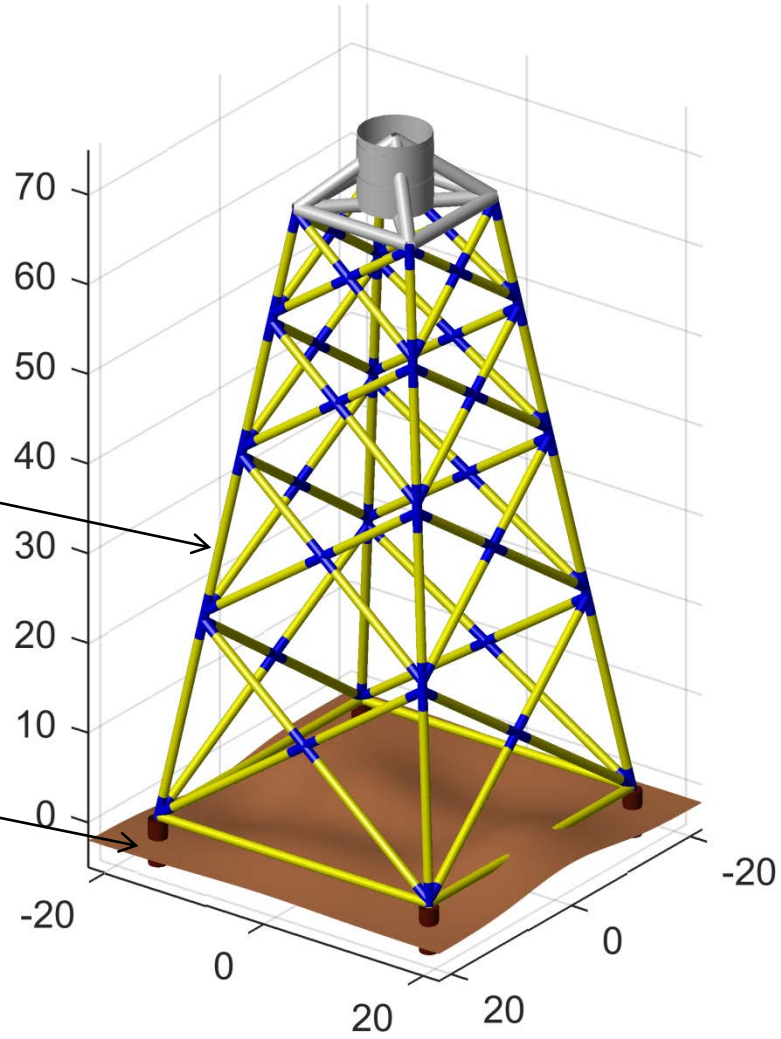
$$\begin{aligned} &\text{minimize} && f(\boldsymbol{x}) \\ &\text{subject to} && \boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0} \end{aligned}$$

Engineering limits:

1. Fatigue limit state
2. Ultimate limit state
3. Soft-stiff frequency range

$\boldsymbol{x}$ = design variables:

1. Diameters & wall thickness
2. Diameters, wall thickness, & length

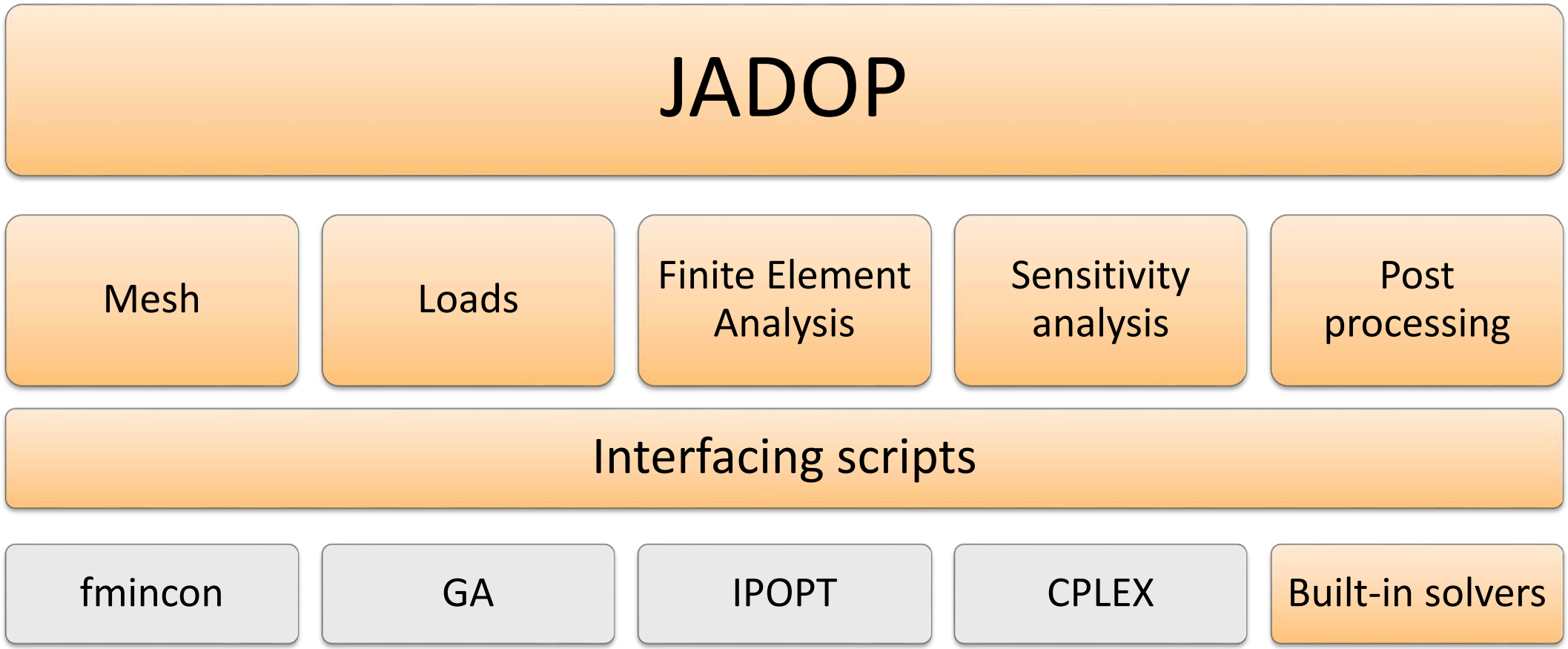


The optimization problem has very few design variables, but a high number of nonlinear constraints

$$\begin{aligned} &\text{minimize} && f(\boldsymbol{x}) \\ &\text{subject to} && \boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0} \end{aligned}$$

- 24 design variables for the jacket
- 3 design variables for the foundation
- 7k constraints for each static load
  - Stress along all tubular welds
  - Shell buckling & column buckling
  - Foundation capacity
- 2 frequency constraints

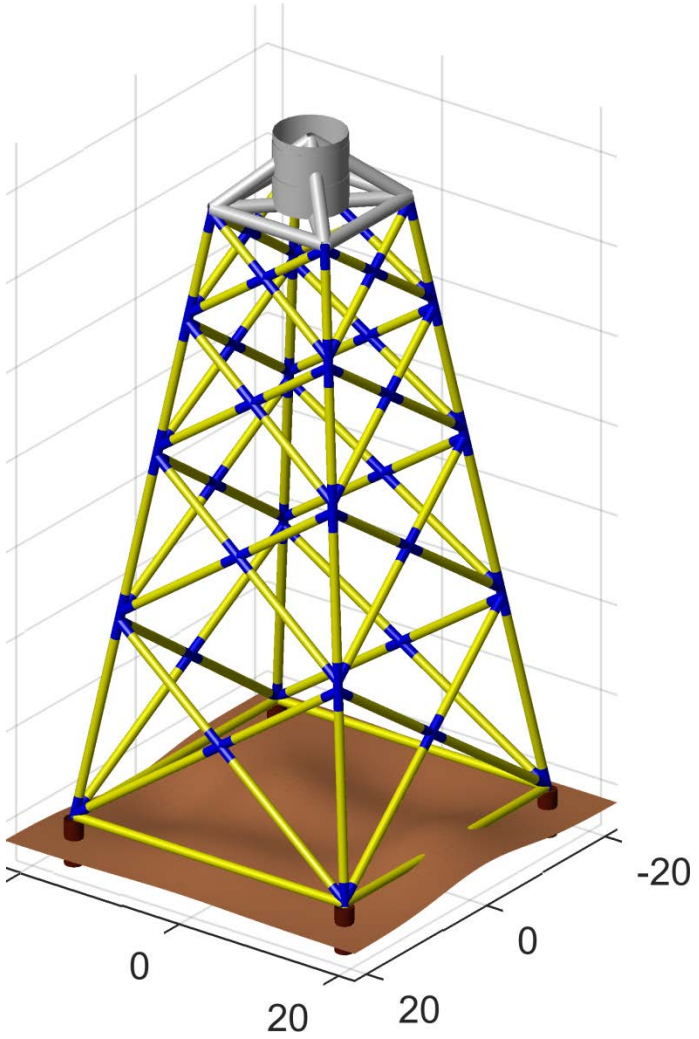
The problem is implemented in the special purpose software JADOP (Jacket Design Optimization)



We make assumptions in the structural analysis which are suitable for the conceptual design phase

- **Timoshenko beam elements** for the support structure
- **Linear 6-dof response** for each foundation
- **4 Damage equivalent loads** for the fatigue limit state
- **3 Extreme static loads** for the ultimate limit state
- **Conservative analysis** of column buckling
- **Stress concentration factors** in welded tubular joints

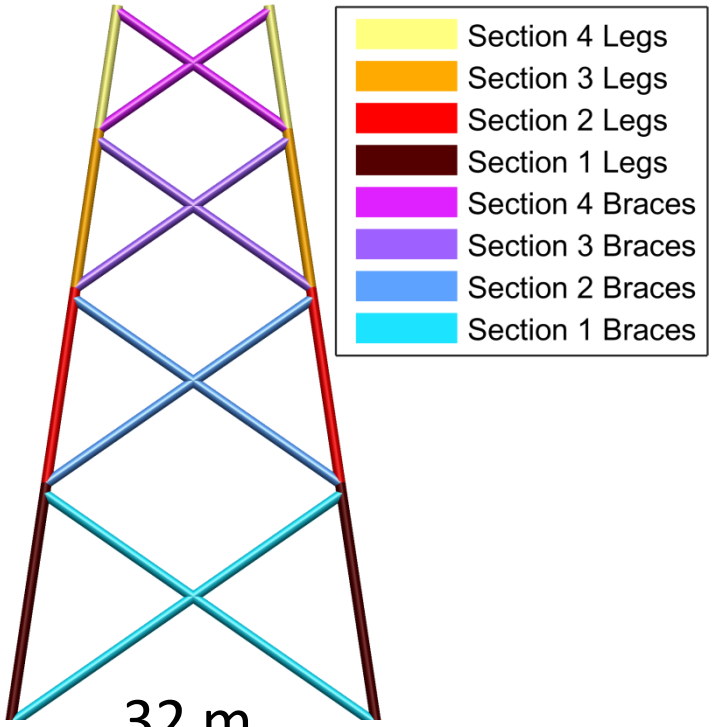
<u>No safety factors are applied in the following examples</u>

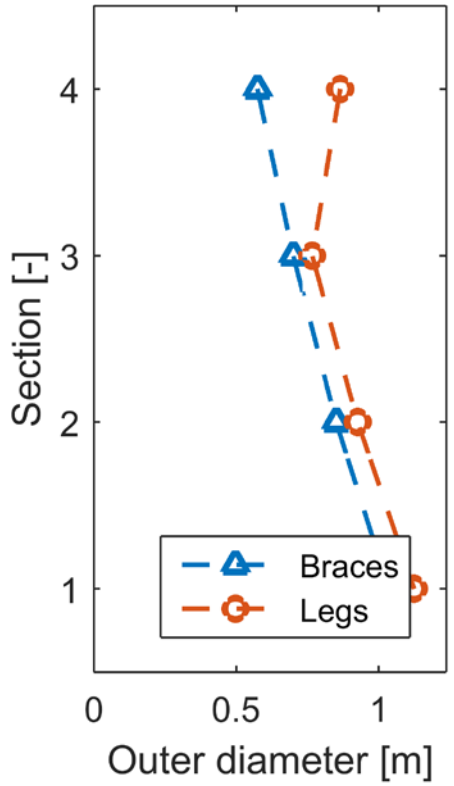


For a given design problem (10 MW turbine, 50 m depth, piles), the total mass was minimized to 631 tons (in 5 minutes on a laptop)

Jacket

Mass: 491 tons





Piles in sand

Diameter: 1.41 m

Length: 50 m

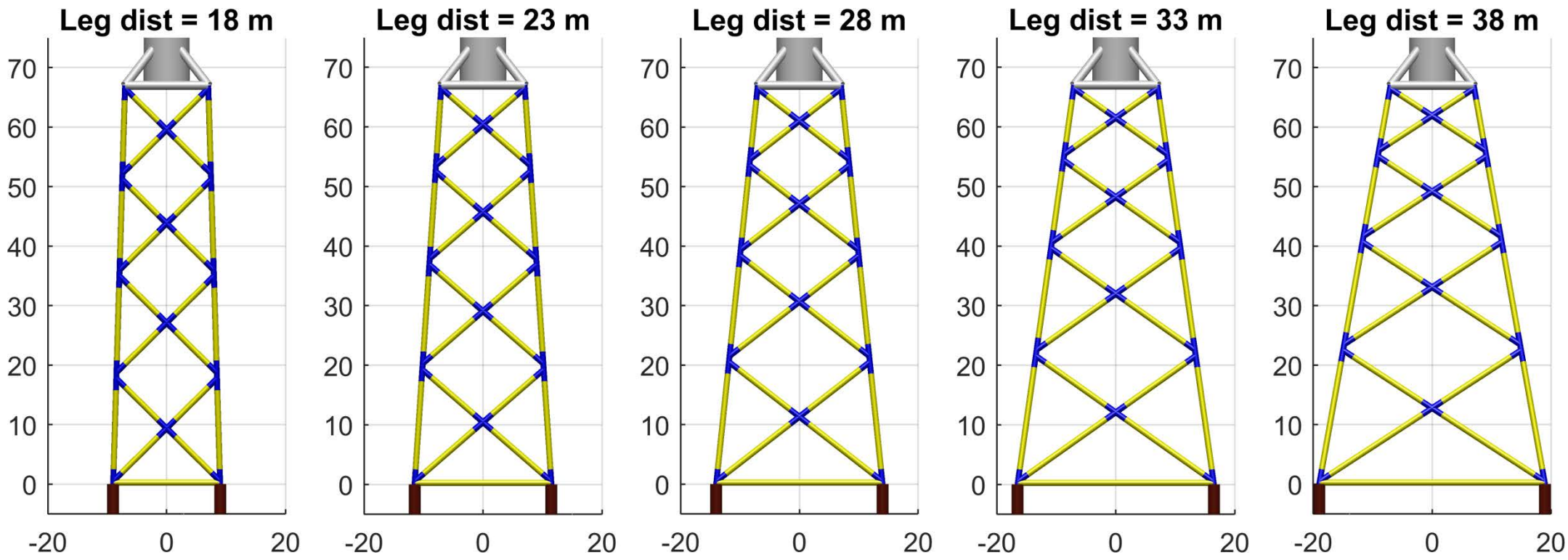
Mass: 140 tons

Soil: Medium stiff sand

Foundation: Piles

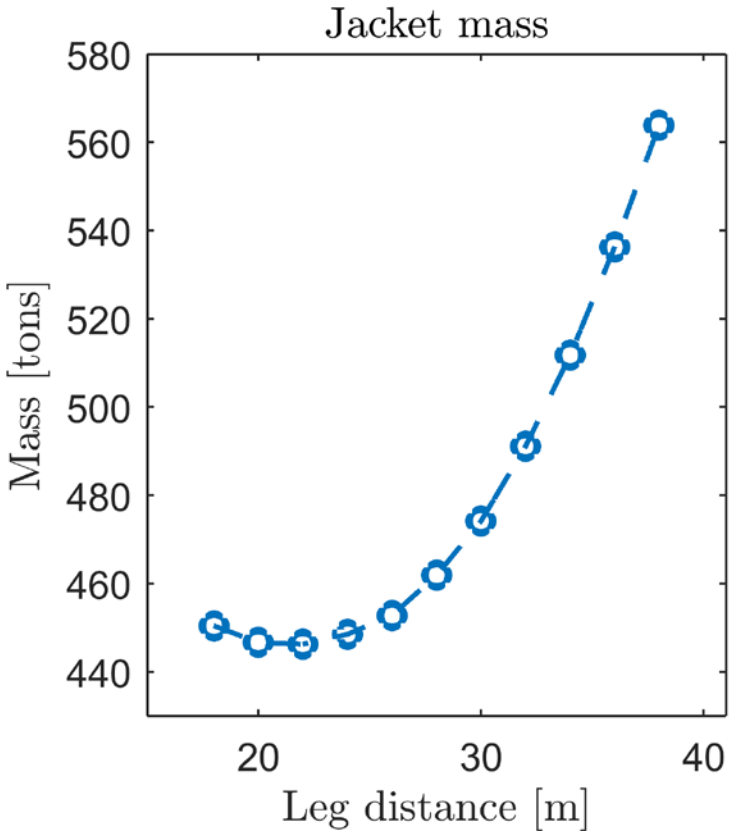
Design procedure: API

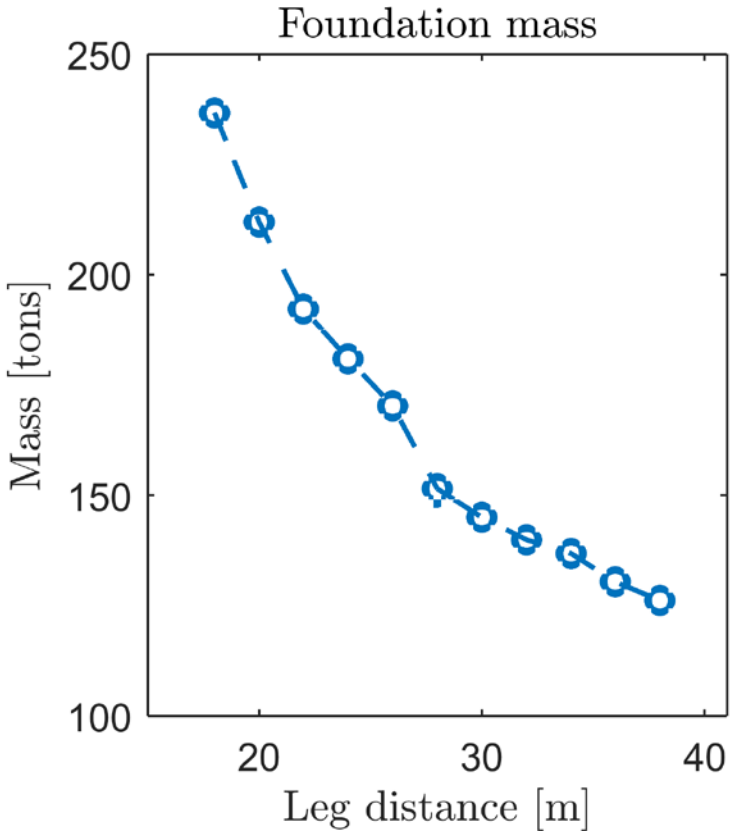
JADOP has a parameterized mesh which makes it a quick task to modify for example the leg distance

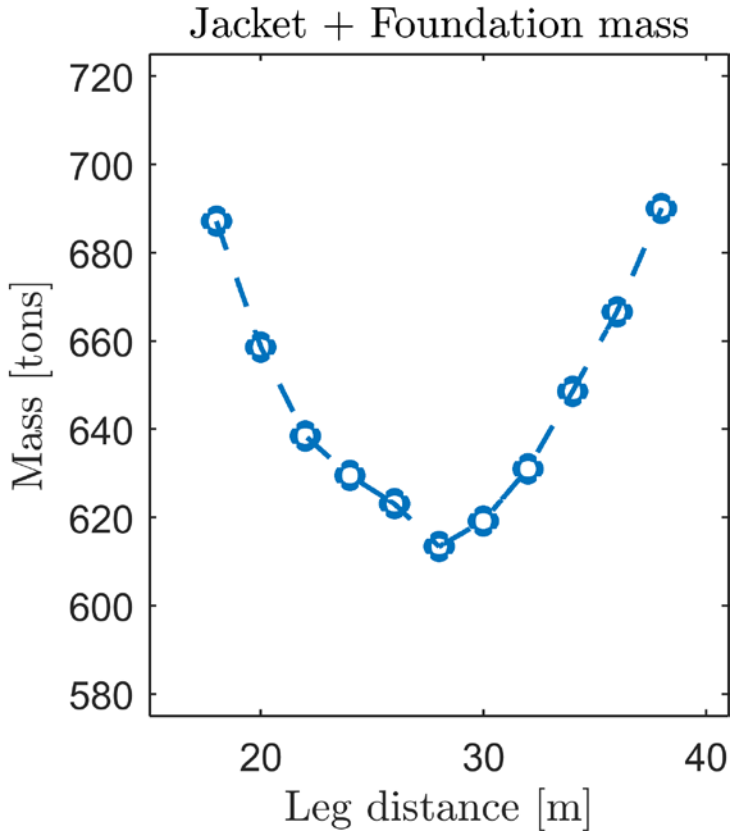


When support structures with different leg distance are optimized, jacket mass and foundation mass show opposite design trends

Medium stiff sand

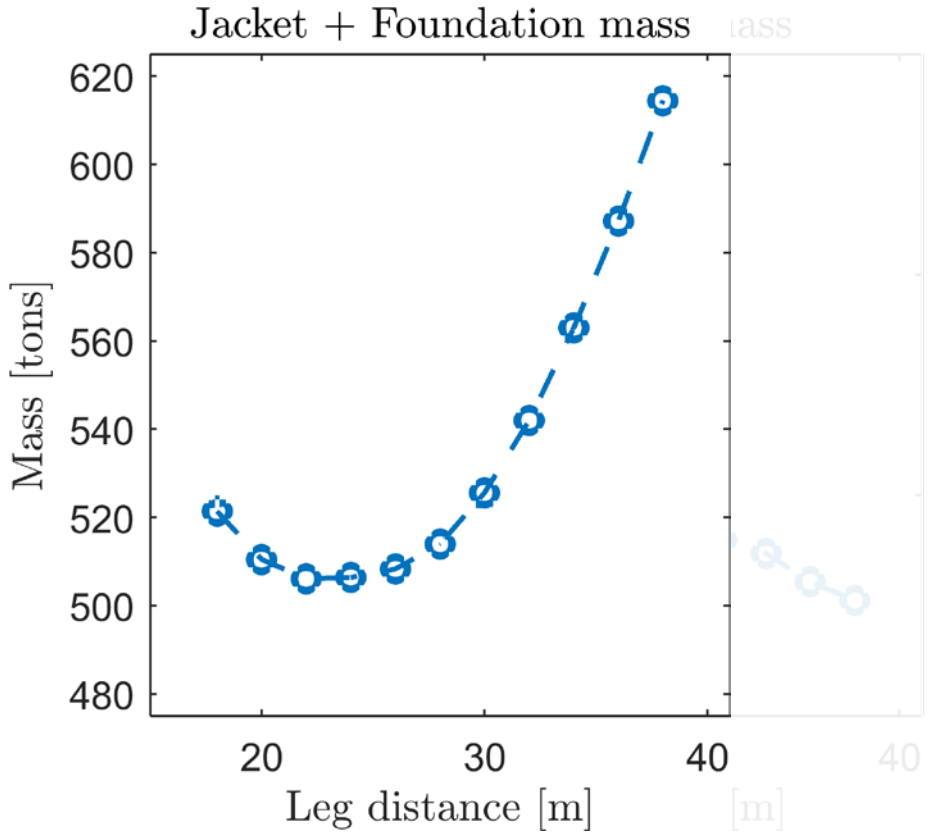




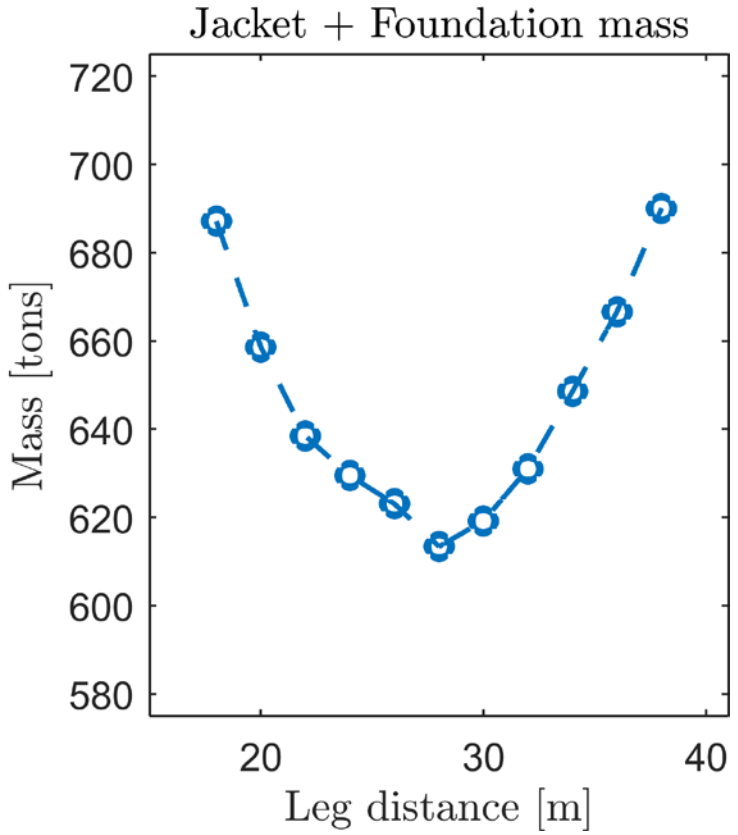


The optimal leg distance will depend on for example the soil stiffness

Very stiff sand



Medium stiff sand

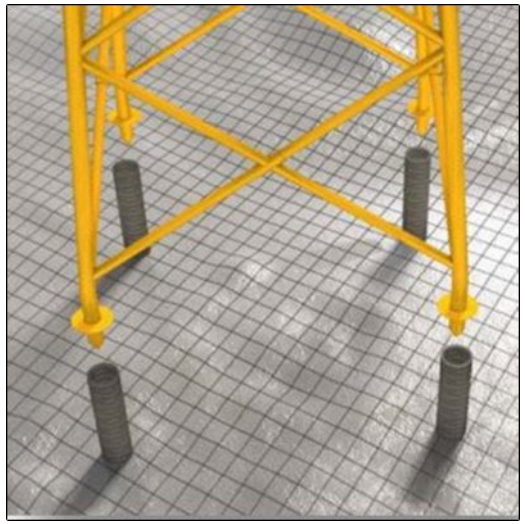


But several other aspects of the anchoring will also influence the design problem

We have looked at:

- Piles & suction caissons
- Sand & clay
- Varying soil stiffness
- Different design procedures for piles

Piles

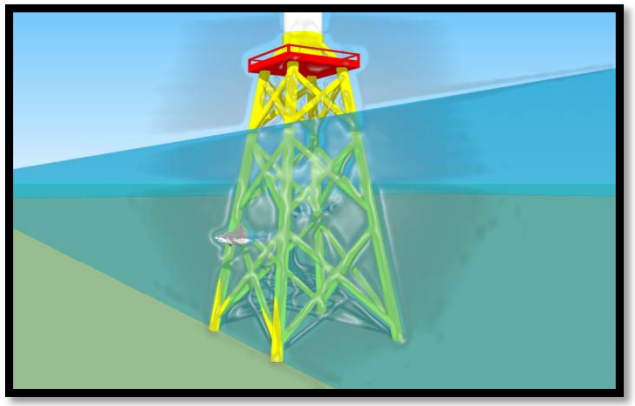


Source: 4coffshore

Suction caisson

Source: SPT Offshore

The design considerations are “translated” into an optimization problem, and it is now a quick task to generate design trends



Design considerations

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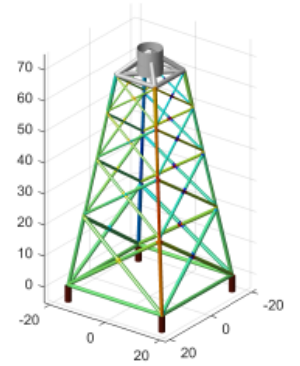
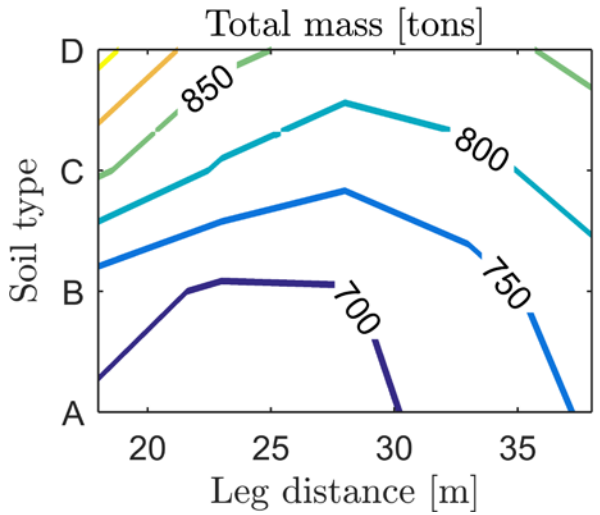
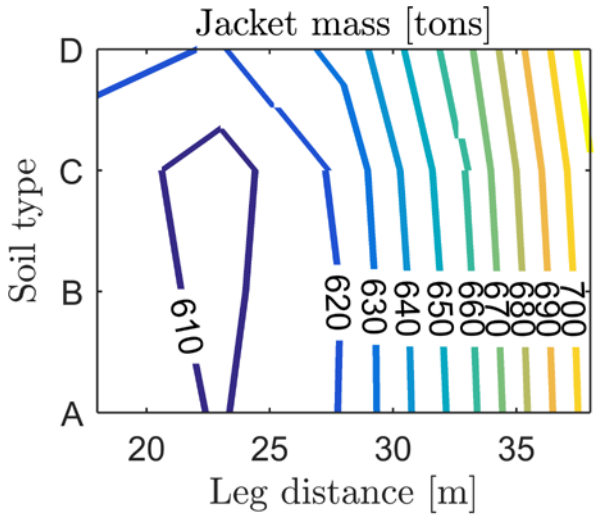


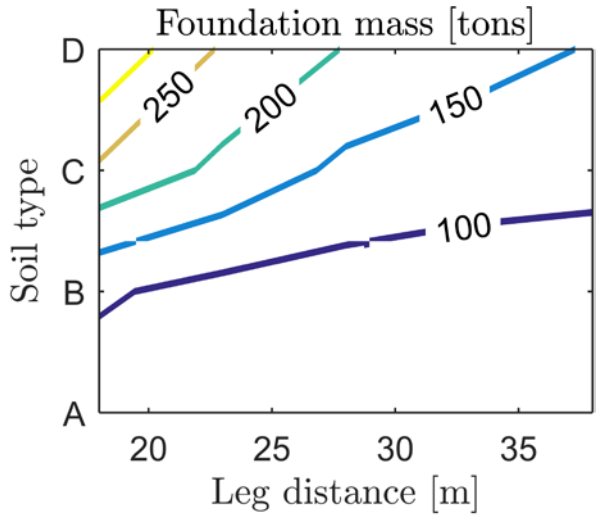
Optimal design problem



Design trends

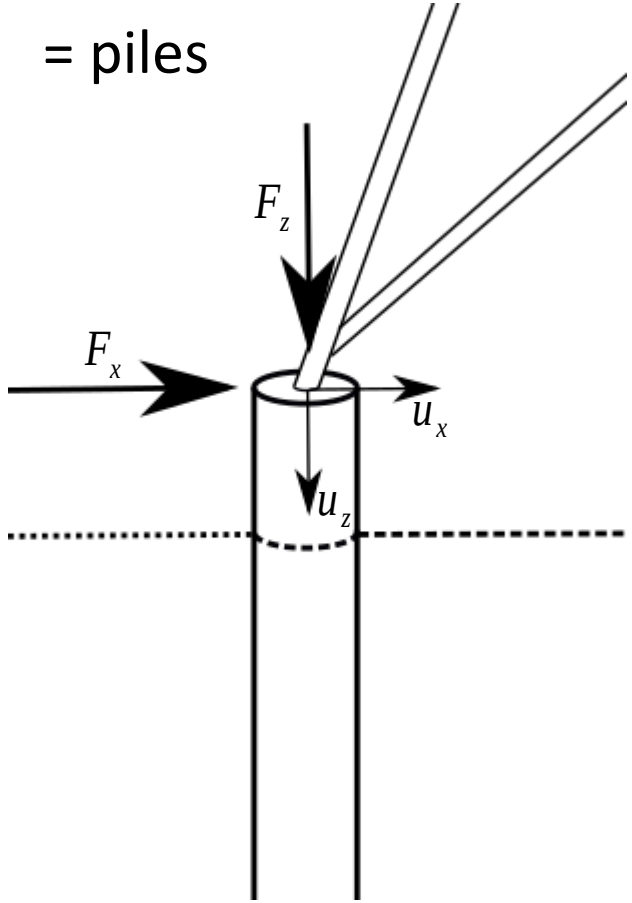
The figure below shows how jacket mass and foundation mass change as functions of both leg distance and soil stiffness (A=stiff, D=soft)



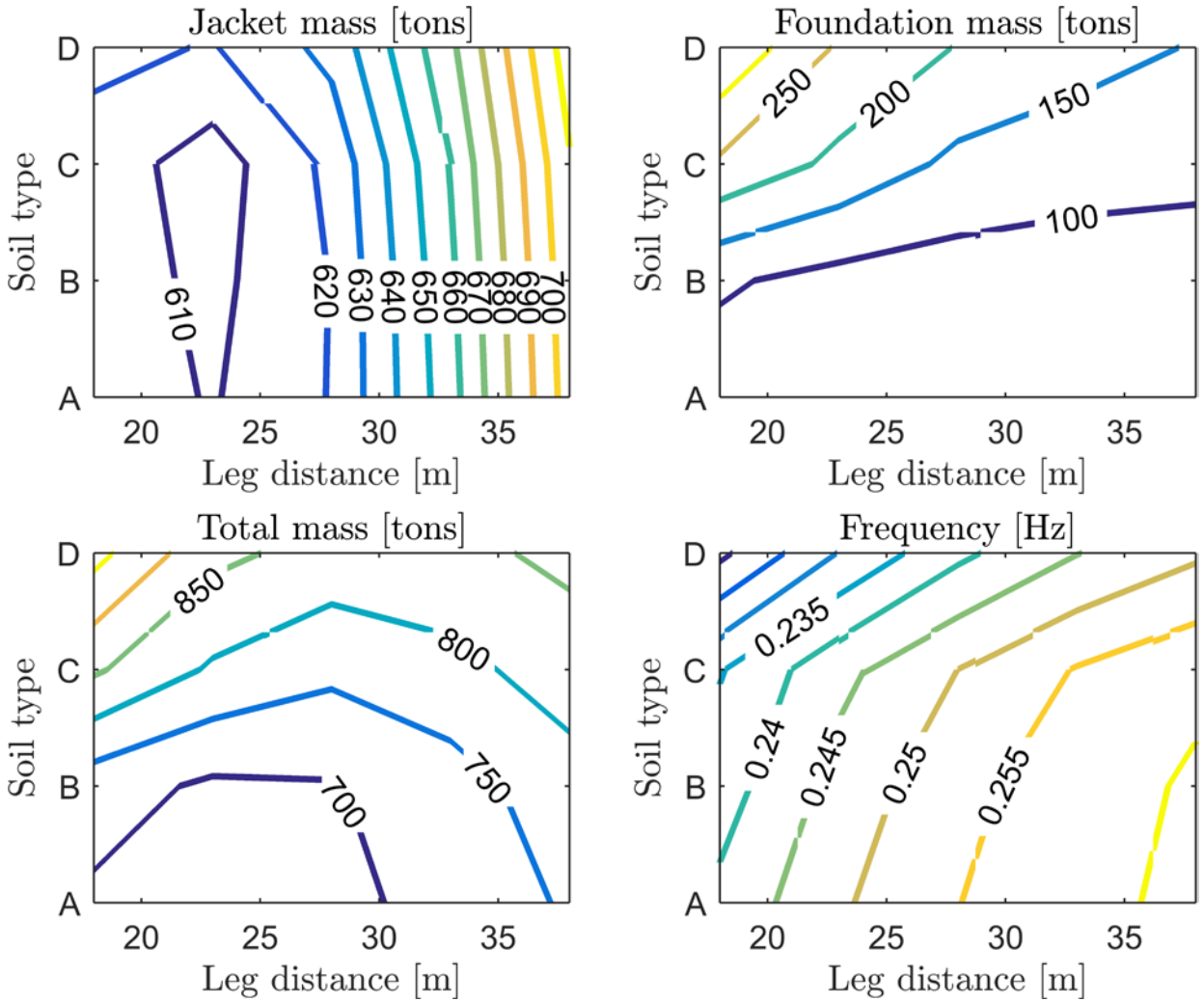


Soil = sand

Foundation = piles



The preferred leg distance now depends on the soil stiffness, and perhaps also the desired fundamental frequency



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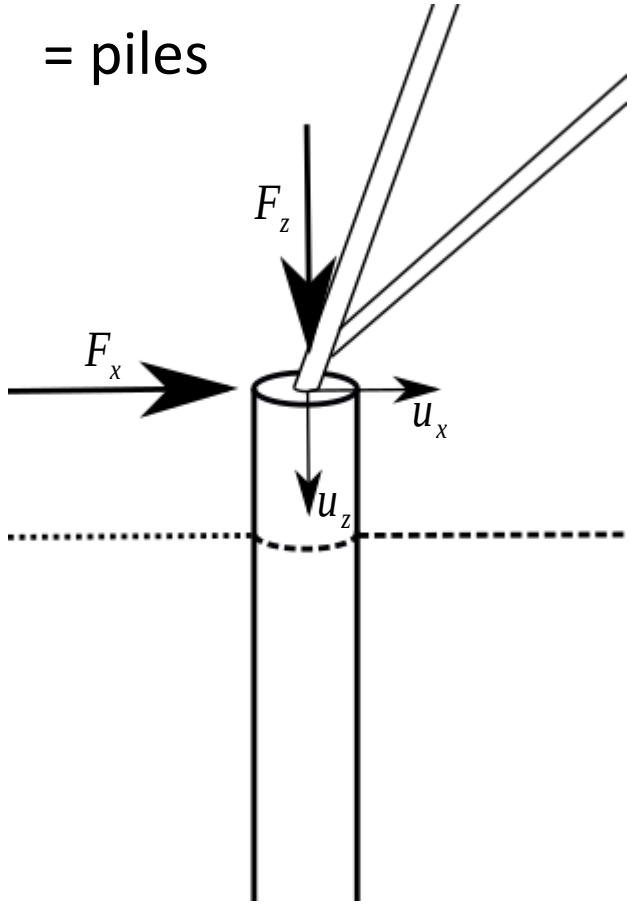


Structural optimization is used to automate the "well-defined" engineering tasks of conceptual support structure design

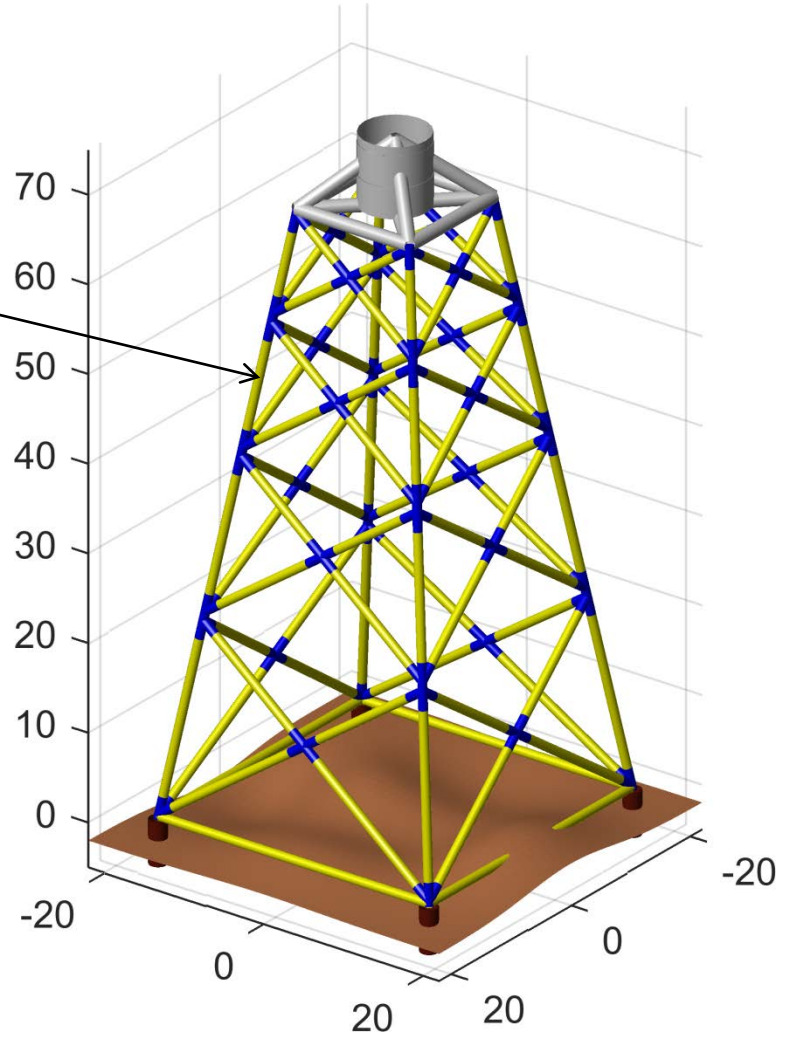
Cost function

$$\begin{aligned} &\text{minimize} && f(\boldsymbol{x}) \\ &\text{subject to} && \boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0} \end{aligned}$$

$\boldsymbol{x}$ = design variables

Engineering limits:

1. Fatigue limit state
2. Ultimate limit state
3. Soft-stiff frequency range



With a tool like JADOP it is then quick & easy to investigate how input conditions influences the design

$$\begin{aligned} &\text{minimize} && f(\boldsymbol{x}) \\ &\text{subject to} && \boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0} \end{aligned}$$