Wind Turbine Optimization

a case study to help you think about your project

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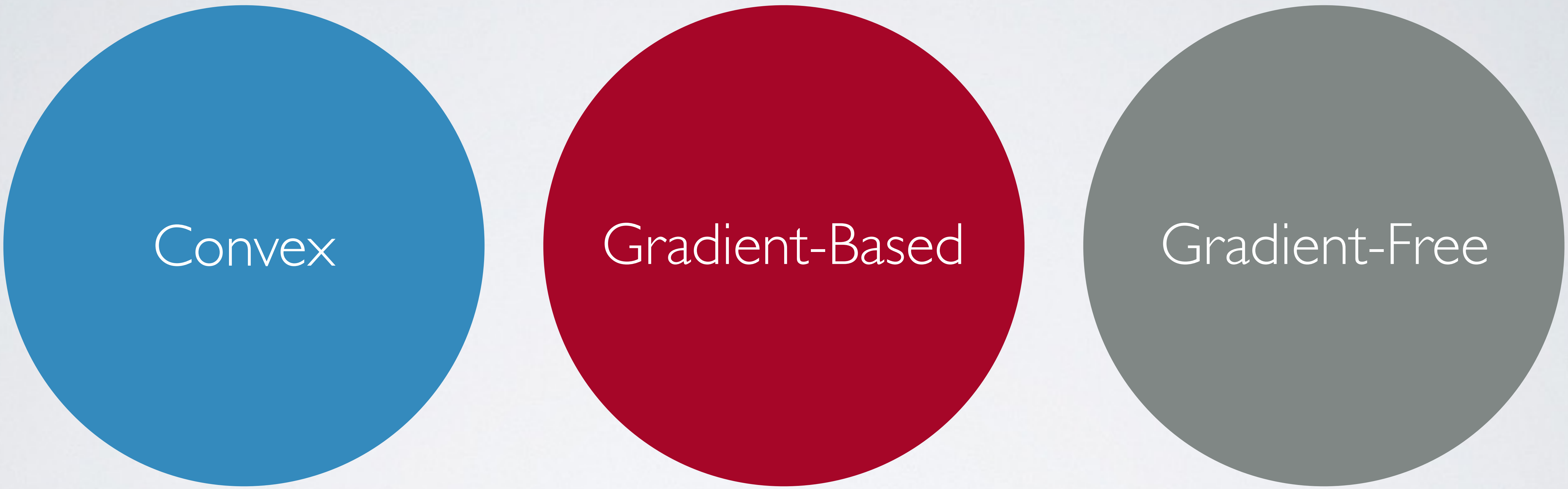
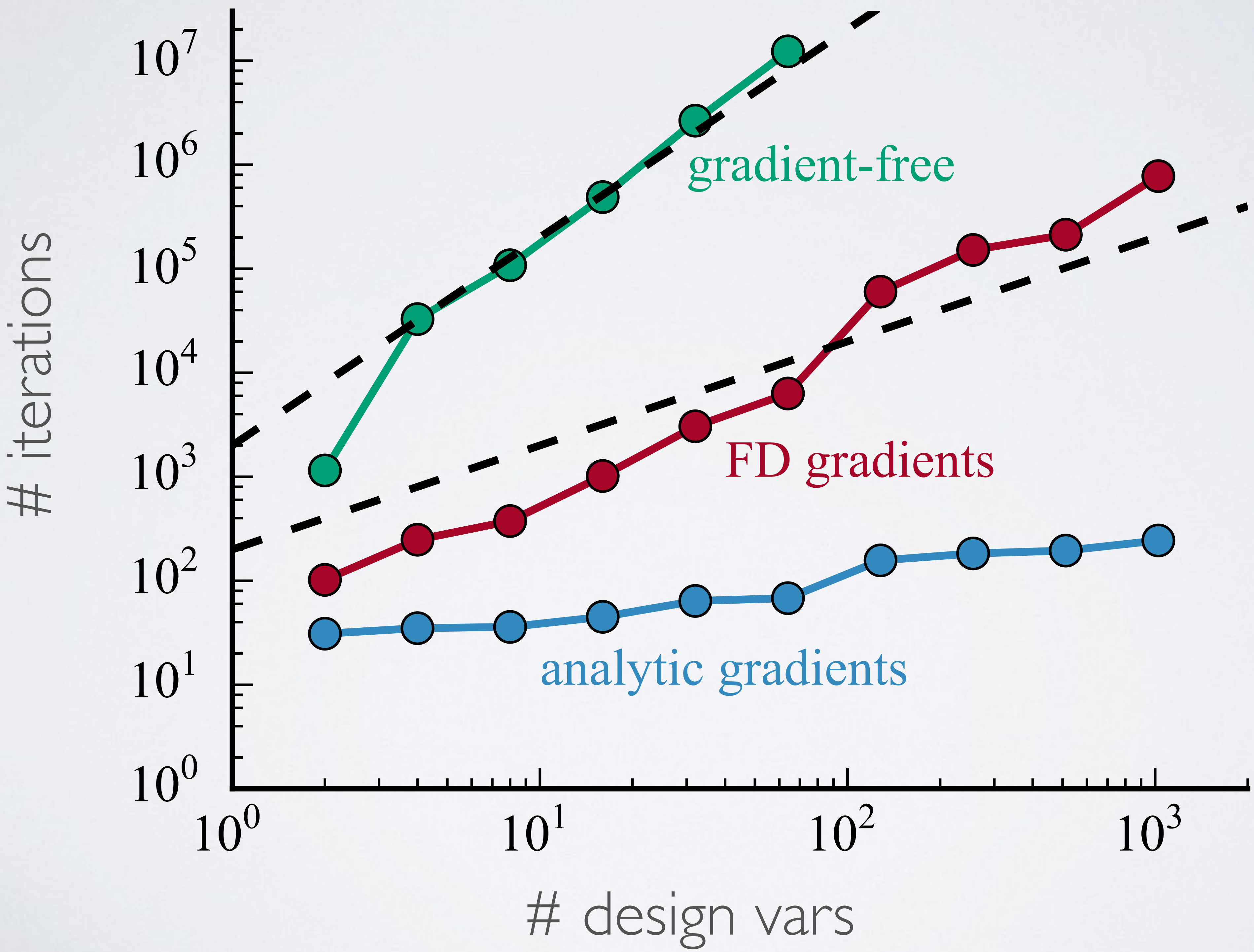
ME 575

Three broad areas of optimization (with some overlap)

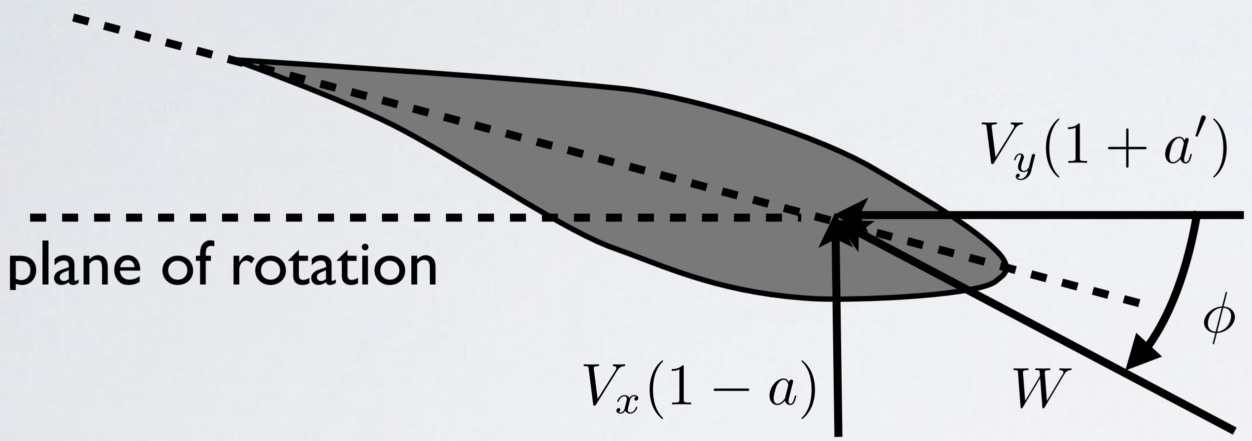


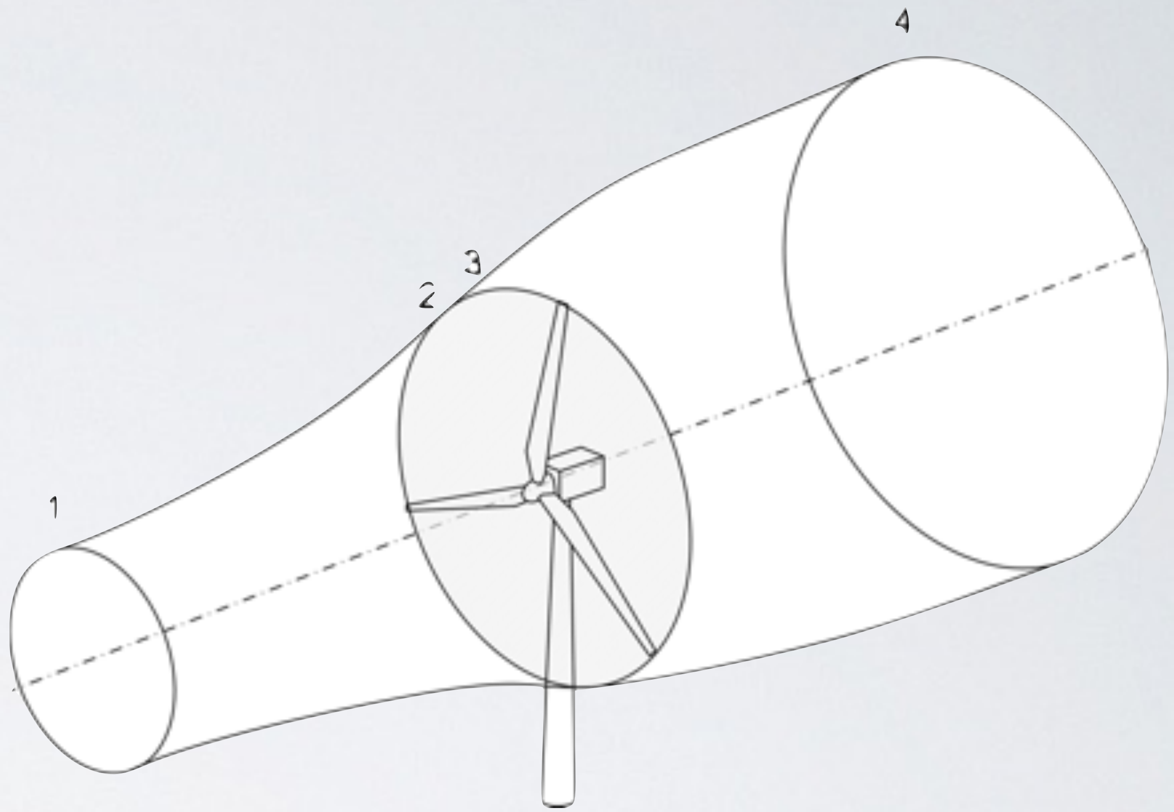
Today we will focus on gradient-based, but for some projects the other areas are more important.

In higher dimensional space, analytic gradients become increasingly important



There is a difference between developing for analysis vs optimization





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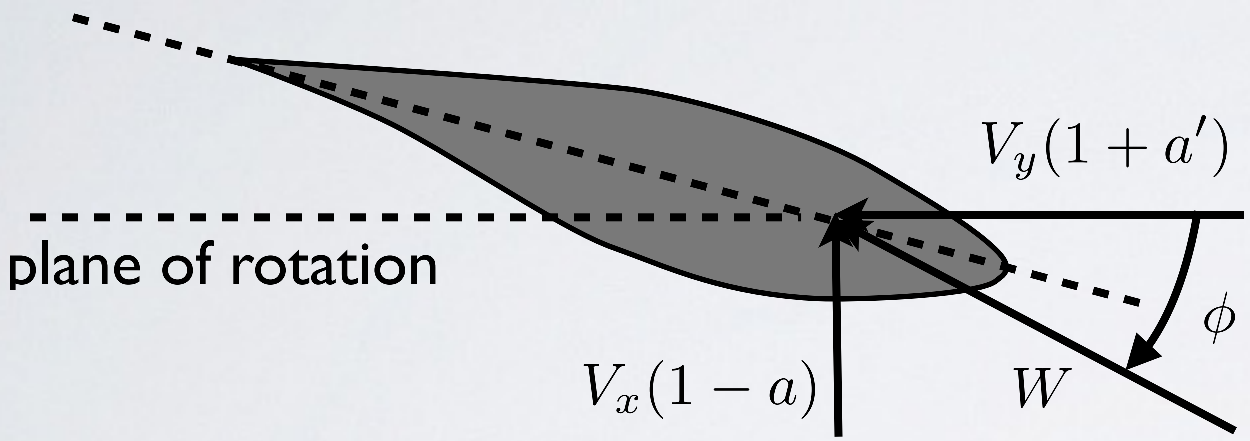
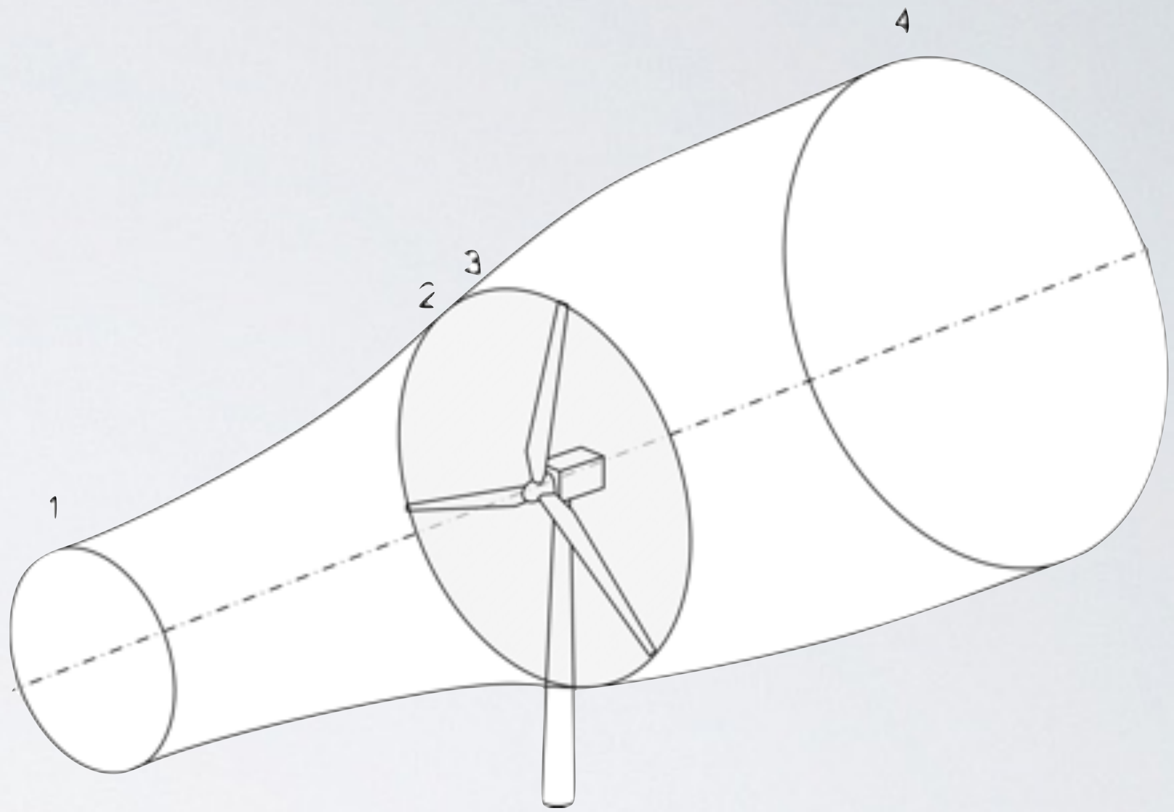




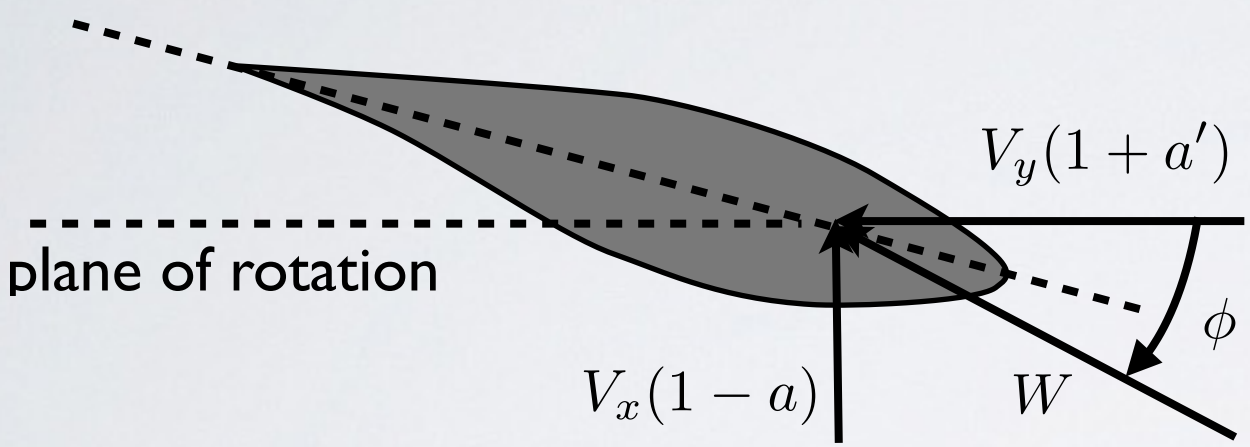
$$C_T = \left(\frac{1-a}{\sin\phi}\right)^2 c_n \sigma'$$

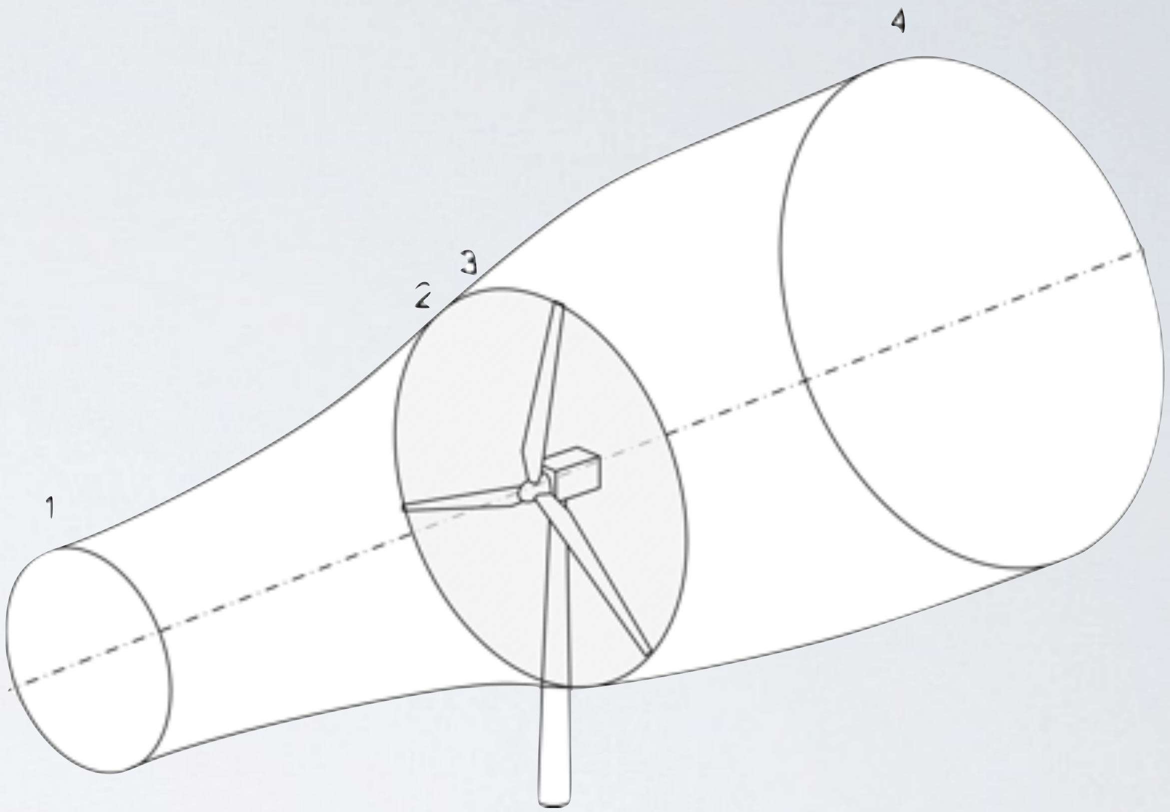
$$C_T = 4a(1-a)$$

$$C_Q = \left(\frac{1+a'}{\cos\phi}\right)^2 c_t \sigma' \lambda_r^2$$

$$C_Q = 4a'(1+a')\tan\phi \lambda_r^2$$

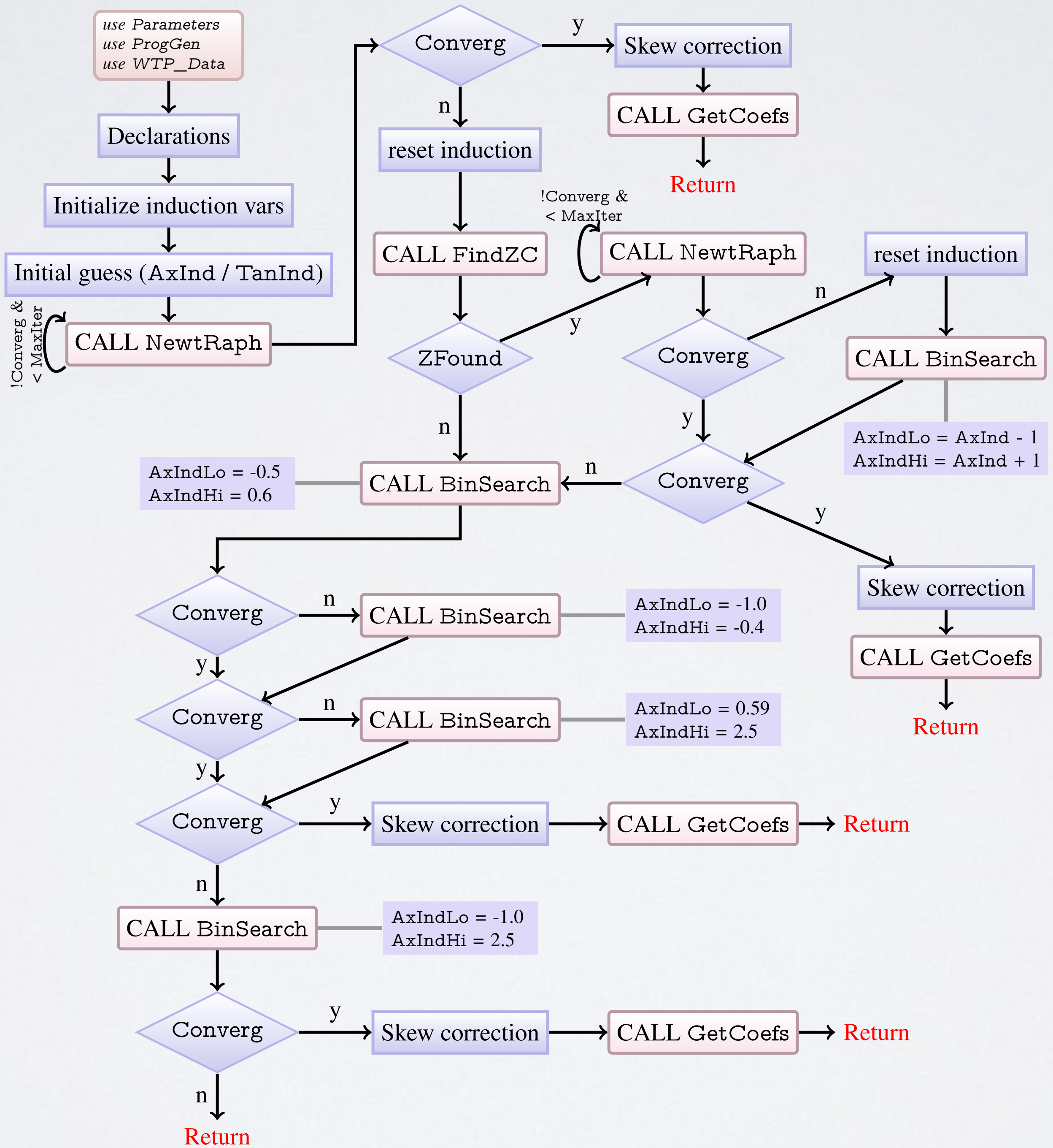
There is a difference between developing for analysis vs optimization



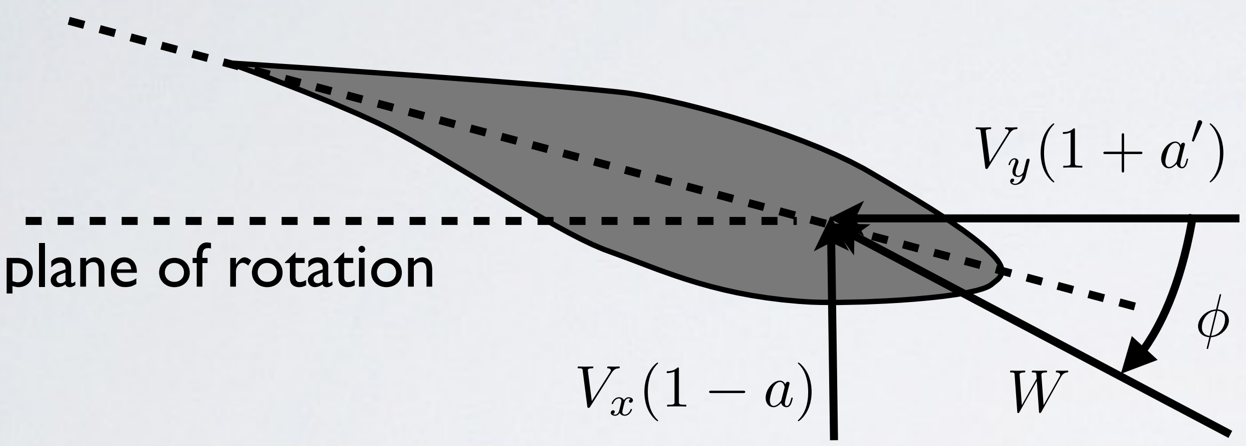


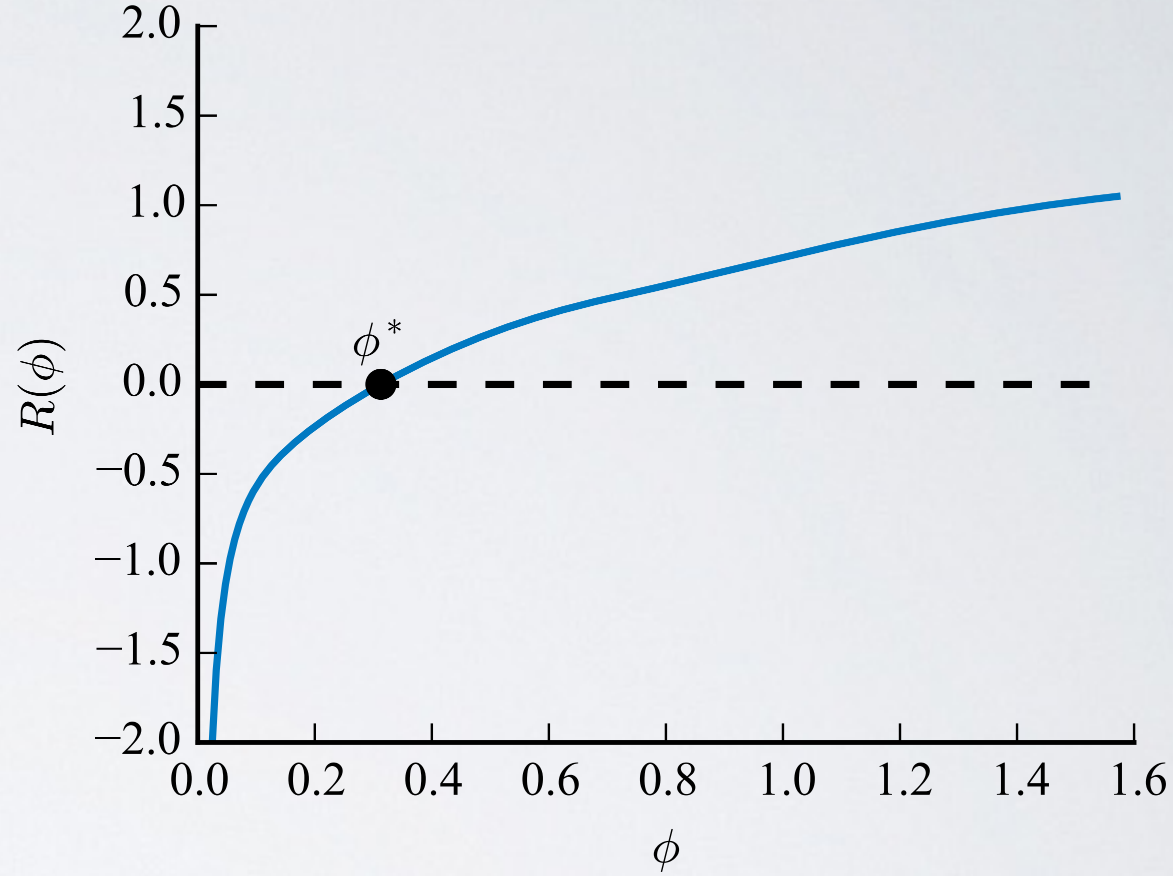
$$a = \frac{1}{\frac{4\sin^2\phi}{c_n\sigma'} + 1} \qquad a' = \frac{1}{\frac{4\sin\phi\cos\phi}{c_t\sigma'} - 1}$$

There is a difference between developing for analysis vs optimization



Sometimes a new solution approach is needed…



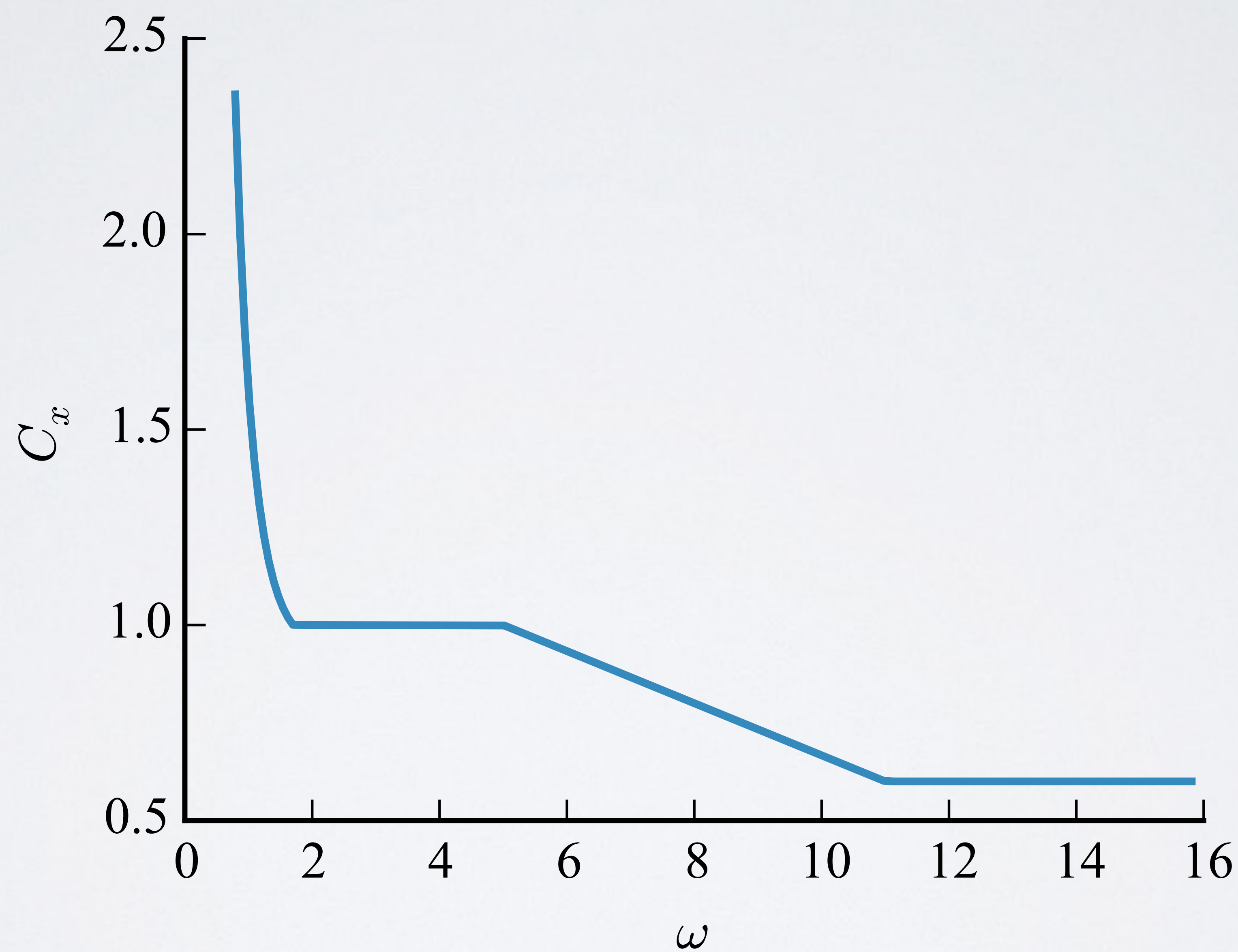


$$\mathcal{R}(\phi) = \frac{\sin\phi}{1-a} - \frac{V_x}{V_y}\frac{\cos\phi}{(1+a')} = 0$$

Sometimes a new solution approach is needed…

Algorithm	Avg. Function Calls	Failure Rate (%)
Steffensen	16.4	16.3
Powell Hybrid	72.3	16.2
Fixed-Point	31.8	12.6
Levenberg-Marquardt	92.3	8.8
Newton	79.0	5.8
New Method	11.3	0.0

But most of the time the changes needed are relatively minor



smoothing empirical factors/corrections

But most of the time the changes needed are relatively minor

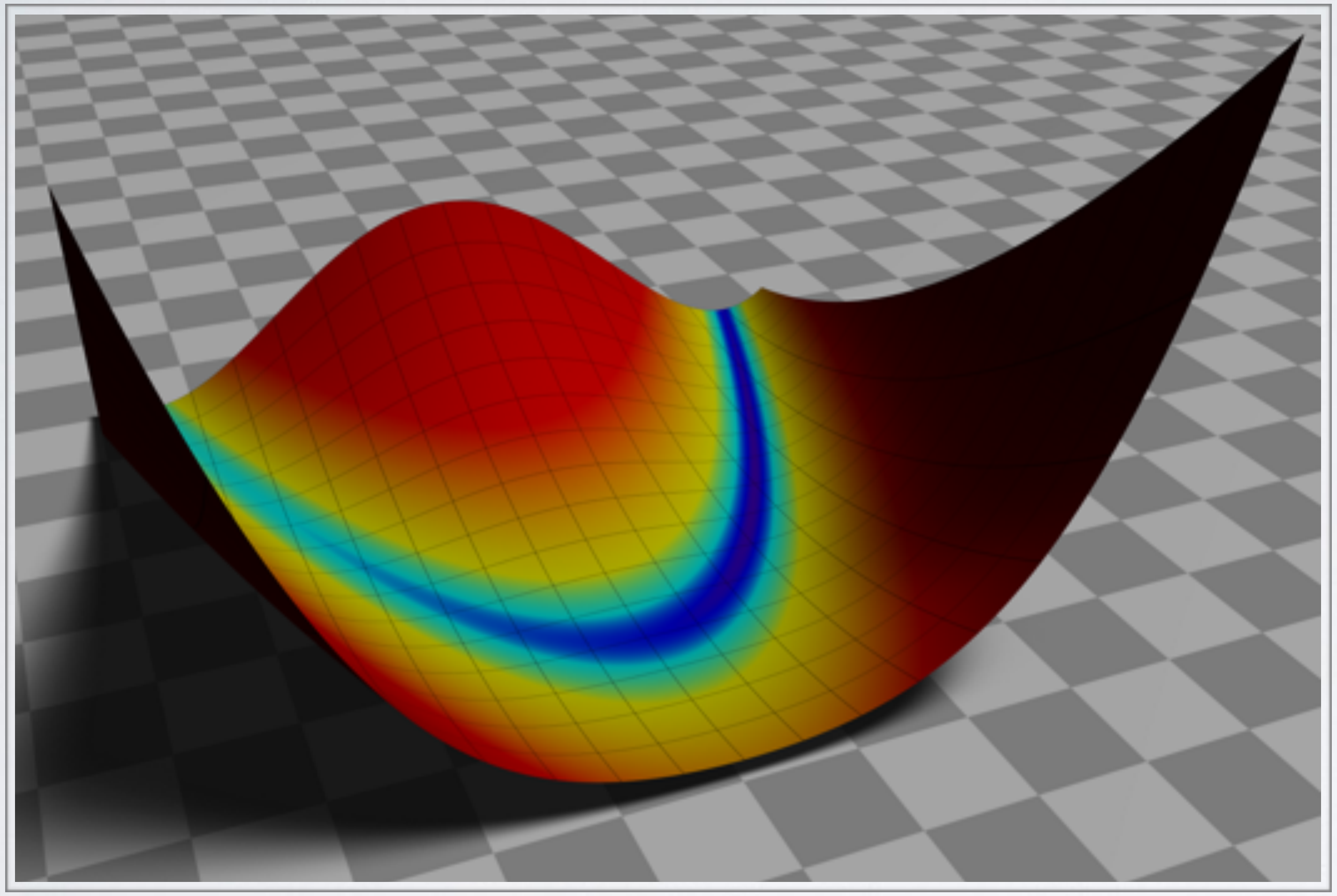
provide alternatives to input files

Planning for optimization at the beginning can help a lot

Try to avoid:

- max/min
- abs
- piecewise functions
- convergence loops,
- noisy output
- empirical models
- discretization

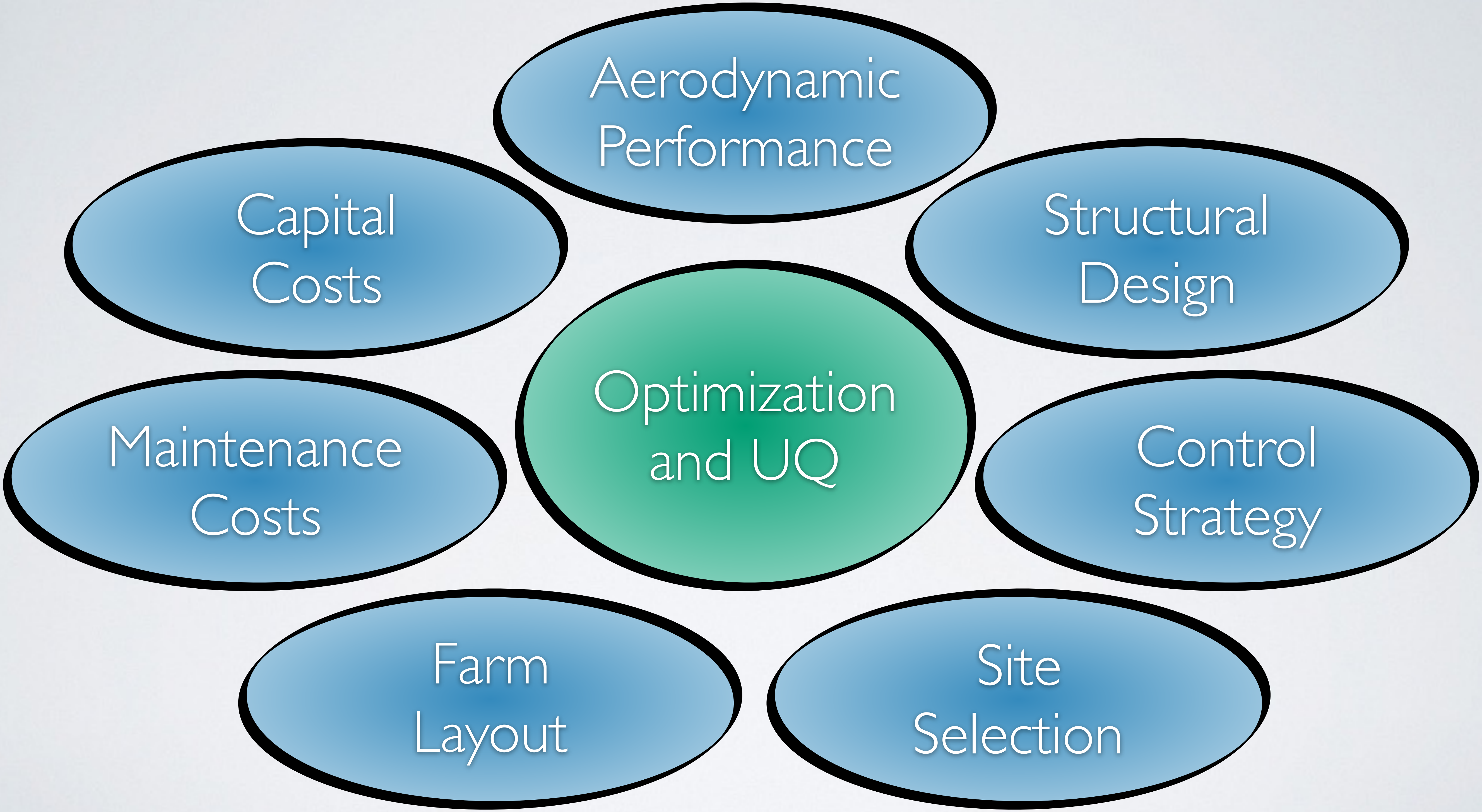
Planning for optimization at the beginning can help a lot



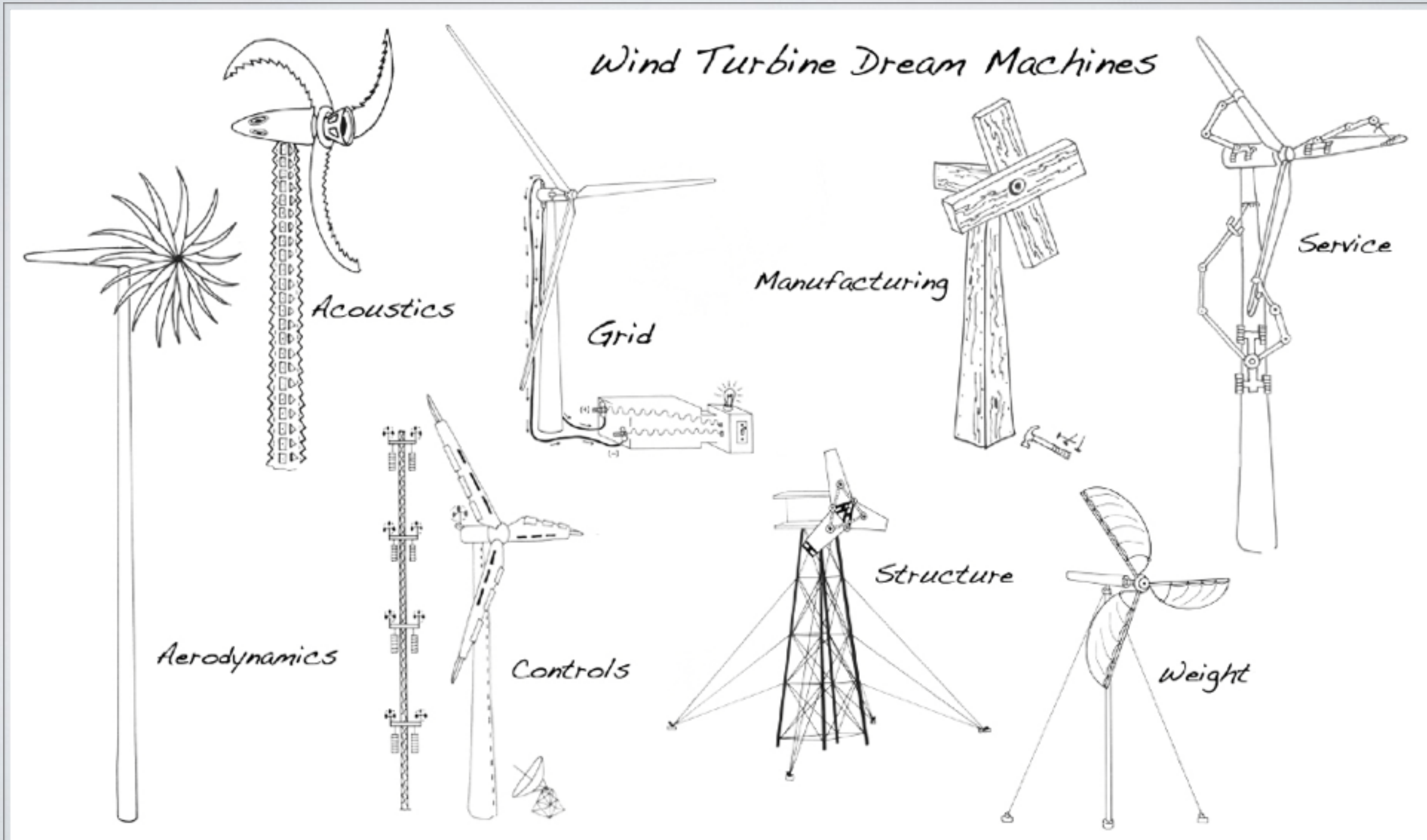
[f, g] = func(x)

Think about gradients upfront

Engineering design is multidisciplinary



Single discipline thinking usually leads to poor solutions



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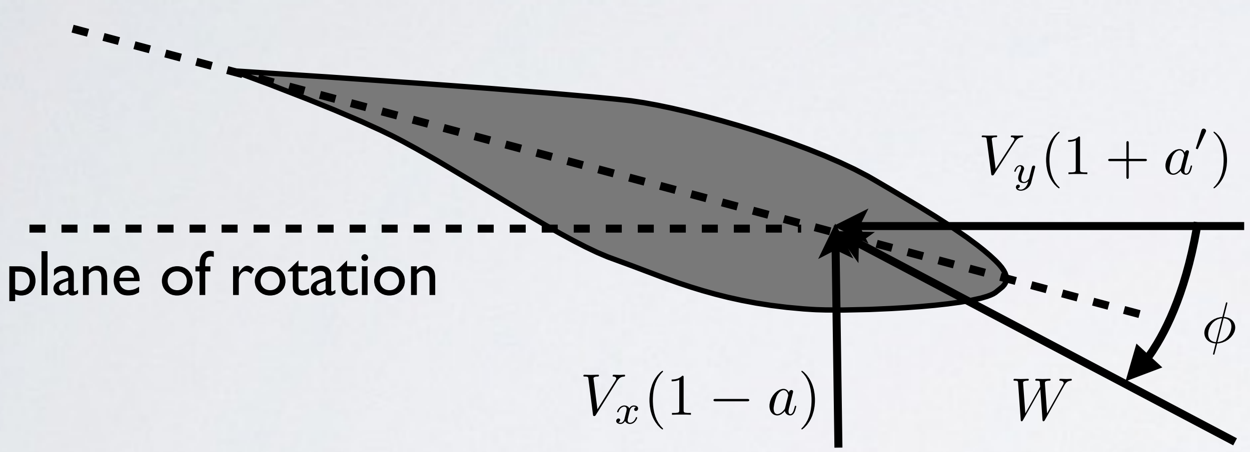
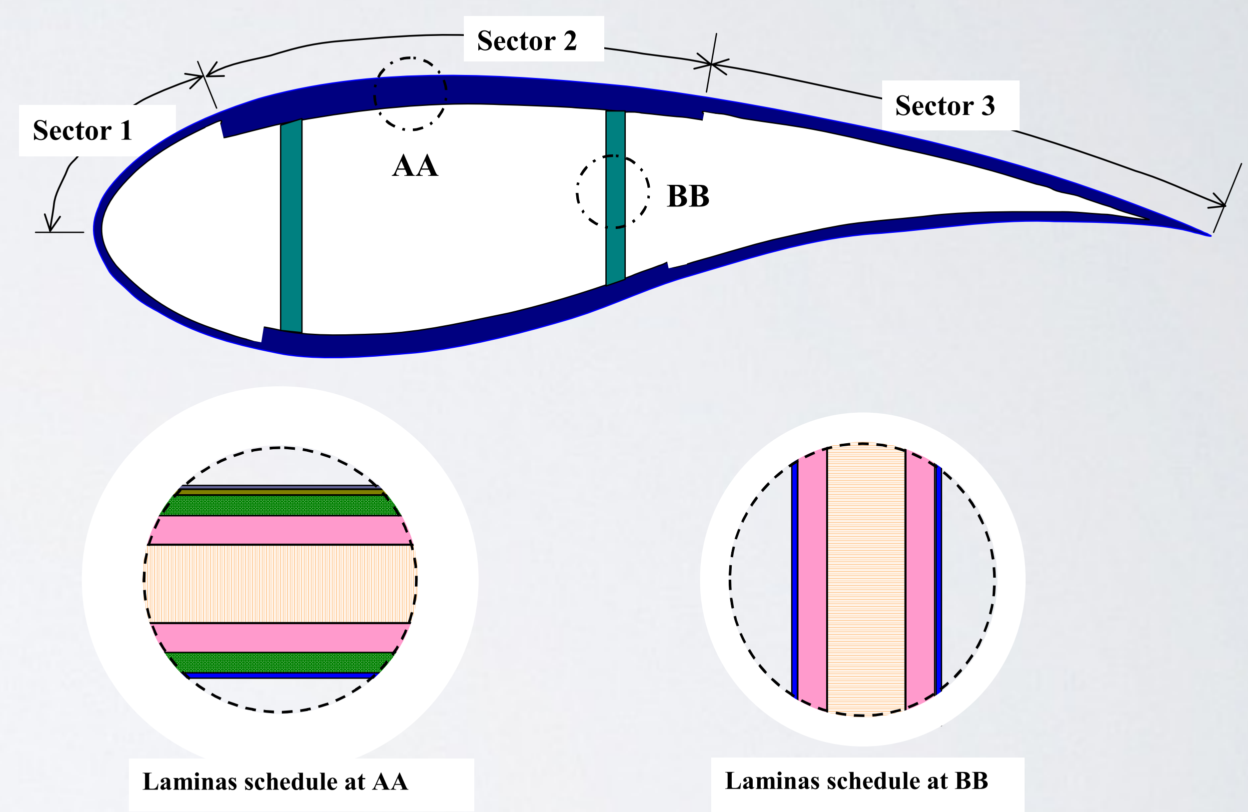
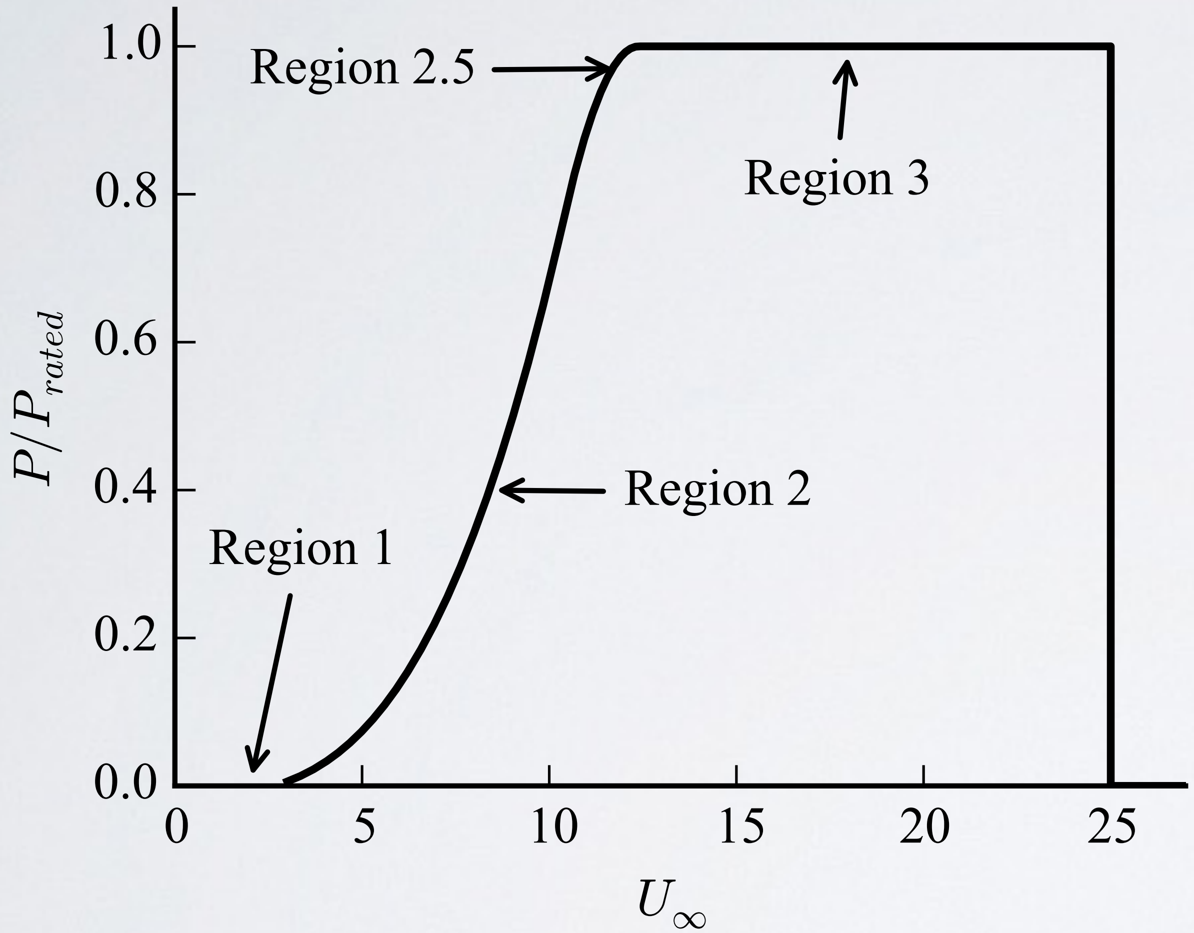


Aerodynamics

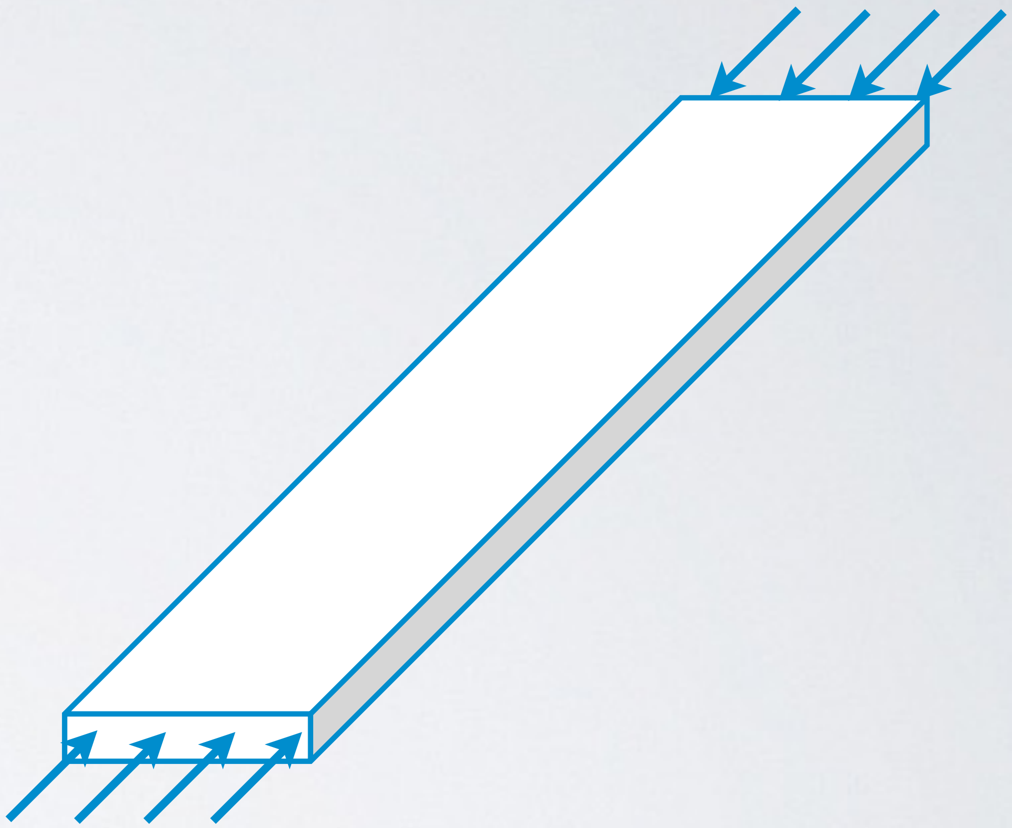


Composite Laminate Theory

Single discipline thinking usually leads to poor solutions

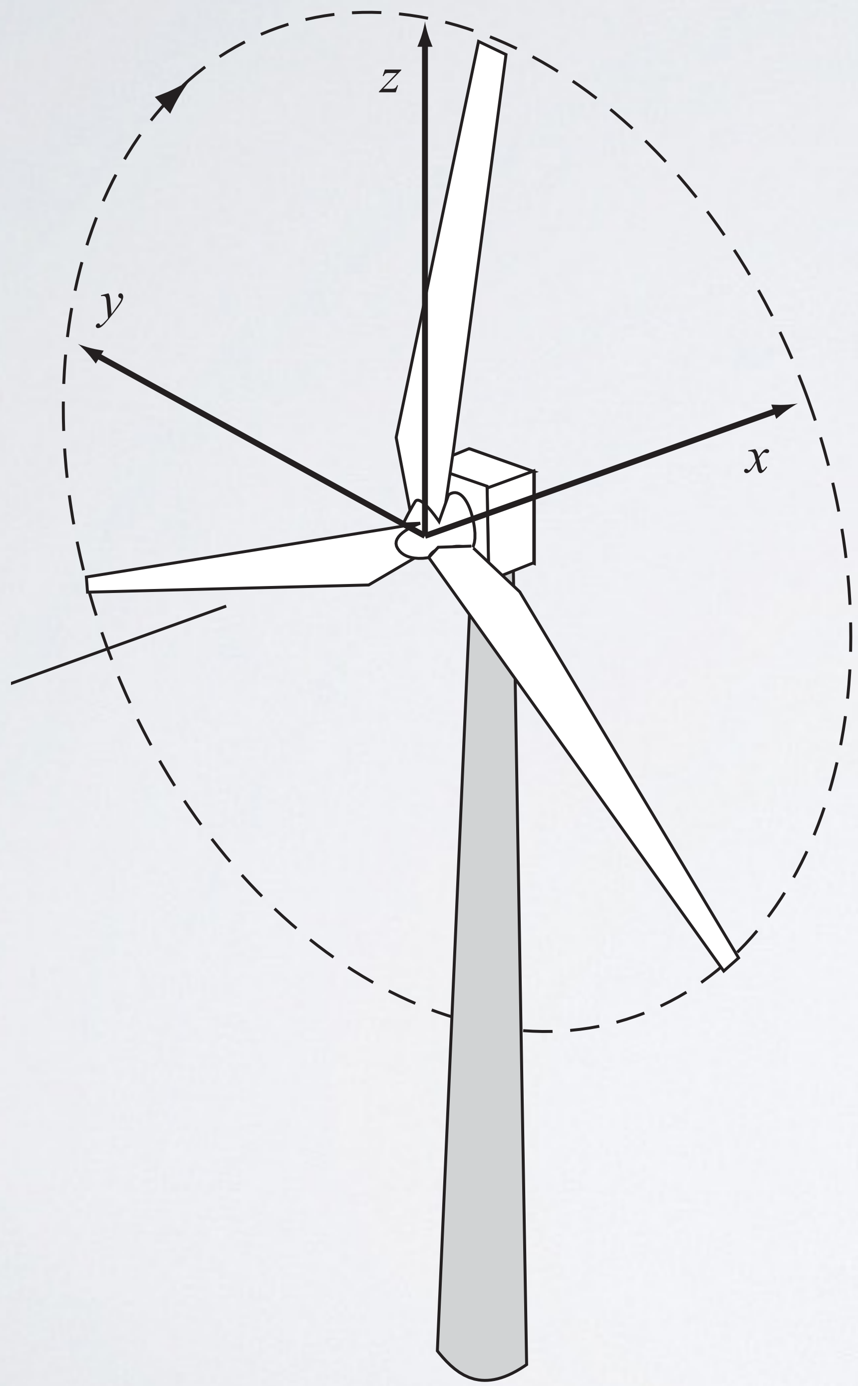


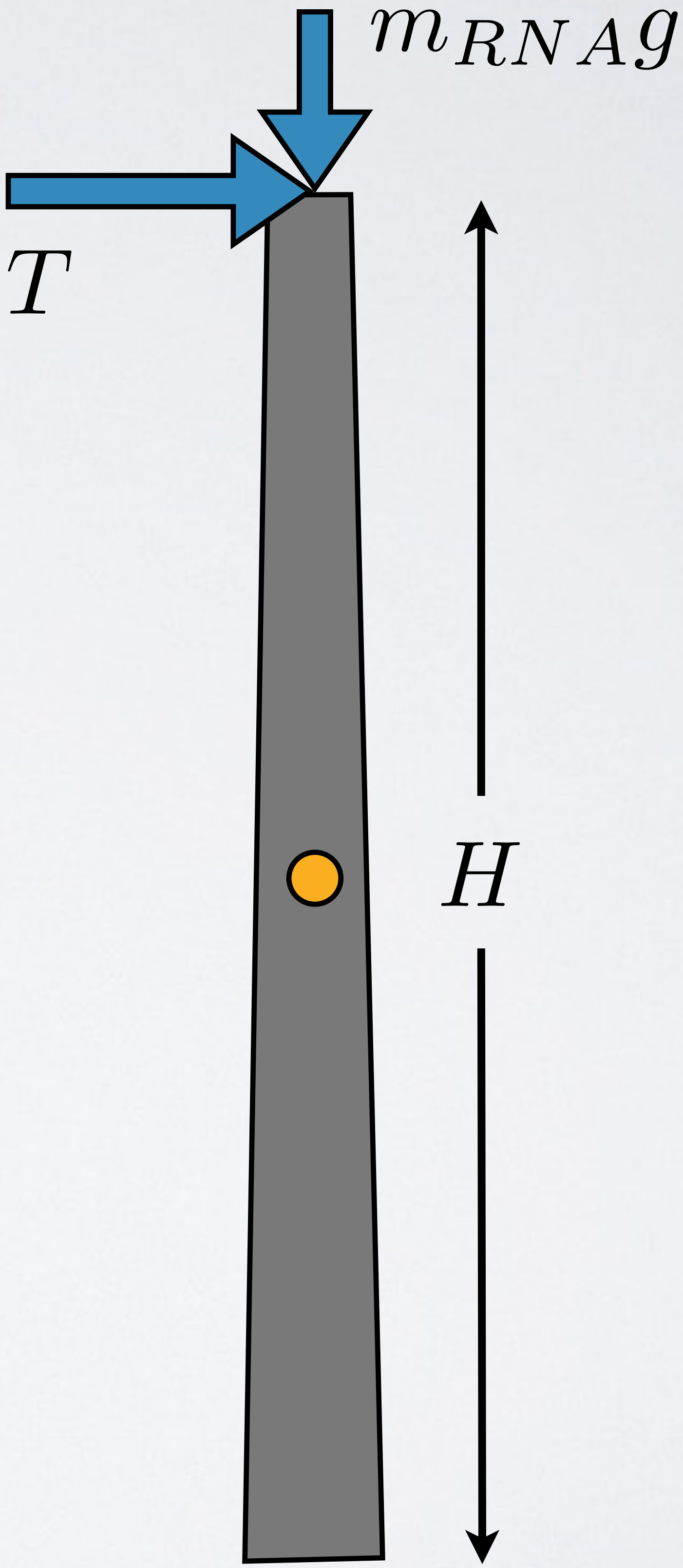
Performance



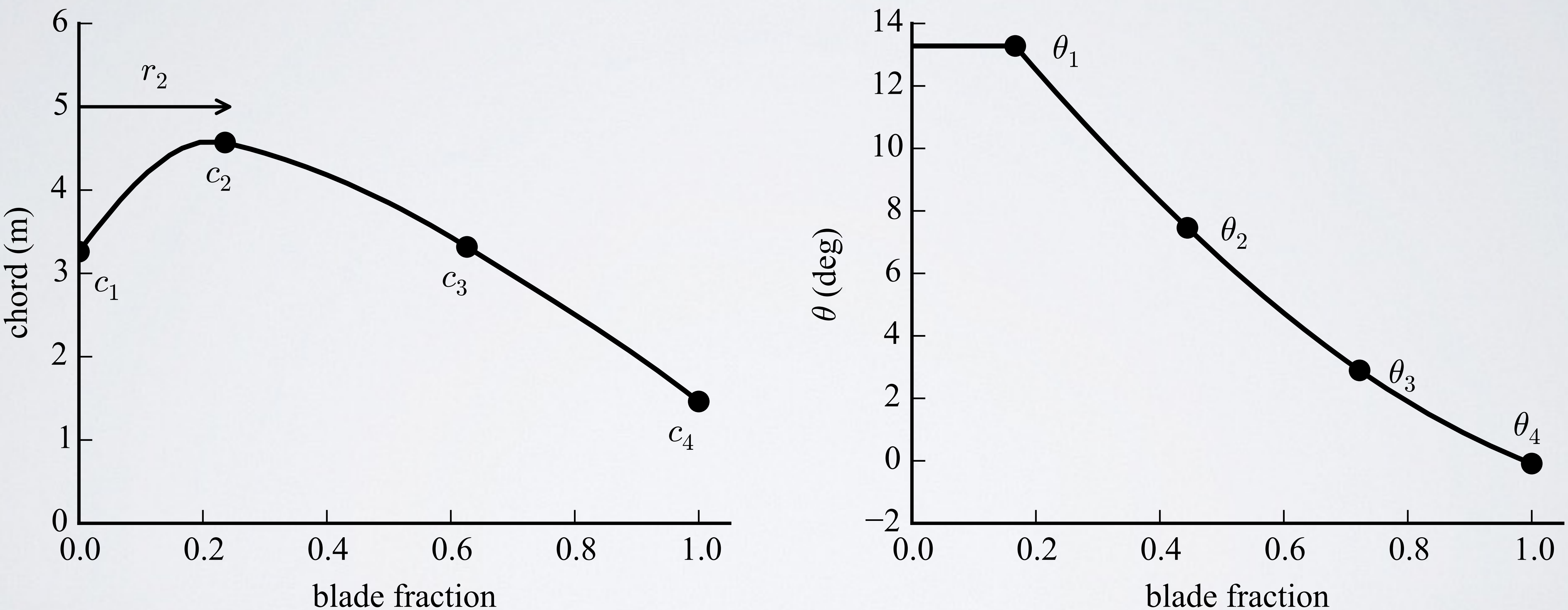
Finite Element Analysis and Buckling

Single *component* thinking usually leads to poor solutions





Splines are an effective way to represent continuous distributions with a small number of design variables



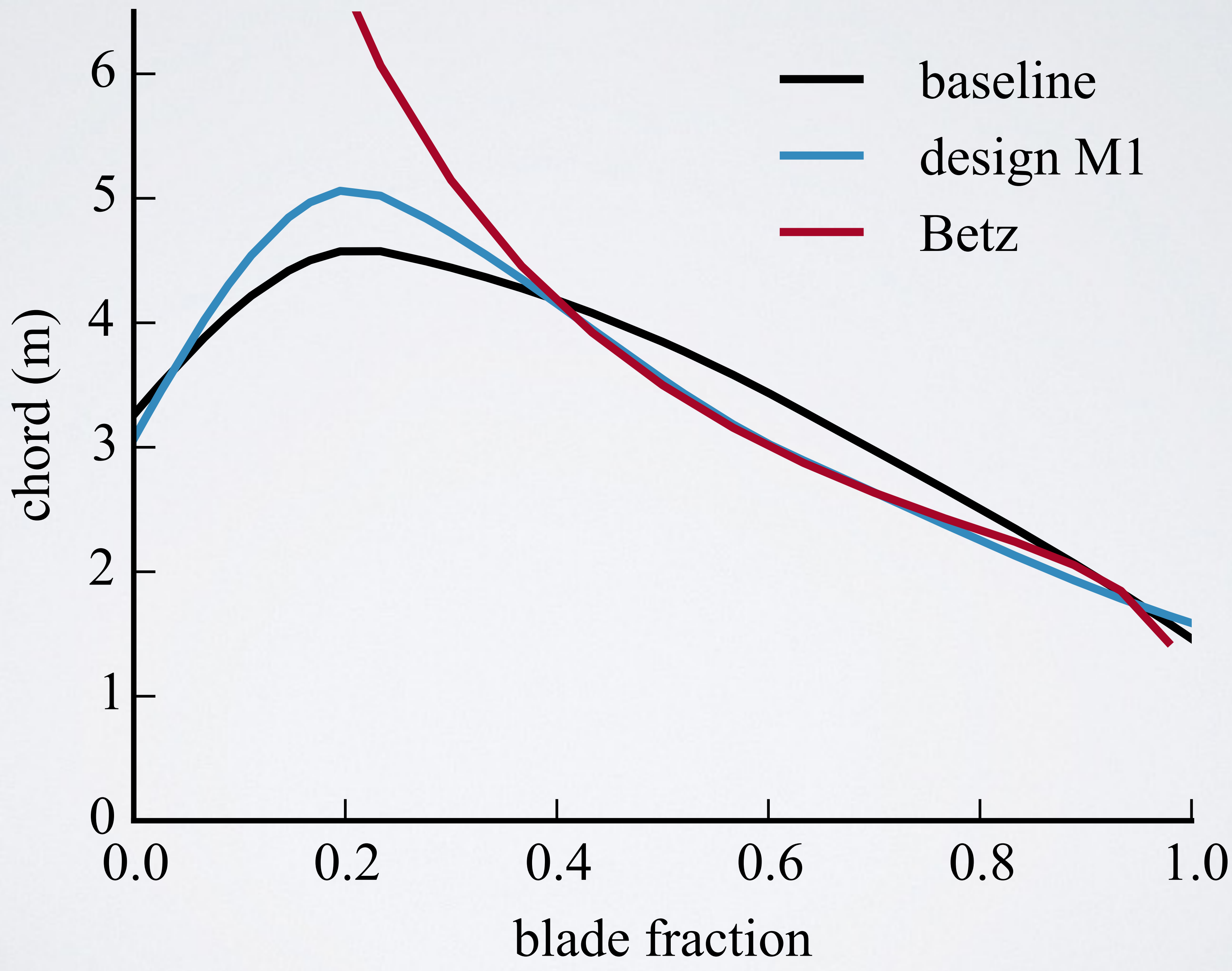
A relatively small number of design variables were used in our early studies

Description	Name	# of Vars
chord distribution	{c}	5
twist distribution	{θ}	4
spar cap thickness distribution	{t}	3
tip speed ratio in region 2	λ	1
rotor diameter	D	1
machine rating	rating	1

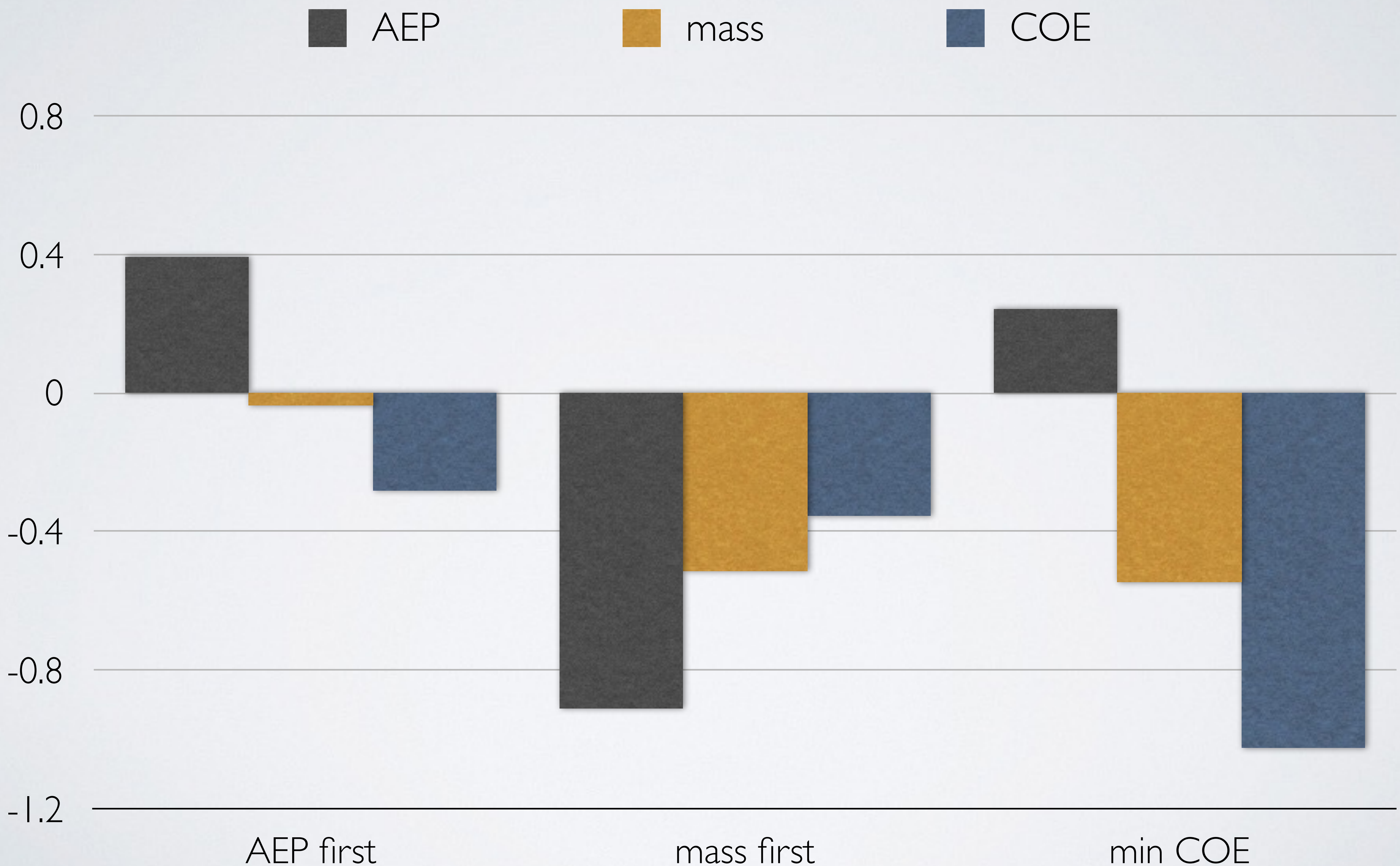
However, we typically used around 100 constraints

$$
\begin{aligned}
\underset{x}{\text{minimize}} \quad & J(x) \\
\text{subject to} \quad & (\gamma_f \gamma_m \epsilon_{50i})/\epsilon_{ult} < 1, \;\; i = 1, \ldots, N && \text{ultimate tensile strength} \\
& (\gamma_f \gamma_m \epsilon_{50i})/\epsilon_{ult} > -1, \;\; i = 1, \ldots, N && \text{ultimate compressive strength} \\
& (\epsilon_{50j} \gamma_f - \epsilon_{cr})/\epsilon_{ult} > 0, \;\; j = 1, \ldots, M && \text{spar cap buckling} \\
& \delta/\delta_0 < 1.1 && \text{tip deflection at rated} \\
& \omega_1/(3\Omega_{rated}) > 1.1 && \text{blade natural frequency} \\
& \sigma_{\text{root-gravity}}/S_f < 1 && \text{fatigue at blade root (gravity loads)} \\
& \sigma_{\text{root-gravity}}/S_f > -1 && \text{fatigue at blade root (gravity loads)} \\
& V_{tip} < V_{tip_{max}} && \text{maximum tip speed}
\end{aligned}
$$

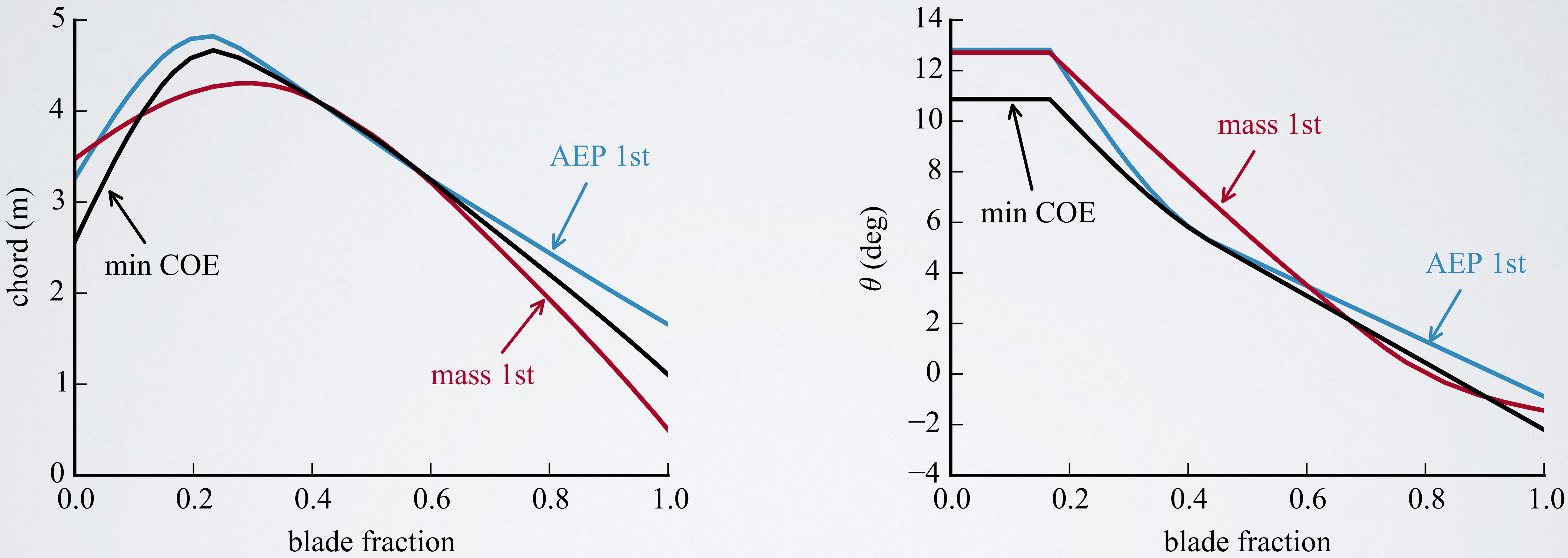
Single discipline optimization lead to inferior results



Even if multiple disciplines were iterated. Integrated optimization is key.



An appropriate objective choice is critical and generally under-appreciated



In higher dimensional space, analytic gradients become increasingly important

Rotor
- Hub Struc
- Rotor Perf
- Rotor Struc
- Rotor Aero
- Blade Struc
- Section Aero
- Section Struc

Nacelle
- LSS/HSS
- Gearbox
- Bearings
- Generator
- Bedplate
- Yaw System

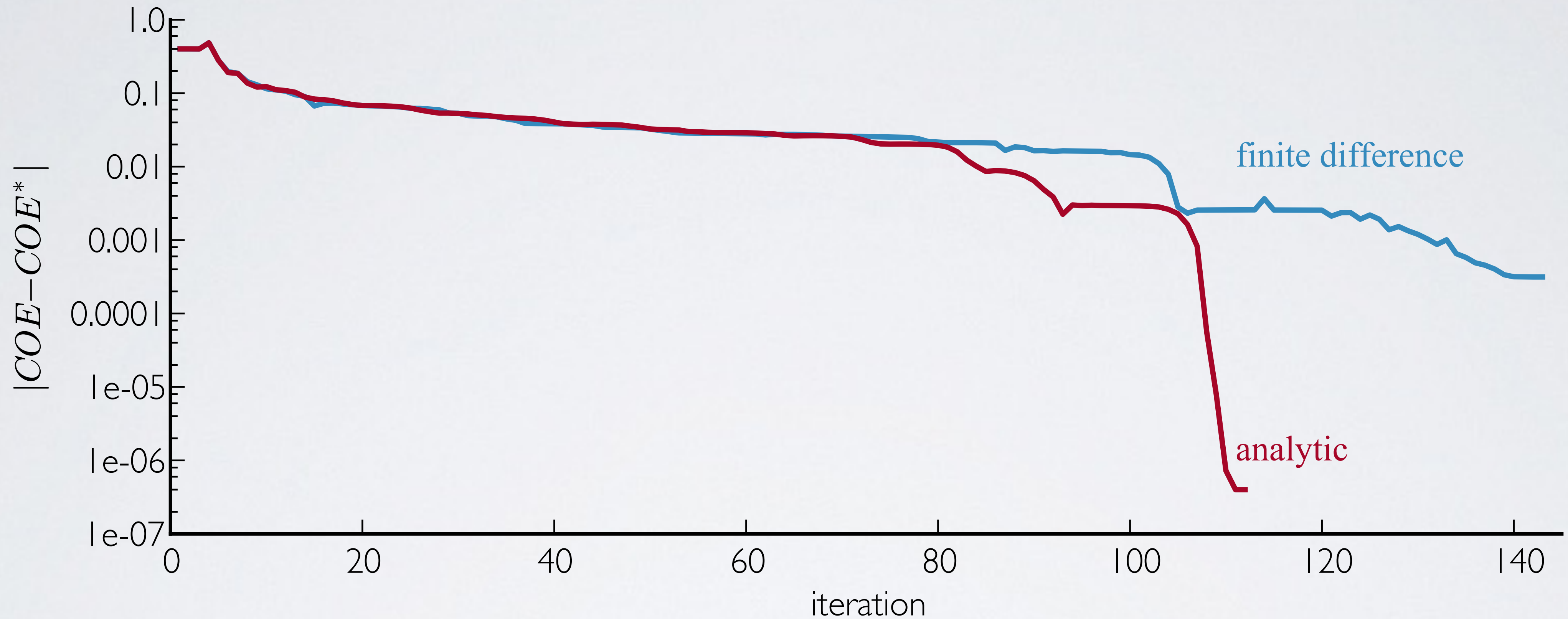
Tower / Foundation
- Tower Struc
- Tower Aero
- Jacket Struc
- Tower Hydro
- Tower Soil

Costs
- TCC
- O&M
- AEP
- BOS
- Finance

In higher dimensional space, analytic gradients become increasingly important

Component	Description	# of vars
Rotor	Chord distribution	5
Rotor	Twist distribution	4
Rotor	Spar-cap thickness distribution	5
Rotor	Trailing-edge panel thickness distribution	5
Rotor	Precurve distribution	3
Rotor	Hub precone angle	1
Rotor	Tip-speed ratio in Region 2	1
Tower	Height	1
Tower	Waist location	1
Tower	Diameter	2
Tower	Shell Thickness	3

As the problem size increases, even finite differencing may not be good enough



	Finite-difference	Analytic
Run time (hours)	5.43	1.11

Some takeaways

- There is a big difference between developing tools just for analysis versus for analysis *and* optimization.
- During analysis development think about gradients, discuss appropriate objectives, and think about the system-level.
- We will discuss later what can/should be done on the optimization side (scaling, multi-start, reformulation, etc.)

Some optimizers you might be interested in

- fmincon: Matlab, 4 algorithms
- SNOPT: commercial tool from Stanford. talk to me about license
- OptdesX, APOPT: tools available at BYU
- scipy.optimize: Python, not great, but easy to use
- KNITRO: academic version
- CVX, Gurobi: convex optimization, Matlab-based
- CPLX: linear and integer programming

Some *frameworks* you might be interested in

- pyOptSparse: Python, a wrapper to many optimizers
- OpenMDAO: Python-based, developed at NASA, not a "black box" approach, coupled derivatives, MDO architectures, HPC support
- ModelCenter or Isight: tool to integrate models with interfaces to other tools like Matlab, Excel, etc.
- DAKOTA: Sandia, only has open-source optimizers, but allows easy coupling to UQ algorithms
- AMPL: a mathematical programming language, supports many optimizers