Taming uncertainty: quantum and classical leaps between physics and engineering

MY-Dagen, Chalmers University, 2019/11/04

F. Santandrea, RISE Applied Mechanics

Outline of the presentation

- Why you should hire me
- PhD: some like it cold
- Quantum Leap: from physics to consultancy (with examples)
- Brownian motion to applied research
- Taming the uncertainty (with examples, probably)
- Let us jump to the conclusions

Why you should hire me

- 2006 – **MSc** Physics, University of Bologna

Thesis: *”The Method of Matrix-Product-States Applied to One-Dimensional Lattice Systems”*

  - Microscopic modelling of magnetic materials

- 2011 – **PhD** Physics, GU/CTH, Condensed Matter Theory Group

Thesis: *”Electronic Control of Flexural Nanowire Vibrations”*

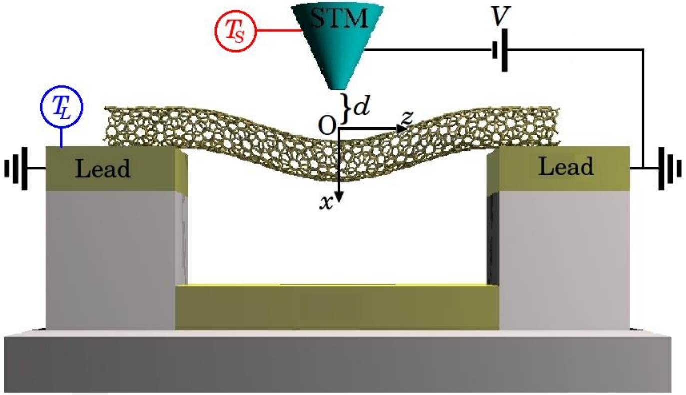
  - Analytical and numerical modelling of NEMS (nano-electromechanical systems):
  - Courses + teaching

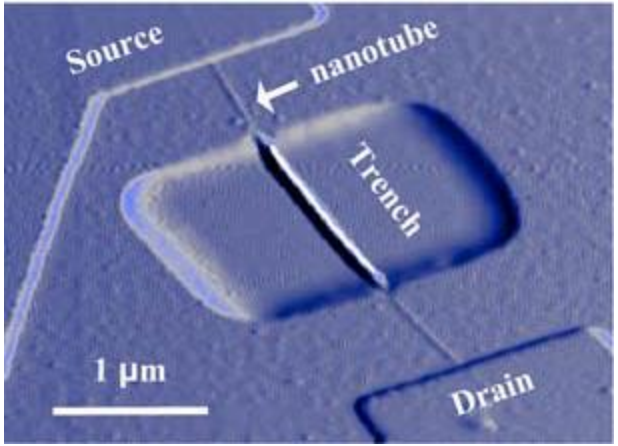
- 2011 – 2015 **Computational engineer** at Epsilon/ÅF
  - Finite Element Method for stress analysis, vibrations, magnetism, heat transfer
  - Computational projects for industrial clients (automotive, offshore)

- 2016 – **Researcher** at SP/RISE (Applied Mechanics)
  - Structural mechanics, reliability, uncertainty quantification

RI.
SE

PhD: NEMS





- Movable element (dot, beam, plate) + electronic device. Materials: metals, semiconductors, graphene, CNT

- Coupling between mechanical and electronic degrees of freedom

- Nonlinear dynamics, ”macroscopic” quantum effects at low temperatures

$$k_B T \ll \hbar\omega \rightarrow \langle n \rangle \ll 1$$

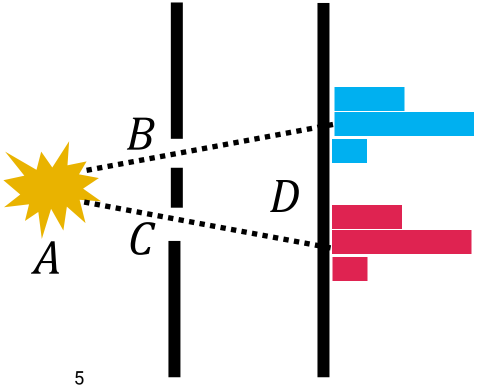
- Link to technological applications: ultrasensitive sensors (mass, displacement)

PhD: some like it cold

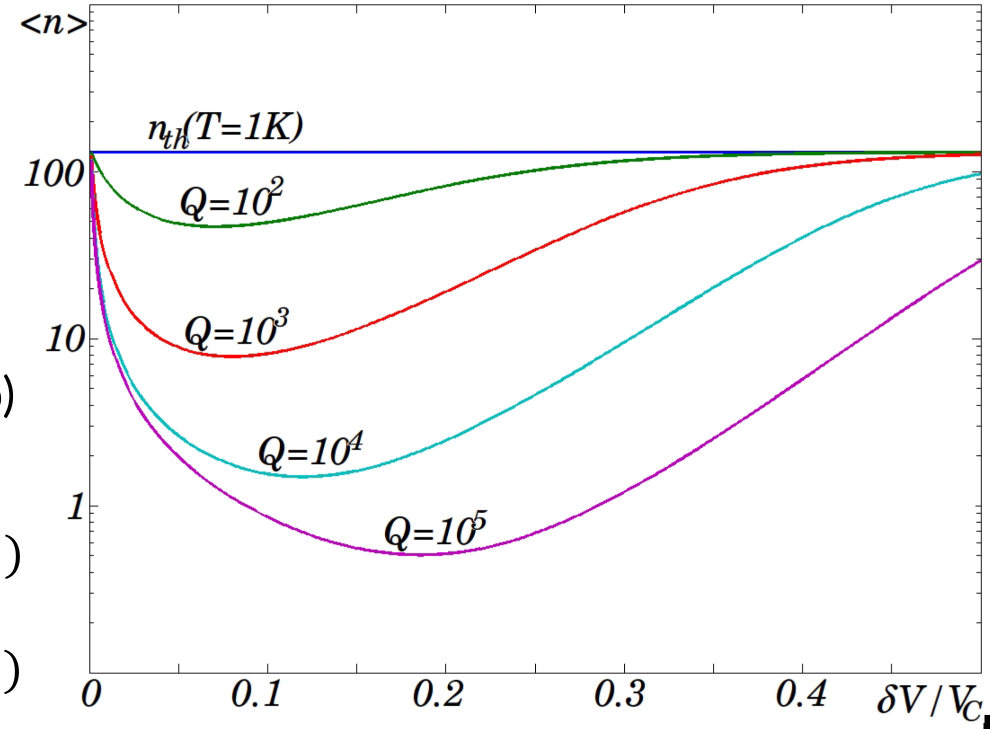
$T \lesssim$ mK for typical ω
Can we do better?

$\rightarrow$ ***Active*** cooling

How does it work? Long story short:
quantum interference (double-slit exp)



$$P(A \rightarrow B \rightarrow D) + P(A \rightarrow C \rightarrow D) \neq P(A \rightarrow D)$$



RISE

PhD: take-home messages

- ***Continuum mechanics*** boils down to… the harmonic oscillator!

$$m\ddot{x} + kx = F(x, \dot{x}, t)$$

- ***Electromagnetism*** boils down to… the capacitor force $F \sim -1/d$

(deviations due to geometry details are left to engineers ☺)

- ***Probability distributions*** do *objectively* exist in Nature, for example:

  - the ground state of electrons, atoms → Gaussian
  - particle velocity distribution in ideal gas at equilibrium → Maxwell
  - distribution of random measurement errors → Gaussian
  - basically the whole statistical foundation of thermodynamics

- ***Analytical methods*** are the best! Numerical approaches and generally computers are for losers

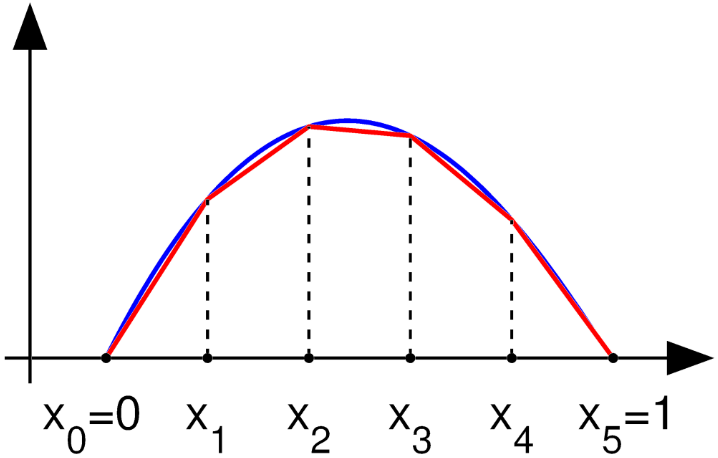
RI. SE

Quantum Leap: from physics to *consultancy*

The ***Finite Element Method*** shall be your trade!

A versatile numerical method to solve partial differential equations (PDE).

A LOT of engineering applications (mechanics, heat transfer, acoustic, electromagnetism…)



Boundary Value Problem

$$\begin{cases} u''(x) = f(x) \text{ in } (0,1) \\ u(0) = u(1) = 0 \end{cases}$$

Weak form

$$\int_0^1 u'' v dx = \int_0^1 f v dx$$

↑ basis

Discretization
→algebraic problem
finite dimensional

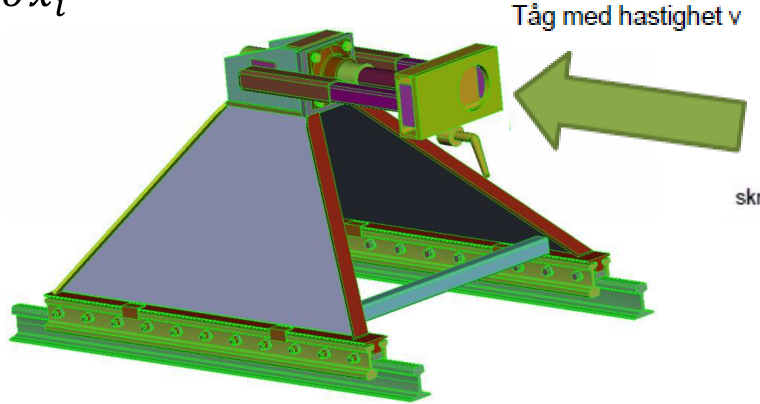
$$-Lu = Mf$$

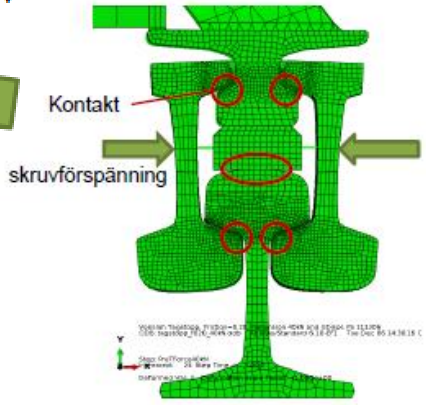
OK, I understand the math, but…

Ex 1 – Buffer Stop (Stoppbock)

… in actual projects equations are nowhere to be seen!

$$\frac{\partial \sigma_{ij}}{\partial x_i} + b_i = 0$$ + friction and bolt pretension

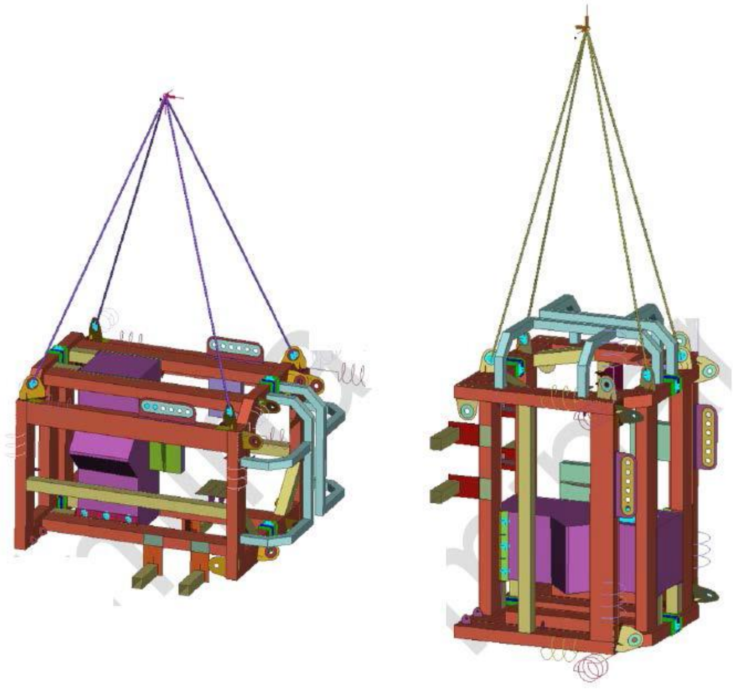




$$\frac{1}{2} M v^2 = F_{brk}(\mu, F_{pre}) L$$

Braking force can be tabulated using FEM

Ex 2 – Offshore Equipment

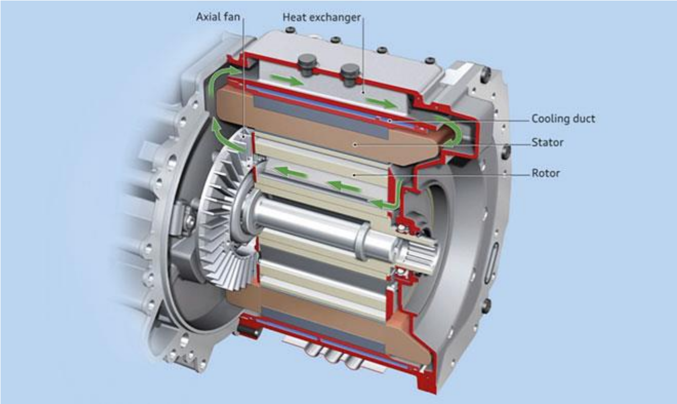


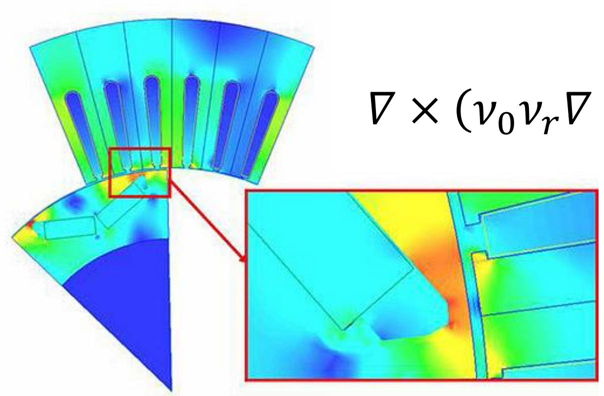
Verification of design compliance of SFT transportation skid and protection frame to DNV code 2.7-3

Where the rules of the code come from? For example, multiply the load by a safety factor γ etc.

→ empirical knowledge and statistical analysis

Ex 3 – Electric Powertrain components





$$\nabla \times (\nu_0 \nu_r \nabla \times A) = J_0$$

FEM-based evaluation of inductance parameters to be used in simplified models of electric motors for HIL (Hardware-In-the-Loop) simulations.

System simulation: is Newton's 2nd law not enough?
"There are more things in heaven and earth, Horatio, Than are dreamt of in your philosophy." People develop software to ***control*** the behaviour of physical systems!

Brownian motion to applied research

RISE in brief

- Present across the whole of Sweden.
- 2,700 employees, 30 % with a PhD.
- Turnover approx. SEK 3 billion (2018).
- A large proportion of customers are SME clients, accounting for approx. 30 % industry turnover.
- Runs 100s of test and demonstration facilities, open for industry, SMEs, universities and institutes

RISE´s Mission from the Swedish Government

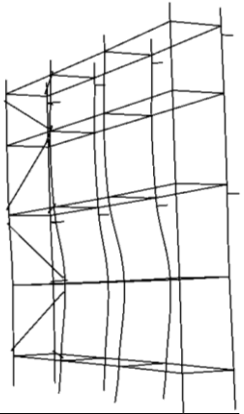
"The industrial research institutes shall be internationally competitive and facilitate sustainable growth in Sweden by strengthening competitiveness and renewal in the business community."

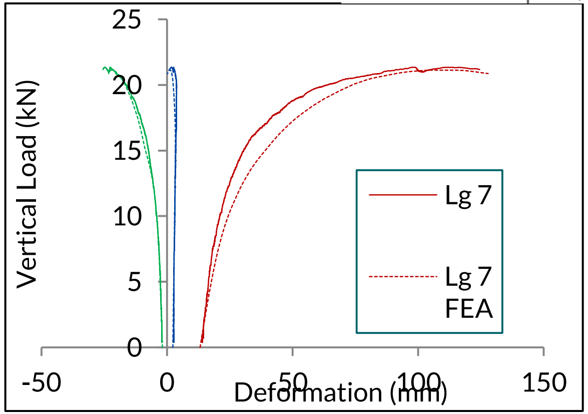
Excerpt from the Research Bill 2016/17: 50 (Kunskap i samverkan).

RI. SE

Applied Mechanics@RISE

Industrial assignments & research projects
~60 test engineers, researchers, project managers

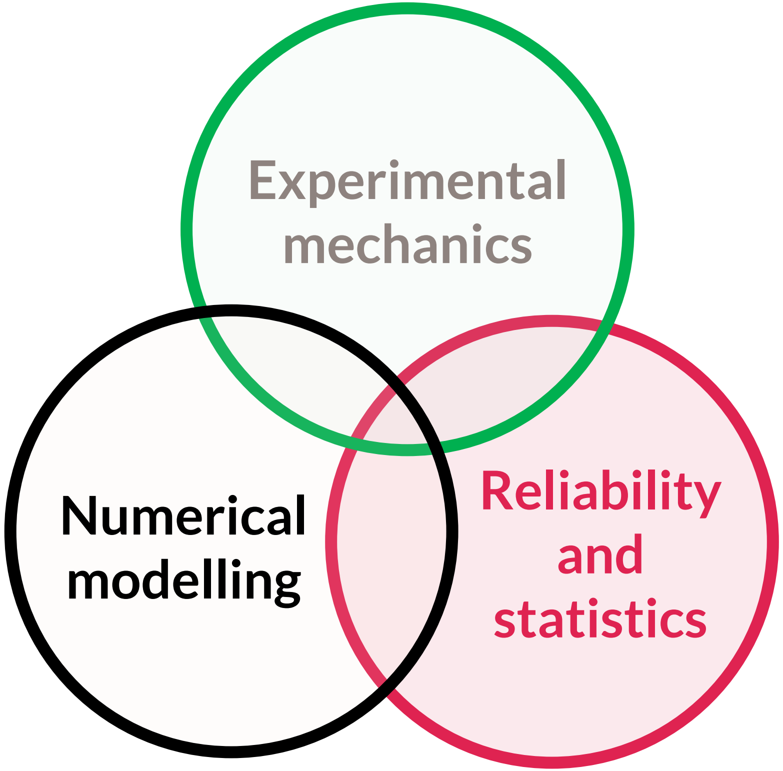




Construction products, protection equipment, infrastructure, automotive…

RI. SE

Applied Mechanics@RISE



Verification and Validation (V&V) of computational models in a nutshell

Increased use of computational models in science and engineering

- reduced product development time
- increased reliability

↓

Are the models “good”?

Modelling credibility assessment

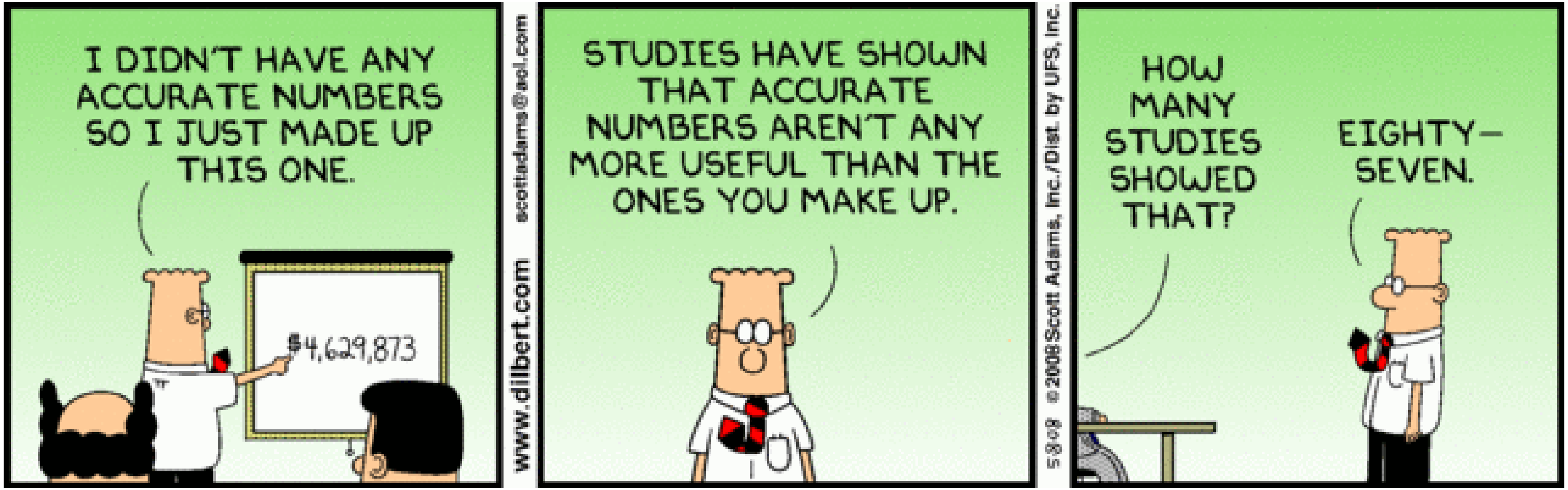
↓

How can the agreement be measured?
When is the agreement “good enough”?

Comparison of predictions to measurements

RI. SE

Uncertainty Quantification



"Until I know this sure uncertainty,
I'll entertain the offer'd fallacy".

W. Shakespeare, *The Comedy of Errors*, Act 2 Scene 2.

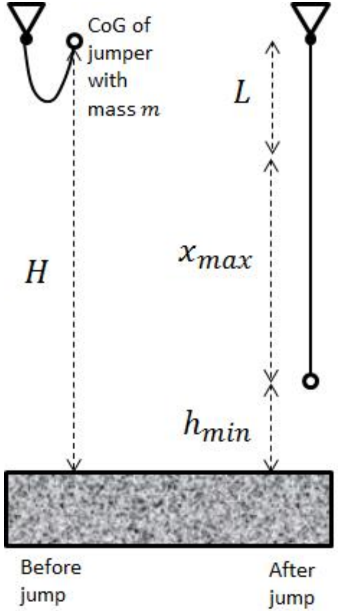
Uncertainty quantification: why?

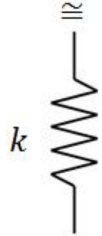
- Models are built on ***assumptions***
- Solutions are computed via ***approximations***
- Material properties and parameters are measured / estimated up to a ***finite precision/accuracy***
- In-service loads and boundary conditions ***might differ*** from test loads
- To err is ***human*** (to solve exactly is divine…)
- Consequences of overconfidence in model predictive capability can be ***catastrophic***

Let us jump to the conclusions

The physical system

The mathematical model





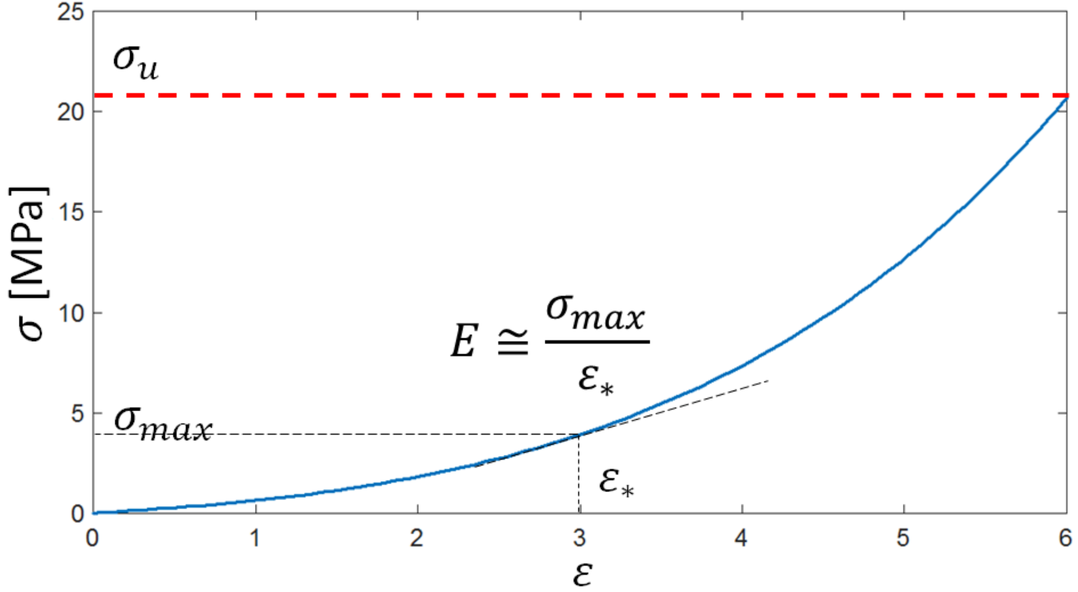
$$k = \frac{AE}{L}$$

$$\varepsilon = \frac{x}{L}$$

Safety requirements for cord design

- The cord should not break after the jump
- The jumper should not impact the ground
- Othe failure modes (e.g. *g*-forces) neglected

$$\varepsilon_{max} \leq \varepsilon_*$$
$$h_{min} > 0$$



Approximate stress-strain curve for natural rubber

Maximum stress allowed

$$\sigma_{max} = \frac{\sigma_u}{\gamma}$$

Safety factor
$\gamma > 1$

Energy conservation

+

Assumptions:

- only CoG dynamics
- no air drag
- massless cord

→ Relationship between safety and design parameters

$$\varepsilon_{max} = \frac{mg}{AE}\left(1 + \sqrt{1 + \frac{2AE}{mg}}\right)$$

$$h_{min} = H - (1 + \varepsilon_{max})L$$

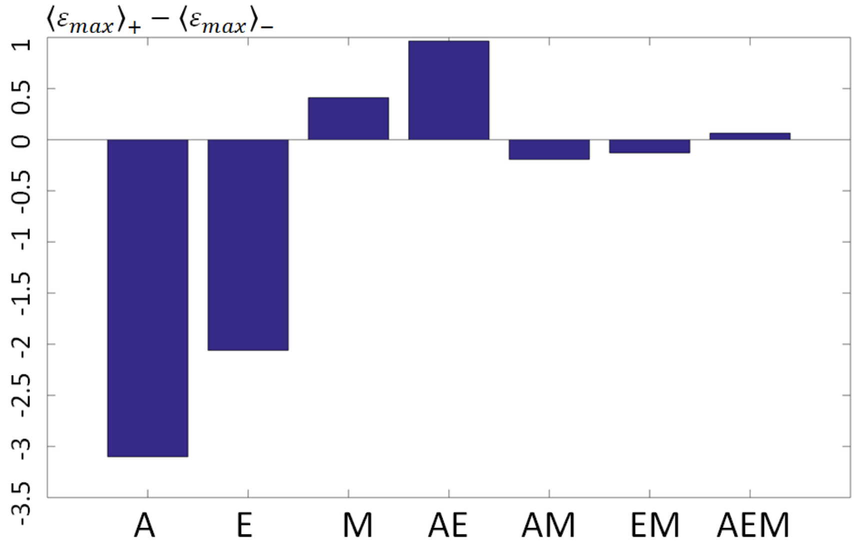
Design parameters are typically determined for assigned safety standards

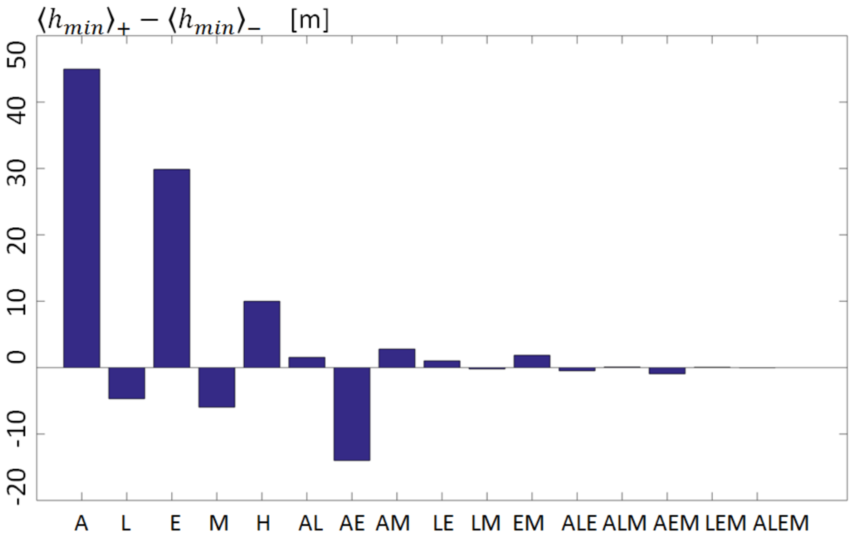
Parameter screening based on 2-level Full Factorial design

Parameter	Units	Lower Level (-)	Upper Level (+)
A	m^2	$5\cdot10^{-4}$	$15\cdot10^{-4}$
L	m	14	15
E	MPa	0.5	1
M	kg	70	80
H	m	70	80

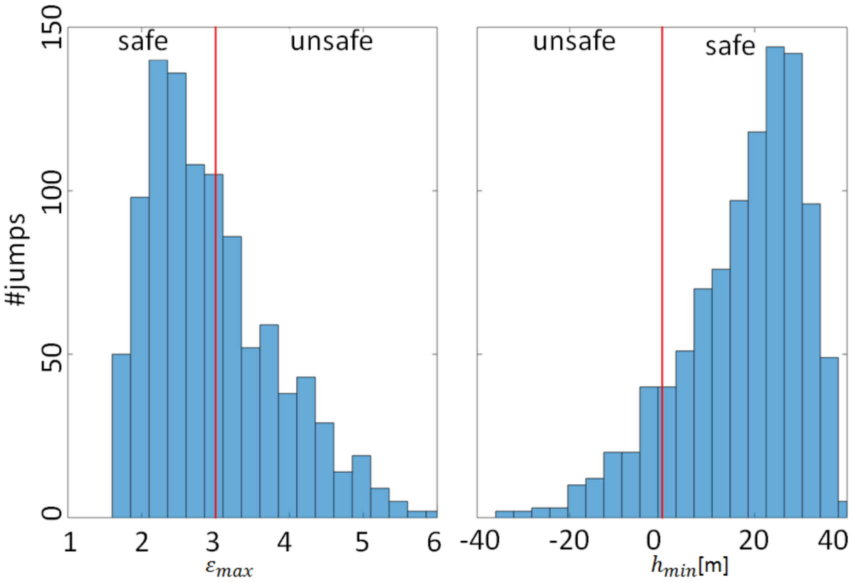
RI. SE

Screening of input factors based on 2-level Full Factorial Design

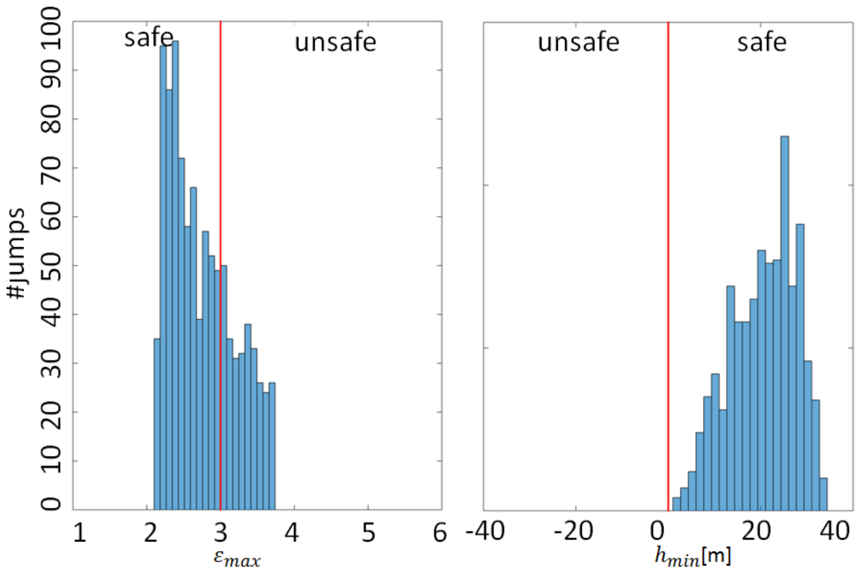




Estimation of output uncertainty based on MC sampling of most influential input factors



Output variance reduction after fixing cord cross section area A



Let us jump to the conclusions

- Experience different paradigms and ways to approach the same problem, e.g. physics, curiosity-driven research vs design, engineering

- In industrial practice, one seldom goes back to the ”naked” math. User-friendly interfaces exist to flatten the learning curve and accelerate the generation of results. However, understanding the math behind the scenes is helpful in many circumstances, including interpretation of the results and essential for development.

- Uncertainty quantification: many potential practical applications related to safe and efficient utilization of resources, it can get quite mathematically sophisticated in some cases.

- Probability distributions as model for subjective judgement – good or bad practice? Pragmatism prevails in applications.