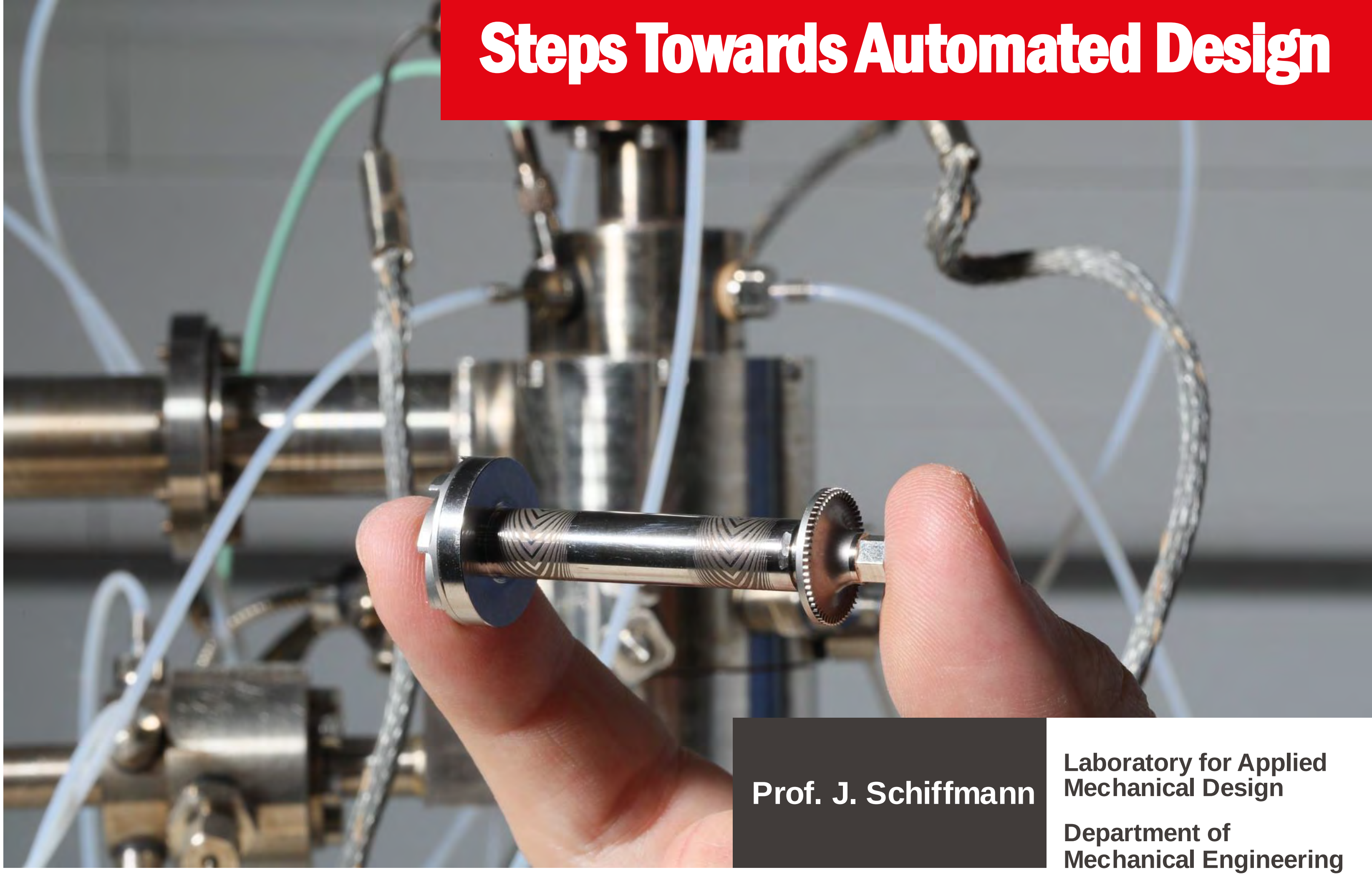
Steps Towards Automated Design



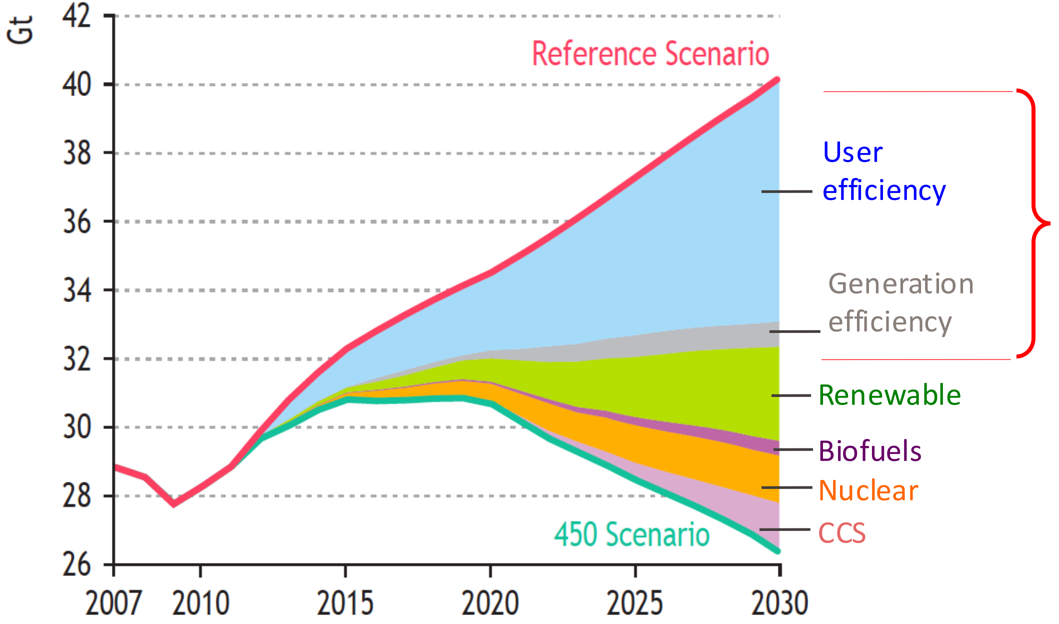
Prof. J. Schiffmann

Laboratory for Applied Mechanical Design

Department of Mechanical Engineering

École polytechnique fédérale de Lausanne

Steps Towards Sustainable Energy Landscape



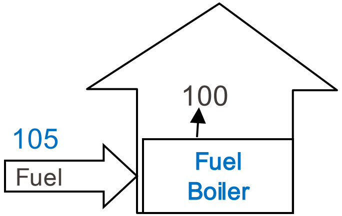
Source: IEA outlook

- Contribute to improve energy conversion efficiency by research & engineering

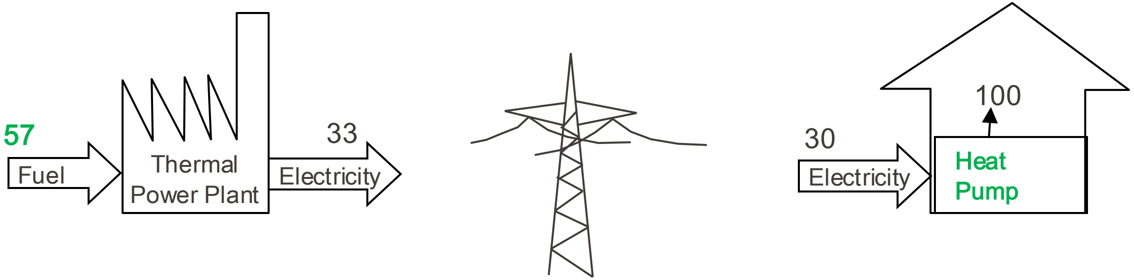
- 50% of required cuts achieved by increasing conversion efficiency
- 27% of primary energy goes into domestic heating and air-conditioning

Prof. J. Schiffmann

Domestic Heating: Comparison of Technology Combinations



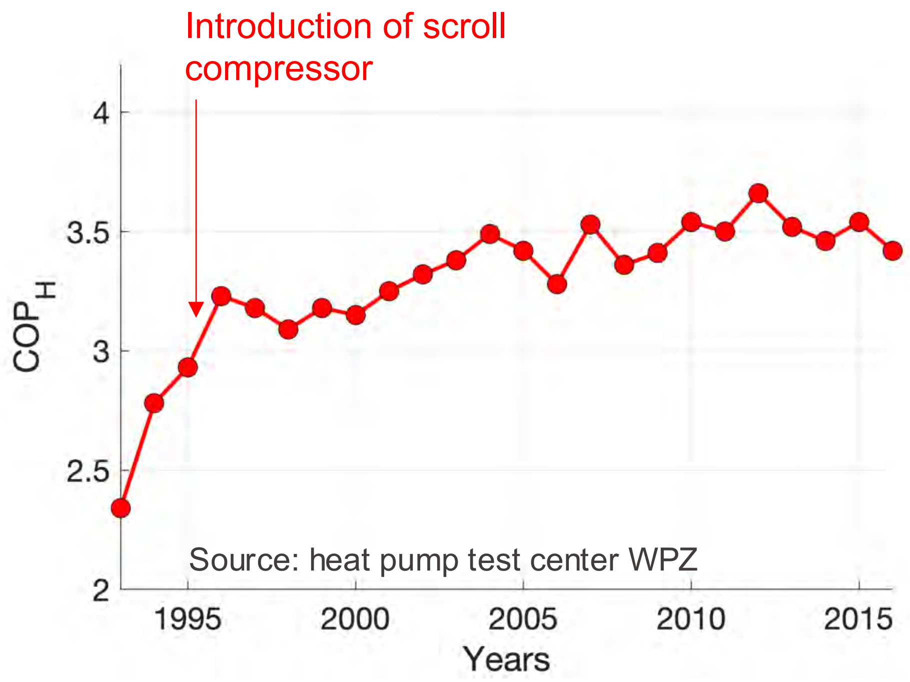
$$\text{Energy ratio} = \frac{100}{105} = 95\%$$



$$\text{Energy ratio} = \frac{100}{57} = 176\%$$

- Heat pumps play key role in reducing energy consumption and CO_2 emissions

Evolution of COP for Heat Pumps



$$COP = \frac{E_{Heat}}{E_{Electricity}}$$

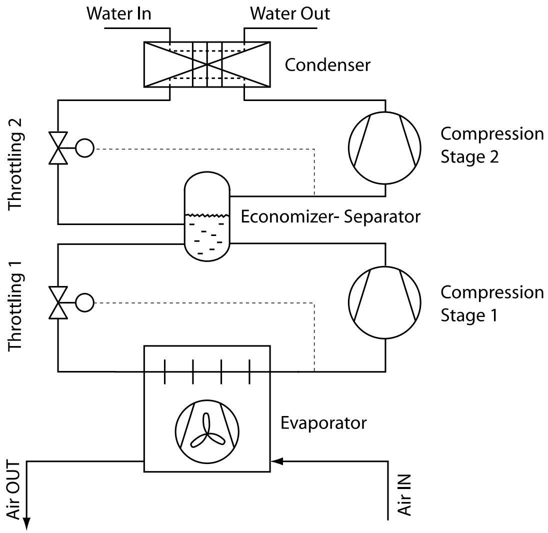
- Since introduction of scroll compressors, COP has been rising slowly
- Key question: can another step-change be achieved and if so, how?

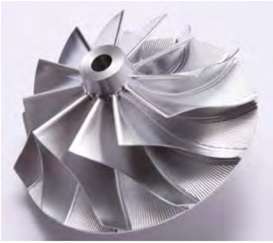
Key Challenges

- Assessment of losses in heat pump cycles
  - Compression 50%
  - Expansion 30%
  - Heat transfer 20%

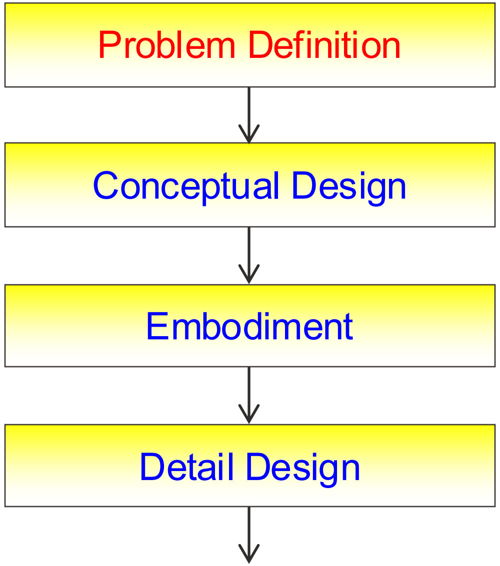
- Possible ways to reduce losses
  - Increase compressor efficiency
  - Use oil-free technology
  - Implement multistage cycles

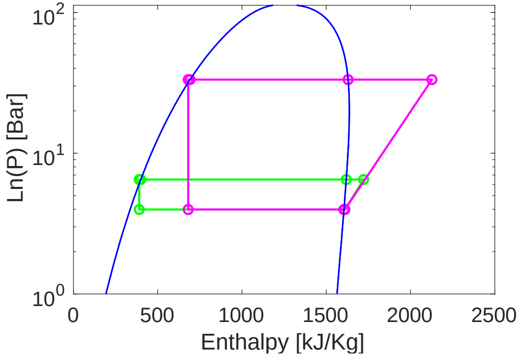
- Potential enabler
  - Turbocompressors on oil-free bearings





Designing an Oilfree Turbocompressor





- Domestic heat pump
- Range of mass-flows, inlet T&P
- Working fluid
- Expected lifetime

Designing an Oilfree Turbocompressor

Problem Definition

↓

Conceptual Design

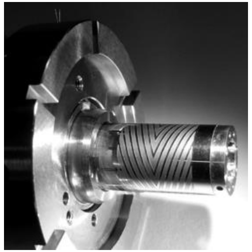
↓

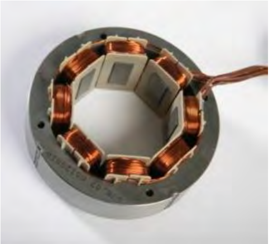
Embodiment

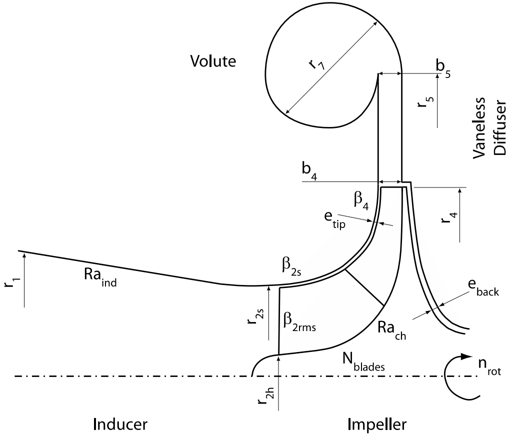
↓

Detail Design

↓







Designing an Oilfree Turbocompressor

Problem Definition

↓

Conceptual Design

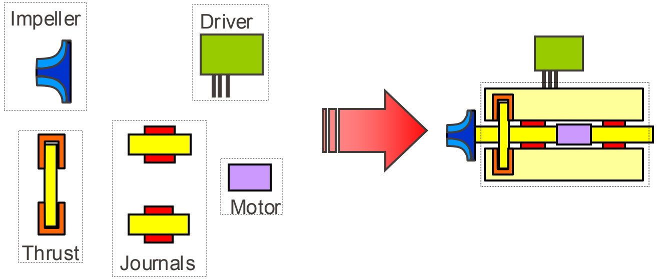
↓

Embodiment

↓

Detail Design

↓



Designing an Oilfree Turbocompressor

Problem Definition

↓

Conceptual Design

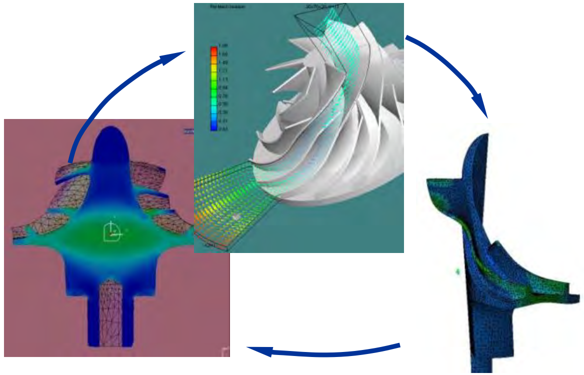
↓

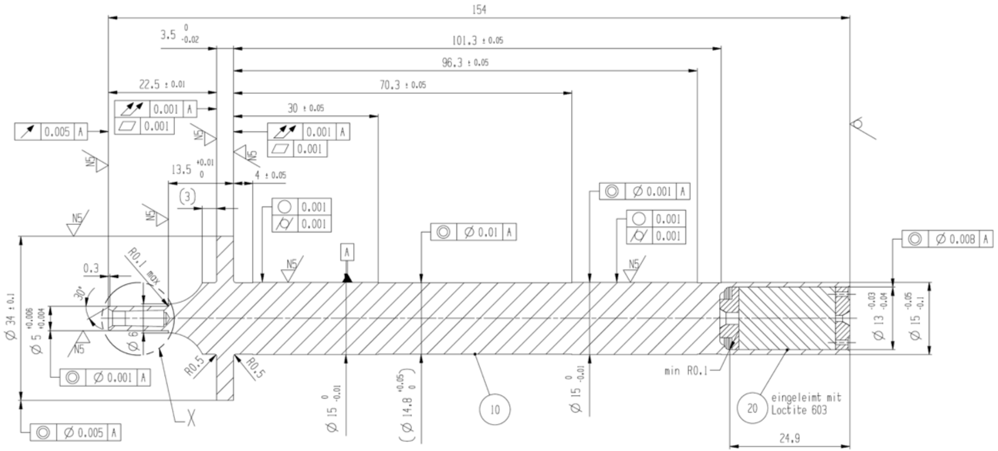
Embodiment

↓

Detail Design

↓



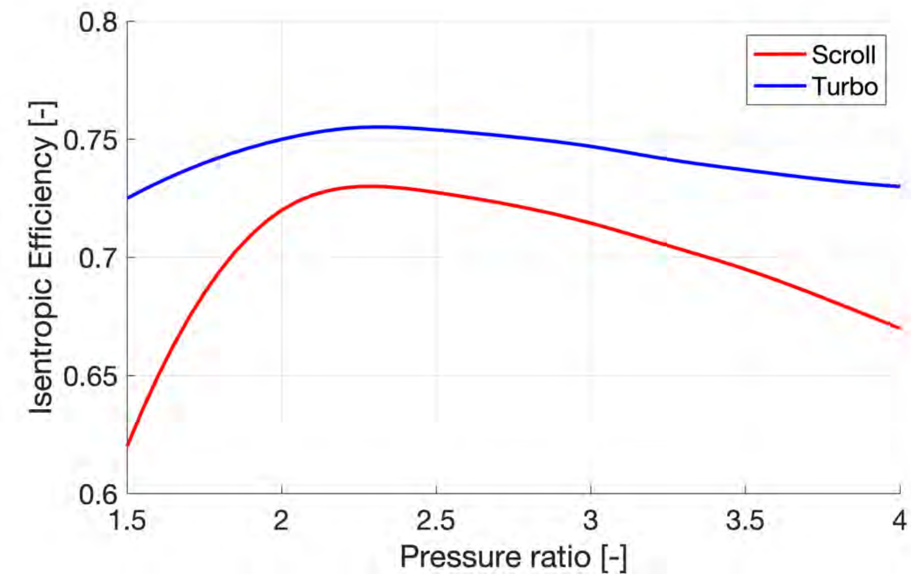


Proof of Concept Single Stage Compressor

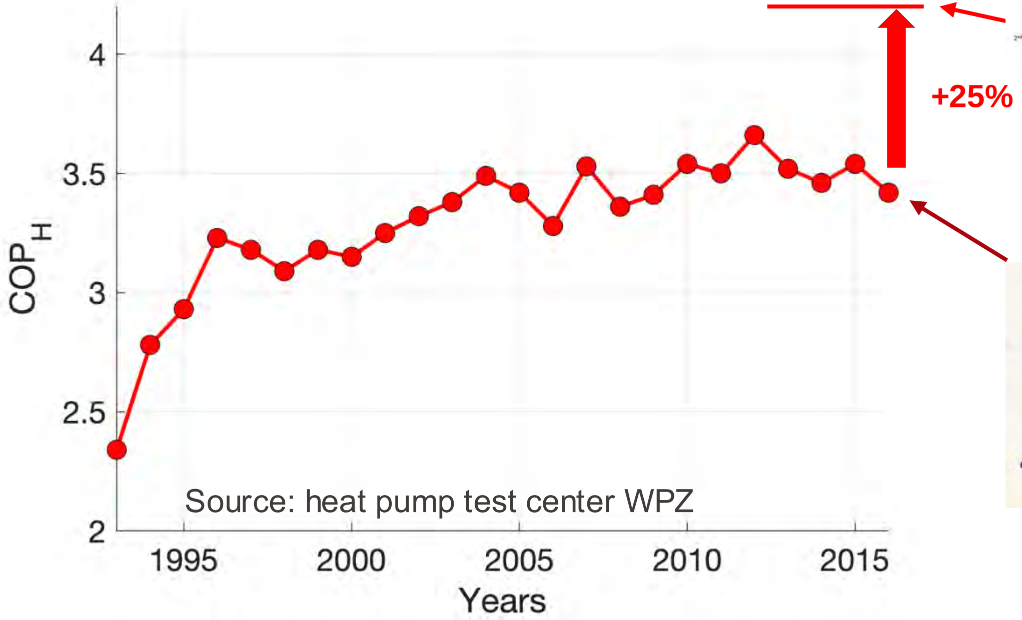
- Experimental demonstration of small-scale turbocompressor
  - Ø20 mm impeller, 210 krpm, 2 kW, Π 3.3
  - Oil-free, R134a-lubricated bearings
  - Increased specific power (x10)

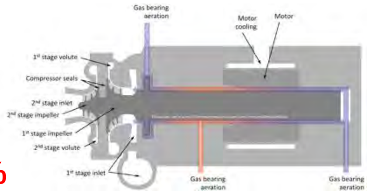
Proof of Concept Comparison

- Turbocompressor achieves higher peak efficiency than positive displacement compressor and improves off-design operation



Potential of Oilfree Turbocompressors on COP



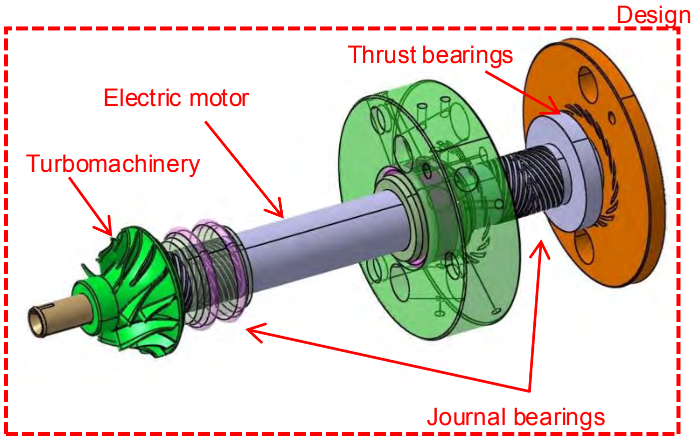


- Turbocompressor
- Multi-stage
- Oilfree

- Scroll compressor
- Single stage
- Oil lubricated

- Key question: can another step-change be achieved and if so, how?
- With multi-stage heat pump cycles driven by oilfree turbocompressors

Design Challenges of High-Speed Turbomachinery



- Pronounced multidisciplinarity
- Strong interactions between components
- Competing design objectives
- High level of design constraints

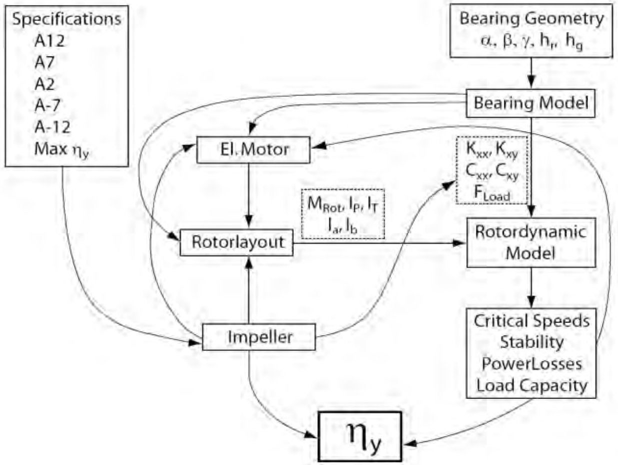
- Traditional design approach based on fragmented component view
  - Tends to neglect component interactions
  - Hindrance to novel solutions
  - Yields suboptimal solutions
  - Manual iterations leave no peace of mind

Integrated Design Approach

- Design problem formulated as multi-objective optimization

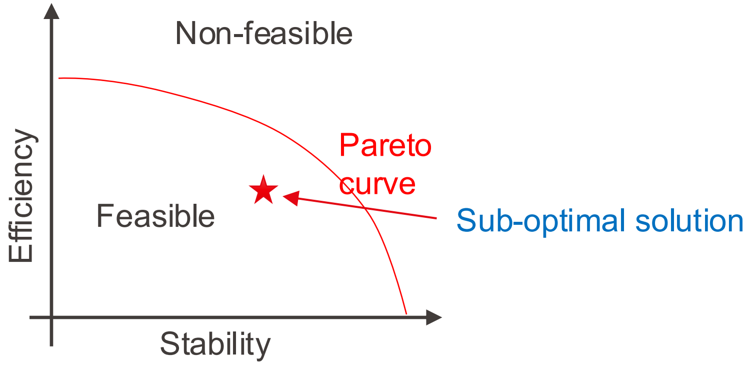
$$min f\left(G\right) = -\left[\eta_{is}\left(G\right), \Gamma\left(G\right)\right]^{T}$$

- Subject to constraints
  - Bearing clearance
  - Bearing load capacity at low speed
  - Thrust bearing load capacity
  - Margin to 1st lateral bending eigenmode
  - Avoidance of compressor surge
  - Mechanical stress below threshold



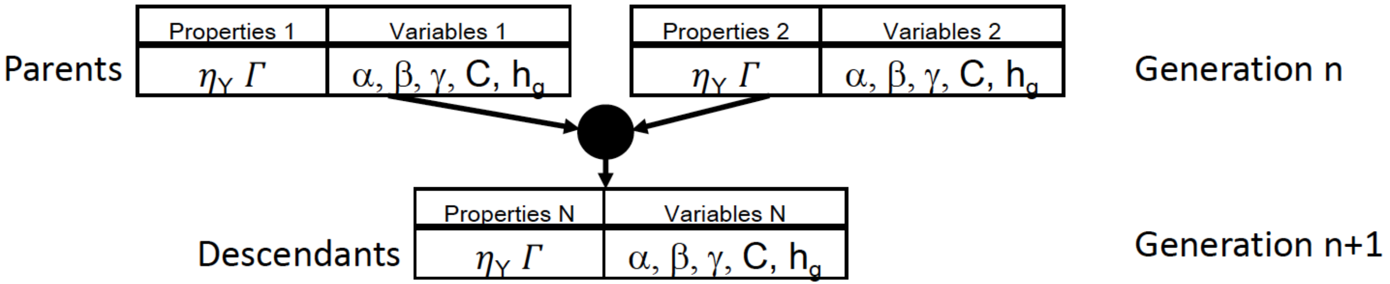
Multi-Objective-Optimization

- Competing objectives result in Pareto curve
  - Pareto curve splits objective domain into feasible and non-feasible regions
  - Pareto curve is a family of non-dominated solutions
  - Selecting “right” objectives can be challenging

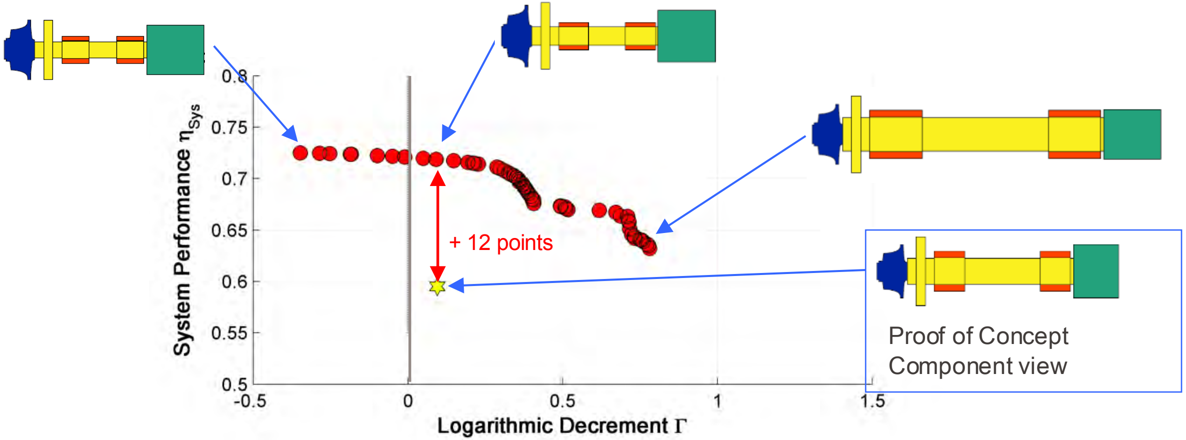


Search for Pareto Curve

- Evolutionary algorithms
  - Procedure is started with initial population of solutions
  - Each individual is characterized by genes (variables) and by resulting performance (indicators)
  - Individual are crossed and descendants generated
  - Fit solutions are kept, unfit ones discarded



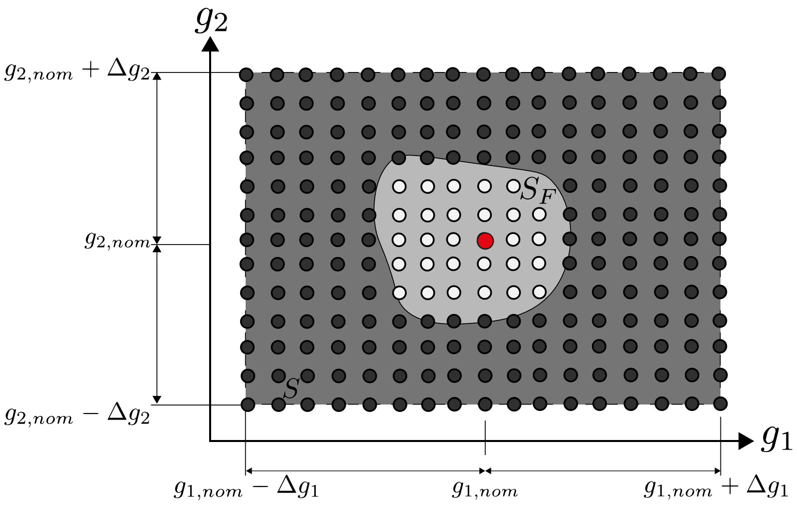
Integrated Design and Optimization



- System approach captures complex interactions and improves compressor performance by 12 points compared to component view
- Are these ”right” objectives? What about robustness?

How to Define Design Robustness?

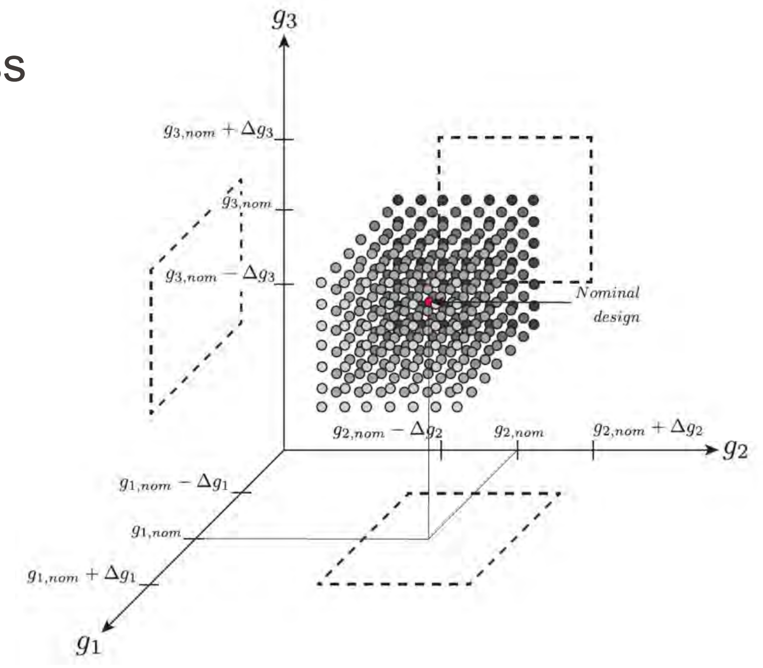
- Maximize hypervolume defined by feasible design within assessed deviation volume around nominal design
- Maximize signal-to-noise ratio to maximize performance and reduce variance across hypervolume



$$S/N_{\mathrm{f}} = 10 \cdot \log_{10}\left(\frac{\mu_{\mathrm{f}}^2}{\sigma_{\mathrm{f}}^2}\right)$$

Challenges to Identify Robust Designs

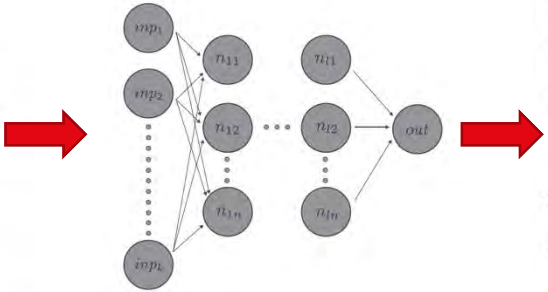
- Increased number of objectives
- Increased number of evaluations to assess effect of deviation requires fast models
- Need fast and accurate surrogate models

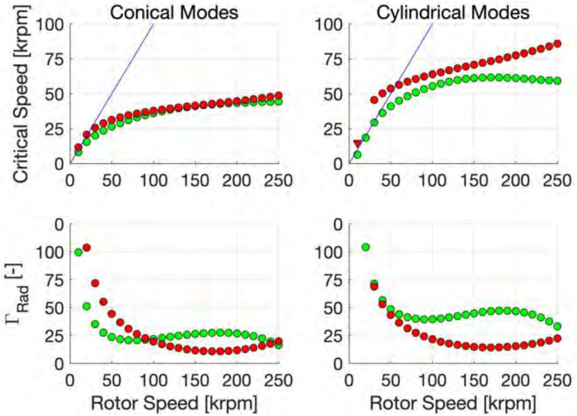


Neural Network Based Surrogate Model

- Input is bearing and rotor geometry, output is whirl speed map
- Relative error <3% between high-fidelity and surrogate model
- Surrogate model based on ensemble of networks

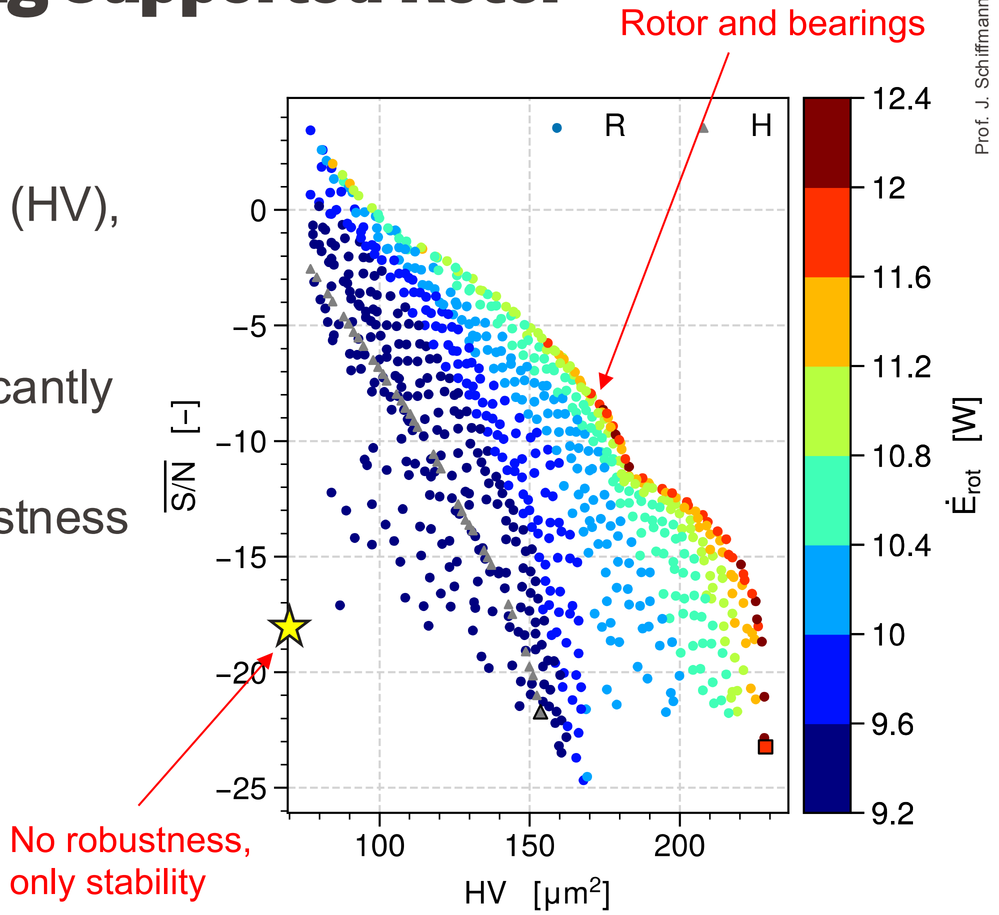
Variable	Symbol
Groove-ridge width ratio	$\alpha = \frac{a}{a+b}$
Groove angle	β
Grooved region ratio	$\gamma = \frac{L_o - L_{land}}{L_o}$
Bearing length to diameter ratio	$LoD = \frac{L_o}{2R}$
Ratio of bearings distances to CG	$H_{gr} = 1 + \frac{h_g}{h_r}$
Mass number	$\overline{M} = \frac{M h_r \Omega^2}{P_a R^2}$
Transverse moment of inertia number	$\overline{I_t} = \frac{I_t h_r \Omega^2}{P_a R^2 L_o^2}$
Polar moment of inertia number	$\overline{I_p} = \frac{I_p h_r \Omega^2}{P_a R^2 L_o^2}$
Bearing A distance to CG	$\overline{L_A} = \frac{L_A}{L_o}$
Bearing B distance to CG	$\overline{L_B} = \frac{L_B}{L_o}$
Compressibility number	$\Lambda = \frac{6 \cdot \mu \Omega \cdot (D/2)^2}{Pa \cdot h_r^2}$



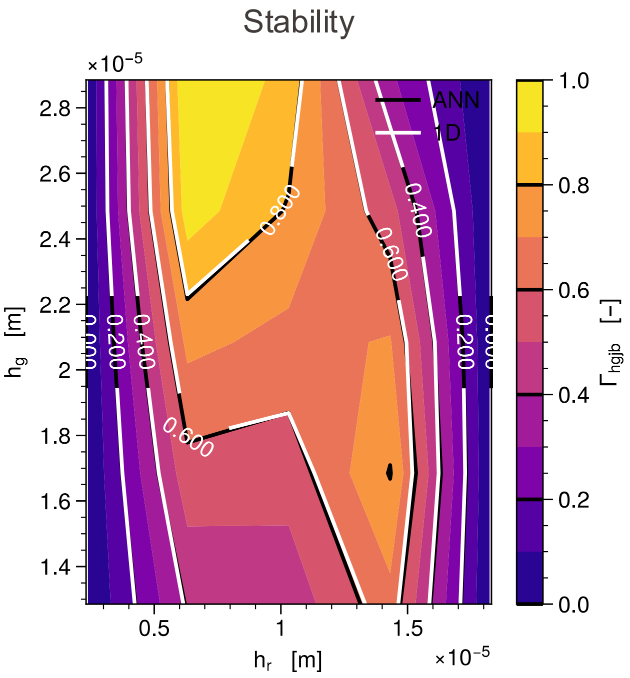


Test Case: Gas Bearing Supported Rotor

- Tradeoff between robustness (HV), losses, and variance (S/N)
- Robustness increased significantly
- Supports idea of design robustness
- Increased robustness offers cost savings

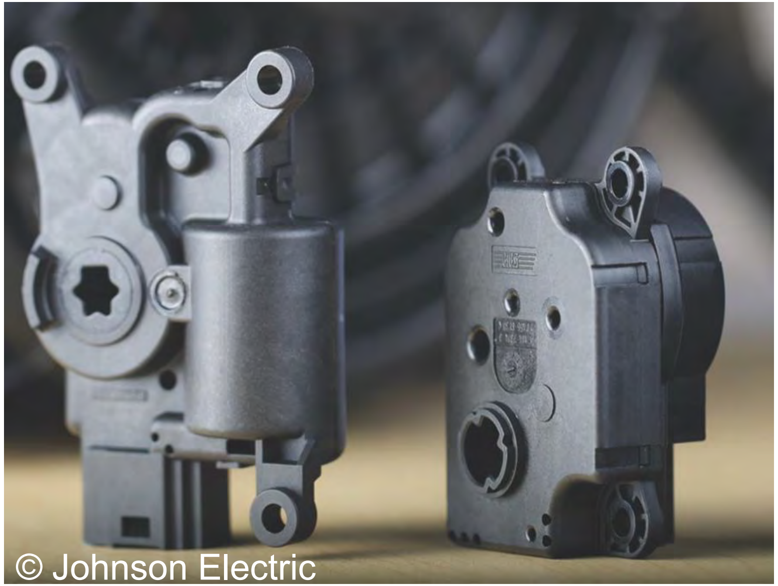


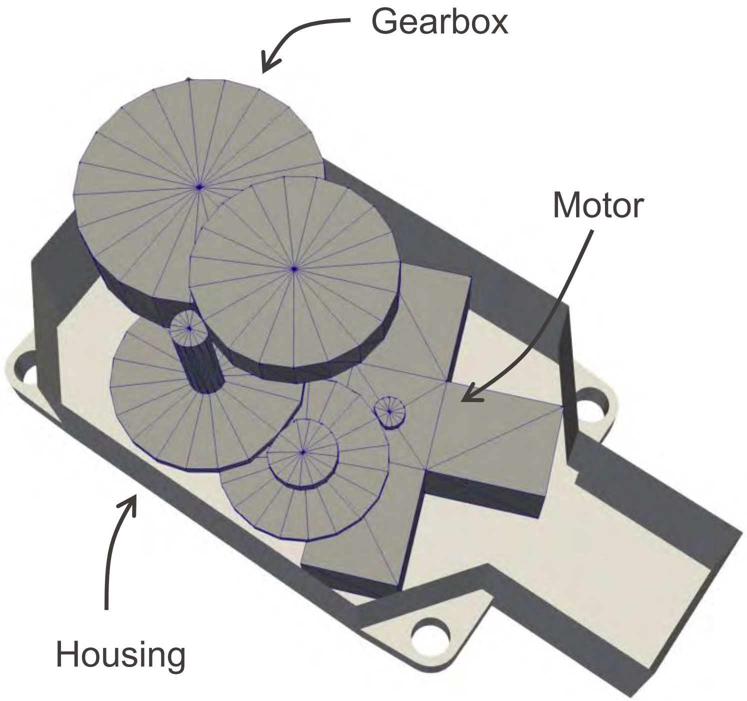
Test Case: Deviation Effects on Objectives



- Stable operation with radial clearance 10±8 μm instead of 7±1.5 μm
- Excellent agreement between high-fidelity and surrogate model
- Baseline model optimization performed on HPC of EPFL
  - 96’000 CPU-core-h, € 1’300, 750kWh
- Surrogate model based optimization performed on GPU
  - 1.5 GPU-h, € 1, 0.5kWh

Design of Electromechanical Actuators

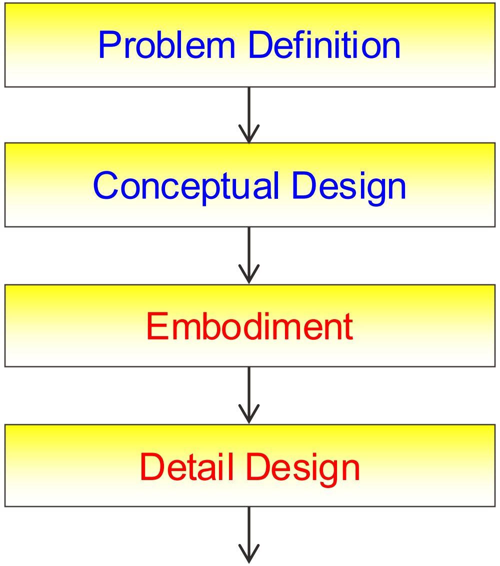




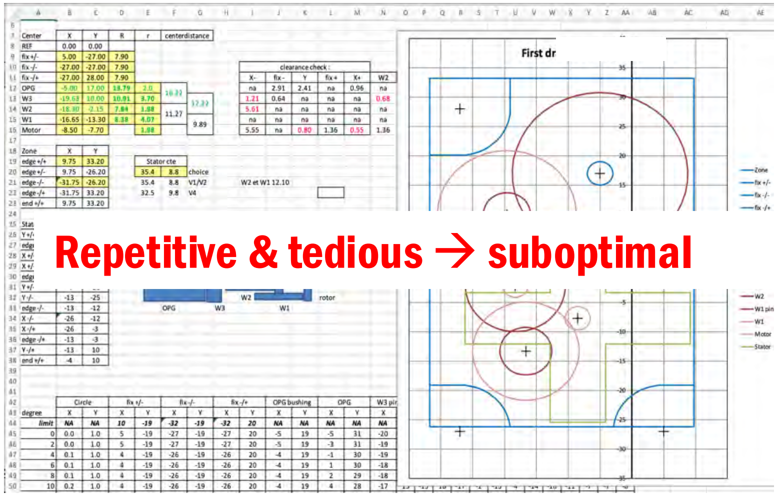
- Actuators for car industry (ventilation, light, grill, parking brake)

Design of Electromechanical Actuators

- Embodiment & Detailed design



- Routine task with manual optimization
- 1 project manager and 2 specialists working ~ 1 month

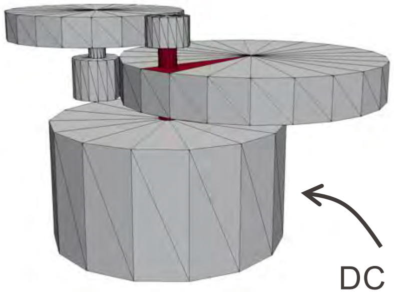


Repetitive & tedious → suboptimal

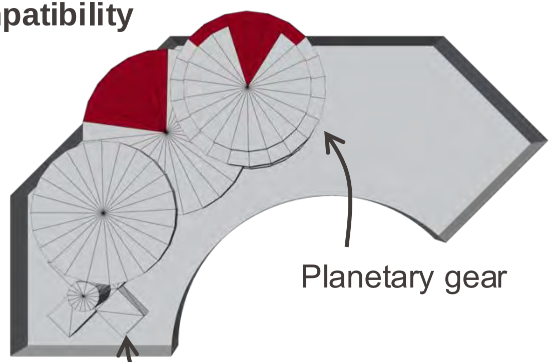
Integrated Actuator Model

- Modular components
  - Physics (motor, gearbox)
  - Cost
- 3-D mesh enables identification of constraints
  - Triangle-triangle collision detection
  - Ray-tracing algorithms

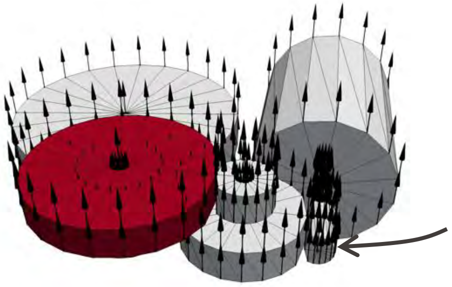
Internal collisions



Packaging compatibility



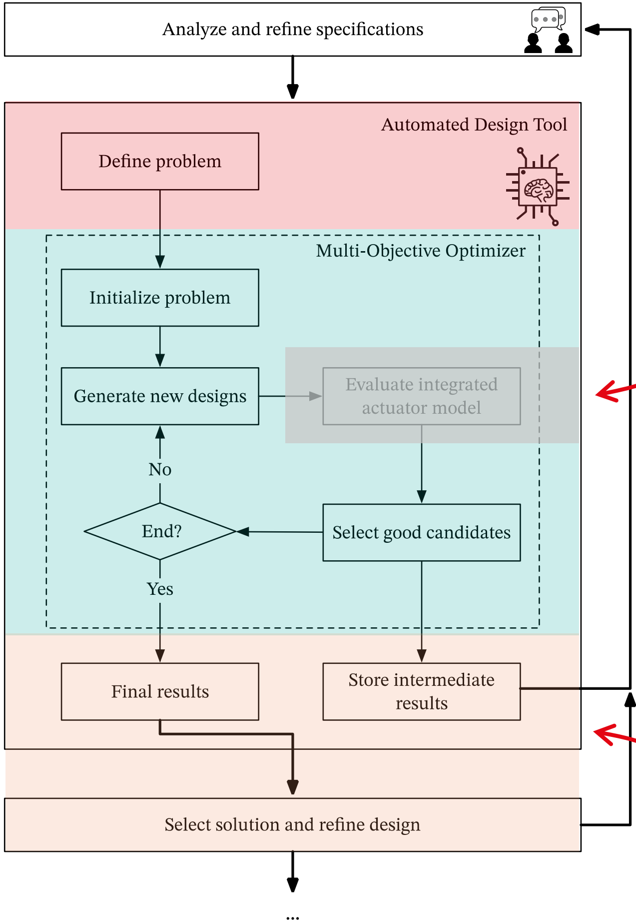
Ease of assembly



Automated Design Tool

Numerical conditioning

Multi-objective optimization via evolutionary algorithms



User input

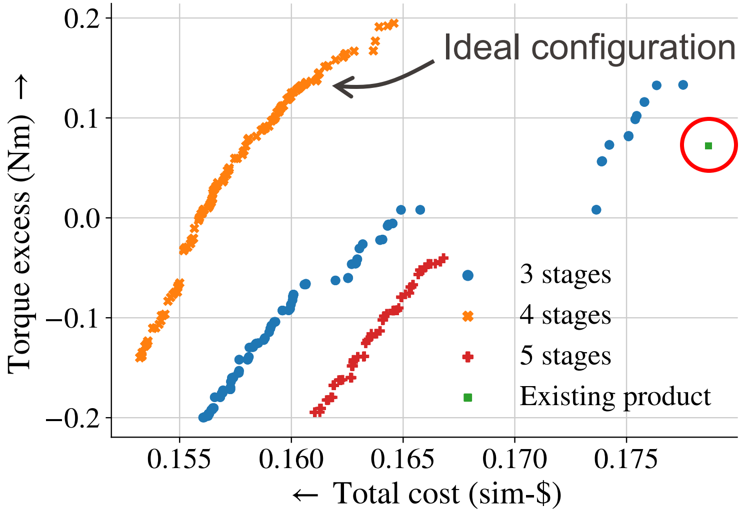
Integrated model

Rapid feedback

Set of solutions for decision-making support

Example: Actuator for Ventilation Flaps

- Optimization for max torque and min cost
- Obtained solutions outperform solution by experienced engineers
- Pareto optimal solution obtained within < 2h on classical laptop



Outlook & Next Steps

- Push design automation towards earlier phases of process
- Refine surrogate modeling techniques
- Alternative optimization methodologies
- Computationally cheap digital-twins for real-time monitoring

EPFL

Thank you for your attention

jurg.schiffmann@epfl.ch

lamd.epfl.ch

Laboratory for Applied Mechanical Design

Department of Mechanical Engineering

École polytechnique fédérale de Lausanne