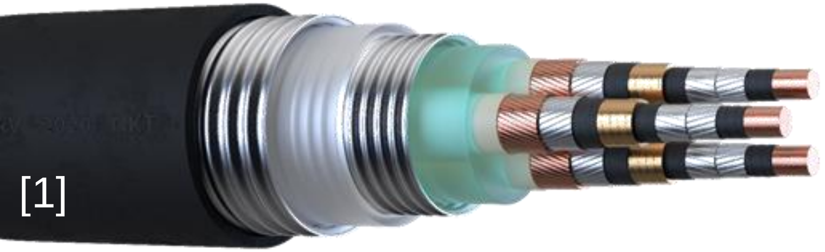
Modelling and optimization of cryogenic mixed-refrigerant cycles for the cooling of superconducting power cables

F Boehm, S Grohmann, **Cryogenic Engineering Conference, Honolulu, C1Or2A-01, July 10, 2023**

SuperLink – 15 km superconduction in Munich

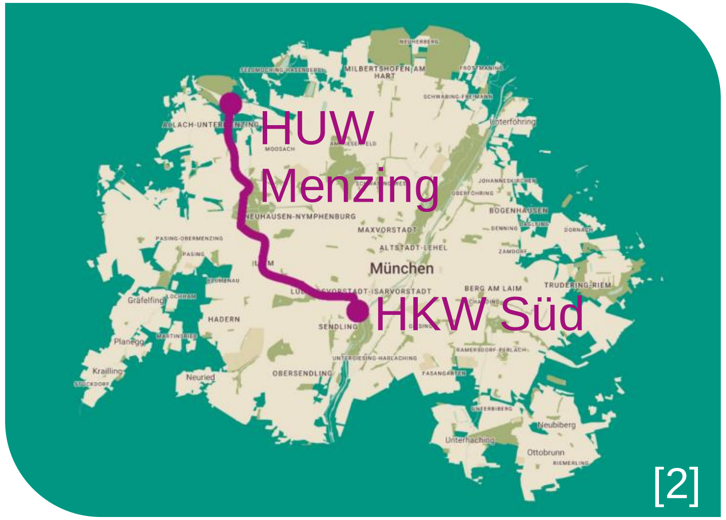
Karlsruhe Institute of Technology

- Progressing electrification due to energy transition
- Upgrading power grid is imperative (age, performance)



[1] www.nkt.de

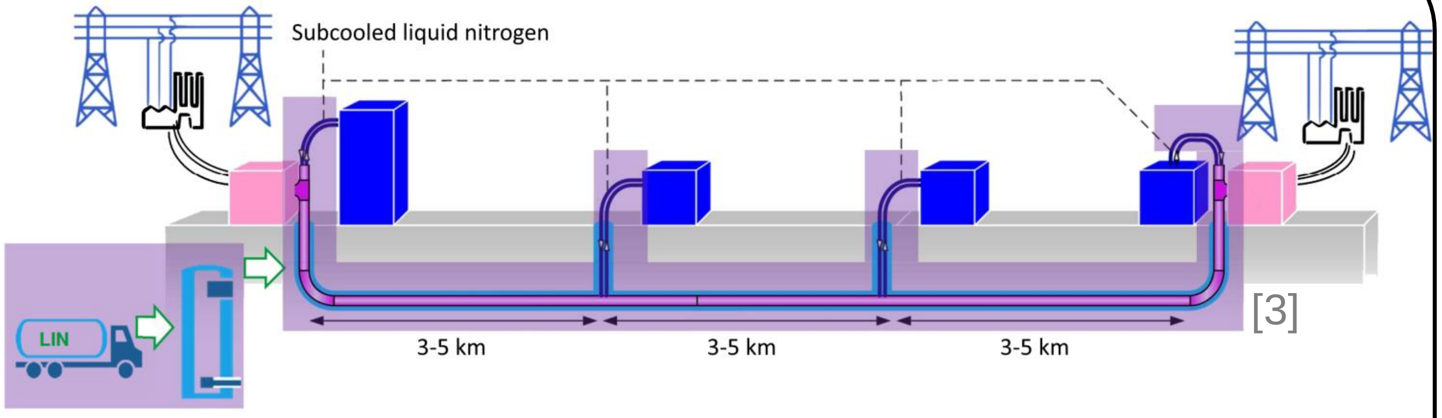
- Lower space demand
- No electromagnetic emissions
- No joule heating
- Higher transmission performance



[2] Google Maps

SuperLink – Cooling stations

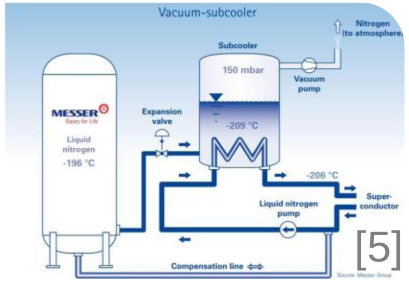
- Cooling temperature below 77 K
- 15-30 kW per cooling station
- Low-maintenance & reliable
- Low space requirement
- Low energy demand



[3]

[3] Alekseev et al. 2020


[4]



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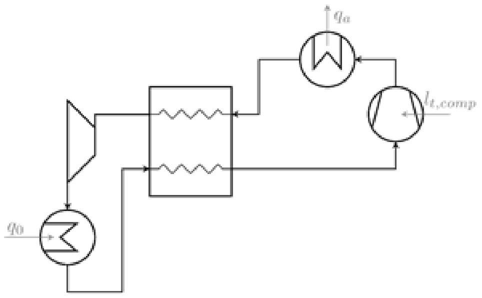
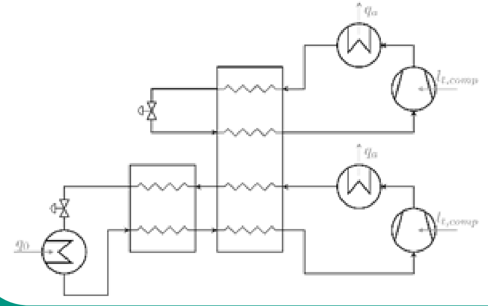
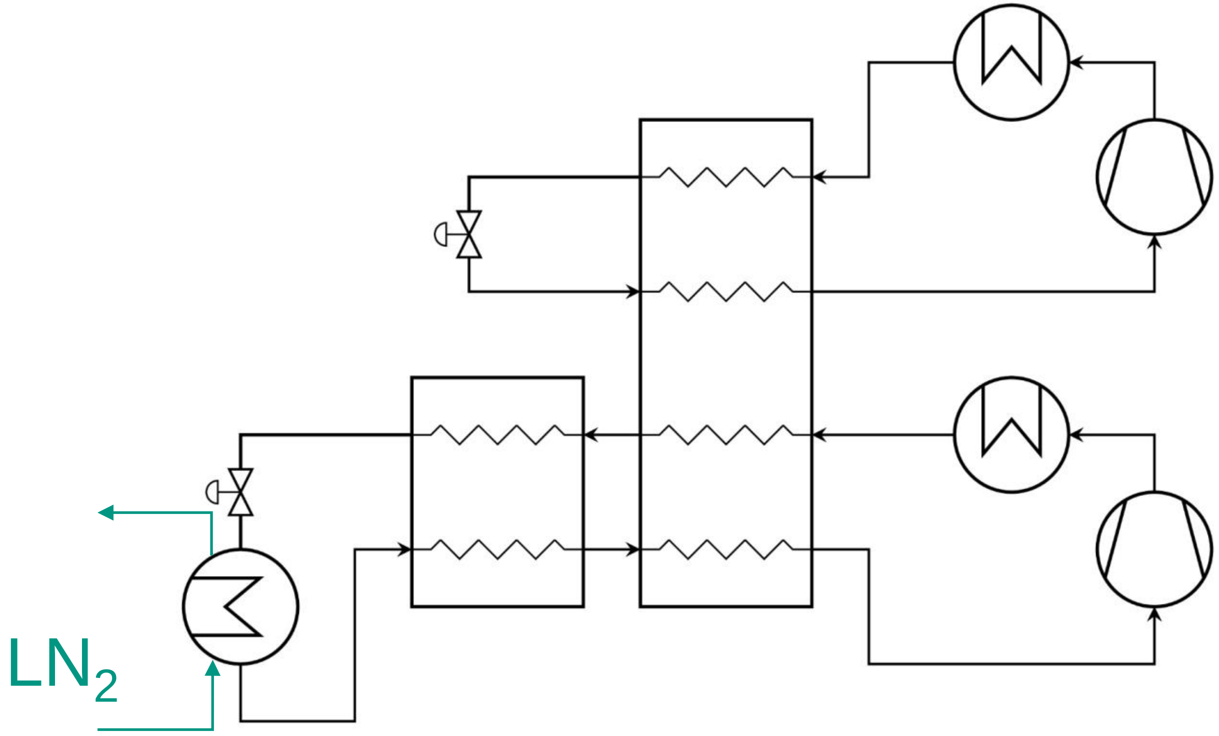




[4] stirlingcryogenics.eu

[5] Herzog et al. 2020

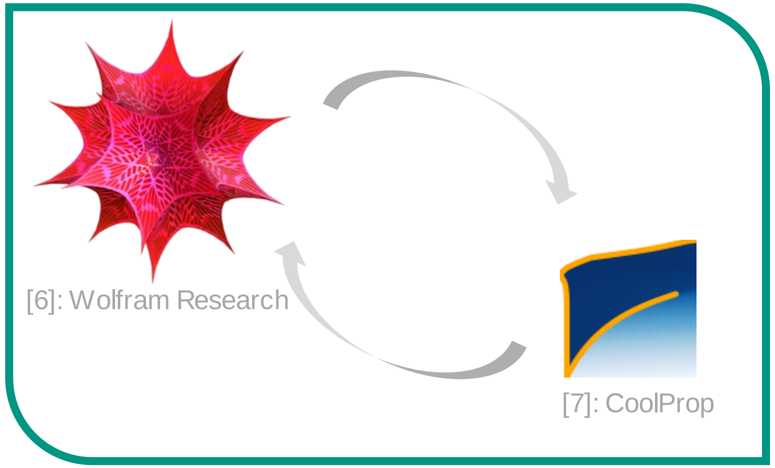
CMRC cascade

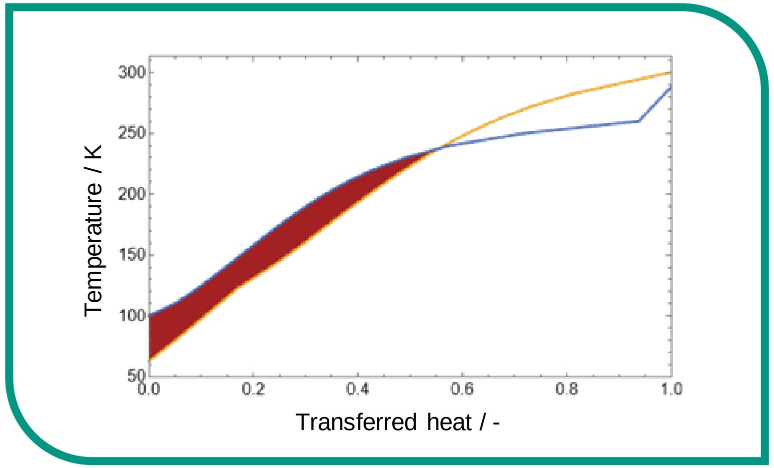


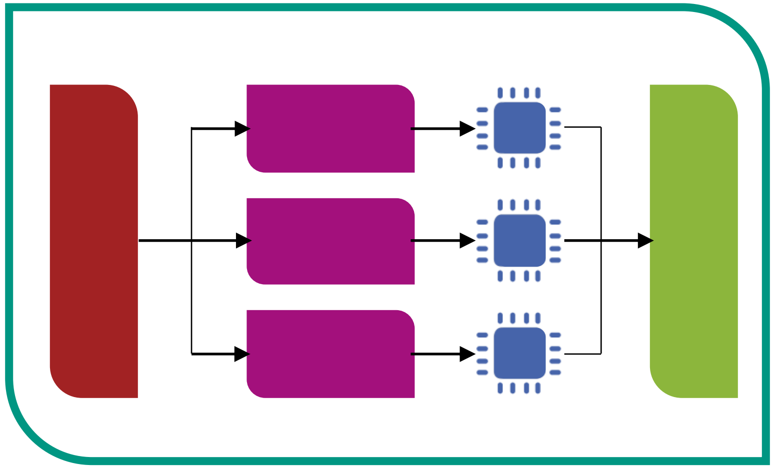
- Single-stage CMRC inefficient for very low temperatures (70 K)
- Model presentation of cascade in future publication

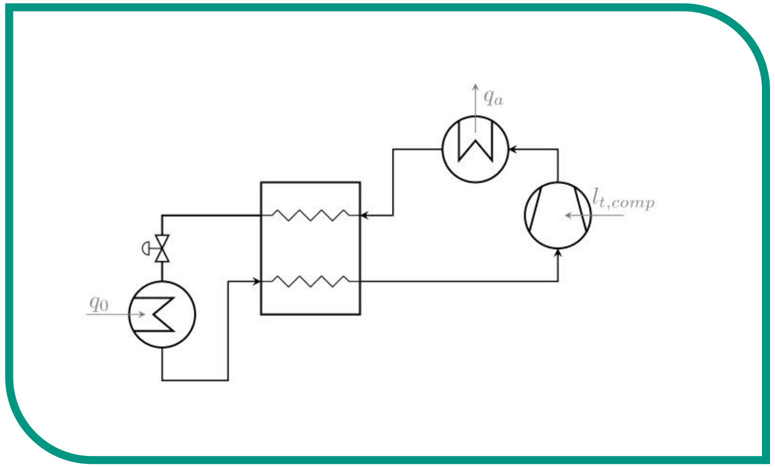
- This presentation:
  - Modelling single-stage CMRC
  - Optimization concept

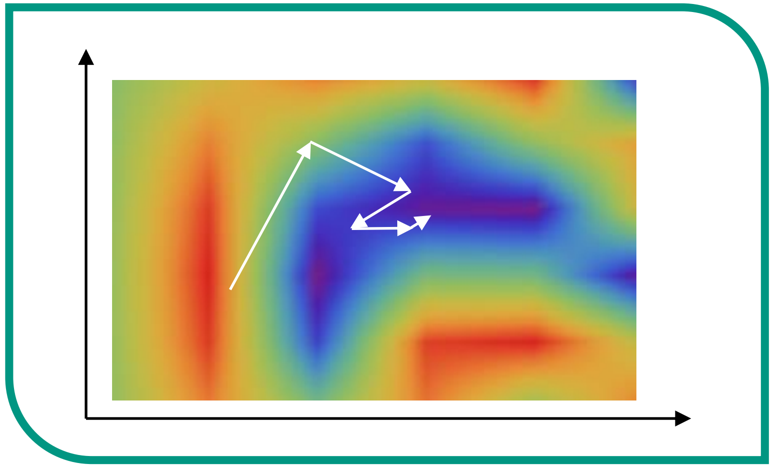
Implementation

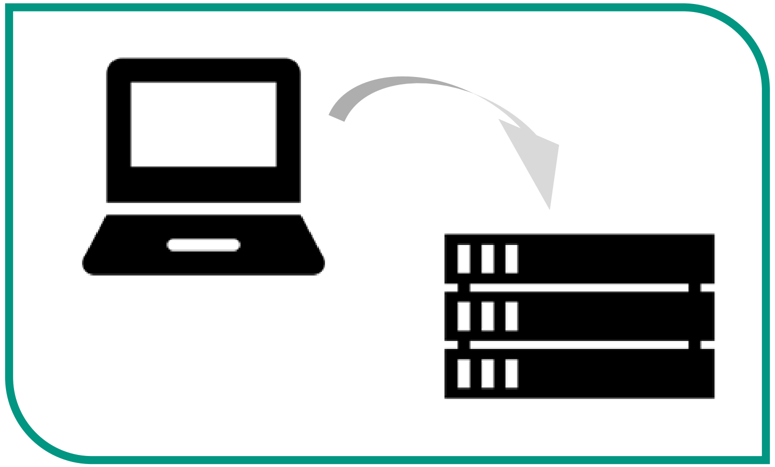






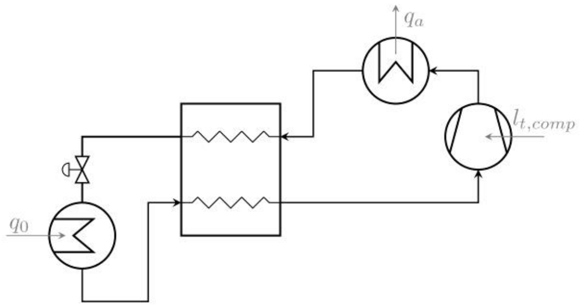






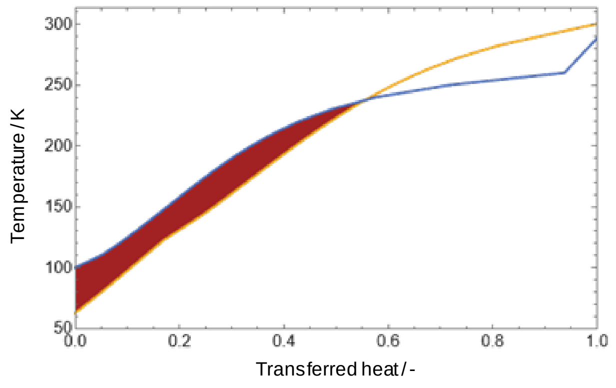
Process Simulation

- Single-stage CMRC (Linde-Hampson)
- Model built in Wolfram Mathematica
- Steady-state simulation
  - Single-stage compressor, fixed efficiency
  - High and low pressures, pressure drop
  - Temperature levels, minimum temperature approach
  - Mixture components and concentrations



- Results
  - Energy demand
  - Temperature profile

Pinch Point Detection



- Finding pinch points through generated temperature profiles
- Quantifiying „physicality“ with equation developed by Kochenburger [8]
  - $$A = \int_0^{|\dot{Q}_{\mathrm{total,HP}}|} \max\left\{0, \Delta T_{\mathrm{min,HX}} - (T_{\mathrm{HP}} - T_{\mathrm{LP}})\right\} \mathrm{d}|\dot{Q}_{\mathrm{HP}}|$$
  - Needed for penalty functions in optimization

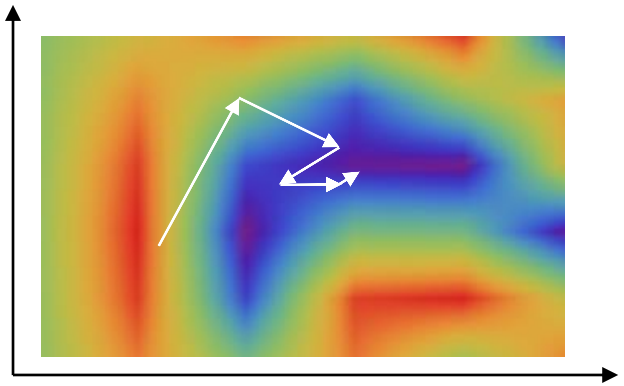
Optimization

- Concentrations
- Pressures
- Temperatures

CMRC circuit

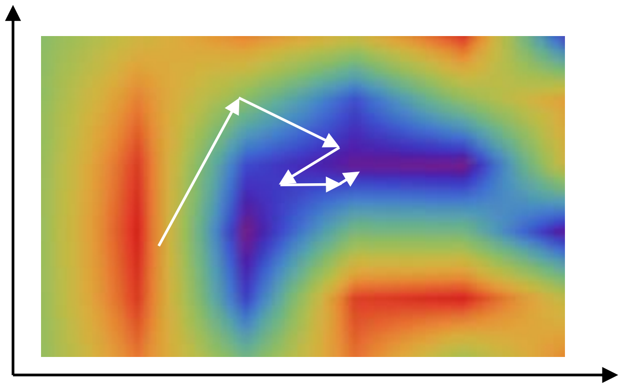
Complex correlations
No derivatives available
→ disqualifies many algorithms

- Energy demand
- Pinch point analysis



Optimization

- No derivatives needed
- Independent of starting values
  - Global optimization
- Treatment of boundary conditions
- Abort criterion definable



Differential Evolution[9,10]

- Genetic algorithm
- Global optimization „Exploration & Exploitation"

Optimization

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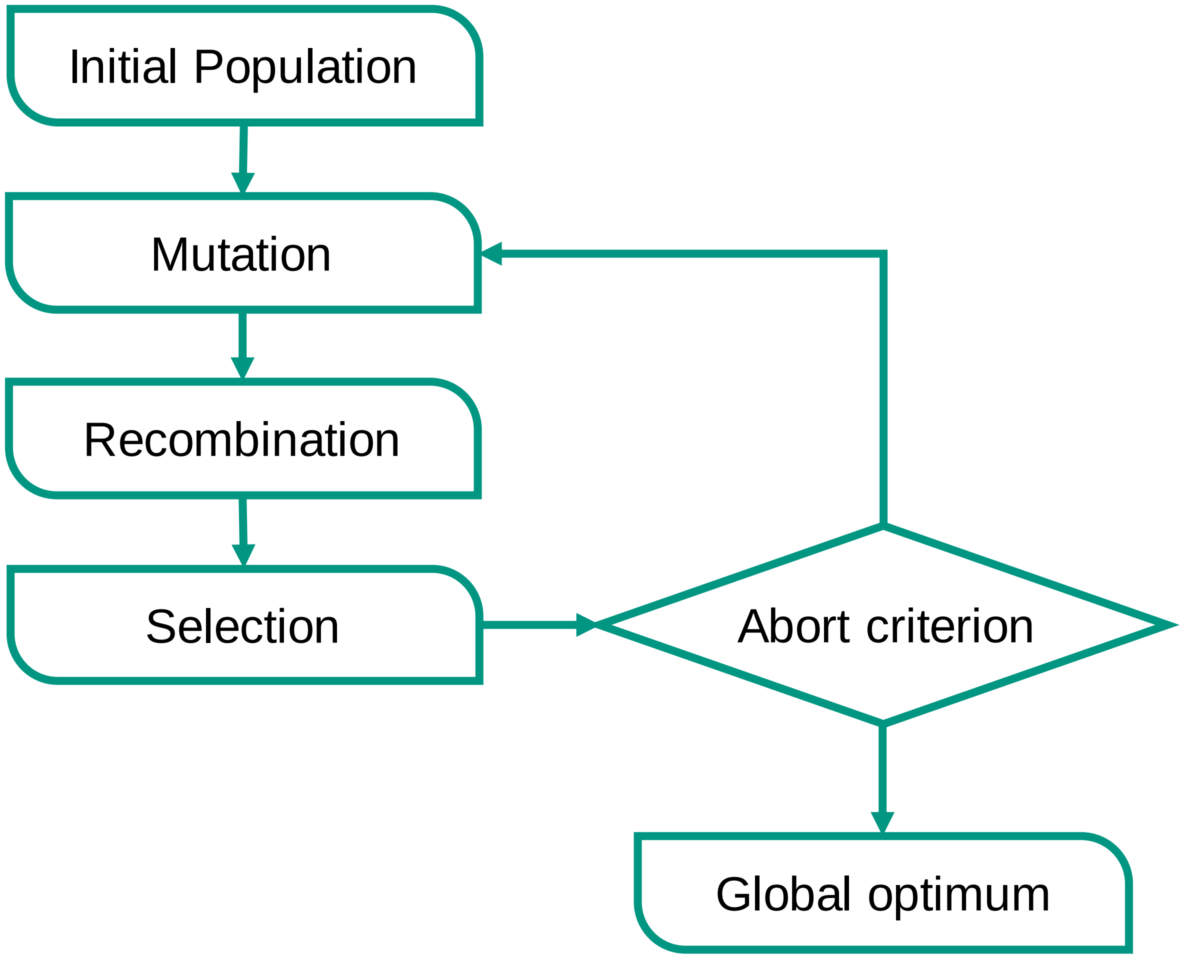
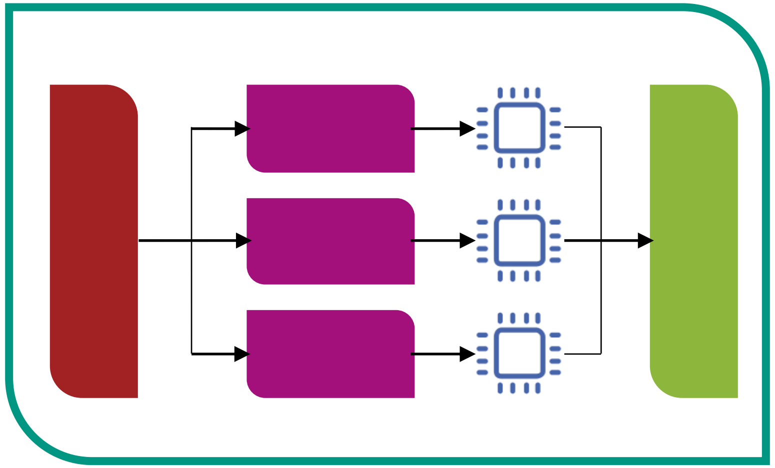


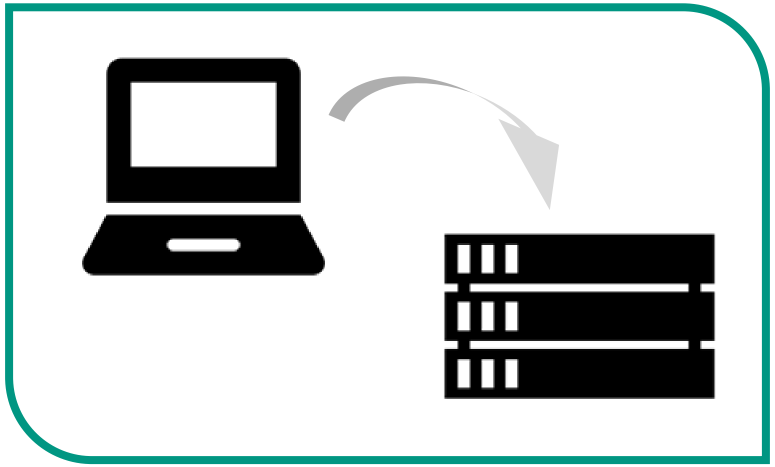
- Population based approach
  - lower chances of local optima
- Runs in “generations”
  - Mutation, Recombination & Selection
- Optimization parameters:
  - Population size
  - Scale factor/differential weight
  - Crossover probability
  - Applying boundary conditions
  - Penalty functions
  - Abort criterion

Parallelization & Cluster Computing

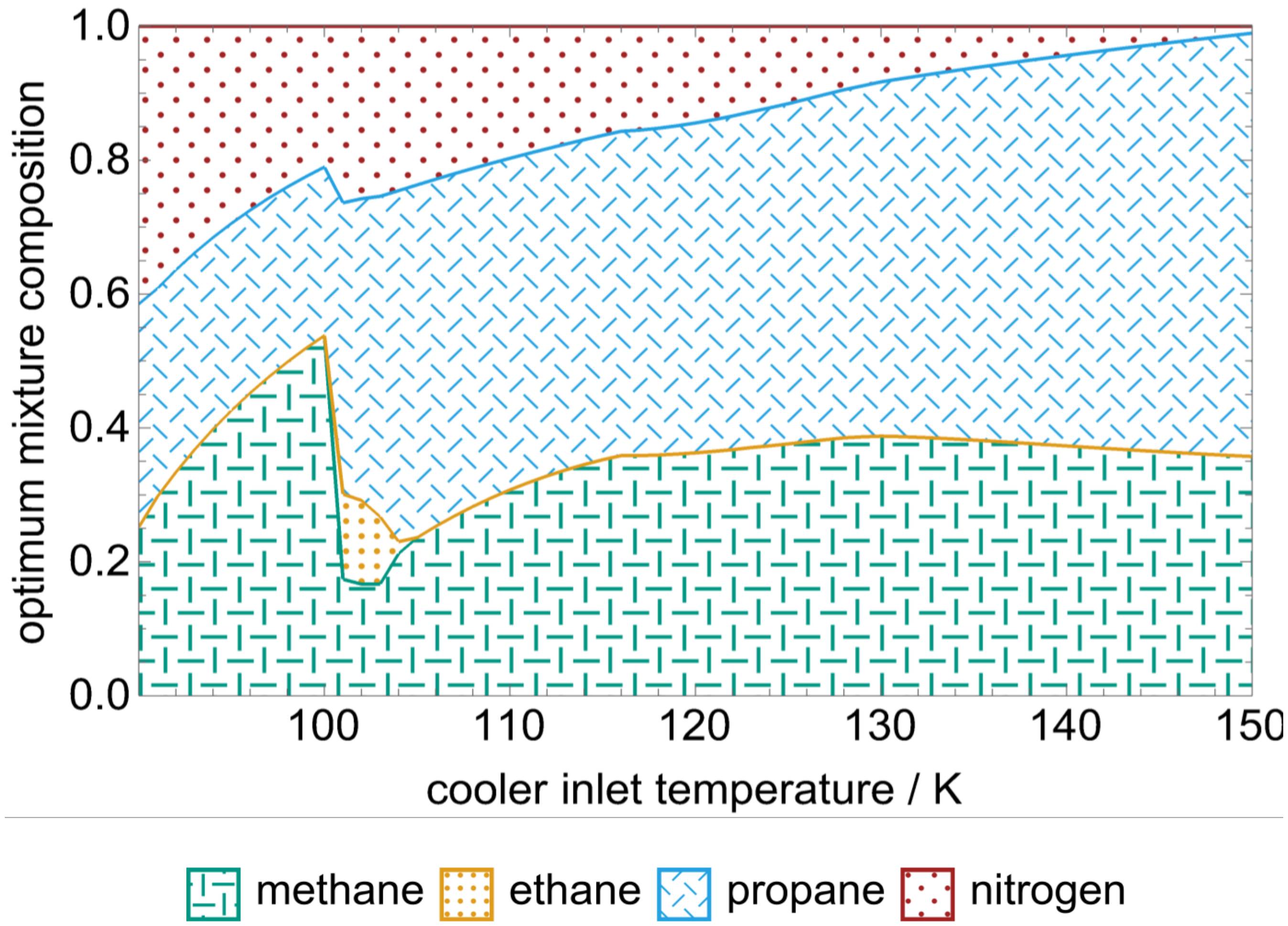
- Differential Evolution lends itself to parallelization
  - Different candidates in the same generation can be calculated independently

- HPC cluster (bwUniCluster 2.0) available @KIT





First results



- Composition optimization for $T_{\text{cooler,in}} = 90 - 150\ \text{K}$
- Constant pressures
  - $p_{\text{HP}} = 16\ \text{bar}$
  - $p_{\text{LP}} = 4\ \text{bar}$
- $\Delta T_{\text{min,HX}} = 2\ \text{K}$

Conclusions and outlook

- Process simulation
  - More advanced single- and multi-stage compressor model
  - CMRC (auto-)cascades

- Optimization
  - Parameters
  - Penalty functions
  - Algorithm modifications

Bibliography

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Thank you for your attention!