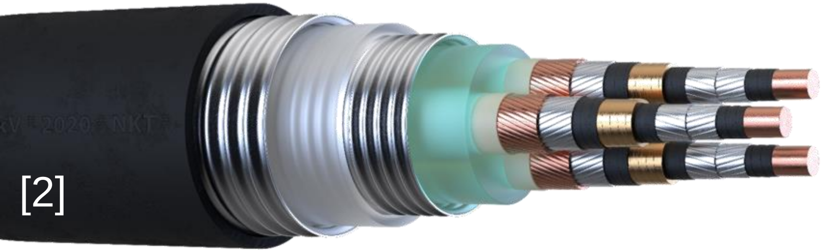
Optimization Potential for Cooling Superconducting Power Cables by Using Cryogenic Mixed Refrigerant Cycles

F. Boehm, **ITEP Young Scientists Workshop, Kristberg, January 11, 2023**

Superconducting cables in the power grid

- Progressing electrification due to energy transition
  → Increasing energy demand
- Upgrading power grid is imperative
  - Transmission performance and age of current cables

[1] A. Keller



- Advantages of superconducting cables
  - Lower space demand
  - No electromagnetic emissions
  - No joule heating
  - Higher transmission performance

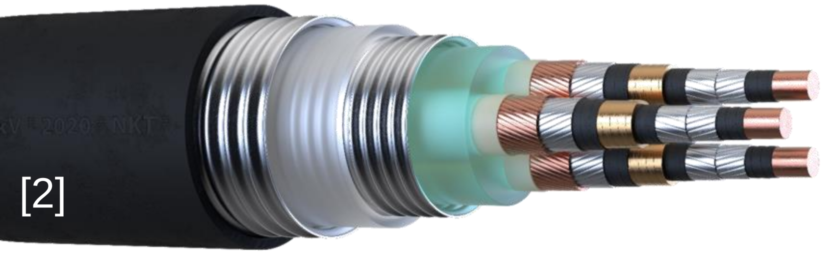
[2] www.nkt.de

SuperLink – 15 km superconduction in Munich

Karlsruhe Institute of Technology

- 110 kV connection of HUW Menzing and HKW Süd
  - 500 MVA in one compact cable
- Will be the longest HTS cable
  - Currently 1 km (AmpaCity Essen)

[3] Google Maps



[2] www.nkt.de

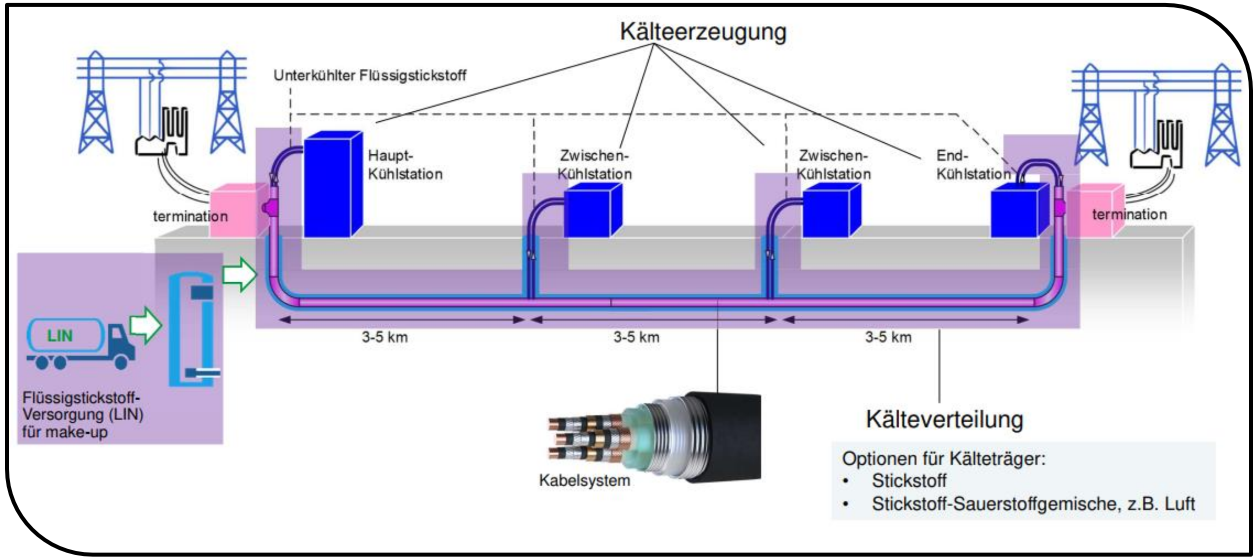
SWM
NKT
THEVA
THE LINDE GROUP
Karlsruhe Institute of Technology
Fachhochschule Südwestfalen
University of Applied Sciences

SuperLink

Gefördert durch:
Bundesministerium für Wirtschaft und Klimaschutz
aufgrund eines Beschlusses des Deutschen Bundestages

SuperLink – Cooling stations

- 15-30 kW per cooling station
- Cooling temperature below 77 K
- Low-maintenance
- Reliable
- Low space requirement



[4]

- Re-cooling of circulated LN_2
- Cooling of current leads

[4] Alekseev et al. 2020

Technologies for providing low temperatures

Stirling cooler

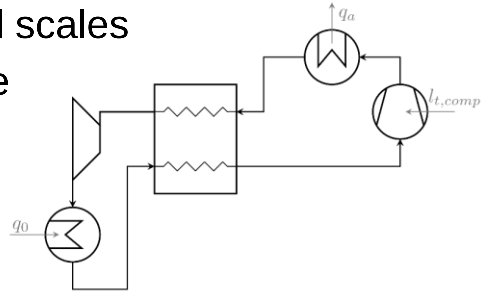
- Medium efficiency
- Low cooling power
  - Number of coolers
  - Economic efficiency
- High-maintenance

[5]

[5] www.aim-ir.com

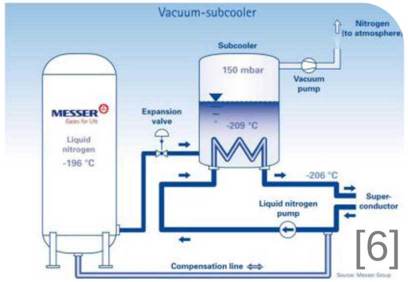
Reverse-Brayton-Cooler

- Highly efficient in commercial scales
- Broad operational experience
- Complex design
- Limited scalability of expander in cold section



Nitrogen subcooler

- Low technical complexity
- Operational experience AmpaCity [6]
- Continuous nitrogen demand

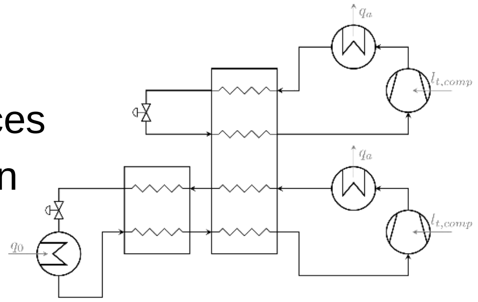


[6]

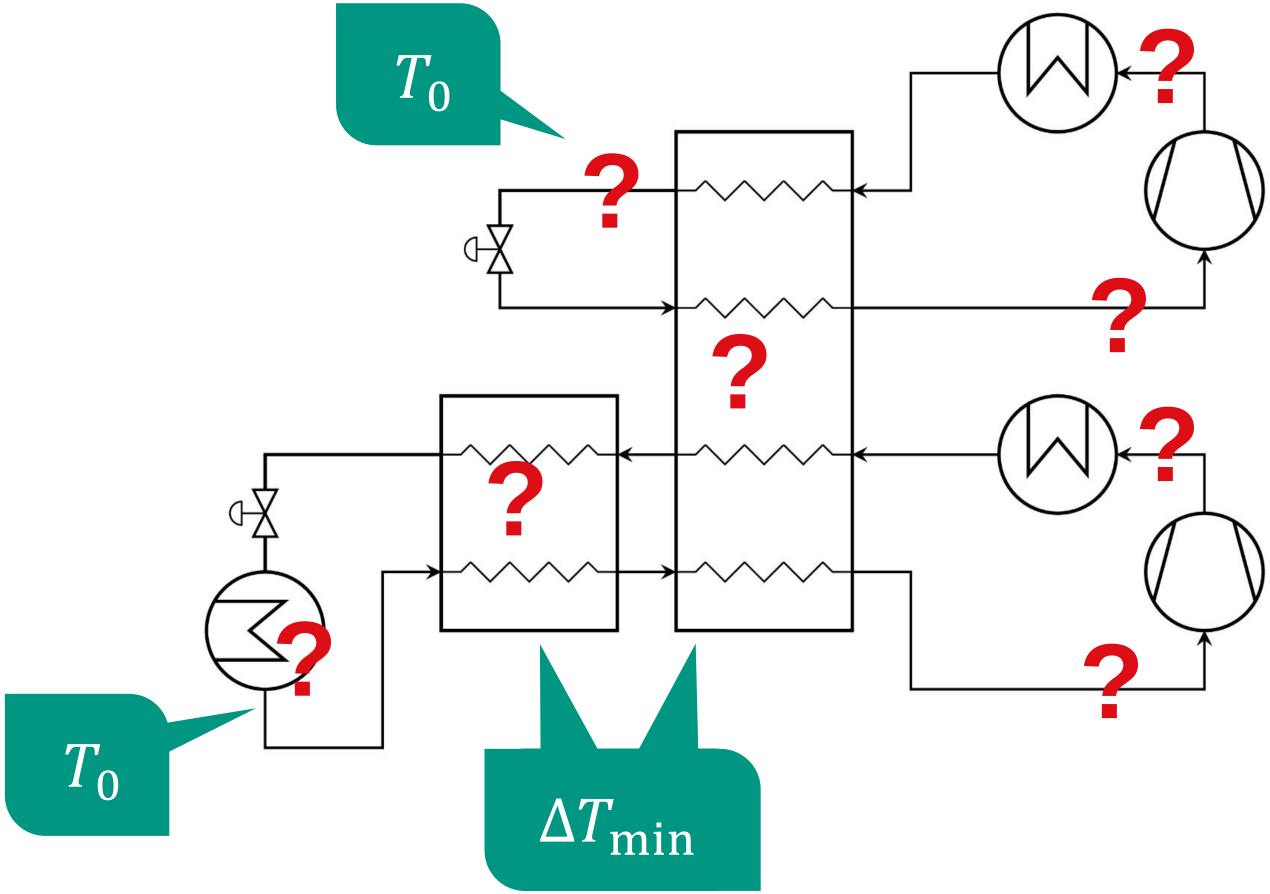
[6] Herzog et al. 2020

Cryogenic mixed refrigerant cycle (CMRC) cascade

- Low pressures
- Matching heat capacity flows
  → Small temperature differences
- No moving parts in cold section



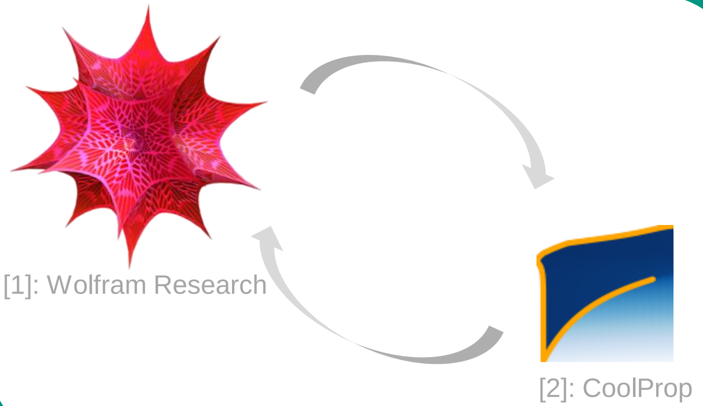
Optimization potential of CRMC cascades

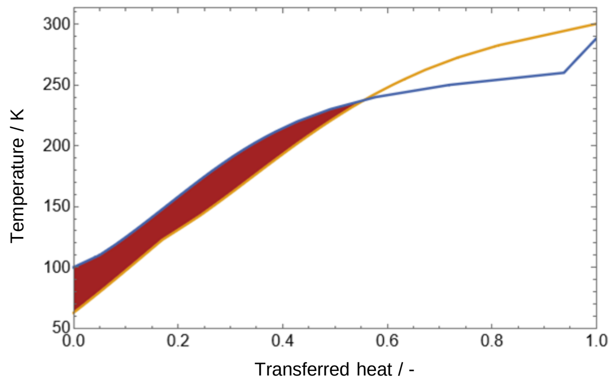


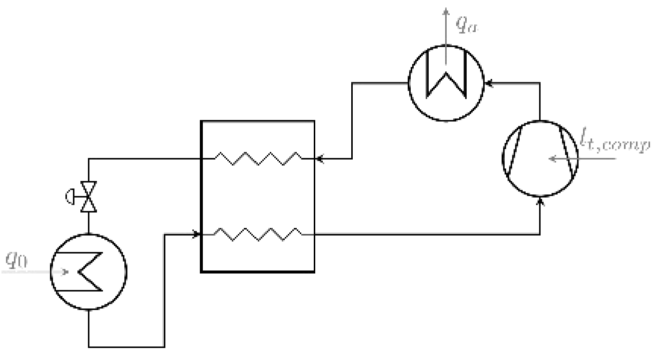
Pressures, mixture components and compositions

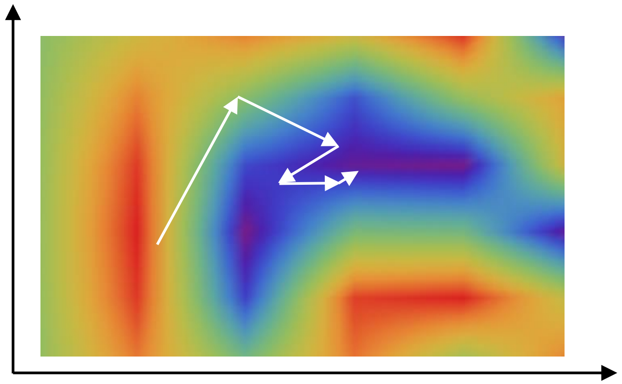
→ **Large number of parameters**

Implementation



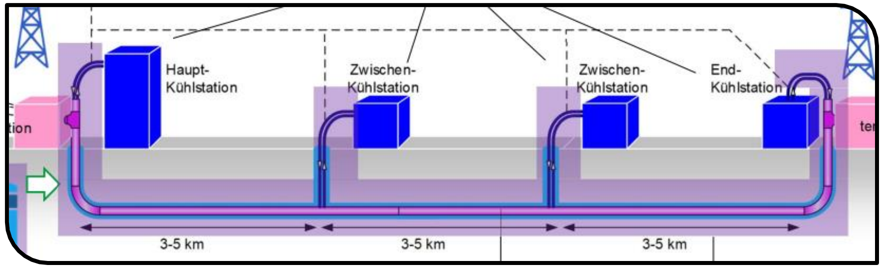






Optimization tasks

- Target figures
  - Energy demand
  - Investment cost
- Different cooling requirements
  - Current lead
  - Re-cooling LN_2



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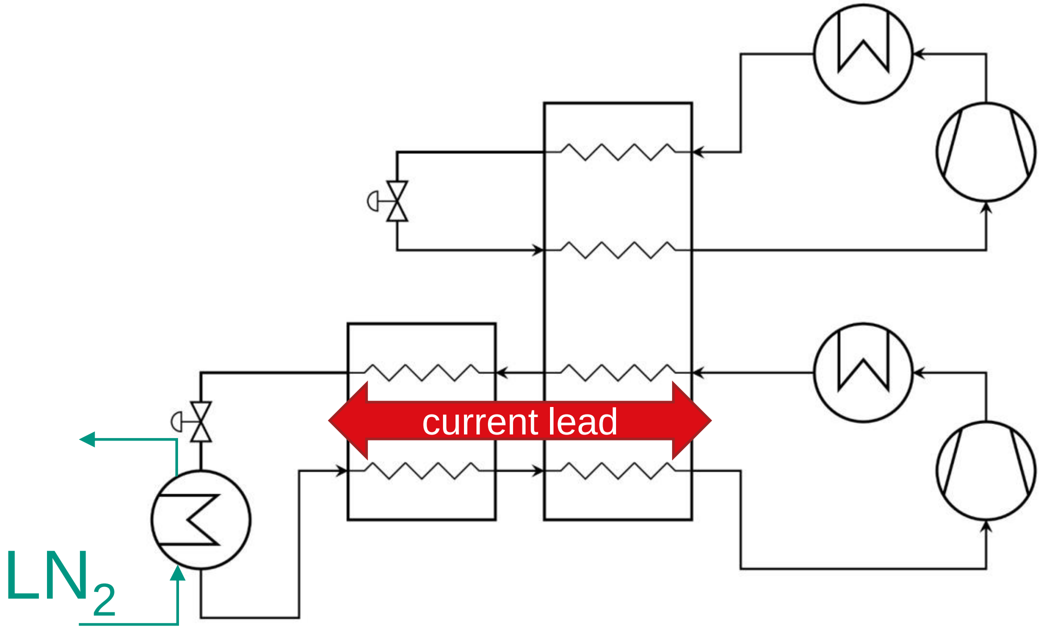
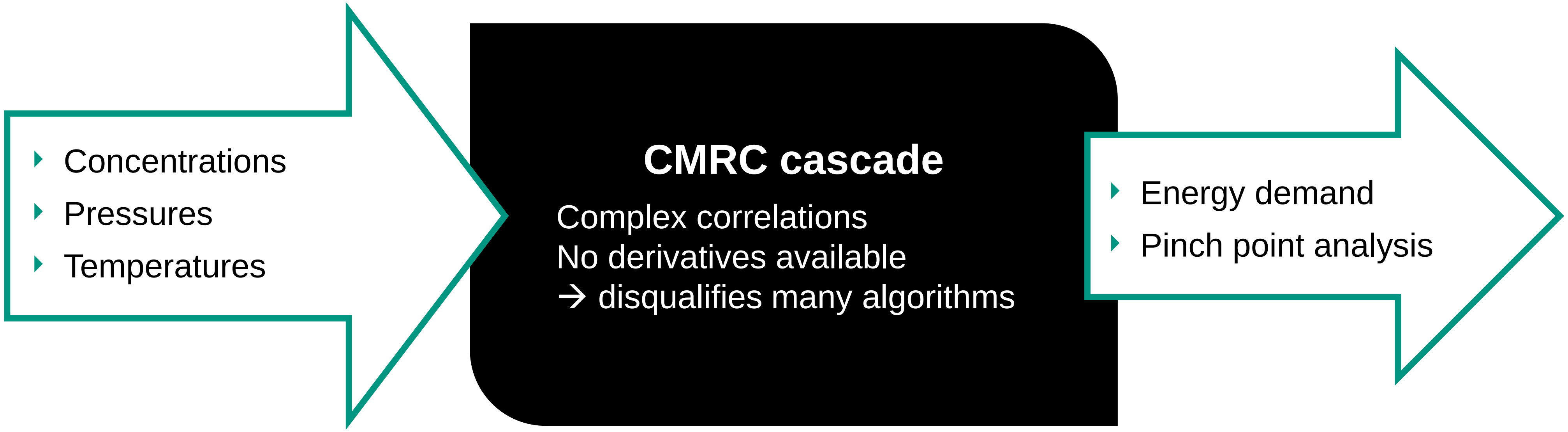


[4] Alekseev et al. 2020

Mixture Optimization



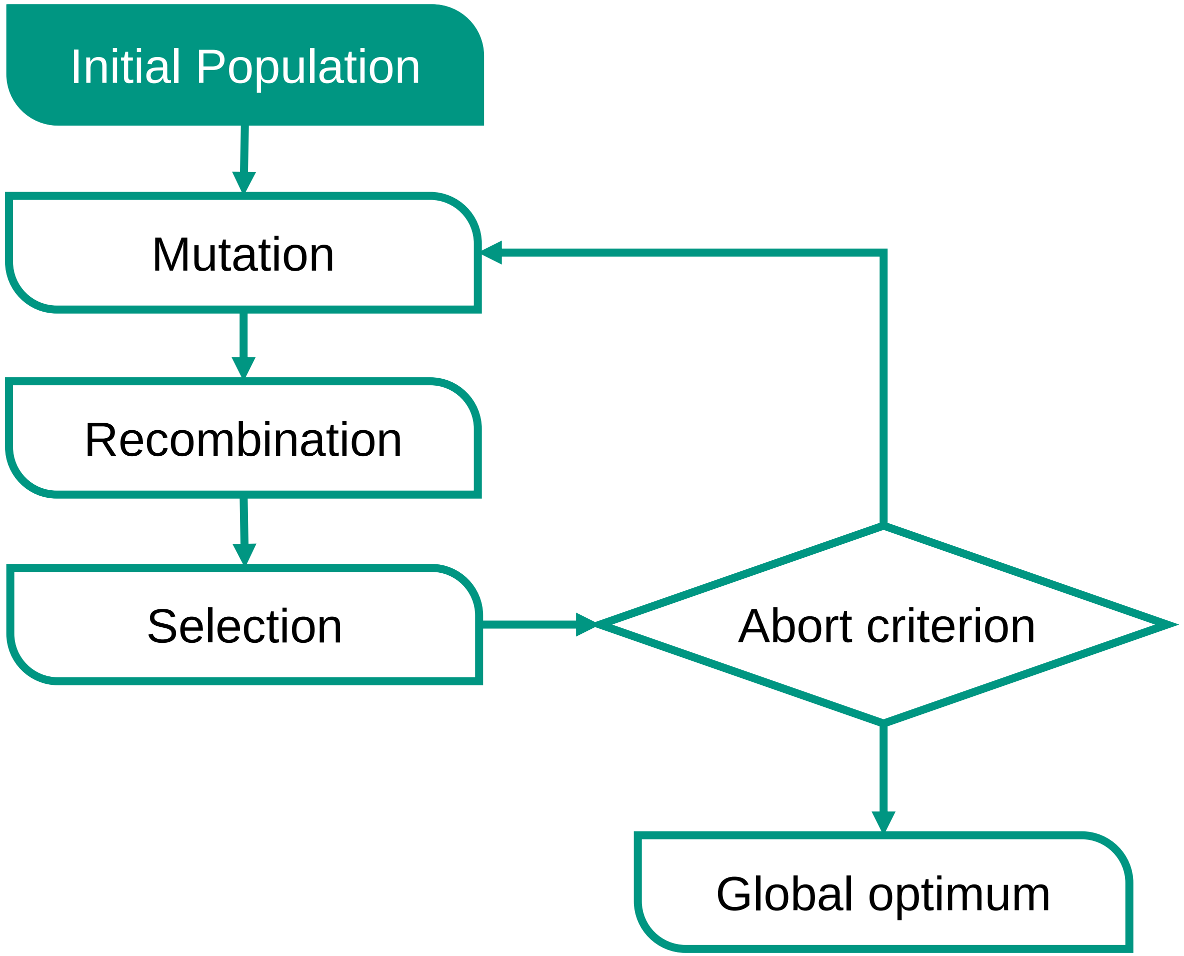
Optimization algorithm requirements

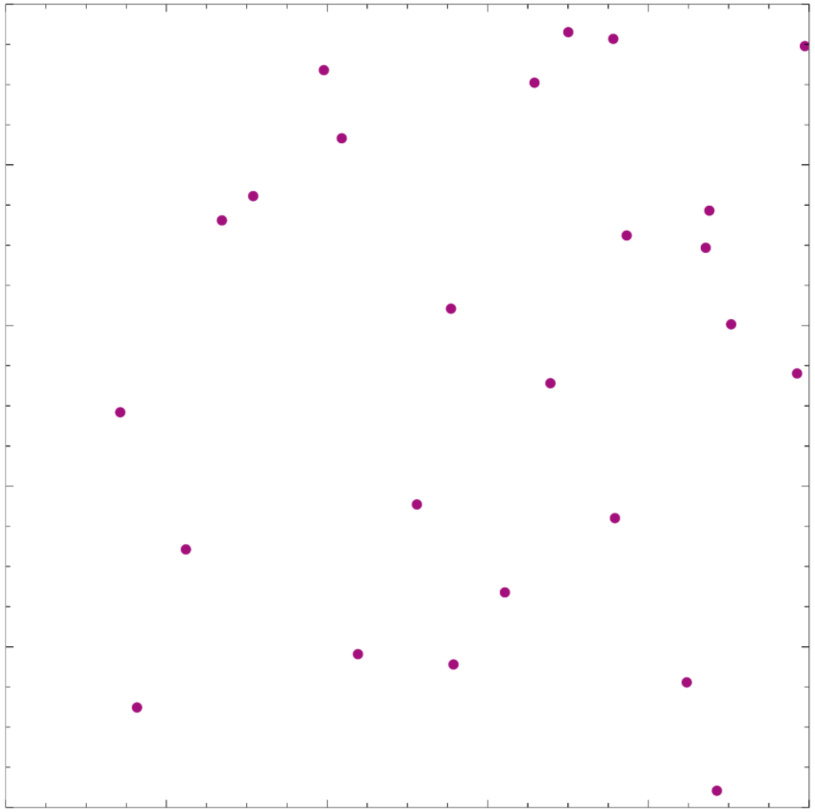
- No derivatives needed
- Independent of starting values
  - Global optimization
- Treatment of boundary conditions
- Abort criterion definable

→

Differential Evolution[7,8]
- Genetic algorithm
- Global optimization „Exploration & Exploitation“

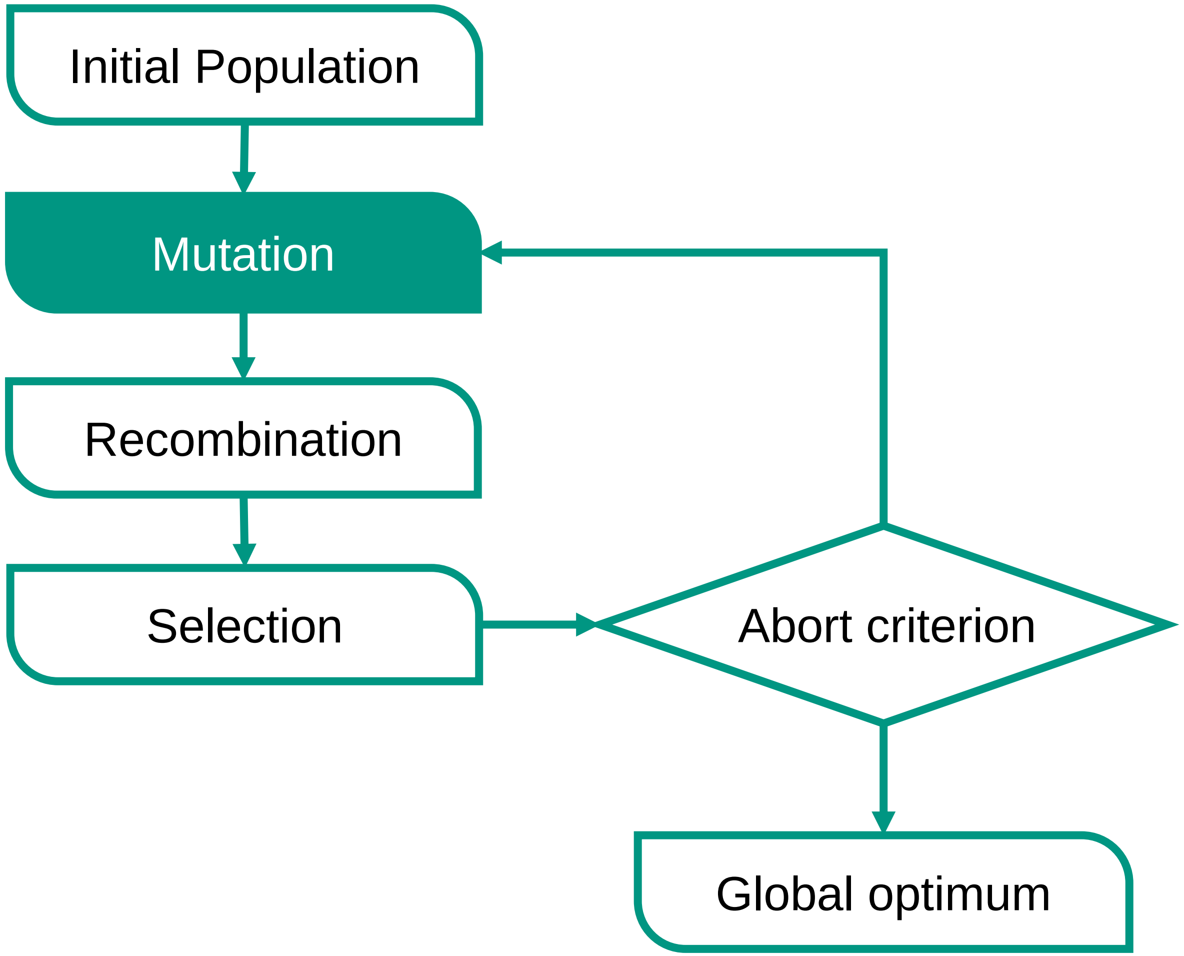
Optimization algorithm

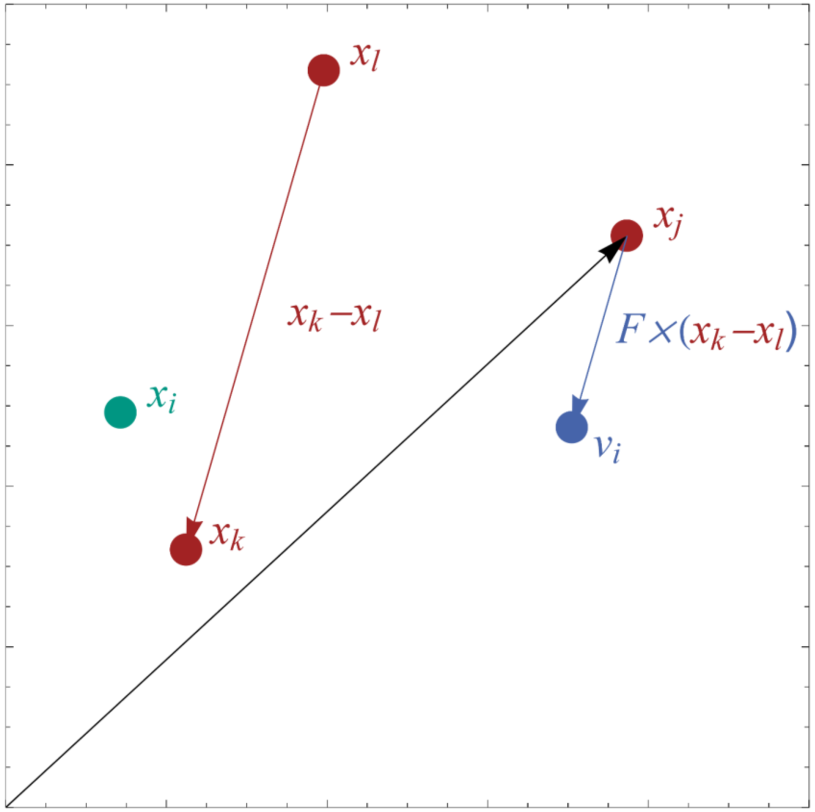




Number of parameters → calculation effort

Optimization algorithm

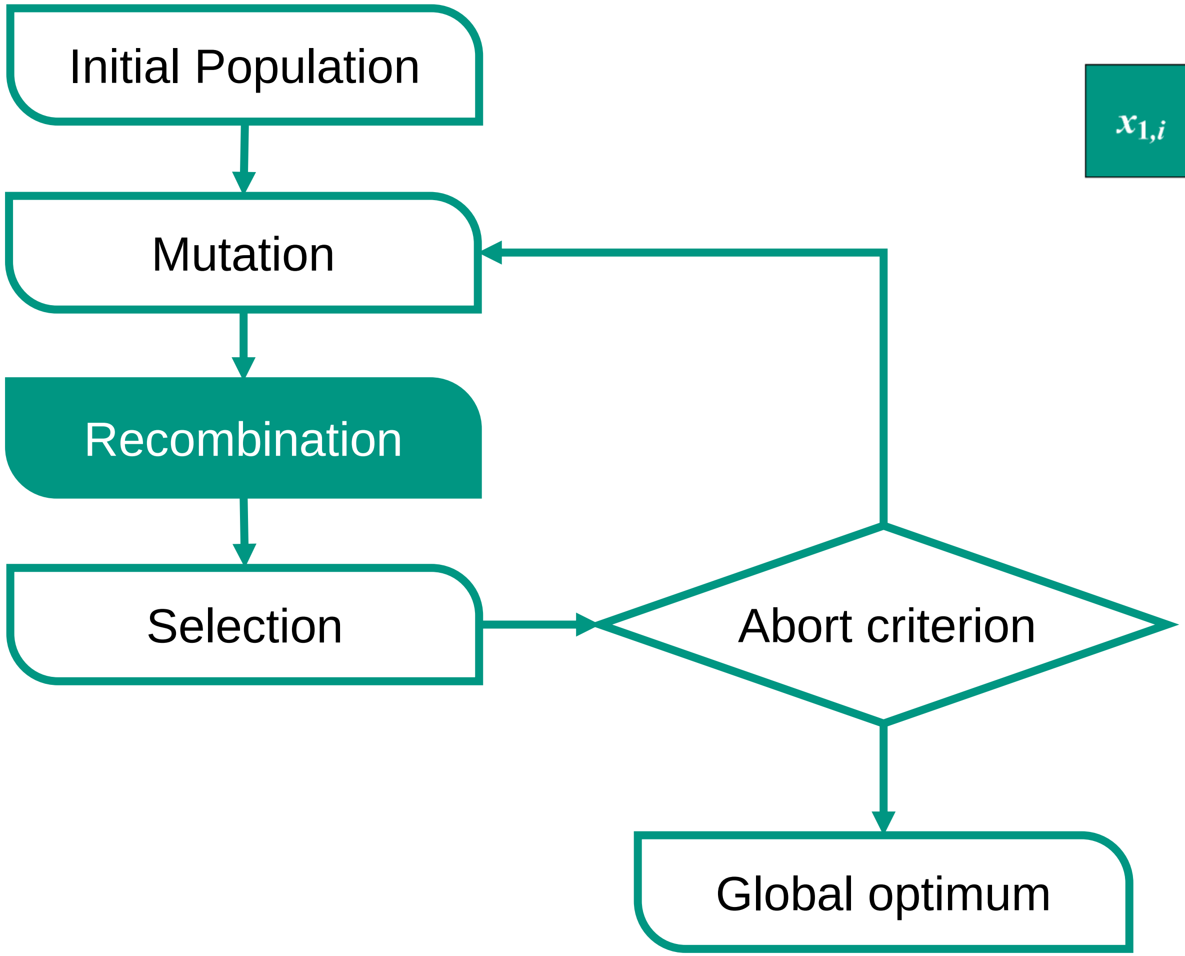


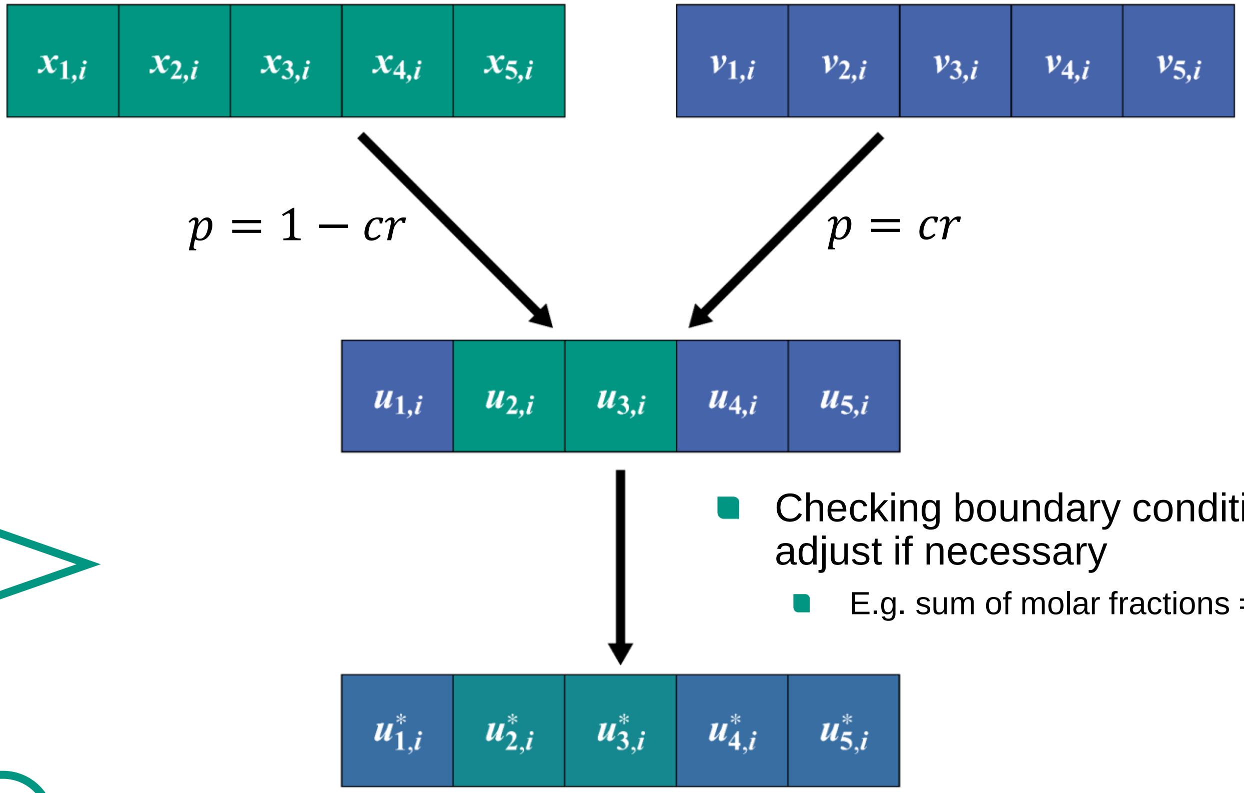


$$v_i = x_j + F \cdot (x_k - x_l)$$

F: Differential weight

Optimization algorithm

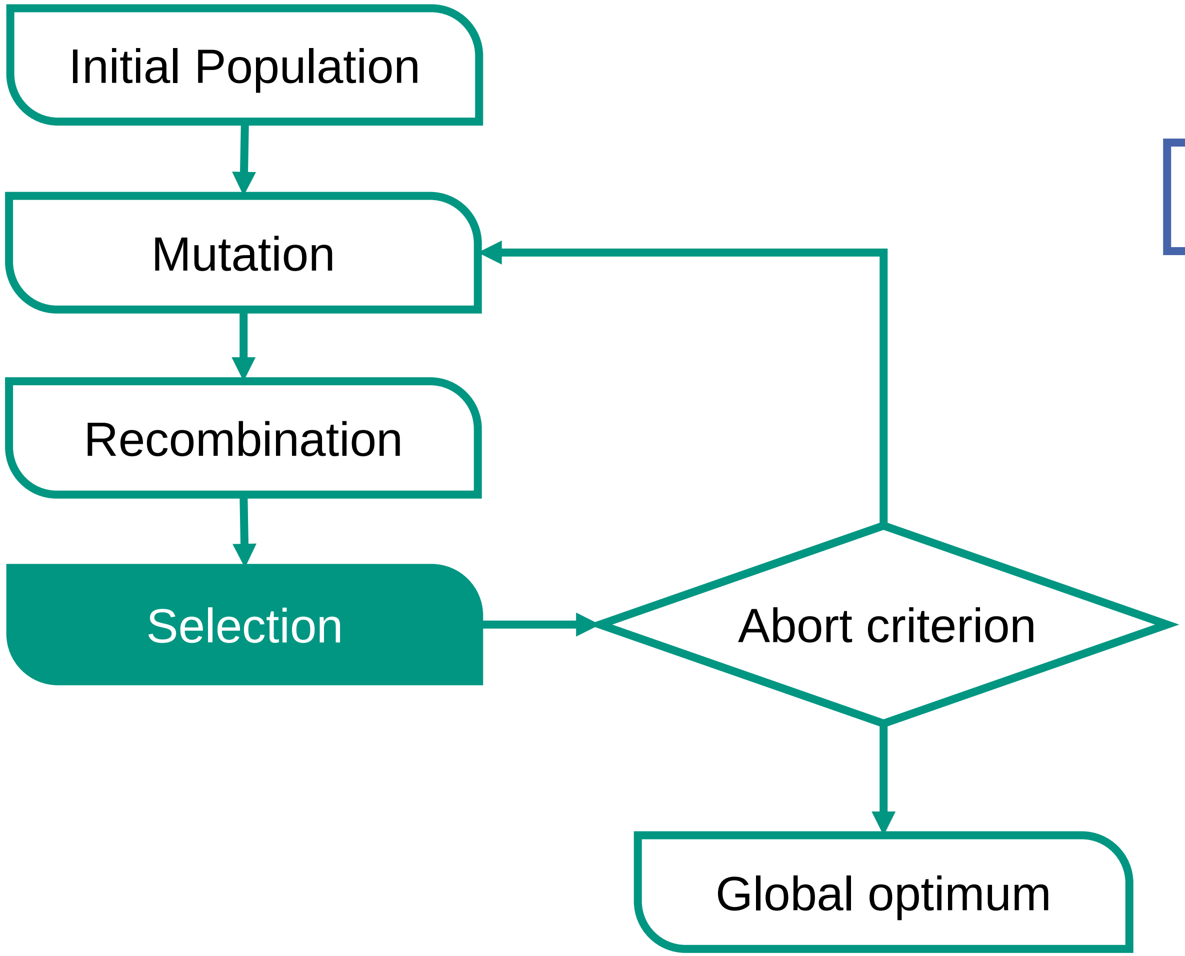


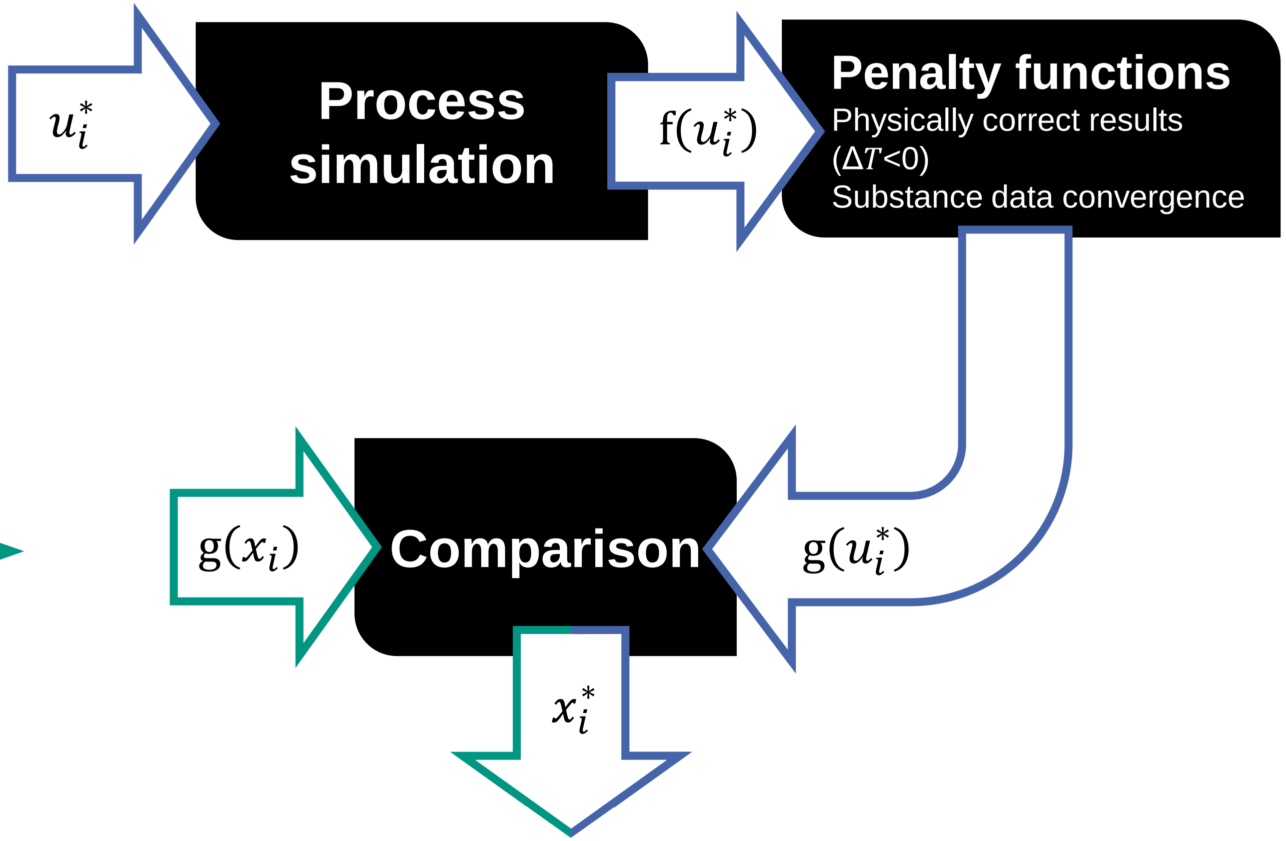


- Checking boundary conditions, adjust if necessary
  - E.g. sum of molar fractions = 1

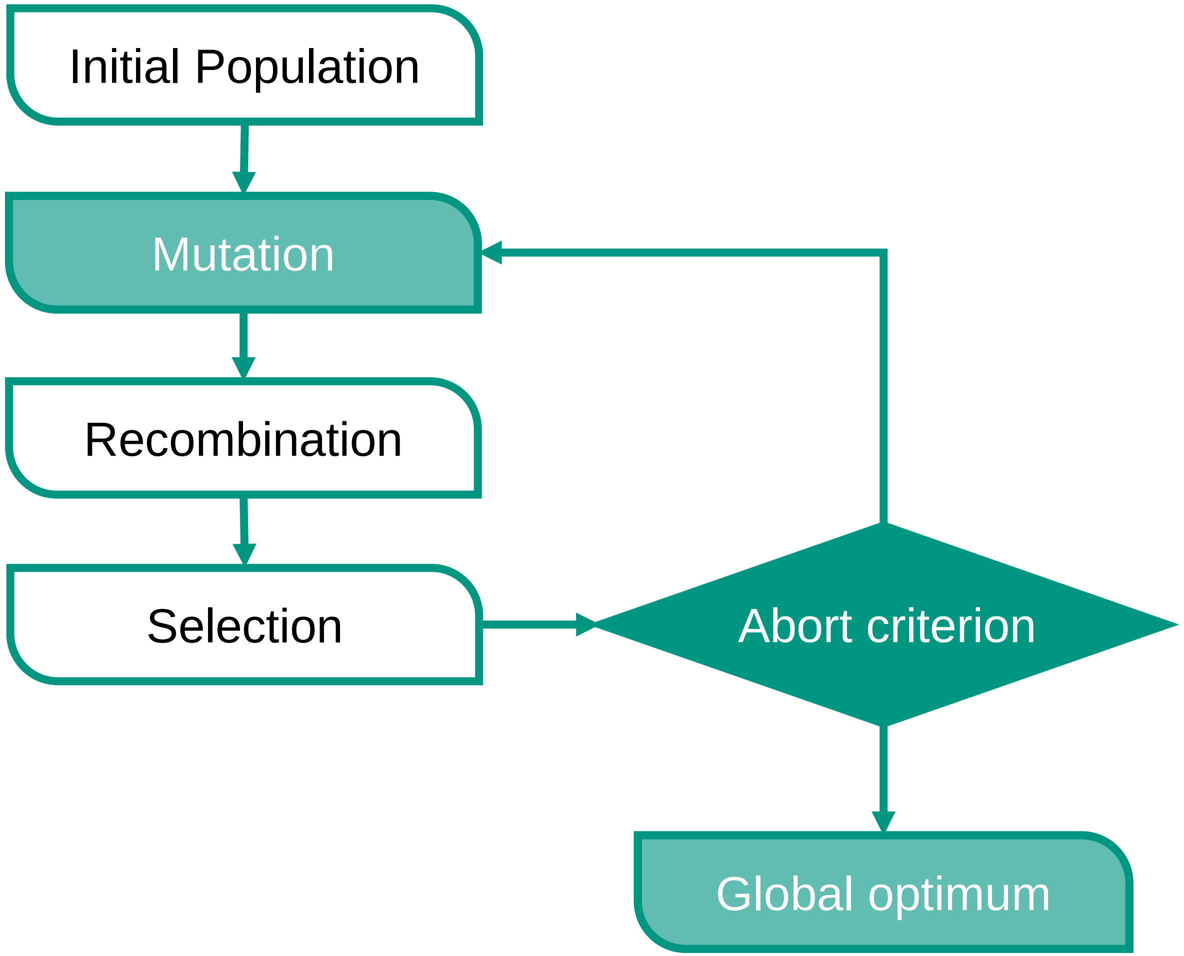
cr: Crossover probability

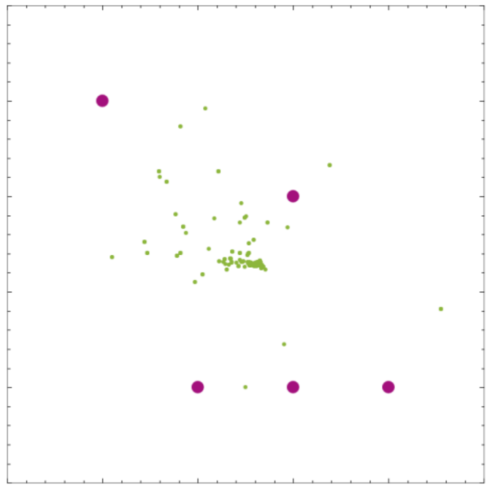
Optimization algorithm





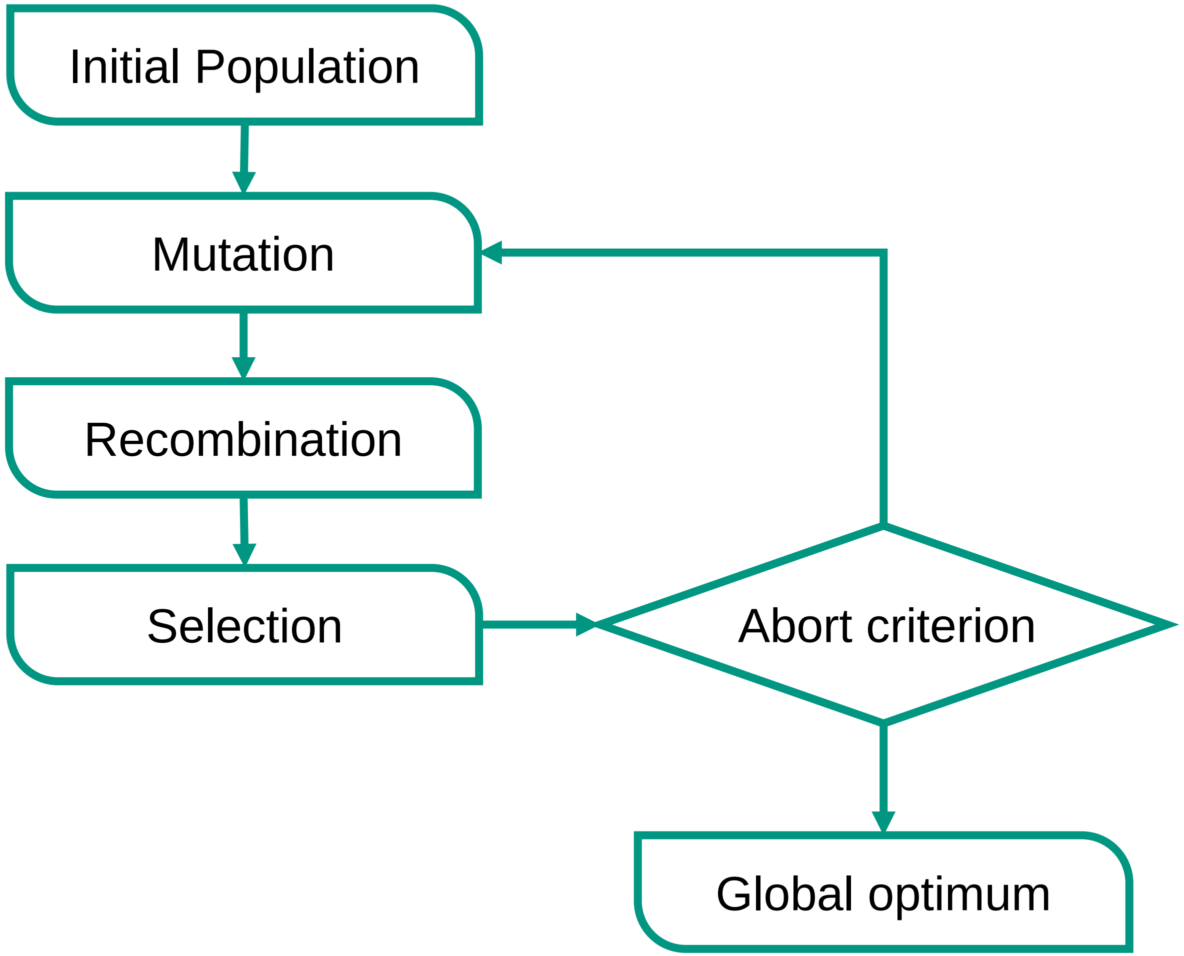
Optimization algorithm





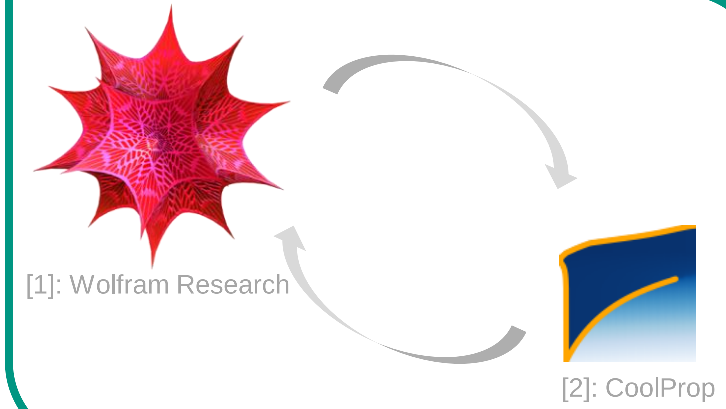
- Convergence of candidates
- Maximum number of generations
- Maximum time

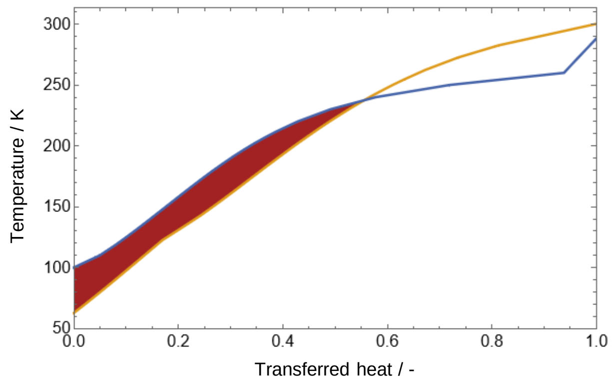
Optimization algorithm

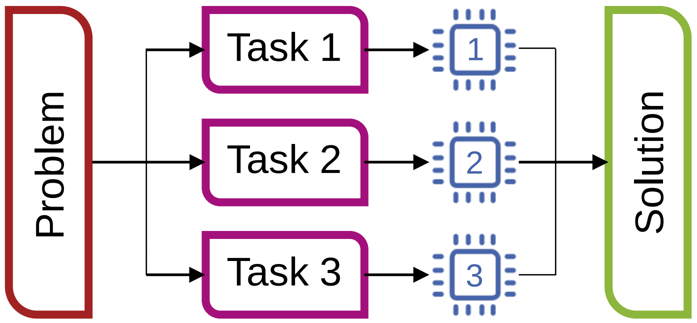


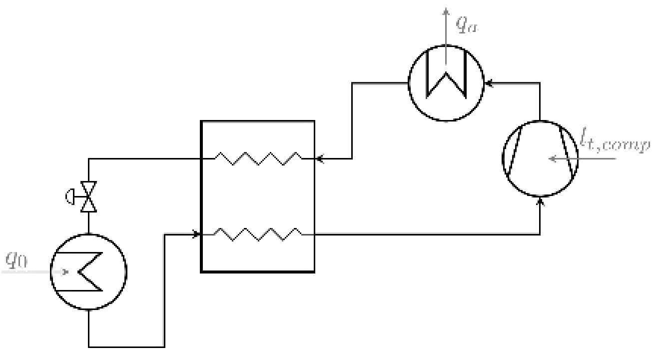
- Optimization parameters:
  - Population size
  - Differential weight
  - Crossover probability
  - Applying boundary conditions
  - Penalty functions
  - Abort criterion

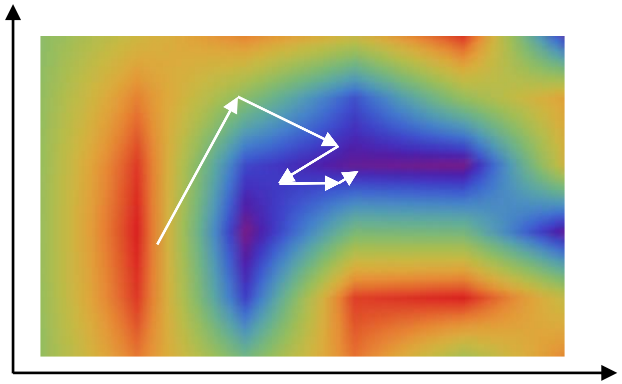
Implementation





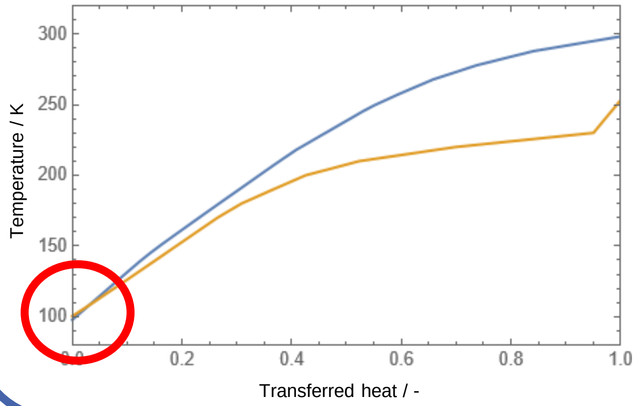


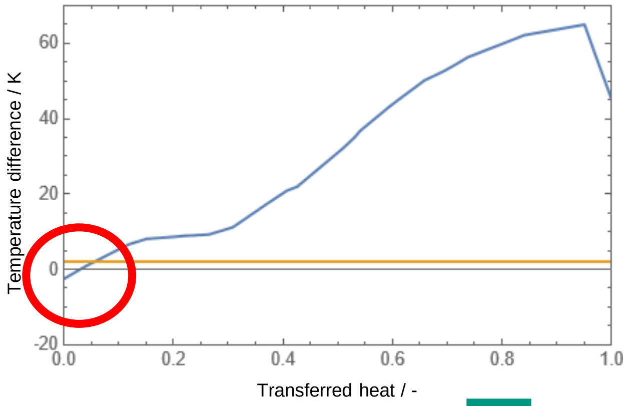




First results

Karlsruhe Institute of Technology





Component	$\tilde{x}$ / mol
Methane	0,143
Ethane	0,143
Propane	0,571
Nitrogen	0,143

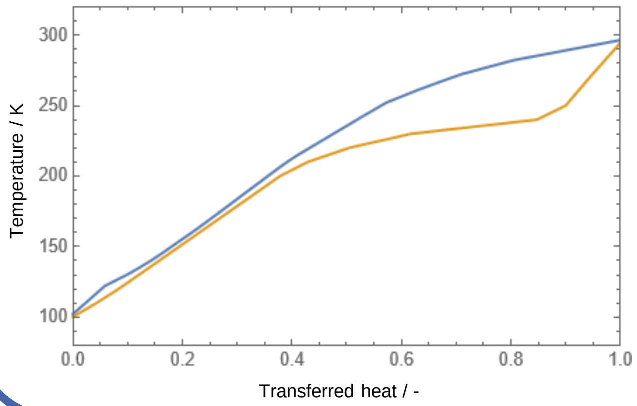
$P_{\mathrm{LP}} = 1{,}46\ bar$

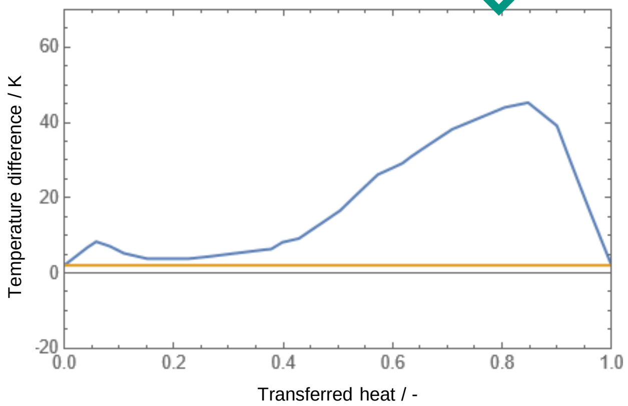
$P_{\mathrm{HP}} = 19{,}70\ bar$

$\Delta T_{\min} = -2{,}57\ K$

$\eta_{\mathrm{Carnot}} = 14{,}35\ \%$

DE





Component	$\tilde{x}$ / mol
Propane	0,544
Nitrogen	0,302

$\eta_{\mathrm{Carnot}} = 24{,}17\ \%$

Improvement of η_{Carnot} by a factor of 1,7

Challenges and outlook

- Optimization parameters
  - Penalty functions
- Substance data
  - Convergence of Peng-Robinson EoS in the two-phase region

- Optimization regarding different targets
  - Energy demand
  - Cost
  - Pareto fronts (multi-objective optimization)

Bibliography

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Thank you for your attention!