Deterministic Global Optimization of the Design of a Geothermal Organic Rankine Cycle

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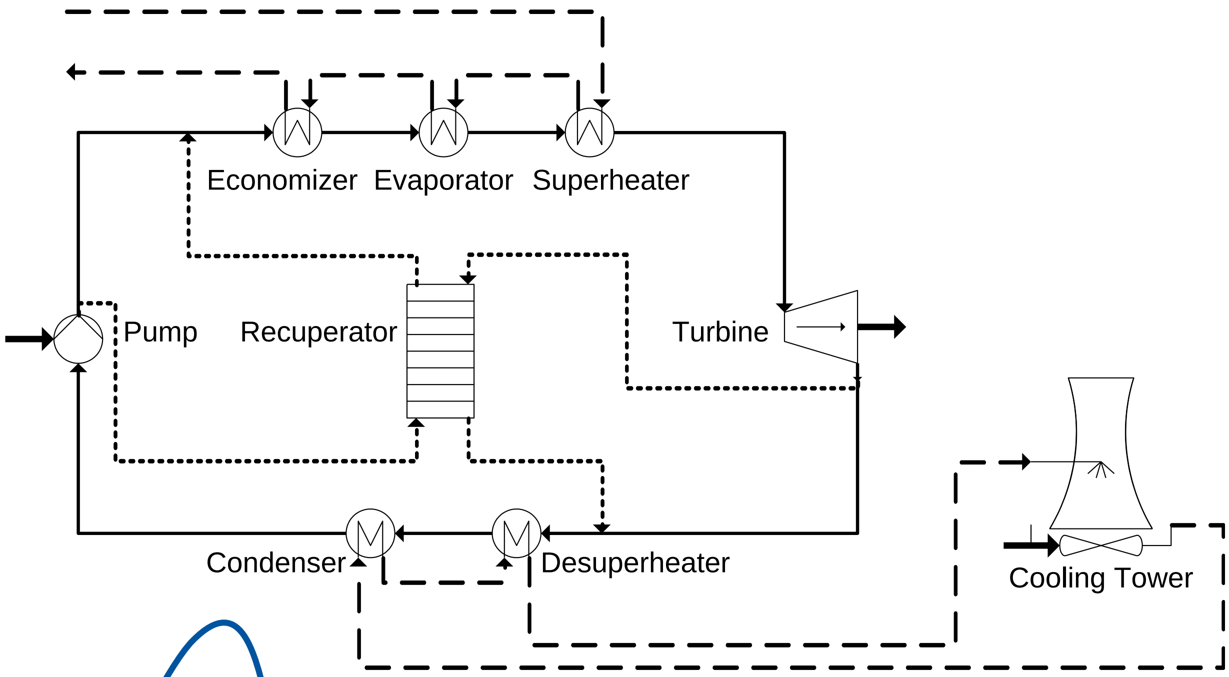
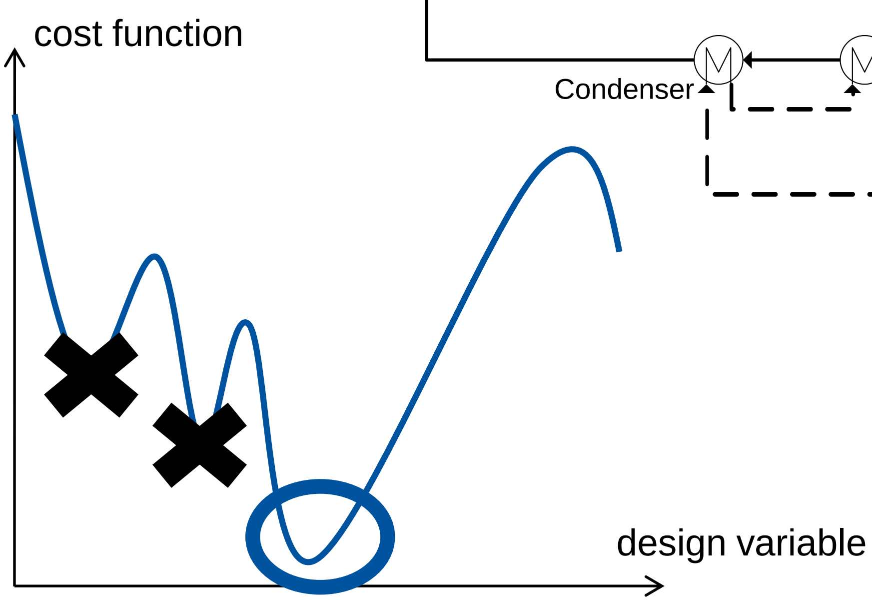
Why Do We Need Global Optimization?





→ Global optimum desirable

→ Especially in process design problems with multiple local minima

Numerical Optimization of Nonlinear Problems

Numerical Optimization

Local Optimization

- fast
- cannot guarantee global optimality/ often do not find global optimum
- e.g. CONOPT[Drud1994], IPOPT[Wächter2003]

Global Optimization

Stochastic Methods

- black-box evaluation
- result dependent on CPU time
- global optimality with infinite CPU time
- e.g. Genetic Algorithm NSGA-II[Deb2002]

Deterministic Methods

- guaranteed global optimality
- existing methods may result in high CPU times
- e.g. BARON[Tawarmalani2005]

Deterministic global optimization challenging for a high number of variables!

Numerical Optimization of Nonlinear Problems

$$\min_{\mathbf{d}\in D,\mathbf{x}\in X} \quad f(\mathbf{d},\mathbf{x})$$
$$\text{s.t.} \quad \mathbf{h}(\mathbf{d},\mathbf{x}) = \mathbf{0}$$
$$\mathbf{g}(\mathbf{d},\mathbf{x}) \leq \mathbf{0}$$

- f : objective function → minimize (- net power), (levelized cost of electricity)
- $\mathbf{d}$: design variables → mass flow, pressure level
- $\mathbf{x}$: dependent model variables → heat exchanger size
- $\mathbf{h}$: equality constraints → mass balances, heat transfer
- $\mathbf{g}$: inequality constraints → temperature & pressure limits

$$n_d \ll n_x$$

<u>Sequential modular mode:</u>
unit operations are evaluated sequentially

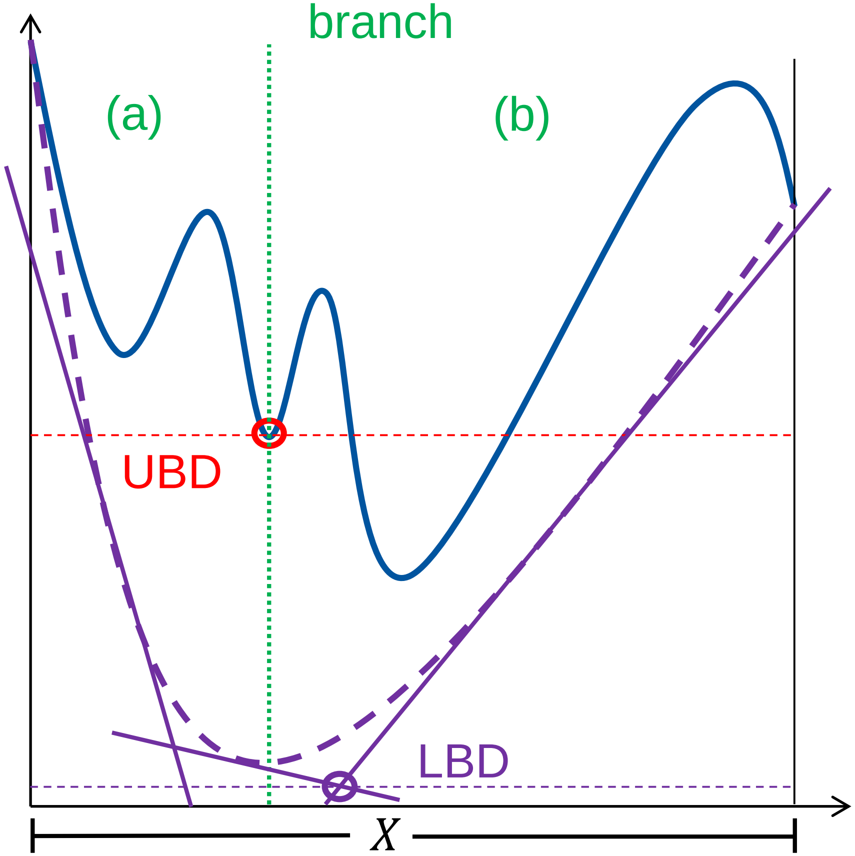
→ number of optimization variables can be reduced, explicit calculation of $\mathbf{x}$ in external functions

<u>Reduced-space formulation:</u>

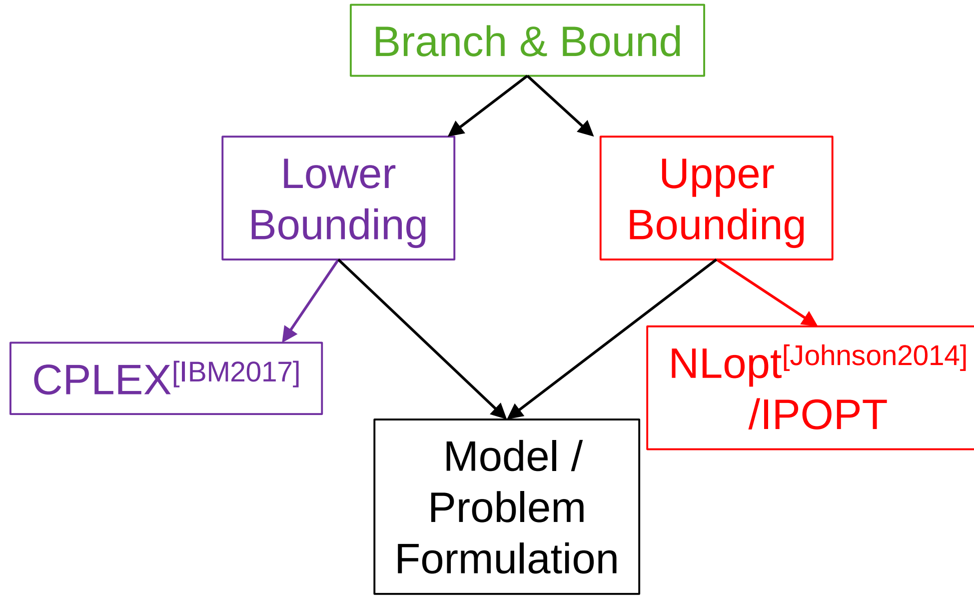
optimizer handles only $\mathbf{d}$ $\quad (\& \ \mathbf{x}_{tear} \ \& \ \mathbf{x}_{mod})$

→ found to decrease CPU times within flowsheet optimization[Bongartz2017a],[Bongartz2017b]

Deterministic Global Optimization Using McCormick Relaxations[McCormick1976]



1. Construct a relaxation
2. Solve relaxation → LBD
3. Solve original locally → UBD
4. Branch to nodes (a) and (b)



- Implementation in C++ using MC++[Chachuat2011]
- McCormick Relaxations & Extensions[Mitsos2009][Tsoukalas2014]

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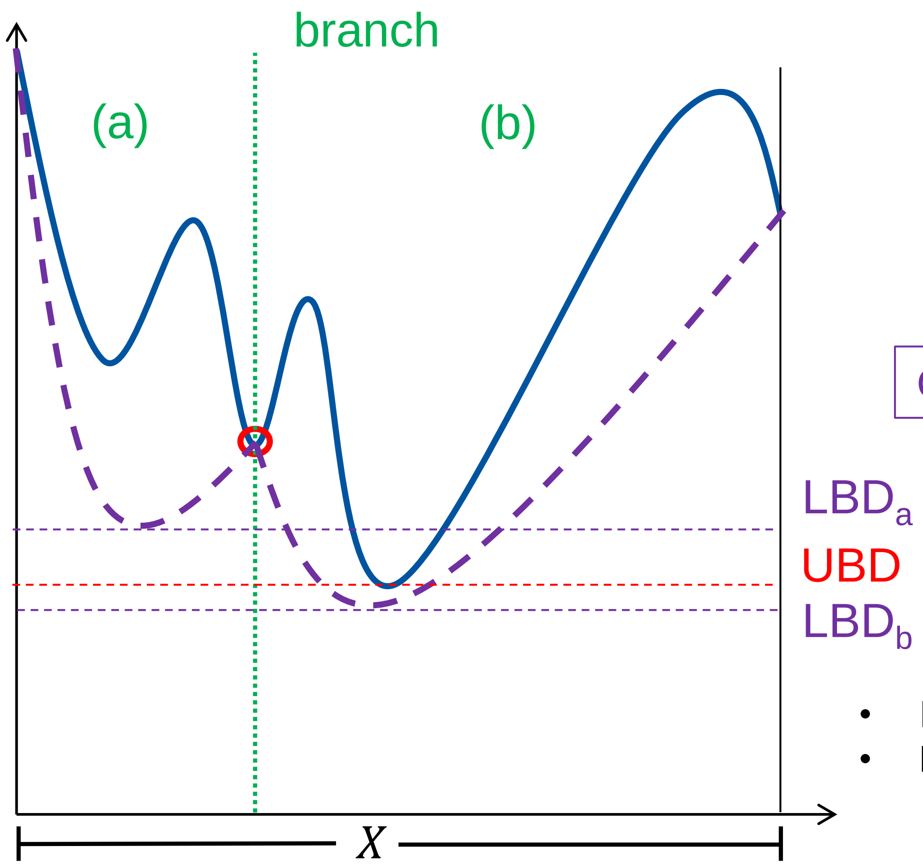

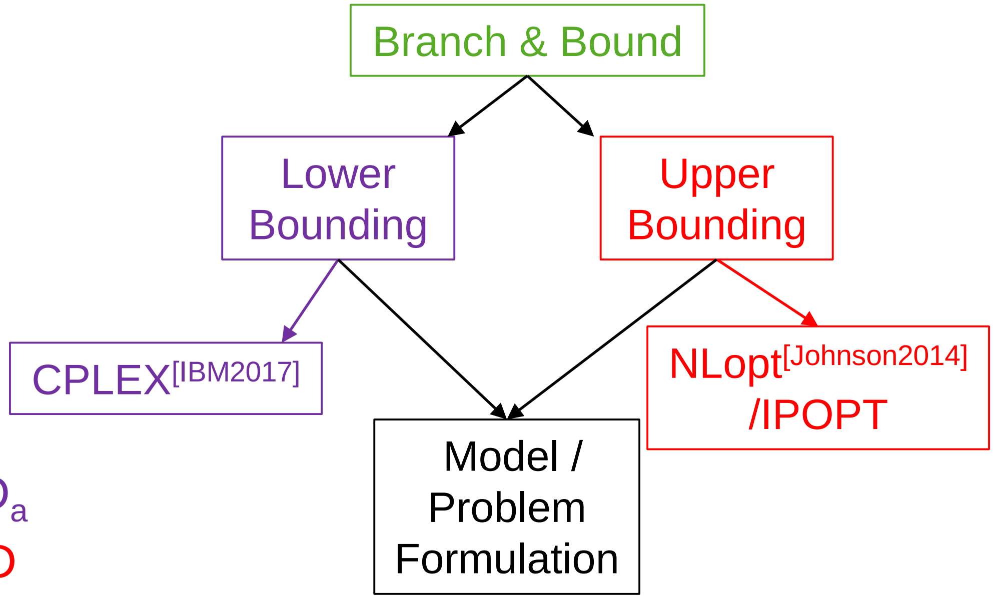

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Repeat, exclude infeasible and suboptimal nodes

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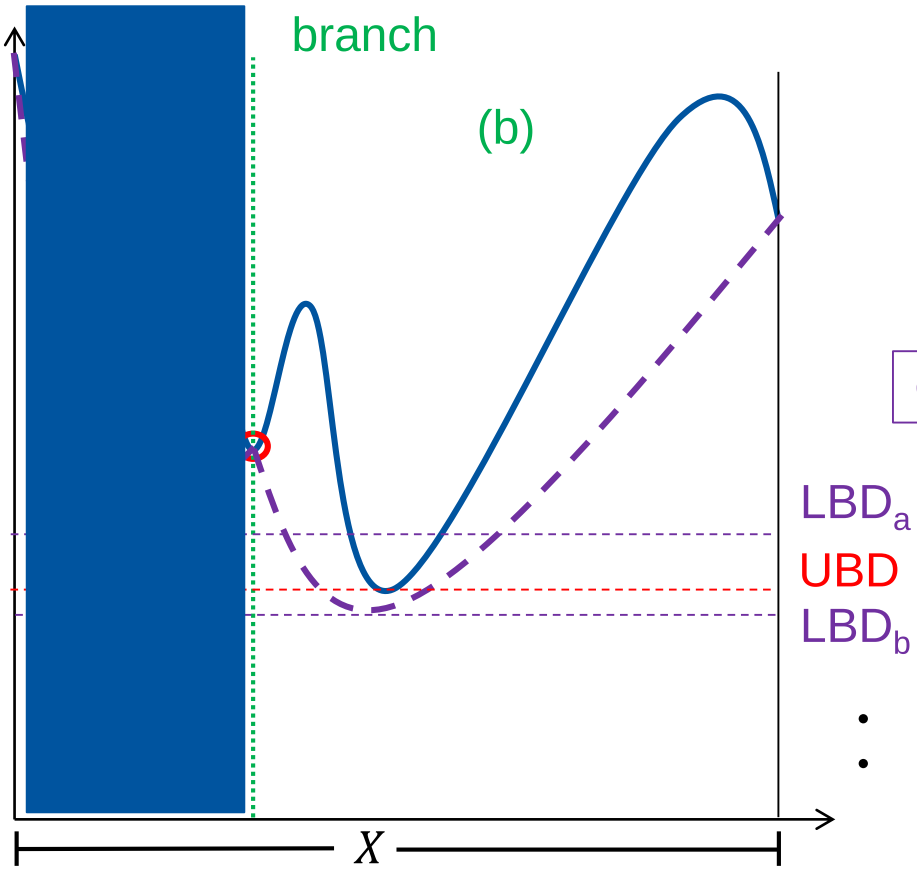

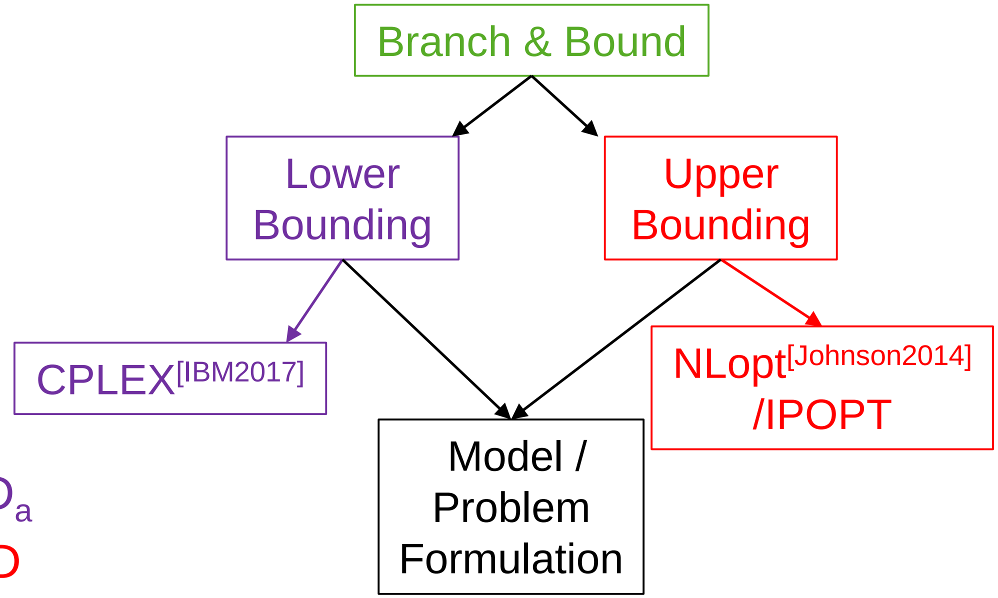

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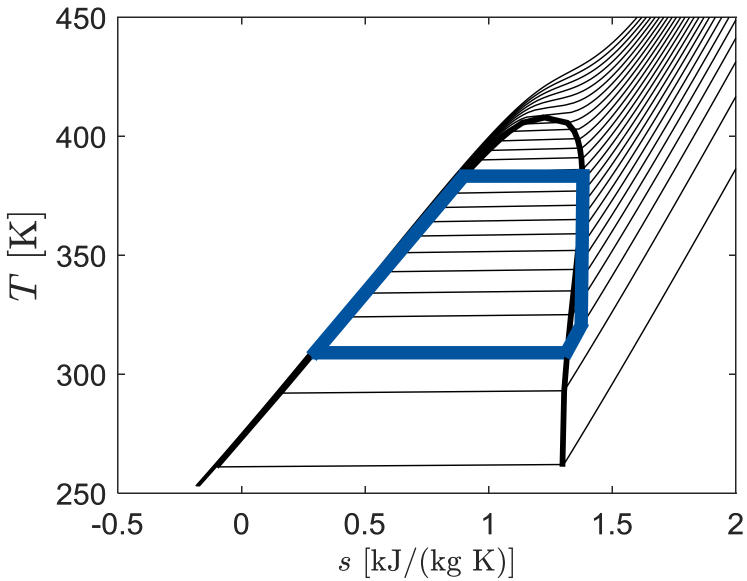
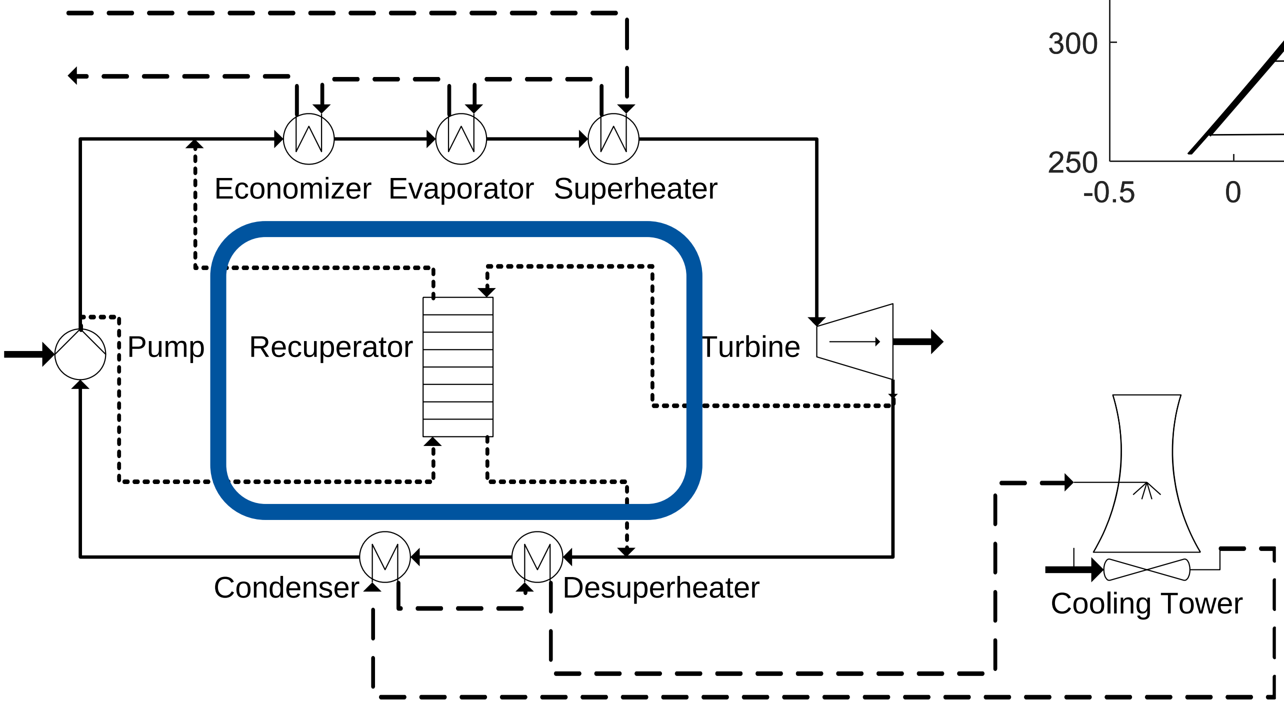
Case Study: Geothermal Organic Rankine Cycle (based on [Ghasemi2013])

- Working fluid: isobutane
- Recuperator optional unit: discrete decision variable

$y_{recup} \in \{0, 1\}$

NLP → MINLP





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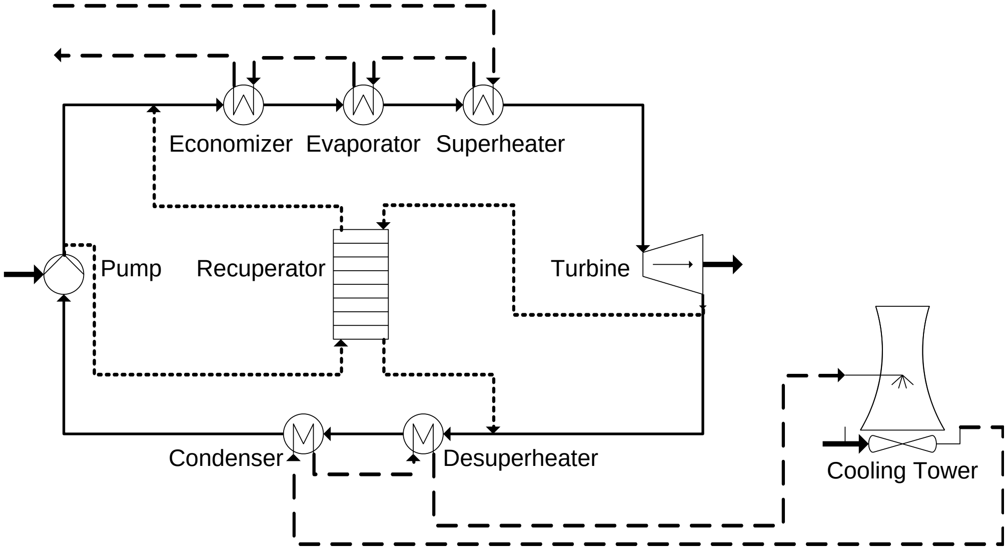
Case Study: Geothermal Organic Rankine Cycle



$$P_{net} = P_{turb} - P_{pump} - P_{fan}$$

$$LCOE = LCOE\left(Inv_{total}, P_{net}\right)$$

- Degrees of freedom: $\dot{m}_{isobutane}, p_{HP}, p_{LP}$
- Heat source: geothermal brine $T_{br,in} = 408\text{ K},\ T_{br,out} = 357\text{ K},\ \dot{m}_{br} \cdot c_{p,br} = 3.63\text{ MW/K}$
- Cooling medium: $T_{cw,in} \in \{268, 273, 288\}\text{ K}$
- Fixed heat transfer coefficients depending on contacting phases
- Assumed pinch point temperature differences
- Fixed efficiencies

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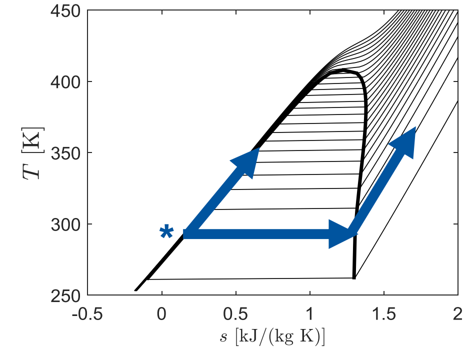
Thermodynamic Formulation of the WF



- Antoine equation: $$T_{sat,i} = \frac{B}{A - \log_{10}(p_i)} - C$$
- Heat capacity: $$c_{p,i} = A_{c_p,i} + B_{c_p,i} \cdot T$$
- Ideal liquid/vapor: $$h_{p,liq}(T) = \int_{T_0}^{T_i} c_{p,liq}\,\mathrm{d}T + \nu_{if} \cdot (p_i - p_0)$$

$$s_{p,liq}(T) = \int_{T_0}^{T_i} \frac{c_{p,liq}}{T}\,\mathrm{d}T$$

$$h_{p,vap}(T) = \Delta h_{evap,p_0} + \int_{T_0}^{T_i} c_{p,vap}\,\mathrm{d}T$$

$$s_{p,vap}(T) = \frac{\Delta h_{evap,p_0}}{T_0} + \int_{T_0}^{T_i} \frac{c_{p,vap}}{T}\,\mathrm{d}T - \mathrm{R} \cdot \ln\left(\frac{p_i}{p_0}\right)$$

→ Simple formulation allowing mostly explicit evaluations of the unit operations in the ORC

- Turbine **can not be evaluated explicitly**

additional optimization variable $T_{turb,out,is}$

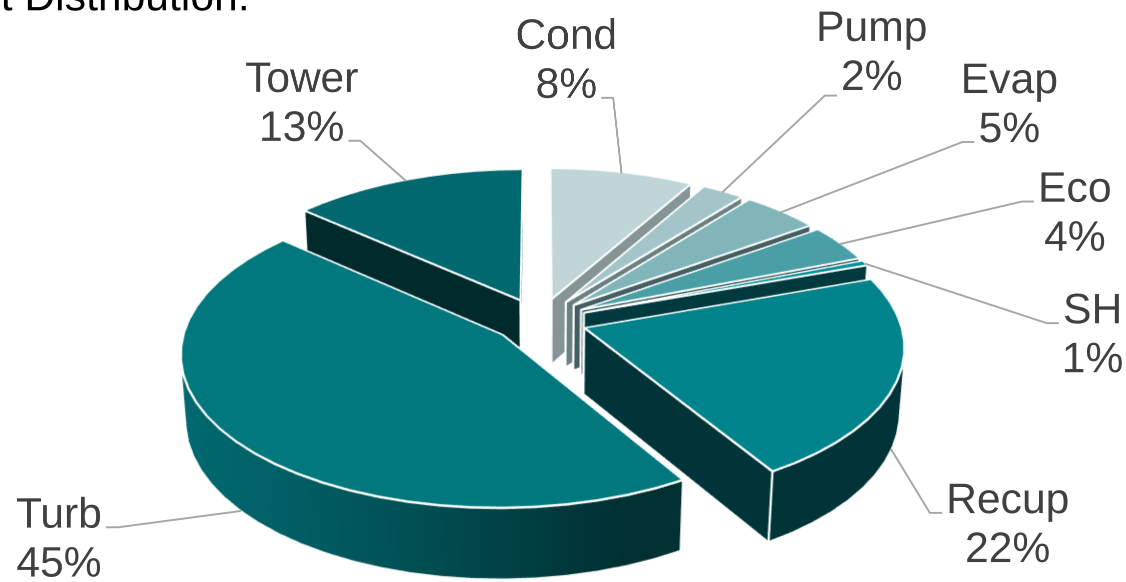
& equality constraint $s_{turb,out,is} = s_{turb,in}$

Results of Optimization – Maximizing Net Power

$T_{cw,in}$ [K]	$\dot{m}_{WF}$ [kg/s]	p_{HP} [bar]	p_{LP} [bar]	$P_{net,max}$ [MW]	η_{th} [%]	$LCOE$ [US-$/MWh]	CPU time [s]
268	408	15.9	2.44	28.4	15.4	45.3	13
273	418	15.7	2.84	26.1	14.1	48.1	15
288	449	14.8	4.37	19.1	10.3	60.3	16

Investment Cost Distribution:

$T_{cw,in} = 268$ K



$y_{Recup} = 1$

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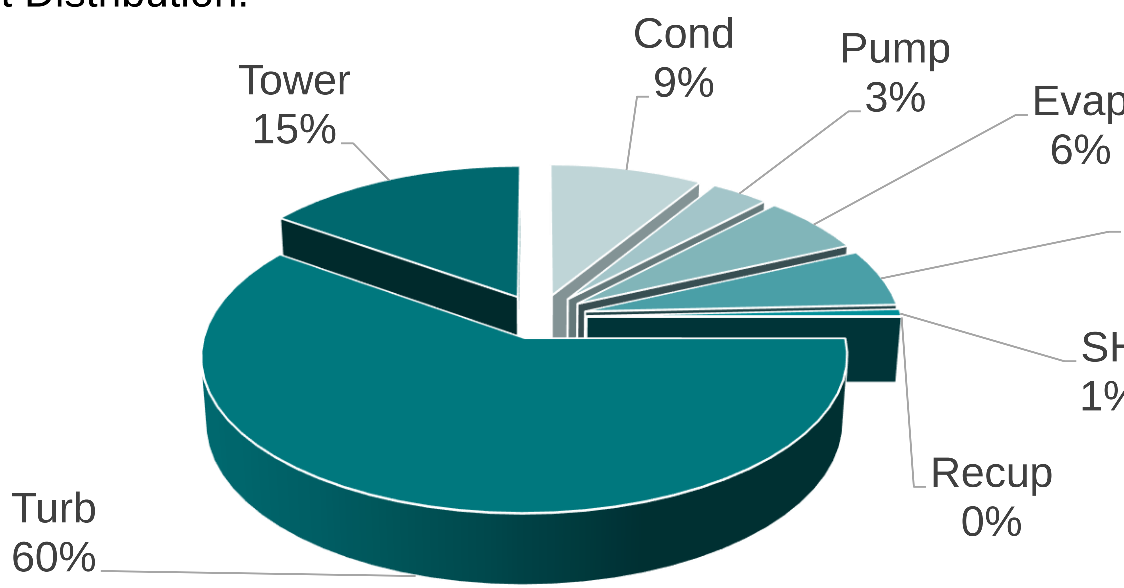
Results of Optimization – Minimizing LCOE

$T_{cw,in}$ [K]	$\dot{m}_{WF}$ [kg/s]	p_{HP} [bar]	p_{LP} [bar]	P_{net} [MW]	η_{th} [%]	$LCOE_{min}$ [US-$/MWh]	CPU time [s]
268	385	16.6	2.66	27.1	14.7	41.2	76
273	396	16.3	3.08	25.1	13.6	43.7	77
288	435	15.2	4.60	18.8	10.2	55.7	41

Investment Cost Distribution:

$T_{cw,in} = 268$ K



$y_{Recup} = 0$

Comparison of CPU Times

	$T_{cw,in}$ [K]	Proposed Method CPU time [s]	BARON CPU time [s]
$P_{net,max}$	268	13	67
	273	15	297
	288	22	149
$LCOE_{min}$	268	76	$4.0 \cdot 10^4$
	273	77	$4.1 \cdot 10^4$
	288	41	$1.0 \cdot 10^4$

- Economic objective function increases CPU times
- Optimization of mixed-integer problem tractable
- Some local solvers (IPOPT) fail to find global optimum

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Conclusion & Outlook

- Deterministic global optimization using sequential modular mode successfully applied to ORC design scenario
- Faster than state-of-the-art global optimization solver
- A recuperator can increase net power, but is not economically sensible
- *LCOE* (40 - 60 US-$/MWh) comparable to realized projects for geothermal power [IRENA2014]

- Implementation of more detailed thermodynamic models & heat transfer correlations
  → cubic equation of state
- More structural degrees of freedom:
  → flowsheet superstructure
  → working fluid optimization
- Solver improvements

Thank you
for your attention!

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