EnergyVille

Towards Adjoint-based Topology Optimization of Thermal Networks

Dr. Ir. Maarten Blommaert

Mechanical Engineering, KU Leuven – Energyville, Belgium

Prof. Dr. Ir. Martine Baelmans

Mechanical Engineering, KU Leuven, Belgium

Europese Unie
Europees Fonds voor Regionale Ontwikkeling
Hier wordt geïnvesteerd in uw toekomst!

provincie Limburg

AGENTSCHAP
INNOVEREN &
ONDERNEMEN

EFRO
EUROPEES FONDS
VOOR REGIONALE
ONTWIKKELING

Context – EFRO-SALK GeoWatt Project

“Towards a Sustainable Energy Supply in Cities”

Research topics

- Optimal design
- Thermal network control
- Flexibility
- Component design
- Geothermal energy
- Fault detection
- Building models

Common case

- City of Genk (B)

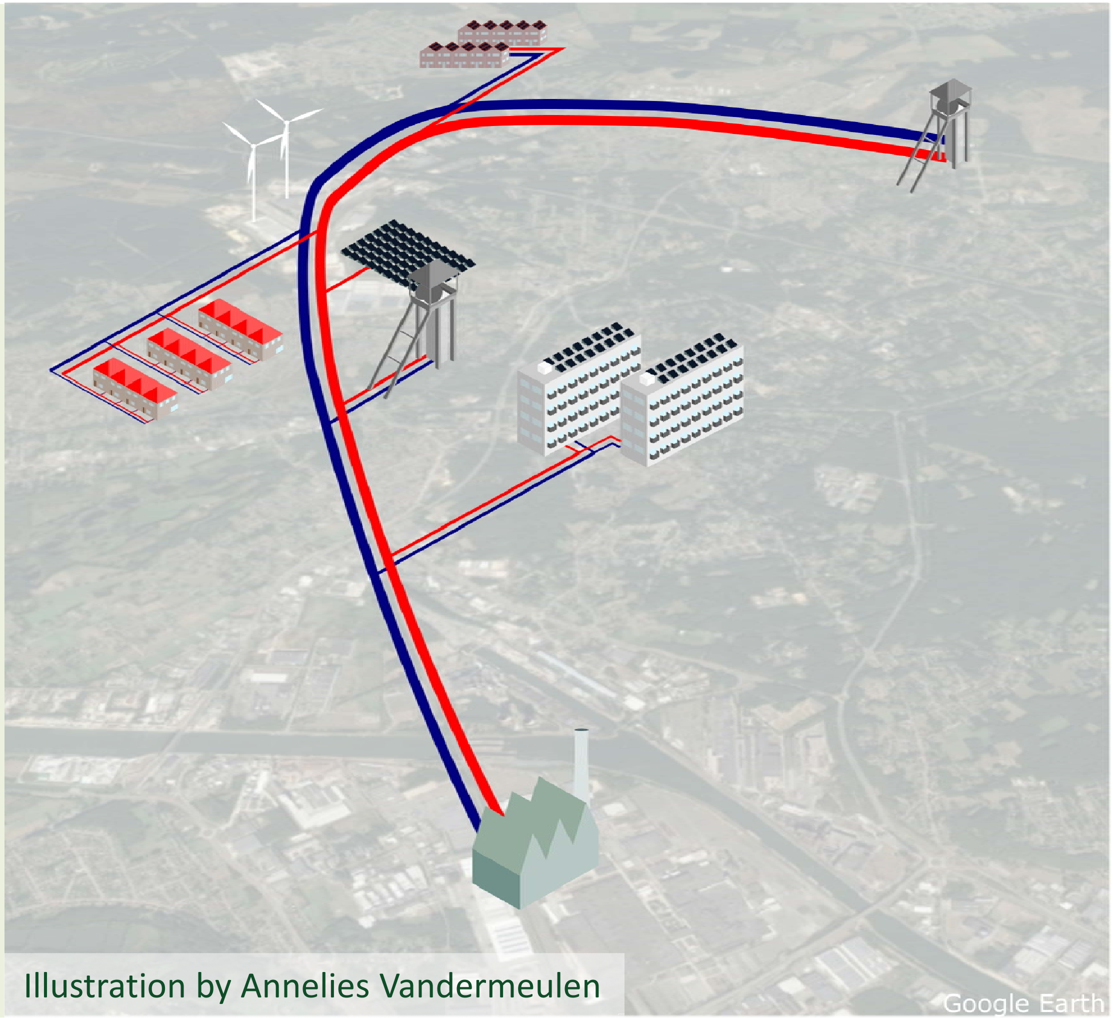


Illustration by Annelies Vandermeulen

Design challenges in thermal network design

- Good methods available for finding shortest possible routes

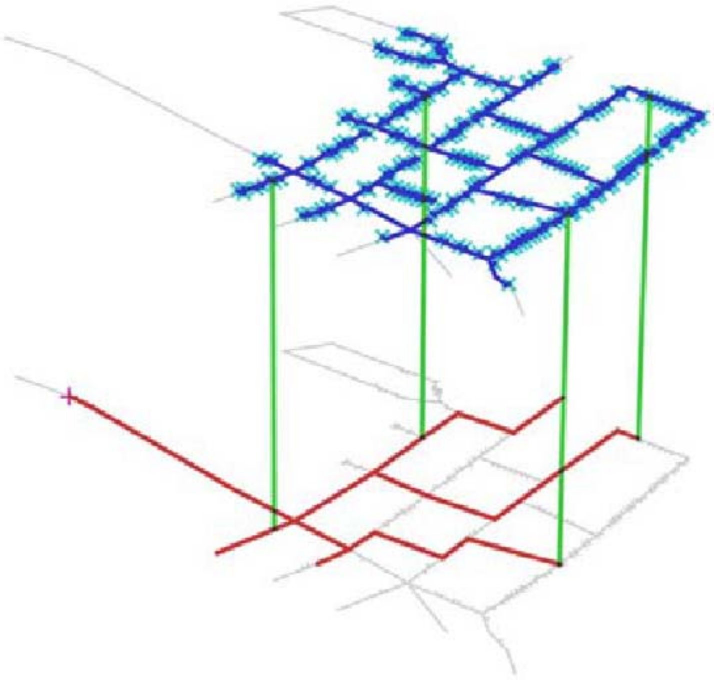
- But finding a **cost-efficient** configuration, accounting for **investment** and **operational costs**, as well as **design constraints** non-trivial

- Especially challenging for reconversion to 4th generation networks with **suppliers at different temperatures**

Network topology optimization with MILP/MINLP

- Recent trend: **topology optimization** of thermal networks
- Idea: Let an optimization algorithm decide on the most cost-effective configuration
- Typically neglects all nonlinearities
  - Pressure drop of turbulent flow
  - Heat losses in pipes
  - Consumer model
  - …
- Or limited to rather small networks

Multicarrier network design



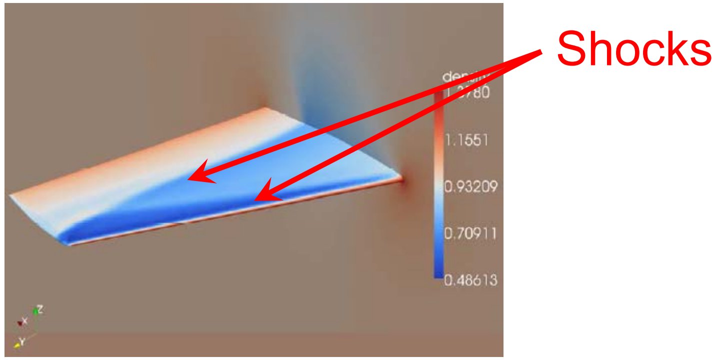
W. Mazairac et al. (2015)

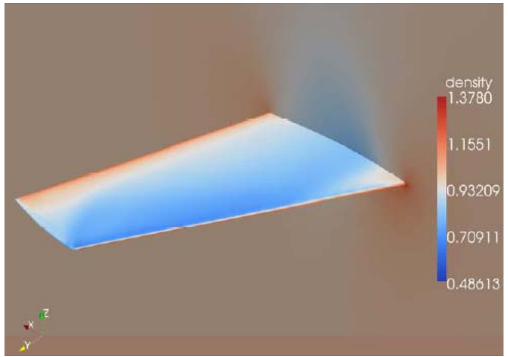
Need for more efficient optimization methods!

“Adjoint”-based design: next step in CFD

Size and shape optimization:

Airfoil design for minimal drag



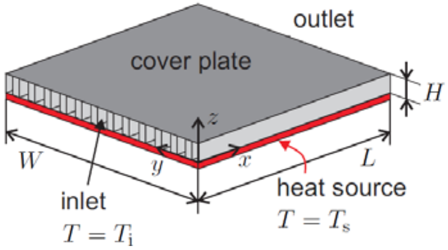


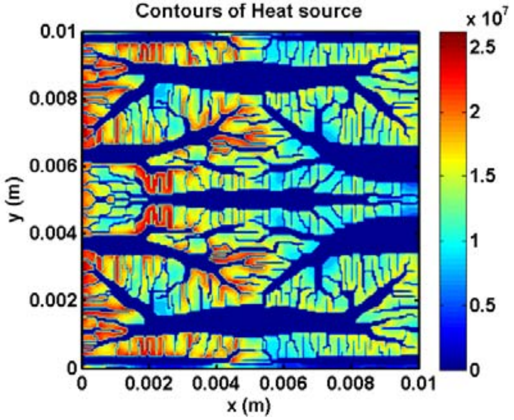
32% drag reduction

Gauger (2010), VKI LS on MDO

Topology optimization:

Heat sink design for maximal heat transfer

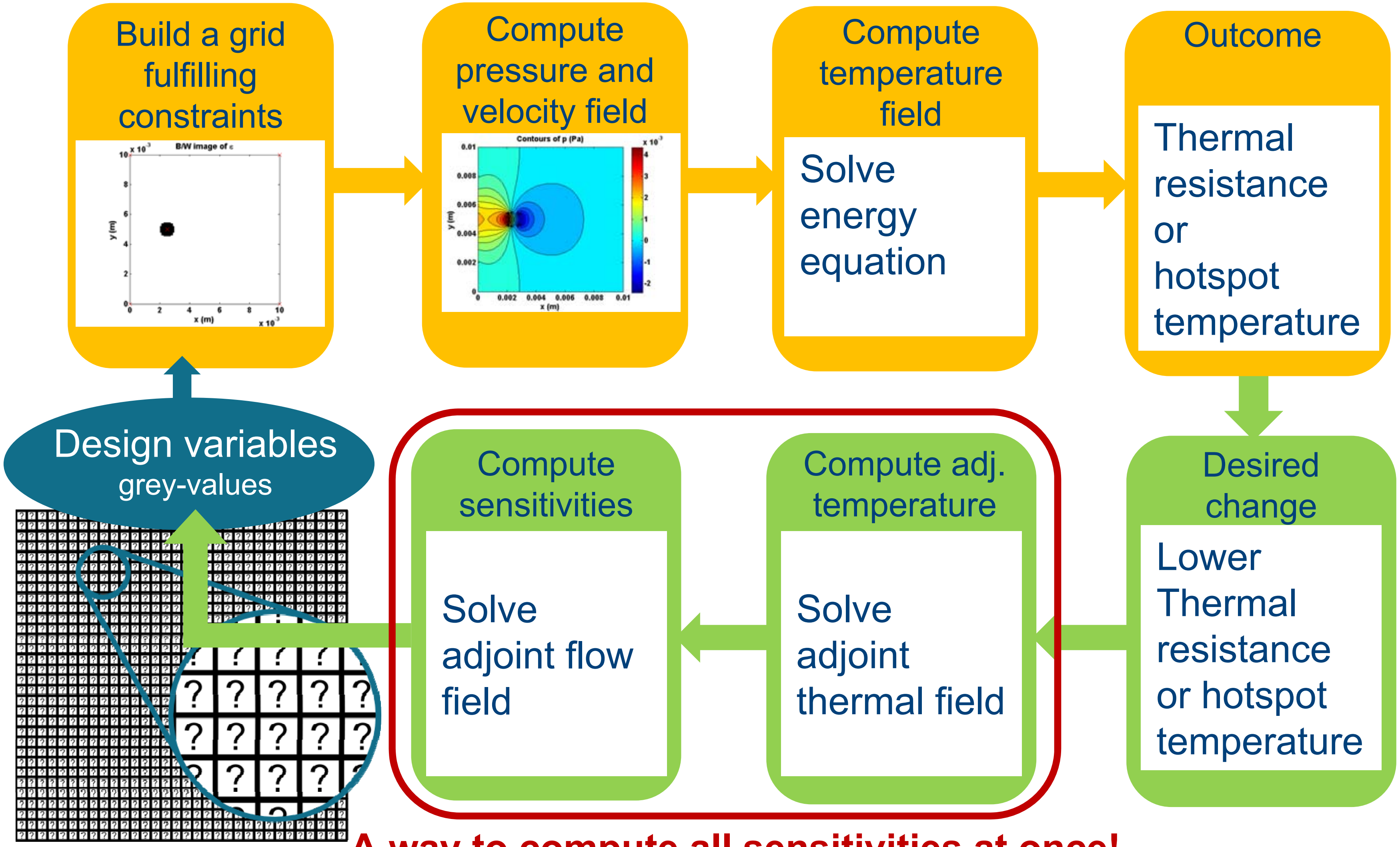




PhD. Thesis T. Van Oevelen

Adjoint: A technique for nonlinear problems with many design variables

Adjoint topology optimization of heat sink



Build a grid fulfilling constraints

Compute pressure and velocity field

Compute temperature field
Solve energy equation

Outcome
Thermal resistance or hotspot temperature

Desired change
Lower Thermal resistance or hotspot temperature

Compute adj. temperature
Solve adjoint thermal field

Compute sensitivities
Solve adjoint flow field

Design variables
grey-values

A way to compute all sensitivities at once!

Adjoint sensitivity calculation

$c(\phi, q) = 0$: Transport equations

q: state variables (e.g. pressure, temperature,…)

ϕ: Control variables (e.g. material porosity)

Define Lagrangian as

$$\mathcal{L}\left(\boldsymbol{\phi}, \boldsymbol{q}, \boldsymbol{q}^{*}\right) = I\left(\boldsymbol{\phi}, \boldsymbol{q}\right) + \left(\boldsymbol{q}^{*}, c\left(\boldsymbol{\phi}, \boldsymbol{q}\right)\right)$$

$\boldsymbol{q}^{*}$: Lagrangian multipliers

The sensitivity then equals

$$\frac{dI}{d\boldsymbol{\phi}}\delta\boldsymbol{\phi} = \frac{d\mathcal{L}}{d\boldsymbol{\phi}}\delta\boldsymbol{\phi} = \frac{\partial\mathcal{L}}{\partial\boldsymbol{\phi}}\delta\boldsymbol{\phi} + \frac{\partial\mathcal{L}}{\partial\boldsymbol{q}}\delta\boldsymbol{q} + \frac{\partial\mathcal{L}}{\partial\boldsymbol{q}^{*}}\delta\boldsymbol{q}^{*}$$

Adjoint sensitivity calculation

Lagrangian

$$\frac{\partial \mathcal{L}}{\partial \boldsymbol{q}^*} = c(\boldsymbol{\phi}, \boldsymbol{q}) = 0$$ Sim

$\boldsymbol{q} = [p, v, T]^T$

$$\frac{\partial \mathcal{L}}{\partial \boldsymbol{q}} = 0$$ Adjoint sim

$\boldsymbol{q}^* = [p^*, v^*, T^*]^T$

$$\mathcal{L}(\boldsymbol{\phi}, \boldsymbol{q}, \boldsymbol{q}^*) = I(\boldsymbol{\phi}, \boldsymbol{q}) +$$

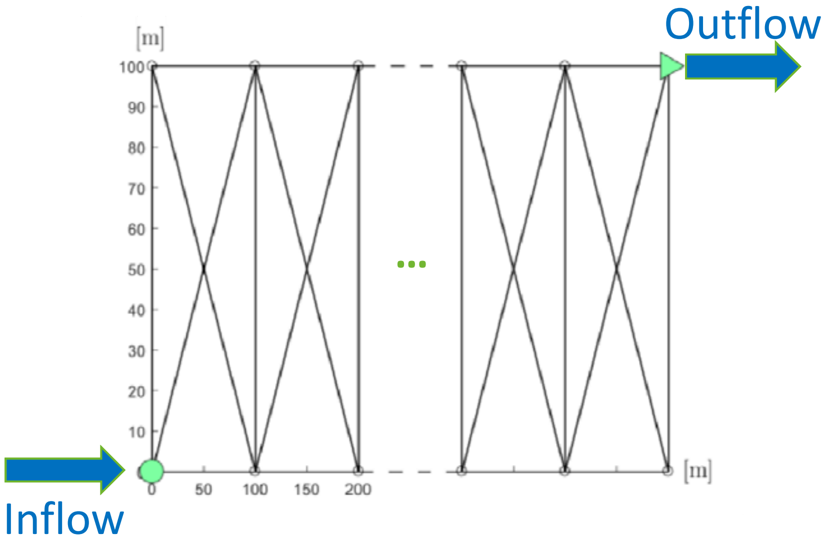
Difficult nonlinea $\boldsymbol{q}(\boldsymbol{\phi})$ drops out!

$$\frac{dI}{d\boldsymbol{\phi}}\delta\boldsymbol{\phi} = \frac{\partial \mathcal{L}}{\partial \boldsymbol{\phi}}\delta\boldsymbol{\phi} + \frac{\partial \mathcal{L}}{\partial \boldsymbol{q}}\delta\boldsymbol{q} + \frac{\partial \mathcal{L}}{\partial \boldsymbol{q}^*}\delta\boldsymbol{q}^*$$

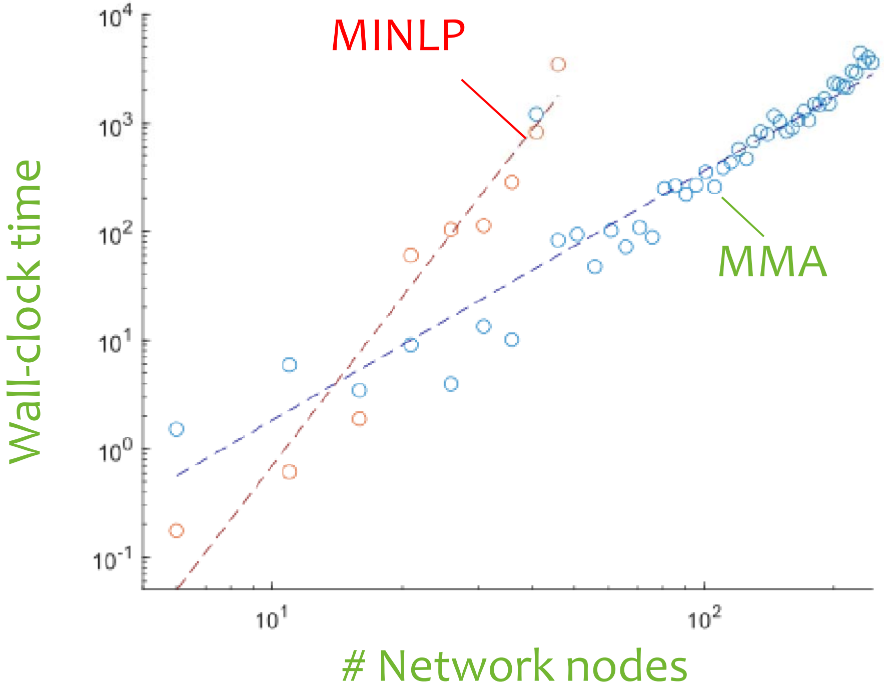
Sensitivity

Adjoint-based network optimization

Check scaling of MINLP and adjoint for turbulent flow network



Optimized **networks of increasing size** for minimal compressor power

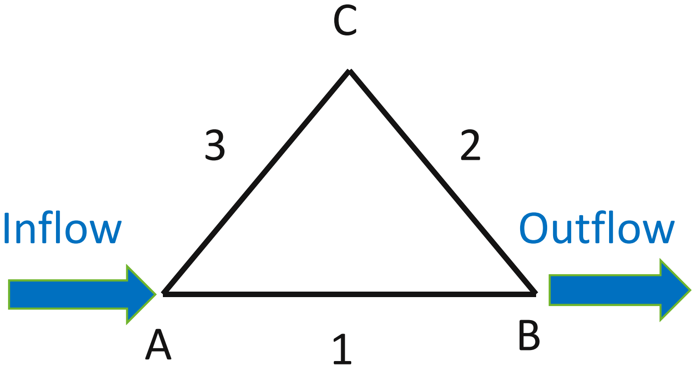


Comparison of MINLP (GAMS/COUENNE) and adjoint topology optimization for hydraulic problem

Master thesis B. Van Dijck

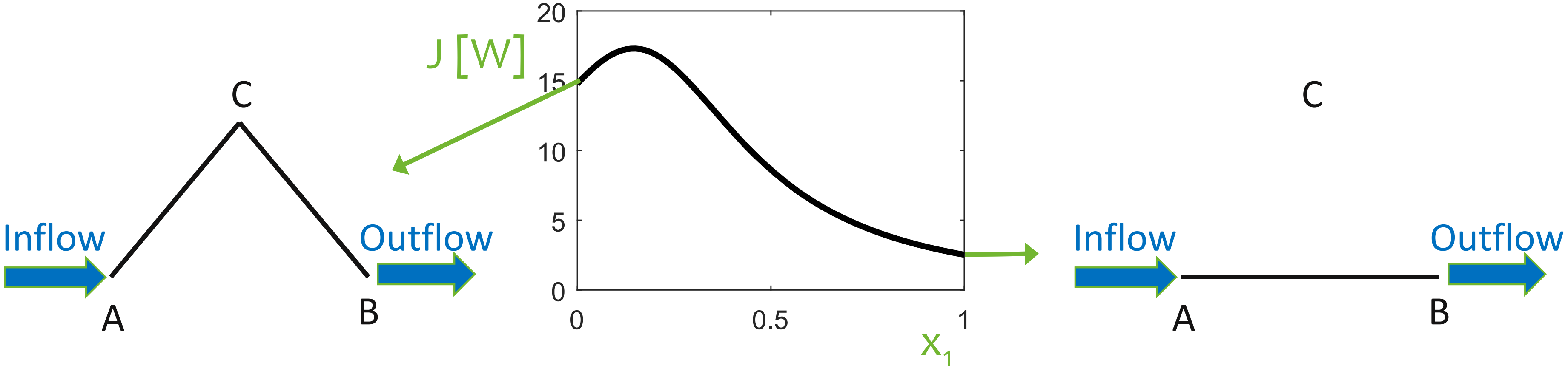
What’s the catch?

- Analyze topology optimization of 3-point laminar hydraulic flow network Solve momentum in vertices and continuity in nodes (Evgrafov)
  - Objective: $\min_{x_i} J = \sum_i \Delta p_i q_i$, subject to $\sum_i x_i < V$
  - x_i = pipe volume, Δp_i = pressure drop, q_i = flow, V = maximal pipe volume



What’s the catch?(2)

- Two local optima!



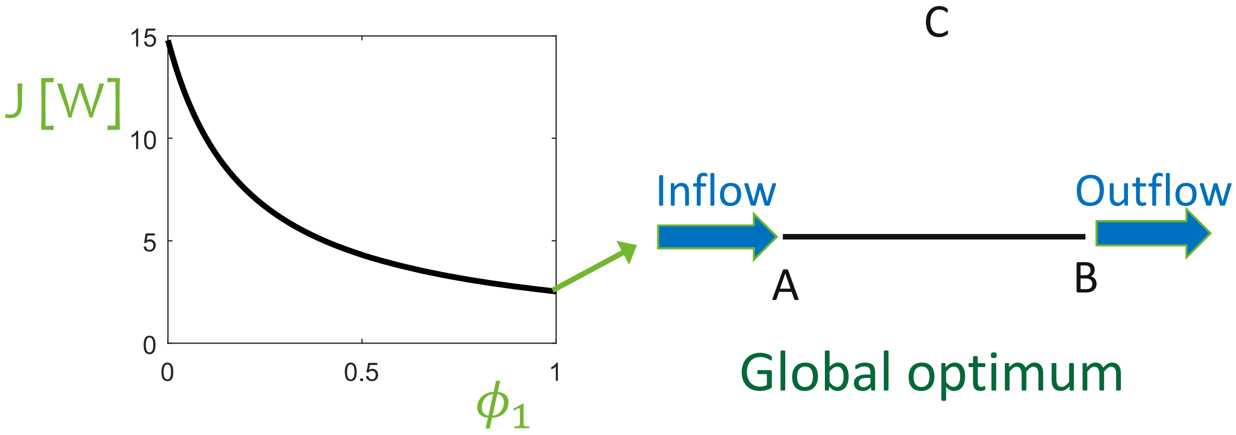
Local optimum

Global optimum

- Due to high flow resistivity of small pipes
  - $J = \sum_i \Delta p_i q_i = \sum_i R_i q_i^2 = R_{123} q_{in}$
  - $R_i = \frac{8\pi\mu l_i^3}{x_i^2}$, $R_{123} = \frac{1}{\frac{1}{R_1}+\frac{1}{R_2+R_3}}$
  - Multiple zeros in denominator

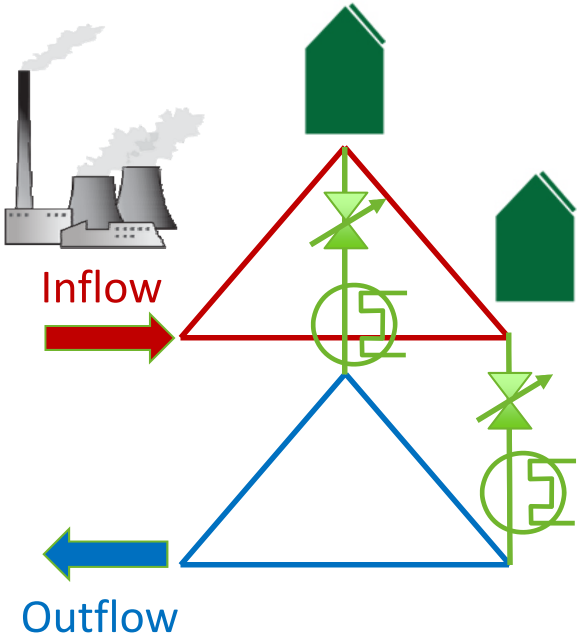
How to deal with local optima (1)

- Manipulate choice of design variables
  - Optimize existence $\phi_i = \frac{x_i^2}{x_{i,nom}^2}$, with constraint $\sum_i \phi_i x_{i,nom} < V$



Global optimum achieved from any design point!

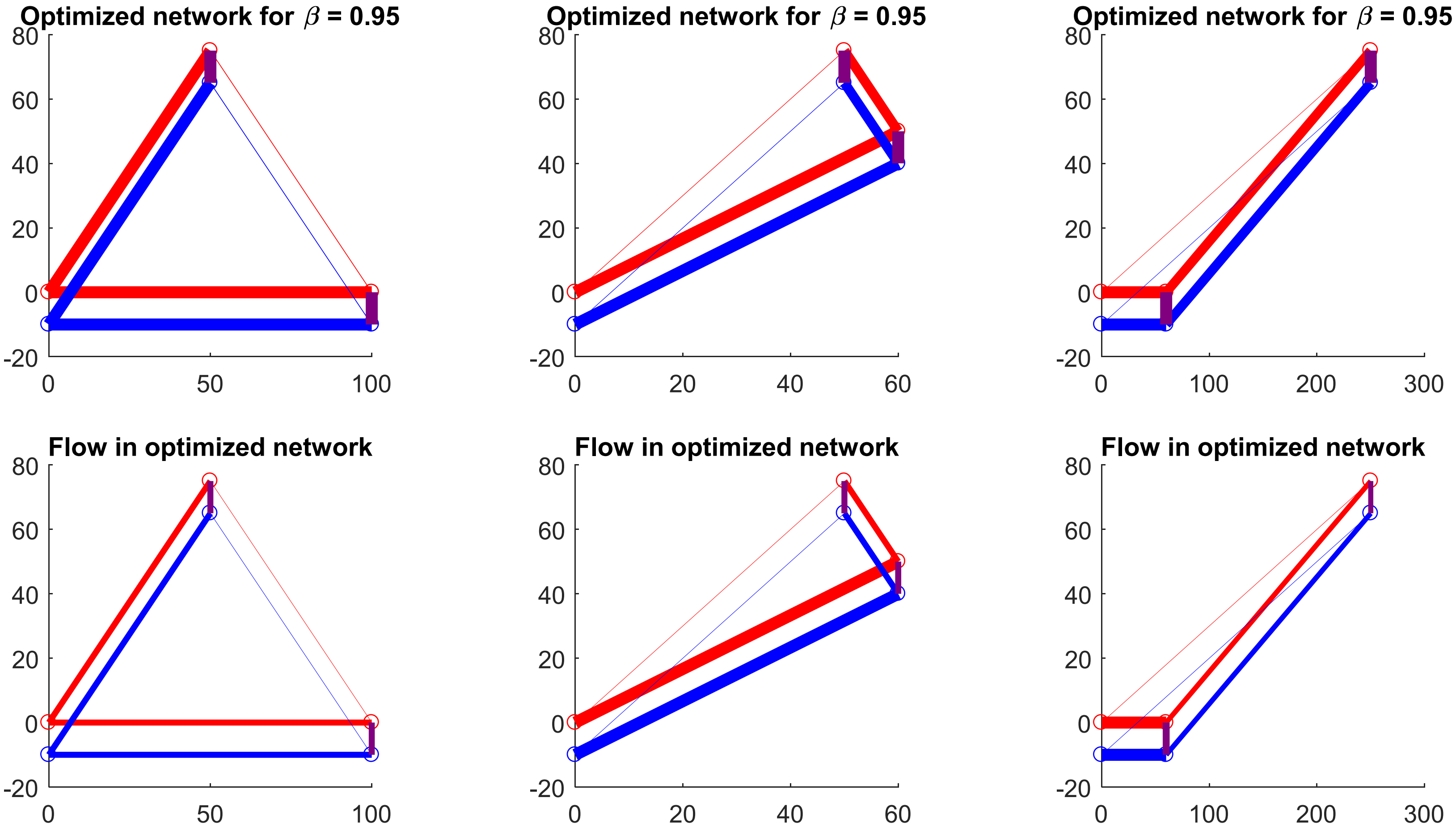
Now for thermal networks…



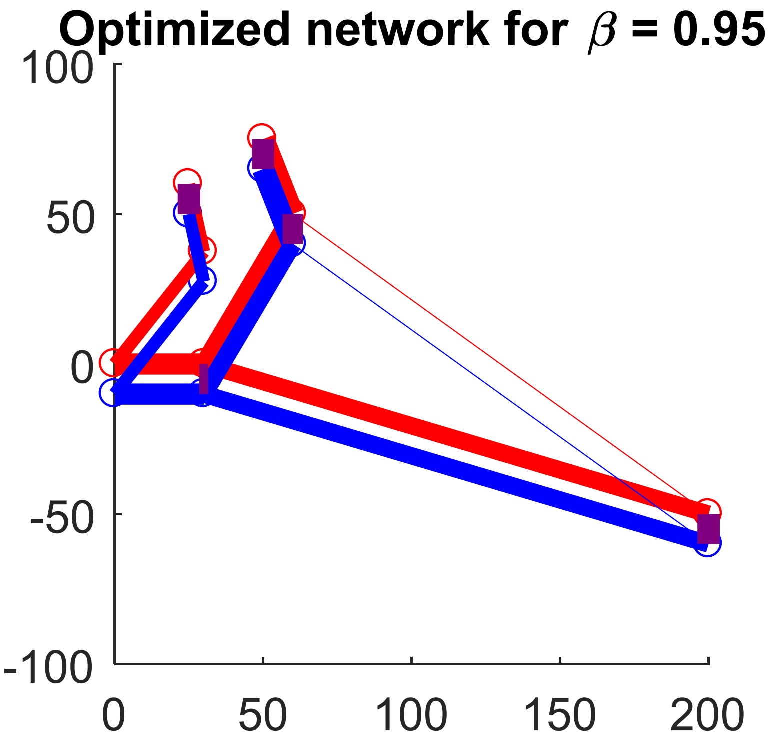
- Thermal network model
  - Haaland correlation for turbulent flow friction in pipes
  - Consumer model with throttle and heat exchanger (for now fixed T-drop)
- Worst-case optimal design
  - Objective: Compromise between compressor power and consumer heat demand
  - $$J = \beta\lambda_Q \left\| \frac{1}{2}(Q_{ic} - Q_{d,i}) \right\|_2 + \lambda_P(1-\beta)\Delta \mathrm{p}_{\mathrm{in}}\mathrm{q}_{\mathrm{in}}$$
  - Control topology, pipe diameters, throttles, and plant inflow

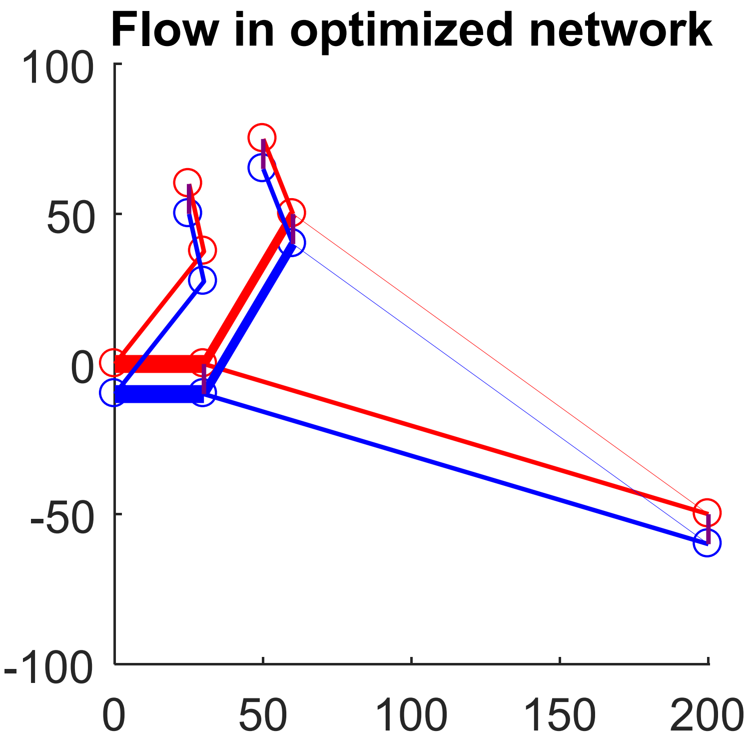
Topology optimization of thermal networks: preliminary results

Some tests with fixed choice of β and $Q_{d,1} = Q_{d,2}$



More than 3 points works as well of course…





Conclusions

- Adjoint methods yield much better scalability to larger networks
- Adjoint methods are compatible with strongly nonlinear design problems
- First tests with adjoint-based tool on thermal networks positive

Ongoing/future work

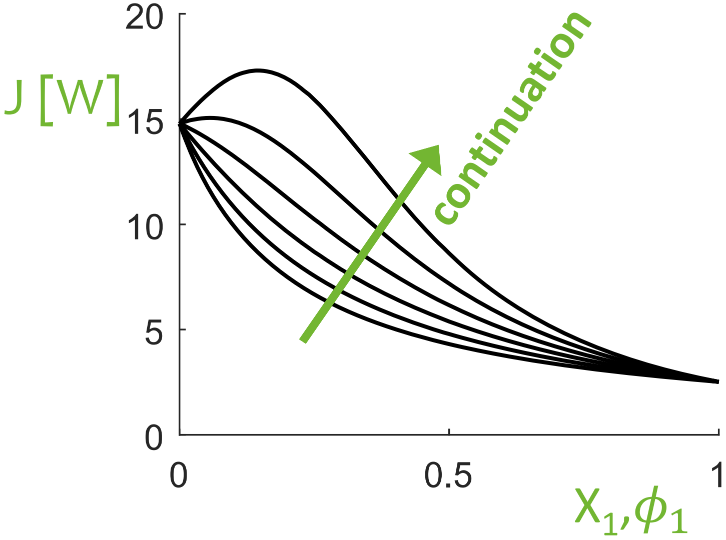
- Extension to energy equation and suppliers at different temperatures
- Heat exchanger model at consumer side
- Add projection/continuation methods for discrete design variables
- Economic cost function with investment costs
- Long term: Combined network/storage optimization,…

Questions?

Extra slides

How to deal with local optima (2)

- Numerical continuation strategy
  - Make homotopy map = continuous transformation of objective and constraints
  - Let convex proxy problem serve as good initial guess



Design challenges in energy applications

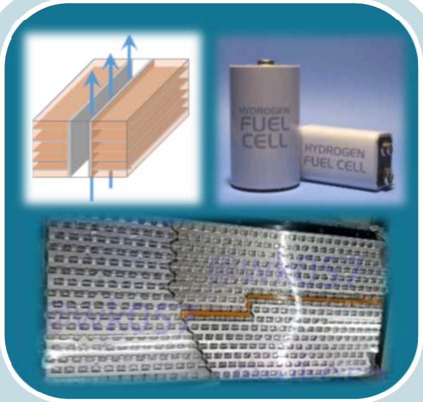
Compact Cooling

- Data centers
- Power electronics
- Photovoltaics

Compact Heat Exchangers

- HVAC Systems

  balanced air ↔ air recuperator
- Micro Gas Turbine Recuperators
- Fuel Cells



High-capacity storage

- Thermal storage in PCM’s

  charge time vs. capacity
- Batteries/fuel cells

  -graded electrodes

  -packing design

Thermal systems optimization

- Thermal networks routing
- Reconversion to 4G networks
- Multicarreer network design

Design challenges in energy applications

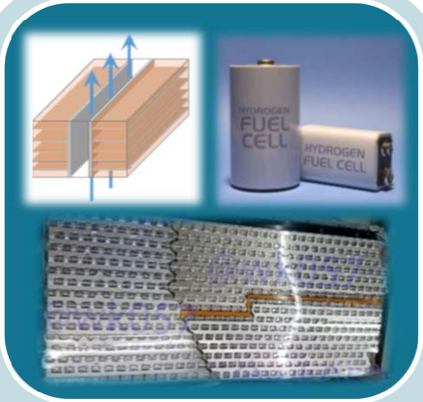
Compact Cooling

- Data centers
- Power electronics
- Photovoltaics

Compact Heat Exchangers

- HVAC Systems

  balanced air ↔ air recuperator
- Micro Gas Turbine Recuperators
- Fuel Cells



High-capacity storage

- Thermal storage in PCM's

  charge time vs. capacity
- Batteries/fuel cells

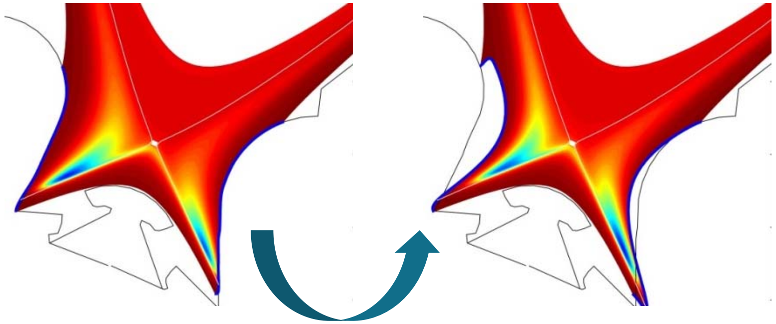
  -graded electrodes

  -packing design

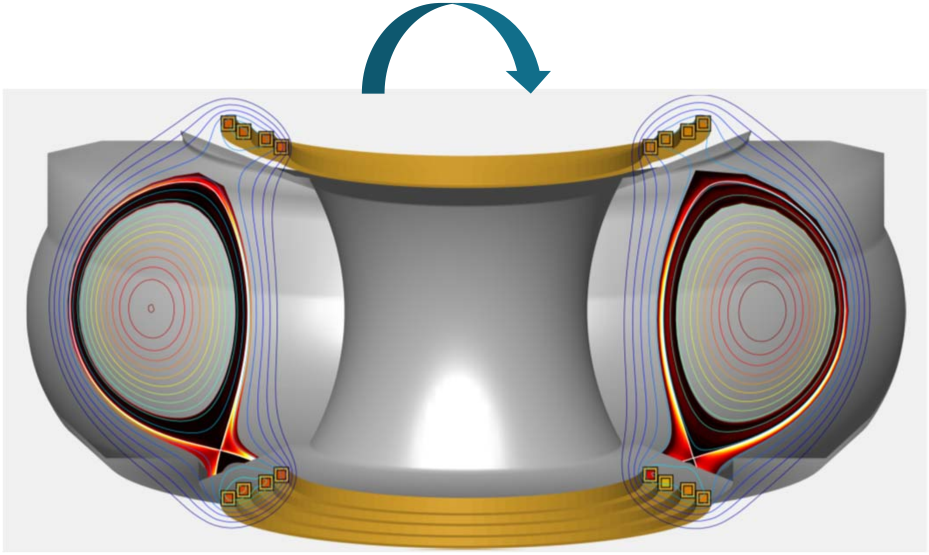
Thermal systems optimization

- Thermal networks routing
- Reconversion to 4G networks
- Multicarreer network design

Applications of *optimization* methodologies

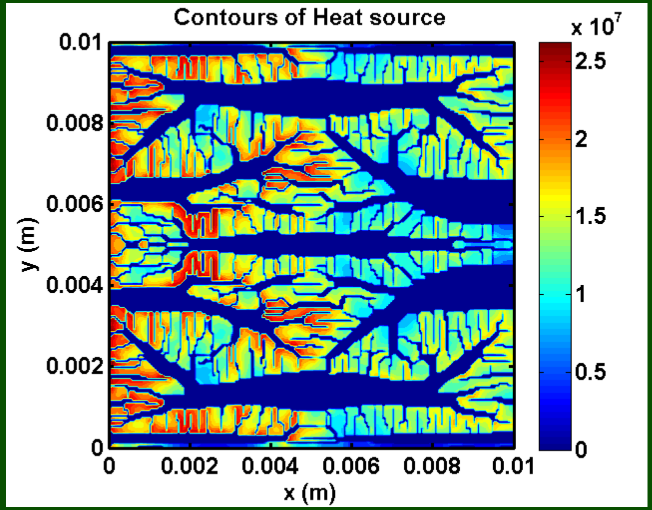


Divertor Shape optimization



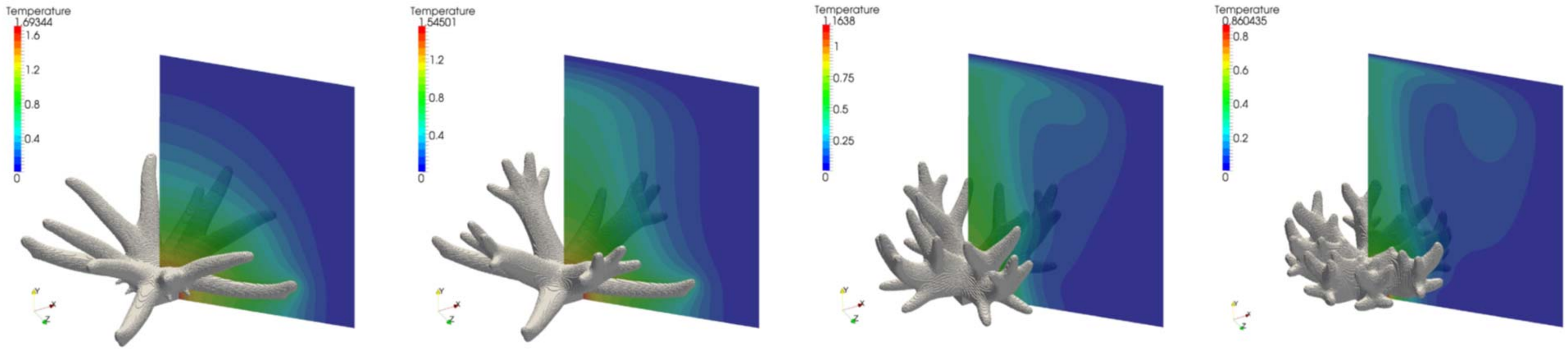
Magnetic field optimization

Heat sink optimization

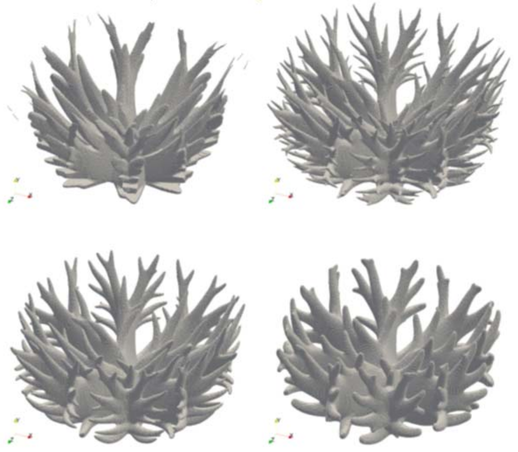


Review paper and references therein: M. Baelmans et al. *Nucl. Fus. 57 (2016)*, no. 036022.

3D Topology optimization
Heat sinks cooled by natural convection



Optimized designs for varying Gr-number at a mesh resolution of 160x320x160. (Gr = 10^3, 10^4, 10^5, 10^6)



optimization cost

- DNS steady laminar flow
- 8,19 M grid cells

10 hours on 1280 cores

Alexandersen, 2016

Simulation-based design

High simulation cost

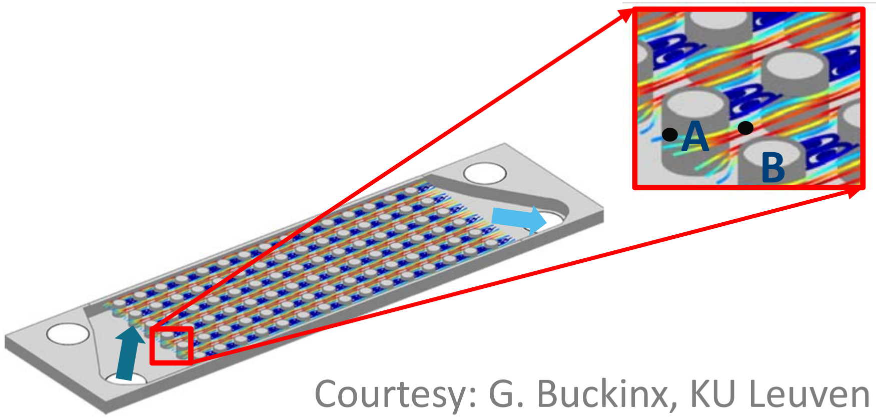
- DNS steady laminar flow
- 1,44 M grid cells/fin

---

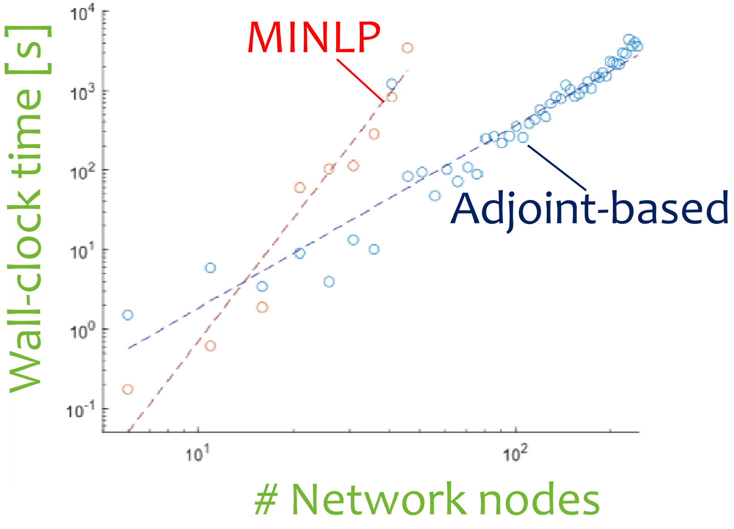
9 hours on 100 processors

High optimization cost

- Thermal network design
- Many design variables
- Bad scalability of traditional methods



Courtesy: G. Buckinx, KU Leuven

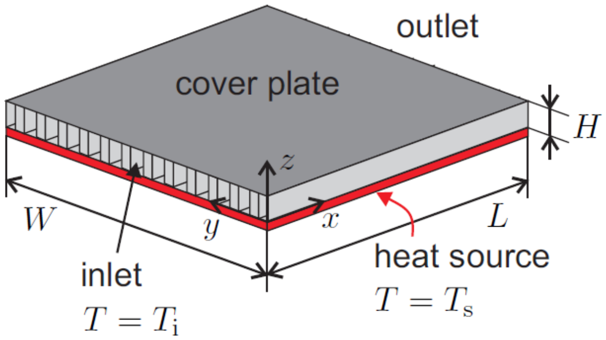


Master thesis B. Van Dijck

Broad design explorations quickly become inaccessible!

Real-size problems inaccessible with traditional methods!

Topology optimization for cooling



Electronics cooling

Silicon micro heat sink: 1cm x 1cm x 500µm

Fixed pressure drop: 10 kPa

Heat source 40 K above coolant inlet T

Heat sink for **constant temperature** heat source

Objective:

Maximal heat removal from the heat source

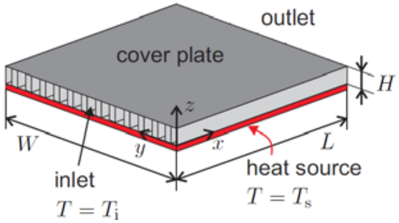
Heat sink for **constant heat flux** source:

Objective:

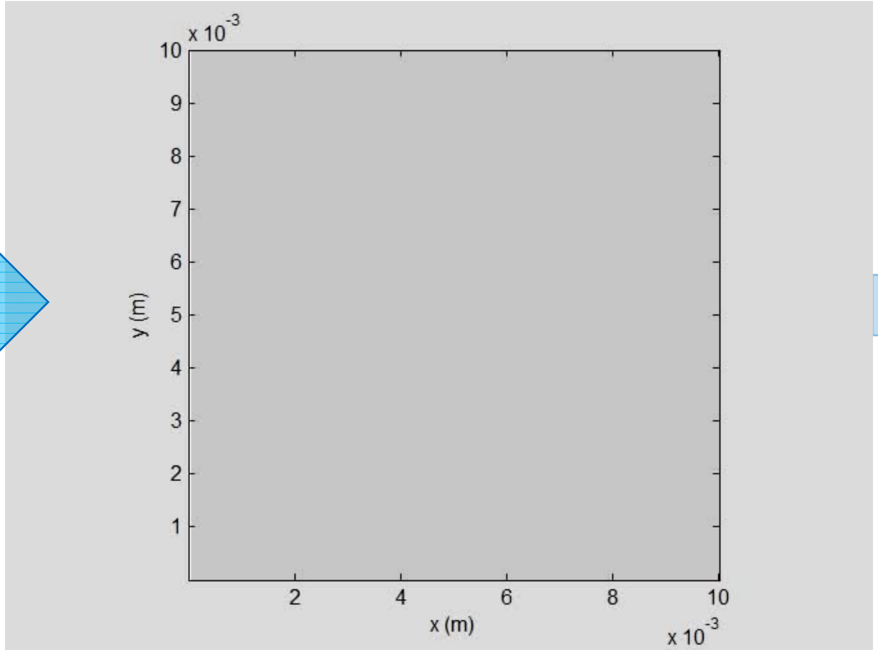
Minimal deviation from desired temperature

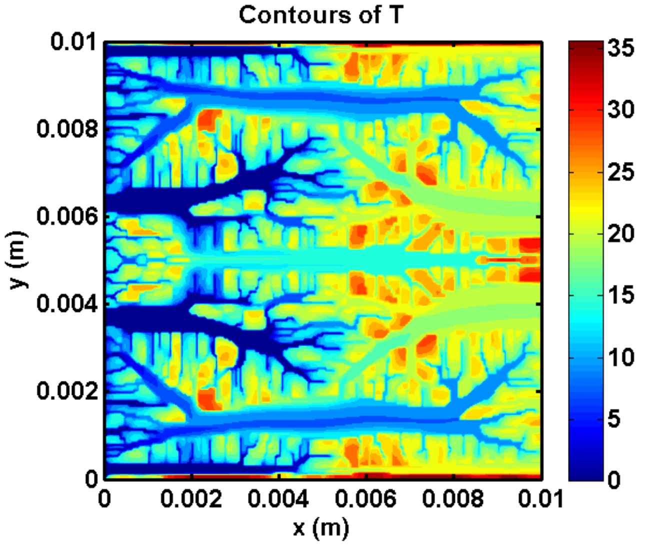
Easily extended to given heat flux profile and desired temperature

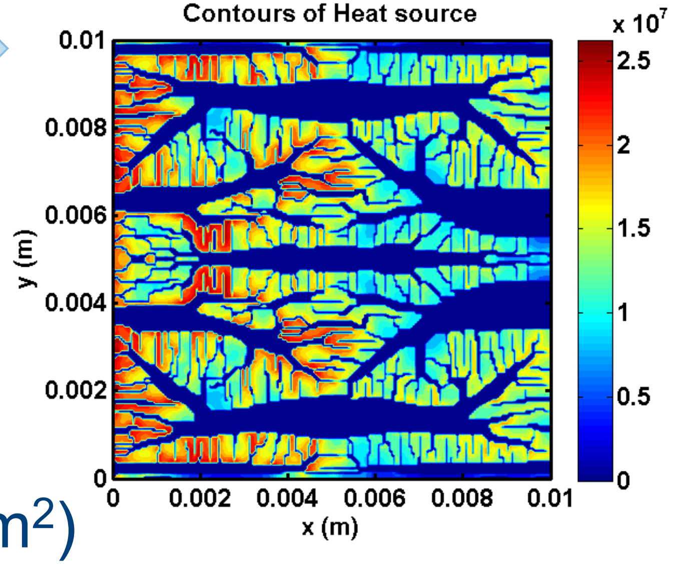
Heat sink topology optimization



Constant T







- Start with grey; evolve to b/w
- Total heat removed: 794 W (≈8MW/m^2)
- 30x better than empty cooler