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Optimal operation of cross-ownership district heating and cooling networks

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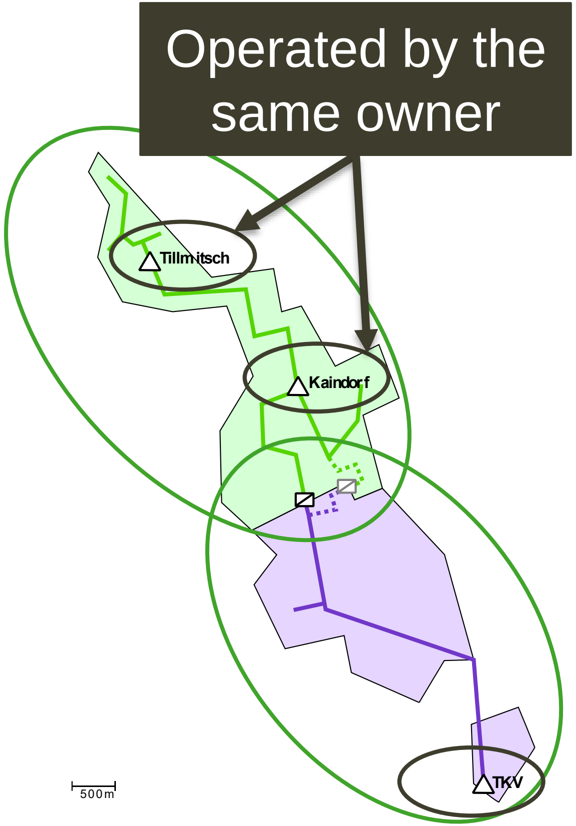
Motivation

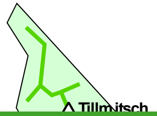
Coupling of District Heating Networks

- Three district heating networks (near Leibnitz in Styria, Austria) have grown and reached the boundaries of their neighbouring networks
- Two owners operate the networks

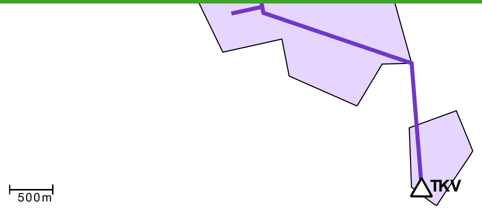


Objective

- **Each network (agent) has local**
  - Production, demand & storage
  - Different technologies and fuel prices
- **Networks are coupled via heat exchangers**
  - Incur losses
  - Operating strategy influences both connected networks
- **Networks are bound by existing contracts**

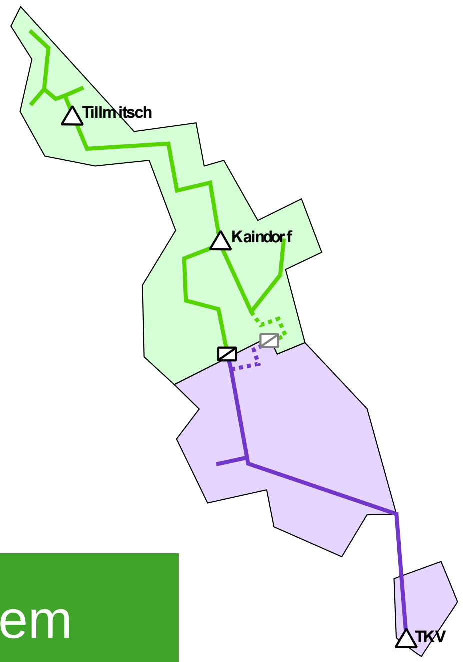


Find **co-ordinated** operating strategies that maximize the profit of every **individual** owner



Problems of Coupled Operation

- **Costs of heat are variable**
  - Depending on current production / demand / storage: transmitting more heat would require running the backup boiler, which is more expensive
- **Direction of heat transport cannot change too often**
  - long transmission lines would cool down
- **Hydraulic limitations do not allow supply of all consumers**
  - Pipes towards/from heat exchanger might not have sufficient capacity



Typical Approach: Solve Optimization Problem

Coupling Representations

Cooperative coupling

- Agents work together to minimize a **global** objective

$$\min_{\boldsymbol{x}_i \in \mathcal{X}_i} \quad \sum_{i=1}^{N} f_i(\boldsymbol{x}_i)$$

$$\text{s.t.} \quad \sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i = \boldsymbol{b}$$

Global / Social **optimum**
Lowest overall costs

Non-cooperative coupling

- Agents minimize only their **local** objective

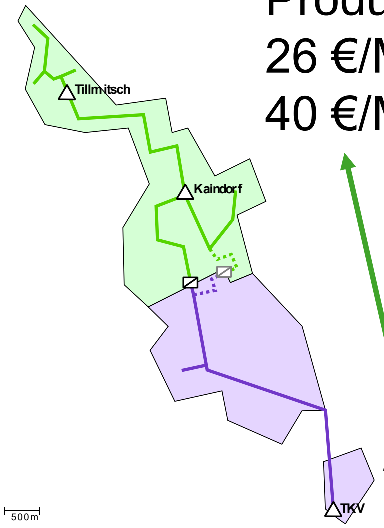
$$\min_{\boldsymbol{x}_i \in \mathcal{X}_i} \quad f_i(\boldsymbol{x}_i), \quad i = 1, \dots, N$$

$$\text{s.t.} \quad \sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i = \boldsymbol{b}$$

Generalised Nash equilibrium
No agent can improve his/her objective by **unilaterally** changing his/her strategy

Cooperative Coupling

- **When is the global/social optimum not the „best“ solution?**



Produces for
26 €/MWh (normal)
40 €/MWh (peak)

Sells for
35 €/MWh

Produces for
24 €/MWh

$$\min_{\boldsymbol{x}_i \in \mathcal{X}_i} \quad \sum_{i=1}^{N} f_i(\boldsymbol{x}_i)$$

$$\text{s.t.} \quad \sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i = \boldsymbol{b}$$

Gains from one agent
cancel out with
losses from the other agent

Global optimum: Produce everything in the south!

Non-Cooperative Coupling

$$\min_{\boldsymbol{x}_i \in \mathcal{X}_i} \quad f_i(\boldsymbol{x}_i), \quad i = 1, \dots, N$$

$$\text{subject to} \quad \sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i = \boldsymbol{b}$$

- Coupling constraint requires communication between agents

***N* coupled opt. problems**

x Iterative algorithm
x No unique solution!
x No notion of "better" or "worse" solution

Solution similar to Distributed Optimization

- Augmented Lagrange functions

$$\mathcal{L}_i(\boldsymbol{x}_i, \boldsymbol{\lambda}_i, \boldsymbol{x}_{-i}) = f_i(\boldsymbol{x}_i) + \boldsymbol{\lambda}_i^T \left(\boldsymbol{A}_i \boldsymbol{x}_i + \sum_{j \neq i} \boldsymbol{A}_j \boldsymbol{x}_j - \boldsymbol{b} \right) + \frac{\rho}{2} \left\| \boldsymbol{A}_i \boldsymbol{x}_i + \sum_{j \neq i} \boldsymbol{A}_j \boldsymbol{x}_j - \boldsymbol{b} \right\|_2^2$$

- Dual ascent

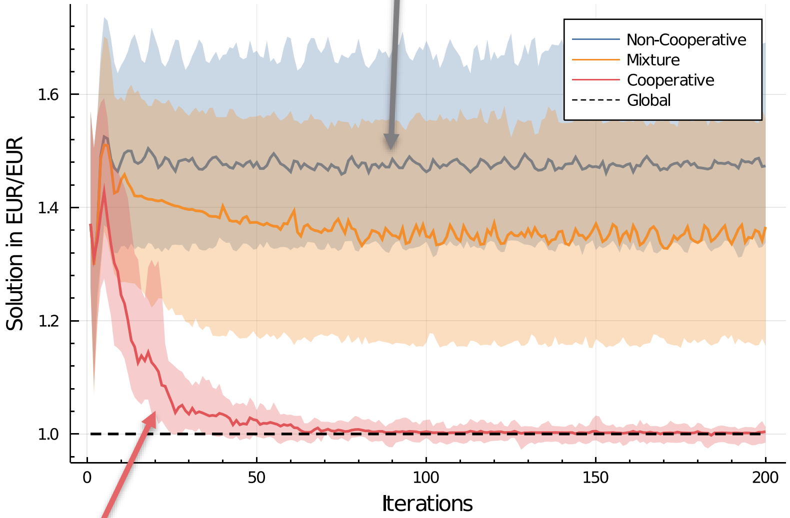
$$\boldsymbol{x}_i^{(k+1)} = \underset{\boldsymbol{x}_i \in \mathcal{X}_i}{\operatorname{argmin}} \; \mathcal{L}_i(\boldsymbol{x}_i, \boldsymbol{\lambda}_i^{(k)}, \boldsymbol{x}_{-i}^{(k)})$$

$$\boldsymbol{\lambda}_i^{(k+1)} = \boldsymbol{\lambda}_i^{(k)} + \rho \left(\boldsymbol{A}_i \boldsymbol{x}_i^{(k+1)} + \sum_{j \neq i} \boldsymbol{A}_j \boldsymbol{x}_j^{(k)} - \boldsymbol{b} \right)$$

Simulation Study
Three grids & two owners

- Prices chosen so that no one will buy heat from neighbors
- Three scenarios:
  - All three grids **cooperative**
  - All three grids **non-cooperative**
  - The two grids that belong to the same owner cooperate; the third does not (**mixture**)

Nash equilibrium → no transactions (overall costs are higher by 50%)



Distributed optimizaton → global optimum

Conclusions

- Operating coupled networks with different owners cannot easily be described as a simple **optimization** problem
  - Competing interests are cancelled out in the cost function

- An iterative algorithm can be used to solve for **Nash equilibria** instead
  - No guarantee that these represent „good“ operating strategies
  - Further investigation into the role of the initial solution
  - Very similar algorithm to distributed optimization

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