CO@Work 2020
Gas Networks Introduction

Topics are:

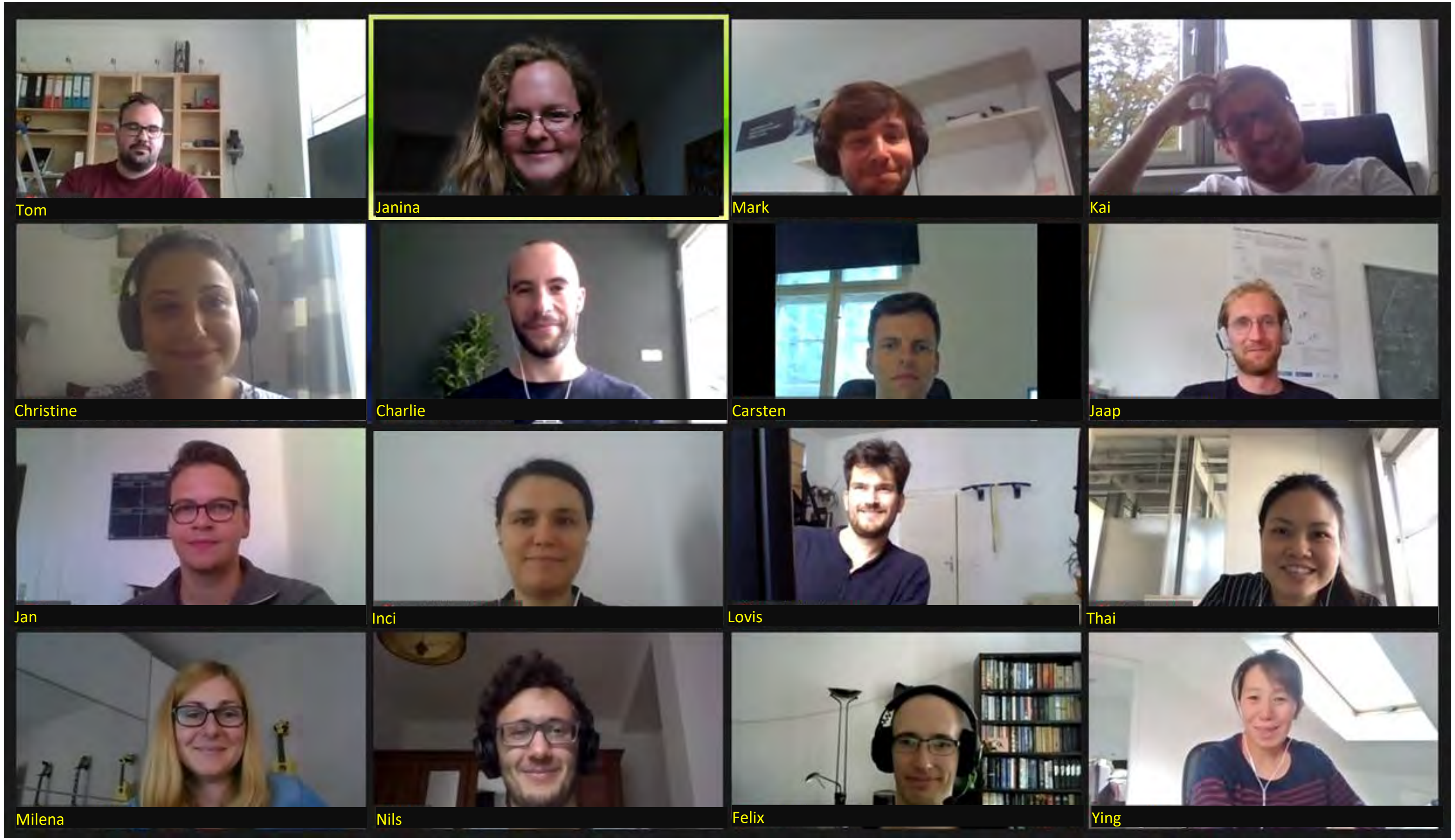
1. European Regulations
2. Gas Network Basics
3. Network Design
4. Gas Network Capacity
5. Gas Network Control

September 2020

Online

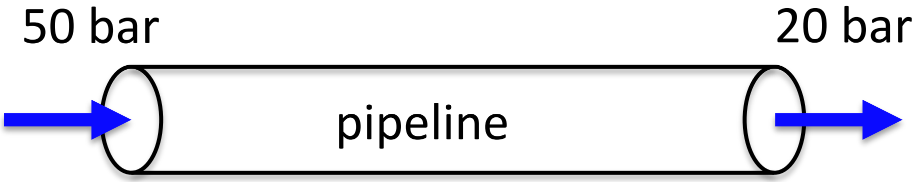
http://co-at-work.zib.de

The Energy Team (ZIB, TU Berlin, MODAL GasLab)



… and me

A pipeline



$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho\, v)}{\partial x} = 0$$

$$\frac{\partial(\rho\, v)}{\partial t} + \frac{\partial(p + \rho\, v^2)}{\partial x} + \frac{\lambda}{2D}|v|\, v\, \rho + g\, s\, \rho = 0$$

$$\frac{\partial}{\partial t}\left(\rho(\frac{1}{2}v^2 + e)\right) + \frac{\partial}{\partial x}\left(\rho\, v(\frac{1}{2}v^2 + e) + p\, v\right) + \frac{k_w}{D}(T - T_w) = 0$$

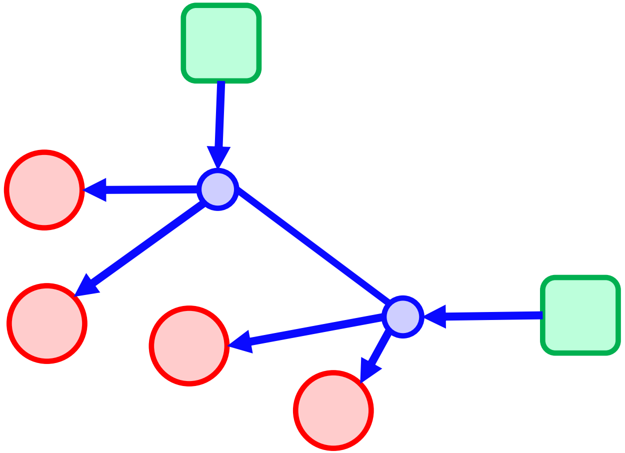
$$\downarrow$$

$$\alpha|q|q = p_{out}^2 - p_{in}^2$$

α depending on dimension and inclination of the pipeline, the friction in the pipeline, gas temperature, gas composition, outside temperature, and more.

The network

Given a graph $G = (V, A)$
with pressure p_u, and flow q_a,
for $u \in V, a \in A$ and $\pi_u = p_u^2$.



Exists $\boldsymbol{q}, \boldsymbol{\pi}$

subject to

$$\sum_{a \in \delta^+(u)} q_a - \sum_{a \in \delta^-(u)} q_a = d_u \qquad \text{for all } u \in V$$

$$\alpha_a \, |q_a| \, q_a = \pi_u - \beta_a \pi_v \qquad \text{for all } a = (u, v) \in A$$

$$\underline{\pi}_u \leq \pi_u \leq \overline{\pi}_u \qquad \text{for all } u \in V$$

$$\underline{q}_a \leq q_a \leq \overline{q}_a \qquad \text{for all } a \in A$$

Line Theorem with bounded variables

Theorem (Maugis, 1977, Collins at al, 1978, Humpola, K., et al, 2013)

Let $d \in \mathbb{R}^V$ be a balanced demand and Φ_a strictly increasing function.
Then the solution space of

exists q, π *subject to*

$$\sum_{a \in \delta^+(u)} q_a - \sum_{a \in \delta^-(u)} q_a = d_u \qquad \text{for all } u \in V$$

$$\Phi_a(q_a) = \pi_u - \pi_v \qquad \text{for all } a = (u,v) \in A$$

$$\underline{\pi}_u \le \pi_u \le \overline{\pi}_u \qquad \text{for all } u \in V$$

$$\underline{q}_a \le q_a \le \overline{q}_a \qquad \text{for all } a \in A$$

is either empty or fulfills the conditions:

1. The flow is unique
2. The squared pressure component π has the form

$$\{\pi^* + \eta^1 \mid \underline{\eta} \le \eta \le \bar{\eta}\}$$

for some $\pi^*, \underline{\eta}, \bar{\eta}$.

Line Theorem: The Line

- ▷ Flow is unique and Φ_a is strictly increasing.
- ▷ $\pi_u - \pi_v$ are uniquely determined for all arcs.
- ▷ Shifting all values by a constant is feasible.
- ▷ Constant shift is the only possible source of difference.

Consider two feasible squared pressure vectors: π' und π''.
Both are shifted in such a way that they coincide in the value at u.
The difference is constant which implies

$$\pi'_u - \pi'_v = \phi_a(q_a) = \pi''_u - \pi''_v.$$

Since $\pi'_u = \pi''_u$, we also have $\pi'_v = \pi''_v$.

Convex Slack Reformulation

The solution space of the problem

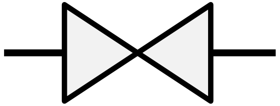
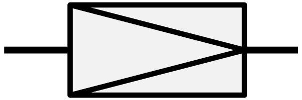
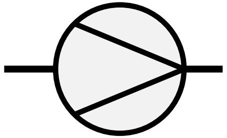
$$\min \sum_{u \in V} \Delta_u + \sum_{a \in A} \Delta_a$$

subject to

$$\begin{aligned}
\sum_{a \in \delta^+(u)} q_a - \sum_{a \in \delta^-(u)} q_a &= d_u && \text{for all } u \in V \\
\Phi_a(q_a) &= \pi_u - \pi_v && \text{for all } a = (u, v) \\
\underline{\pi}_u - \Delta_u &\leq \overline{\pi}_u && \text{for all } u \in V \\
\pi_u + \Delta_u &\geq \underline{\pi}_u && \text{for all } u \in V \\
\Delta_u &\geq 0 && \text{for all } u \in V \\
q_a - \Delta_a &\leq \overline{q}_a && \text{for all } a \in A \\
q_a + \Delta_a &\geq \underline{q}_a && \text{for all } a \in A \\
\Delta_a &\geq 0 && \text{for all } a \in A
\end{aligned}$$

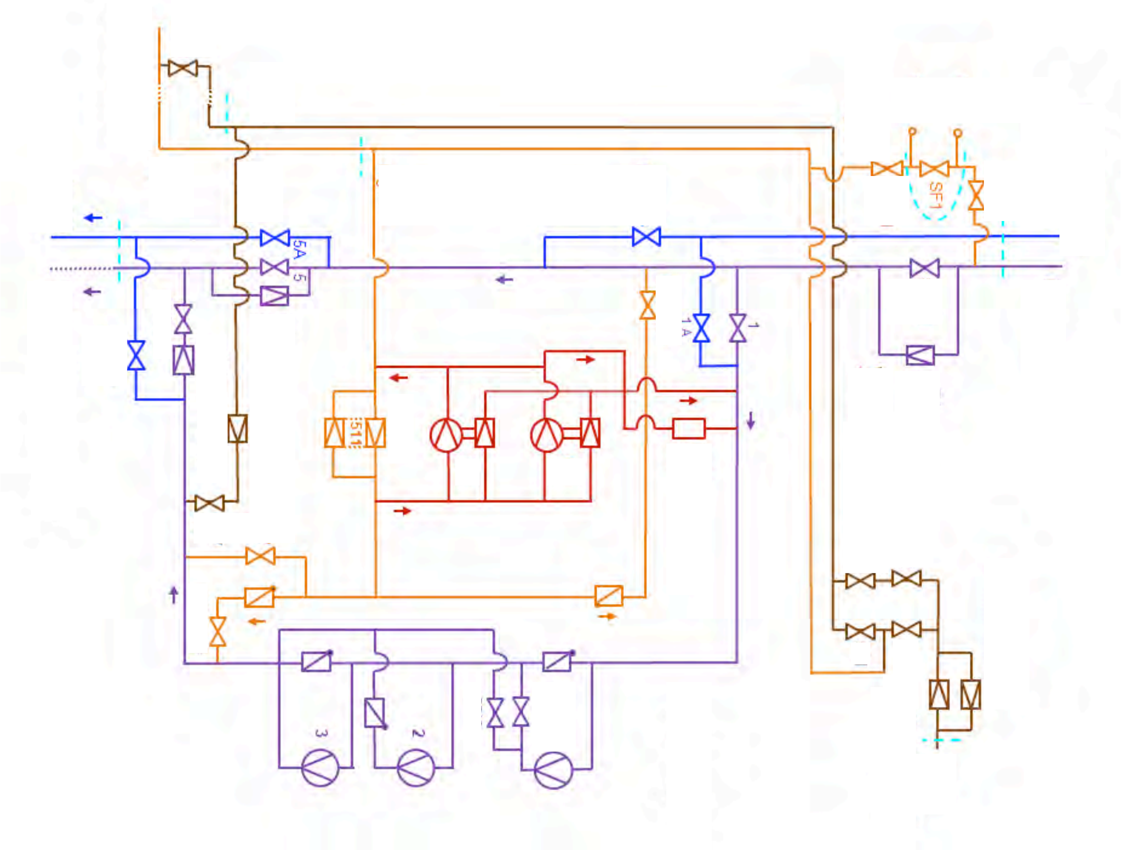
is non-empty and is convex.

Active elements in gas networks

Element	Function	Symbol
Valve	Switch on/off	
Regulator	Decrease pressure	
Compressor	Increase pressure	

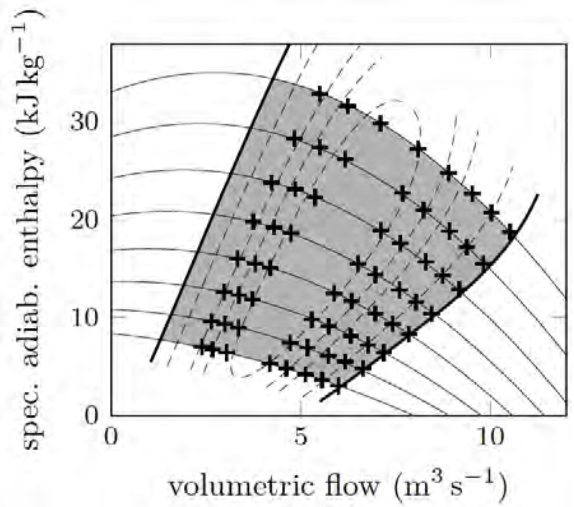
Controllable Networks

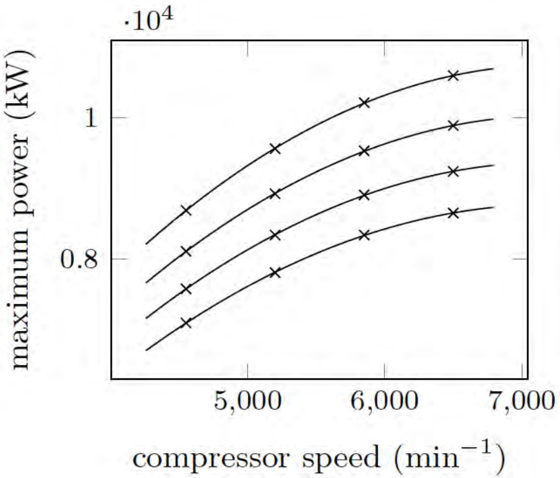
This is an example of just a compressor station



Compressor machines

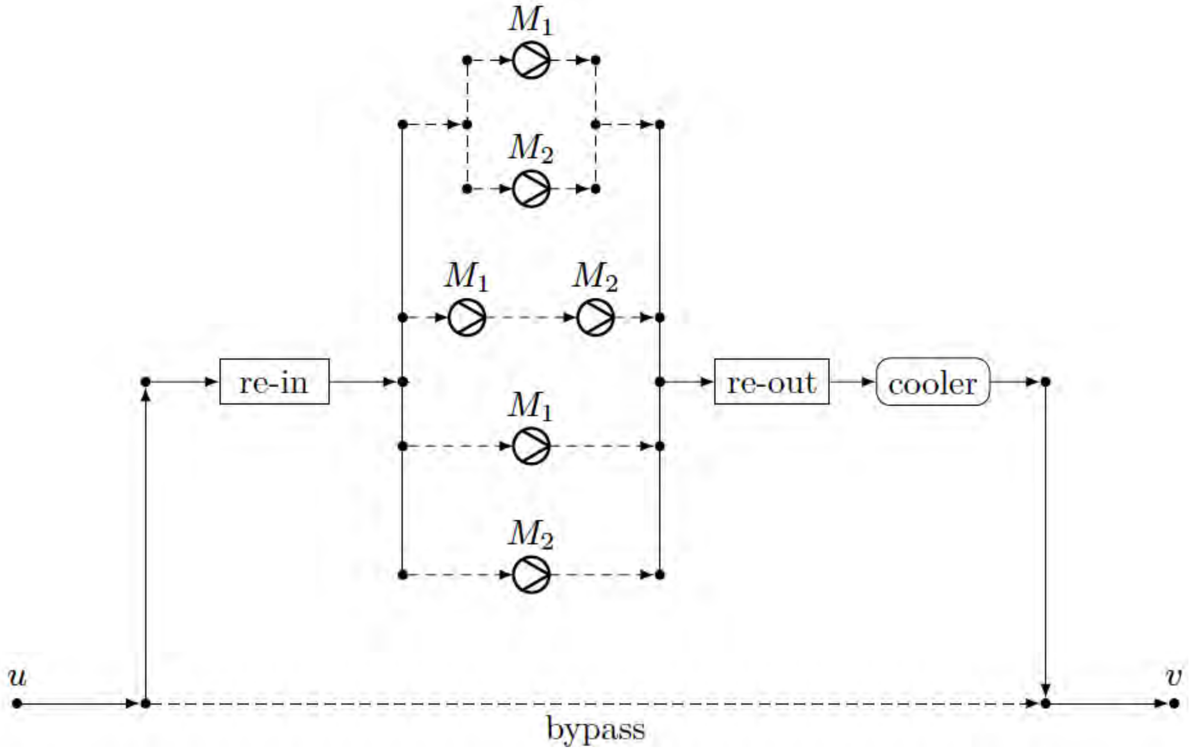
Compressor performance depends on input pressure, output pressure, flow, temperature, composition, compressor power.





Compressor stations

How precise can we model a compressor?
Let us assume we assume the gas temperature 10°C too low.
This gives about 3% more power to the compressor station.
This might be enough to get another 1500 MW gas through.



3 Questions

- Design a new network
  (or extend an existing one)

- Determine the capacity
  of a given network

- Control a network to achieve
  maximum efficiency

Network Design

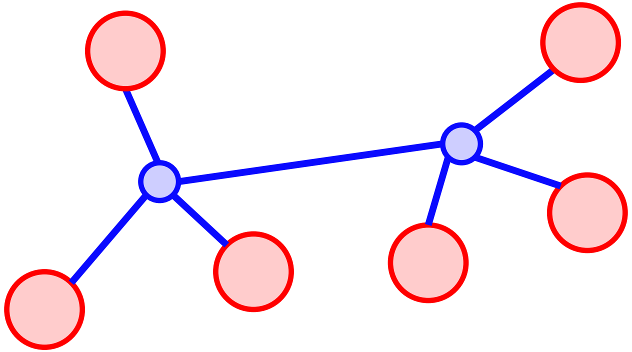
(Just a teaser)

Thorsten Koch

CO@Work

Online, September 2020

Network Construction Steiner Tree



The Steiner tree problem in graphs (STP)

Given an undirected connected graph $G = (V, E)$,
costs $c: E \rightarrow \mathbb{Q}^+$ and a set $T \subset V$ of *terminals*,
find a minimum weight tree $S \subset G$ which spans T.

The STP is one of the classical 21 $\mathcal{NP}$-hard problems.

Direct Cut Integer Programming Formulation for SAP

min $c^T y$

subject to

$y(\delta_W^+) \geq 1, \qquad$ for all $W \subset V, r \in W, (V \setminus W) \cap T \neq \emptyset$

$y(\delta_v^-) \begin{cases} = 0, \text{if } v = r; \\ = 1, \text{if } v \in T \setminus r; \\ \leq 1, \text{if } v \in N \end{cases} \qquad$ for all $v \in V$

$y(\delta_v^-) \leq y(\delta_v^+), \qquad$ for all $v \in N$;

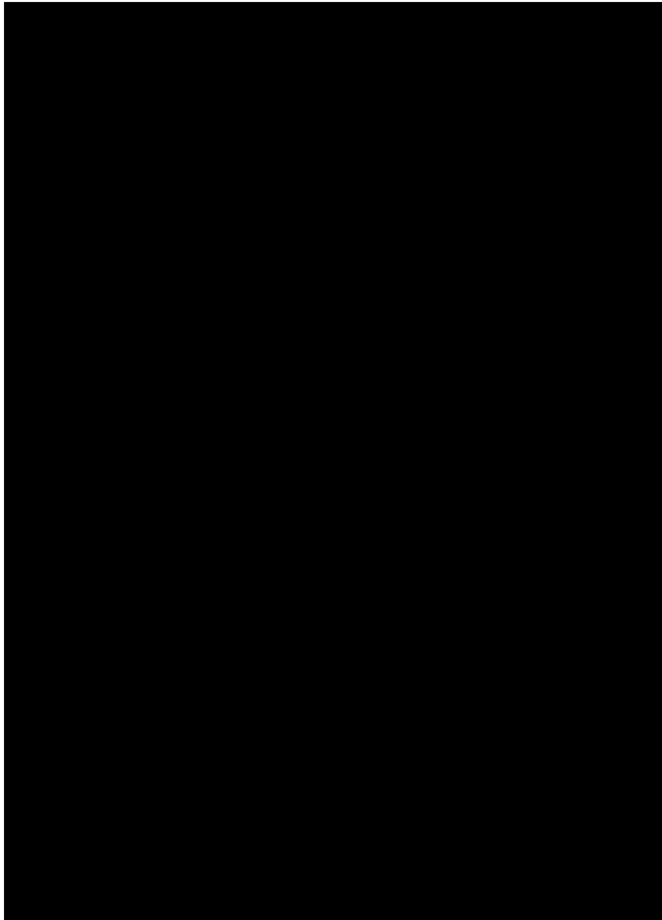
$y(\delta_v^-) \geq y_a, \qquad$ for all $a \in \delta_v^+, v \in N$;

$0 \leq y_a \leq 1, \qquad$ for all $a \in A$;

$y_a \in \{0,1\}, \qquad$ for all $a \in A$,

where

$N = V \setminus T, \delta_X^+ := \{(u,v) \in A | u \in X, v \in V \setminus X\}, \delta_X^- := \delta_{V \setminus X}^+$ for $X \subset V$.

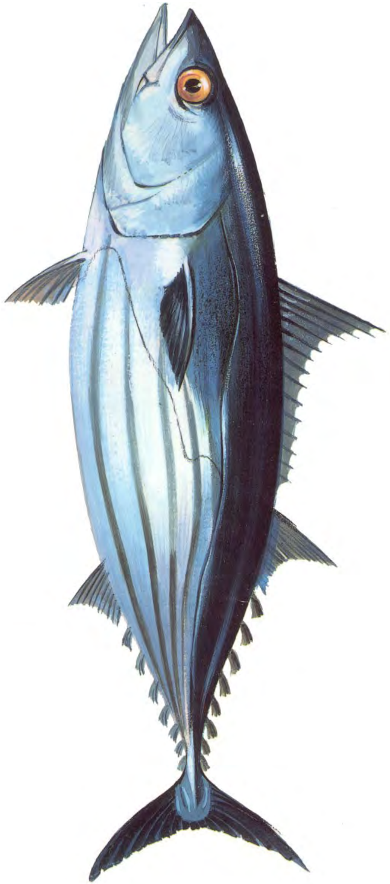


See, e.g., Koch, Martin, *Solving Steiner tree problems in graphs to optimality, Networks* (1998)
Polzin, *Algorithms for the Steiner problem in networks,* Uni Saarland, 2004,
Rehfeldt, Koch, Combining NP-Hard Reduction Techniques and Strong Heuristics in an Exact Algorithm for the Maximum-Weight Connected Subgraph Problem, SIAMOPT (2019),
Shinano, Rehfeldt, Koch, *Building Optimal Steiner Trees on Supercomputers by Using up to 43,000 Cores,* CPAIOR 2019, LNCS 11494, and the references there in.

SCIP-Jack is a solver for Steiner Tree Problems in Graphs

It is part of the SCIP Optimization Suite and can solve:

- ▷ Steiner Tree Problem in Graphs (STP)
- ▷ Steiner Arborescence Problems in Graphs (SAP)
- ▷ Rectilinear Steiner Minimum Tree (RSMTP)
- ▷ Node-weighted Steiner Tree (NWSTP)
- ▷ Prize-collecting Steiner Tree (PCSTP)
- ▷ Rooted Prize-collecting Steiner Tree (RPCSTP)
- ▷ Maximum-weight Connected Subgraph (MWCSP)
- ▷ Degree-constrained Steiner Tree (DCSTP)
- ▷ Group Steiner Tree (GSTP)
- ▷ Hop-constrained directed Steiner Tree (HCDSTP)



http://scipopt.org

Please continue with the lecture on Gas Network Cacapcity

Gas Network Capacity

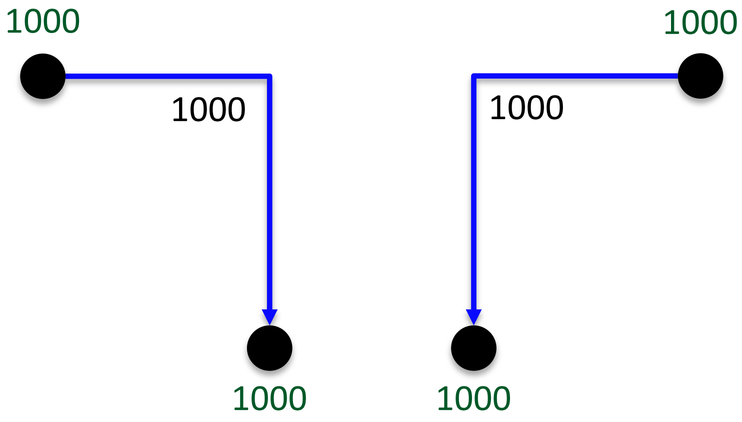
Thorsten Koch

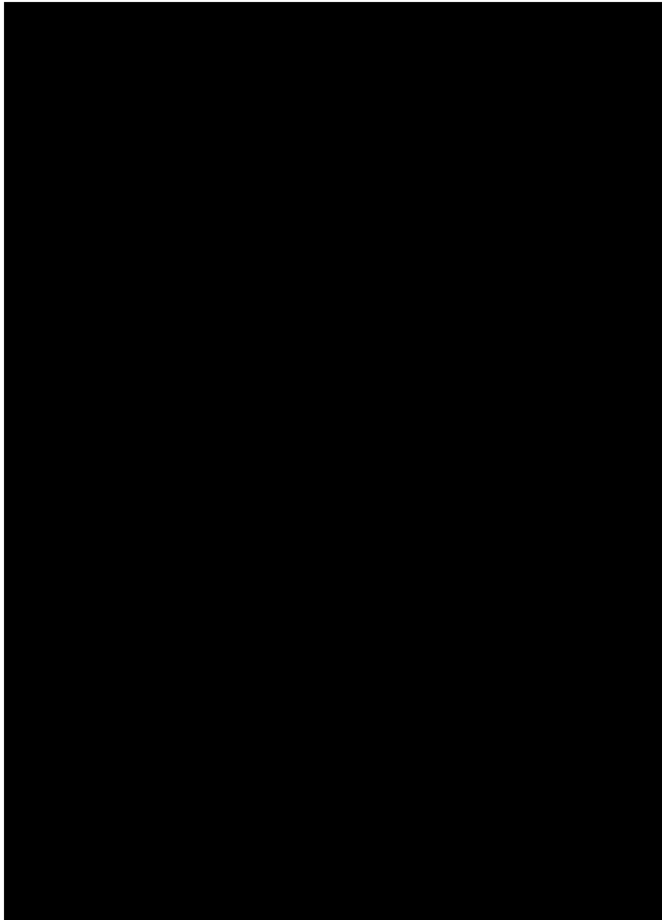
CO@Work

Online, September 2020

What does “Capacity of the Network” mean?

The *Technical Capacity* is defined as the maximum flow bounds at the entry- and exit-nodes, such that any possible balanced demand scenario within these bounds can be fulfilled by the network.

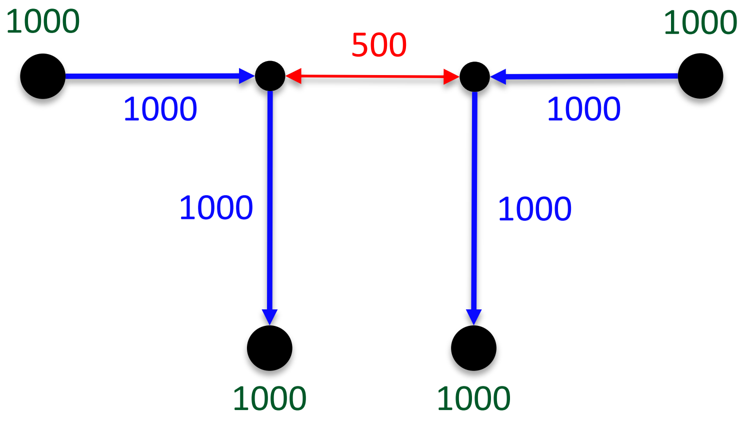




What does “Capacity of the Network” mean?

The *Technical Capacity* is defined as the maximum flow bounds at the entry- and exit-nodes, such that any possible balanced demand scenario within these bounds can be fulfilled by the network.

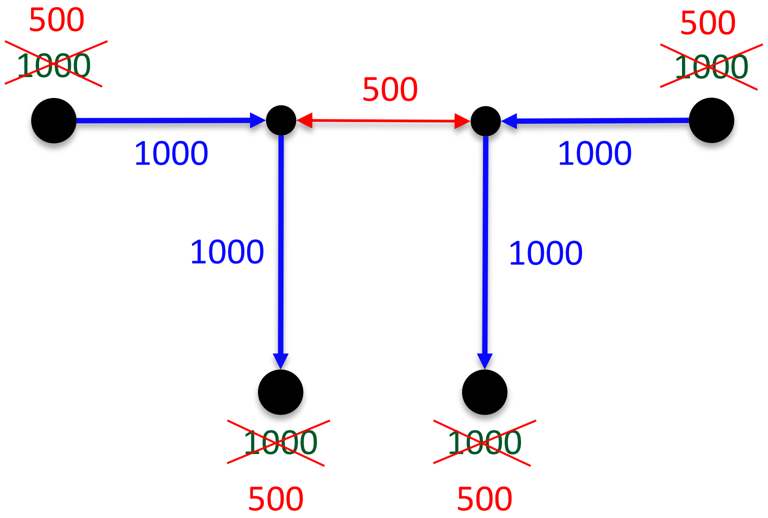
Now adding a connection…



What does "Capacity of the Network" mean?

The *Technical Capacity* is defined as the maximum flow bounds at the entry- and exit-nodes, such that any possible balanced demand scenario within these bounds can be fulfilled by the network.

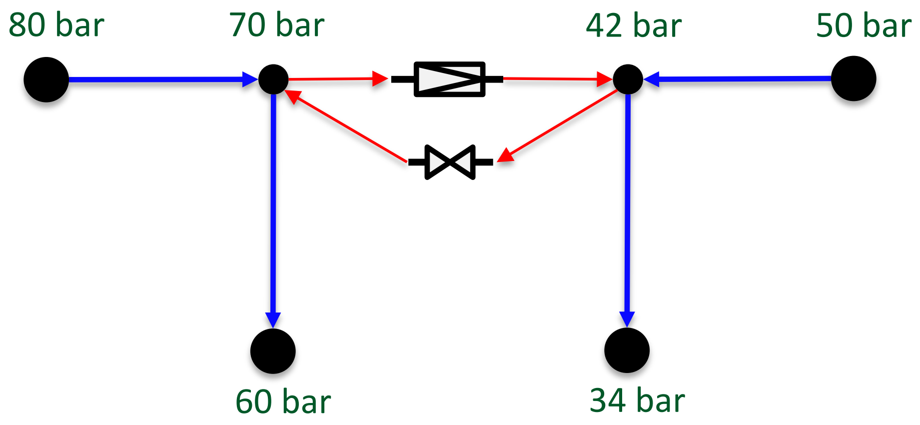
Now adding a connection … does not necessarily increase it.



What does “Capacity of the Network” mean?

The new connection also adds restrictions due to pressure coupling. Not all splits of the inflow between the two entries are easily possible anymore.

See also Braess’s paradox.



Transient Models

Transient models describe the network state over time.

Advantages

- ▷ **This is quite realistic** (depending on the time step size)

Disadvantages

- ▷ Can only be computed over a finite time horizon
- ▷ Requires a forecast of the in- and outflow over time
- ▷ Requires a start state, which is not known for planning
- ▷ Deviations between the predicted and the physical network state grow over time

If we want to decide the feasibility of a future demand scenario should we test against:

- ▷ A worst case start state? Far too pessimistic
- ▷ All possible start states? Infinitely many
- ▷ A suitable start state? Likely overly optimistic

Stationary Models

Stationary models describe a (timeless) equilibrium network state.

Advantages

- ▷ Stable situation (by definition)
  modelling an “average network” state
- ▷ No start state needed, no time horizon to consider
- ▷ Ensures that the situation is sustainable
  (we cannot paint ourselves easily into a corner)
- ▷ Much less data requirements, simpler physics

Disadvantages

- ▷ Using pipes as gas storage (linepack) cannot be modelled
- ▷ Transition between states cannot be modelled
- ▷ Too pessimistic, especially regarding short-term peak situations

Often better suited for medium and long-term planning.

Demand Scenarios

Given a directed graph $G = (V, A)$ that models a gas network. The arcs represent the elements of the network. We distinguish between passive network elements (pipes and resistors), whose behavior cannot be influenced, and active network elements (valves, control valves, and compressors), which allow to control the network. The active and passive elements are collected in the arc sets A_{active} and $A_{passive}$, respectively.

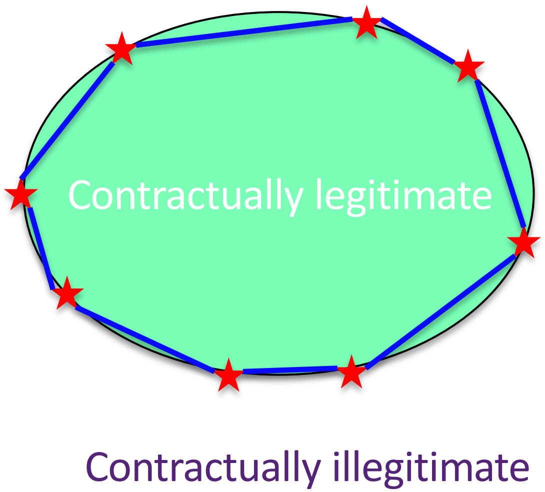
Demand Scenario

d specifies for each $u \in V$ the amount of flow that enters $(d_u \geq 0)$ or leaves $(d_u \leq 0)$ the network at u. The scenario d is balanced, i.e., we have

$$\sum_{u \in V} d_u = 0.$$

The task is to decide, whether or not the scenario *d* can be realized in the network by controlling the active elements.

Are all contractually legitimate scenarios technically feasible?



A possible approach:

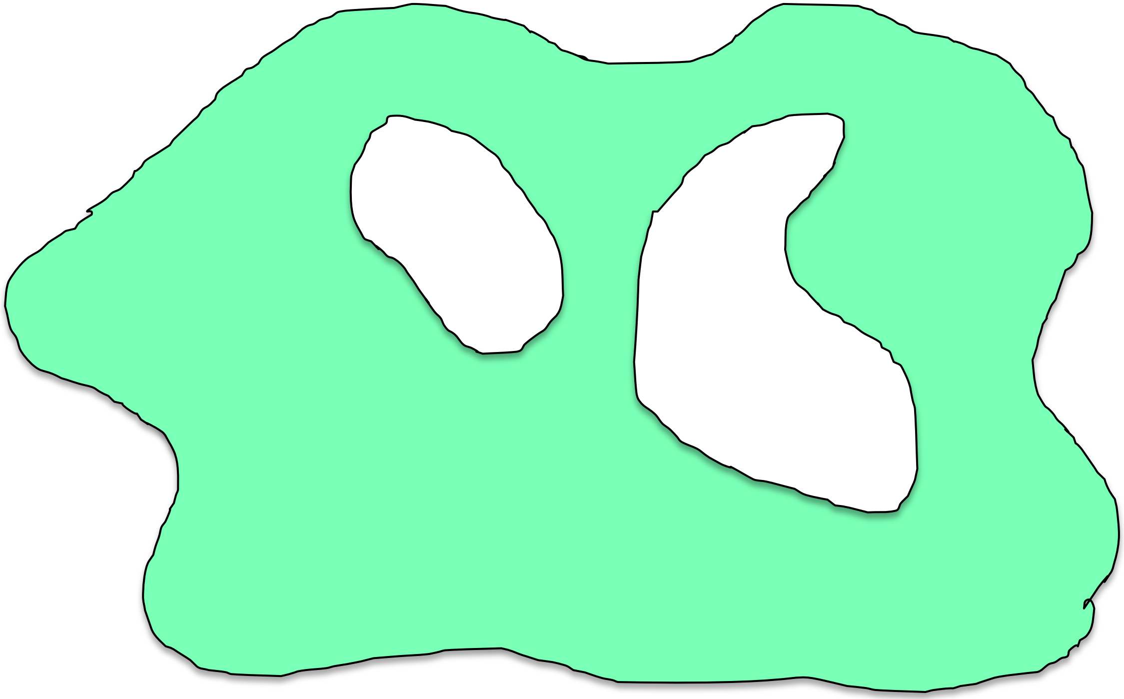
1. Experts derive scenarios that are on the border of feasibility.
2. These scenarios are checked using stationary models.
3. If they are feasible, it is concluded that also all other scenarios are feasible.

Assumptions on the Set of all feasible Scenarios

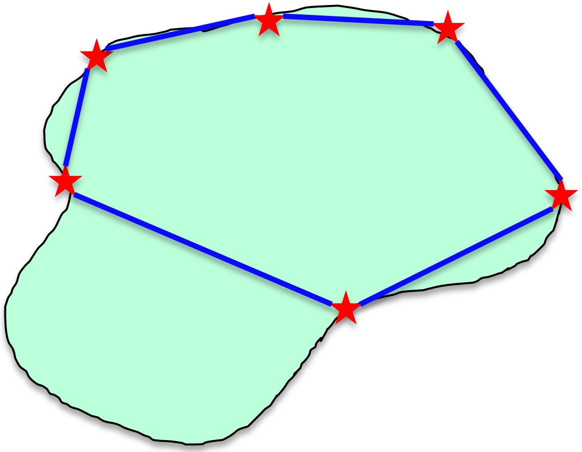
Non-smooth

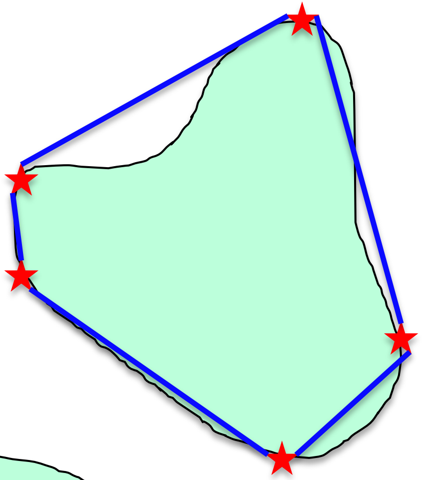
Non-convex

Non-compact

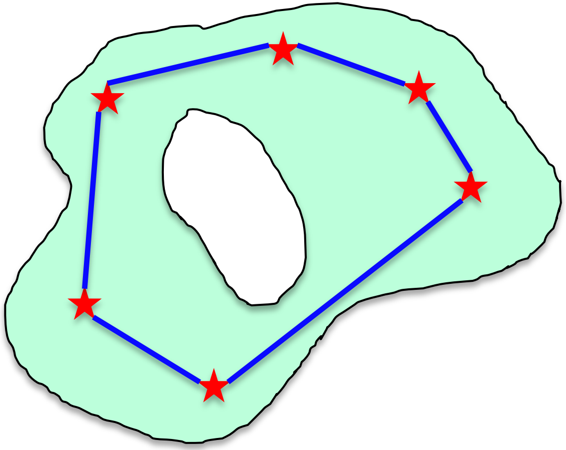


Assumptions on the Scenarios



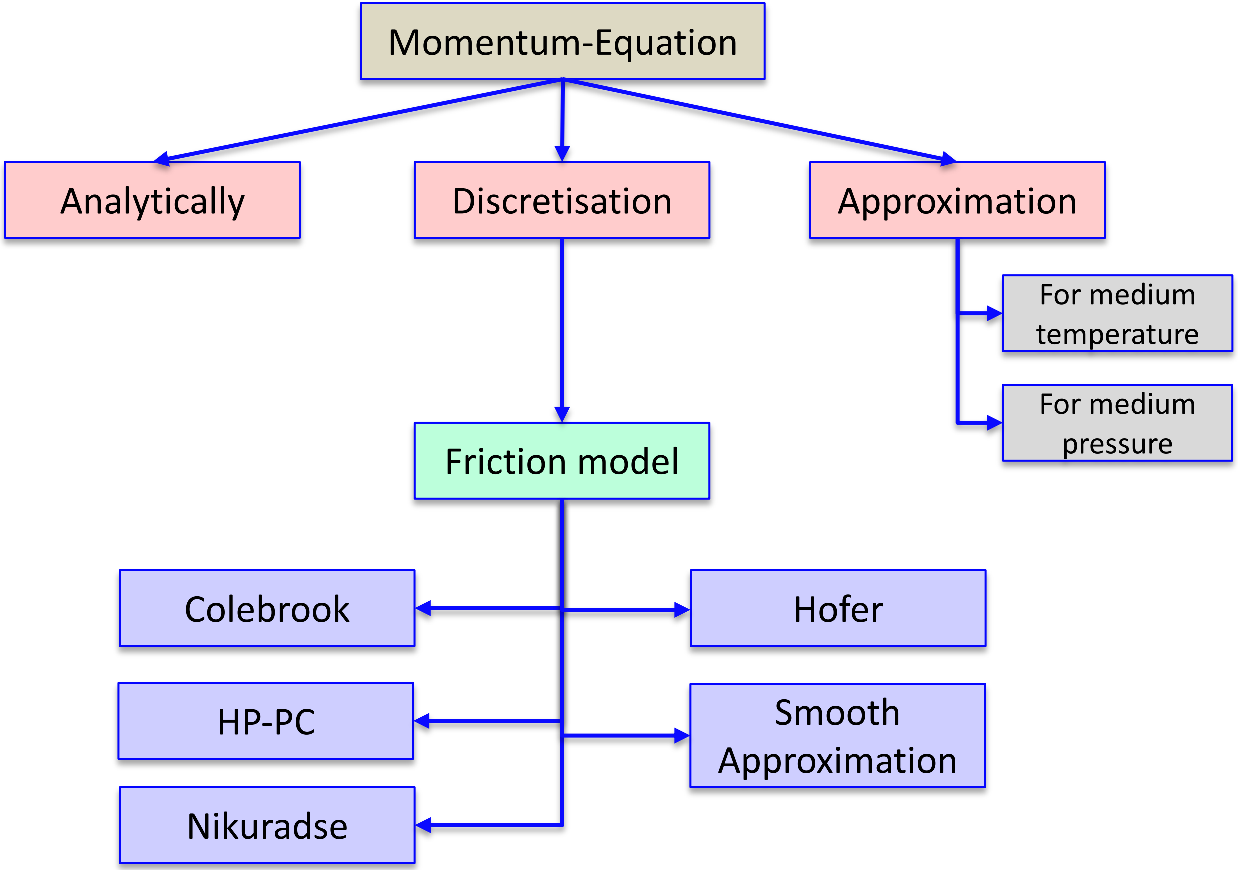


- ▷ Span the set
- ▷ Convexity
- ▷ Sweep the border
- ▷ Monotonicity

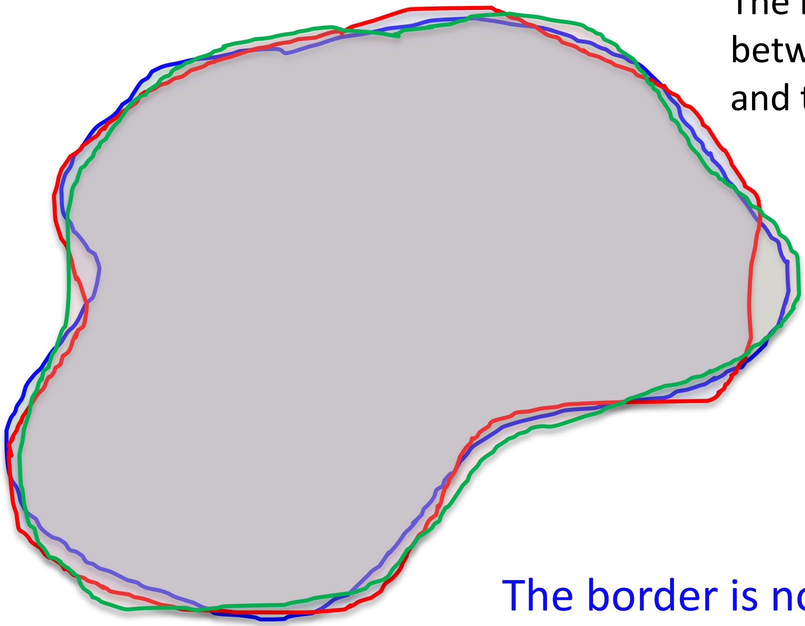


Decisions regarding the Momentum-Equation

Thorsten Koch



Assumptions on the Border

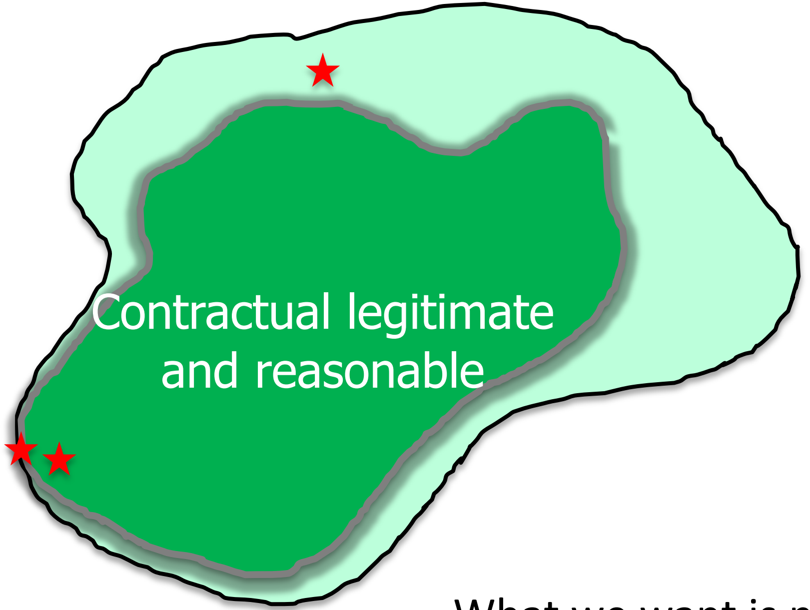


The border is the frontier between technical feasible and technical infeasible.

The border is not unique

- ▷ different Models/Methods
- ▷ different Parameters
- ▷ different Implementations

Assumptions on the Border



What we want is not the contractual legitimate area, but the contractual legitimate and reasonable area.

This area is not well defined.

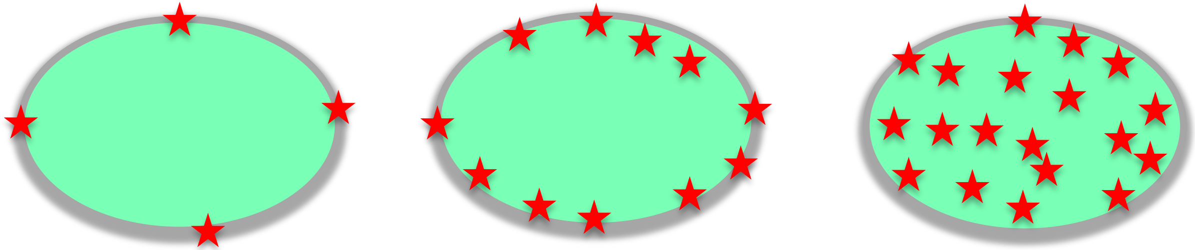
Shit!

Scenario Generation

We are able to generate scenarios and test their technical feasibility (with some limitations)**.**

Generation of scenarios:

- Manual generation of **expert scenarios**
  - limited number,
  + high quality
- Automatic generation of **extreme value scenarios**
  - difficult to distinguish between contractual legitimate and reasonable,
  + high number
- Automatic generation of **stochastic scenarios**
  - seldom extreme,
  + reasonable, + high number, + probable distribution



Manual Expert Scenarios

Advantages:

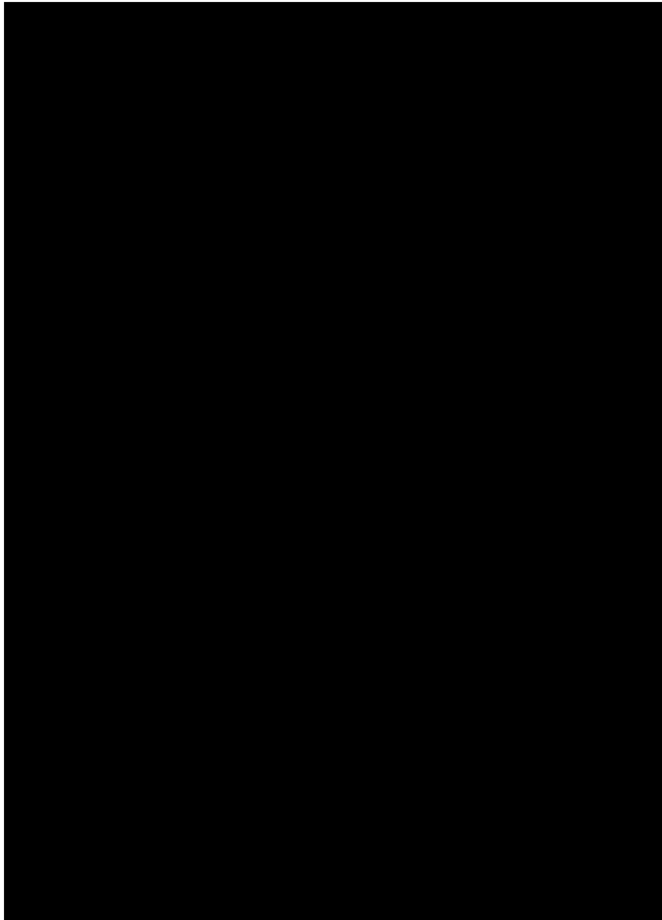
- High Quality
- Very well understood

Problems:

- Risk of being too much tuned towards a particular model, parameter setting, or implementation
  „let us see how far we can drive this"

Disadvantages:

- Small number
- Complete coverage of the feasible set is hard to ensure
- Only extreme value scenarios, i.e., the probability for the scenarios to happen in reality is nearly zero



Automatic Extreme Value Scenarios

Advantages:

- High number
- Can be generated with different methods

Problems:

- Hard to detect *contractual legitimate but unreasonable*

Disadvantages:

- Only the border of the feasible set is covered
- Only extreme value scenarios, i.e. the probability for the scenarios to happen in reality is nearly zero

Stochastic Scenarios

Advantages:

- High number
- Can be generated with different methods
- Realistic
- Coverage of the inner part of the feasible set
- Can be attributed with probabilities

Problems:

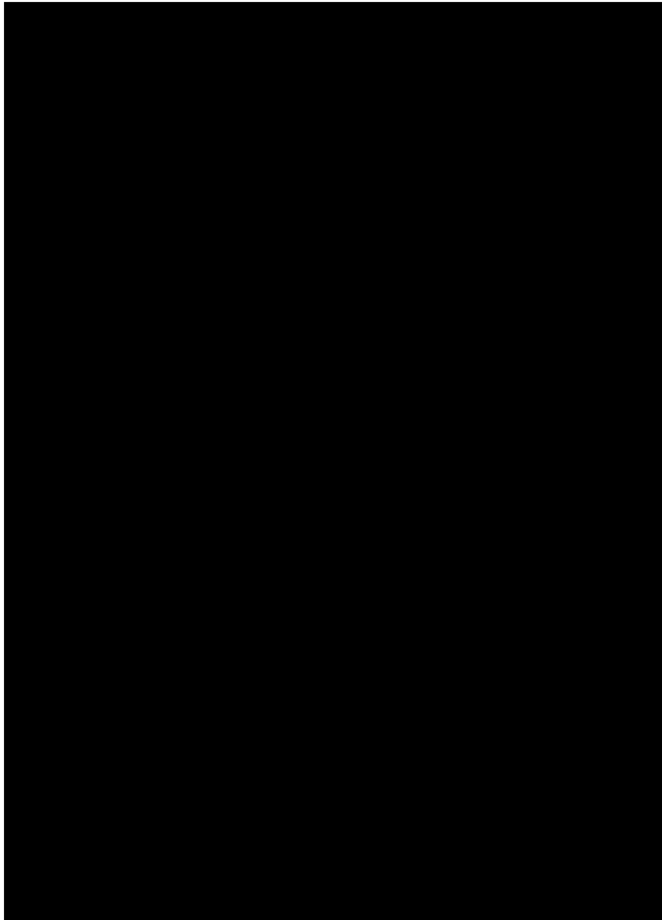
- Methods for generation are involved and need much data
- Refer to the past

Disadvantages:

- Extreme values occur seldom since they are not probable to happen

Combination

- **If all three methods are combined, there are nearly no disadvantages left.**
- This may lead to a huge number of scenarios of which many are possibly similar.
- This can be countered by methods for scenario reduction.
- Testing the technical feasibility of the scenarios has necessarily to happen automatically.
- This can be troublesome regarding extremal value scenarios.
- Now it is possible to automatically validate scenarios.
- This can be extended to compute capacities.
- It is possible to extend these concepts to answer more sophisticated questions, e.g. looking at probabilities for buy back happening when overbooking.



Using Optimization rather than Simulation

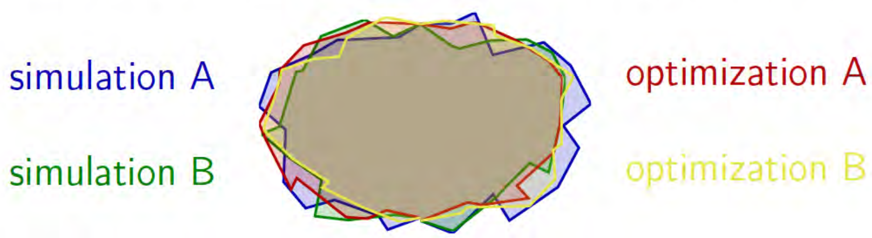
Simulation:

- allows very accurate gas physics models
- Relies on human experience to decide feasibility
- Therefore cannot determine infeasibility

Optimization:

- Works on simplified models of gas physics
- Automatically finds settings for active elements
- Eventually can prove infeasibility of a scenario

Beware: different solution spaces due to different modeling



Forschungskooperation Netzoptimierung

Zuse-Institute Berlin
Mathematical Optimization Methods
Prof. Dr. Thorsten Koch

Friedrich-Alexander Universität Erlangen-Nürnberg
Economics · Discrete Optimization · Mathematics
Prof. Dr. Alexander Martin

Technische Universität Darmstadt
Discrete Optimization
Prof. Dr. Marc Pfetsch

Universität Duisburg-Essen
Department of Mathematics
Prof. Dr. Rüdiger Schultz

Humboldt-Universität zu Berlin
Department of Mathematics
Prof. Dr. Werner Römisch

Leibniz-Universität Hannover
Institute for Applied Mathematics
Prof. Dr. Marc Steinbach

Weierstraß-Institut für Angewandte Analysis und Stochastik (WIAS)
Nonlinear Optimization and Inverse Problems
PD Dr. René Henrion

BMWi
Projektträger Jülich
Energy Business Area

Open Grid Europe GmbH
Netzplanung und -steuerung / Netzoptimierung
Klaus Spreckelsen

develOPT GmbH
Big Data Optimization
Dr. Antonio Morsi, Dr. Björn Geißler

atesio GmbH
Dr. Andreas Eisenblätter,
Dr. Benjamin Hiller

Nova: Nomination Validation

Goal of the project:

Build an automatic system that given a network and a set of supplies and demands at the border points computes settings for the active elements of the network such that the resulting stationary scenario is feasible.

Nova Progress

EURO Award 2016

Hereby, EURO, the Association of the European Operational Research Societies within IFORS

certifies that the

EURO Excellence in Practice Award

was awarded to

Thorsten Koch, Benjamin Hiller, Marc E. Pfetsch, Lars Schewe, Dagmar Bargmann, Mirko Ebbers, Armin Fügenschuh, Björn Geißler, Ralf Gollmer, Uwe Gotzes, Christine Hayn, Nina Heinecke, Holger Heitsch, René Henrion, Jesco Humpola, Imke Joormann, Veronika Kühl, Thomas Lehmann, Ralf Lenz, Hernan Leövey, Alexander Martin, Radoslava Mirkov, Andris Möller, Antonio Morsi, Antje Pelzer, Werner Römisch, Jessica Rövekamp, Martin Schmidt, Rüdiger Schultz, Robert Schwarz, Jonas Schweiger, Klaus Spreckelsen, Claudia Stangl, Marc C. Steinbach, Isabel Wegner-Specht, Bernhard M. Willert

Evaluating Gas Network Capacities

on 6th July 2016 at the 28th EURO Conference in Poznań, Poland

Jury: Ton G. de Kok (chair), Ulrich Dorndorf, Erik Demeulemeester, Marco Laumanns, Markus Bohlin

EURO

Prof. Elena Fernández, President

IBM

Subject: E.ON
Date: 19.05.2008 14:14
To: <koch@zib.de>

Dear Thorsten,

Here is the phone number of Mr.xxxxxxxxxxxxxxxxxxxxxxxxxx
Would you please call him back!

Best,
Bettina

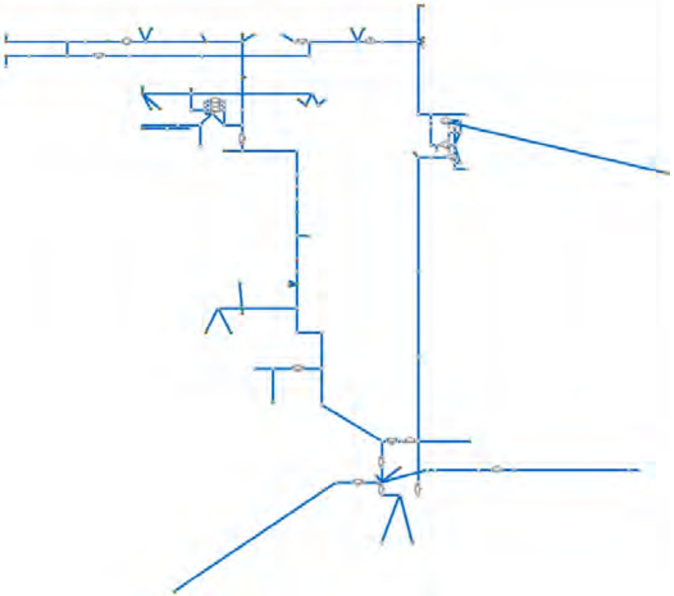
Start of project

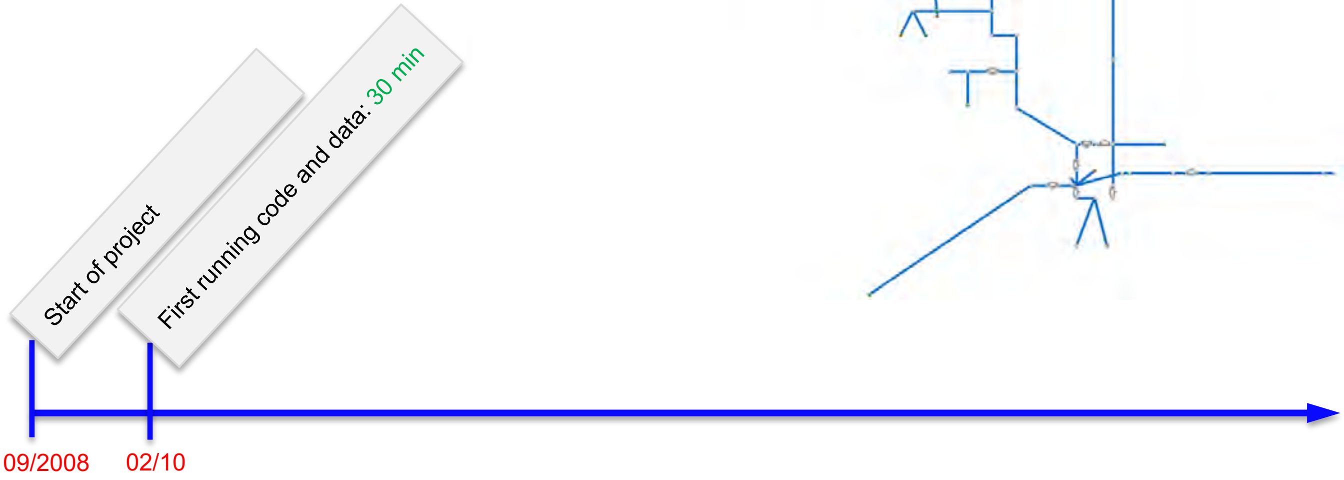
09/2008

07/2016

Simplified Subnetwork

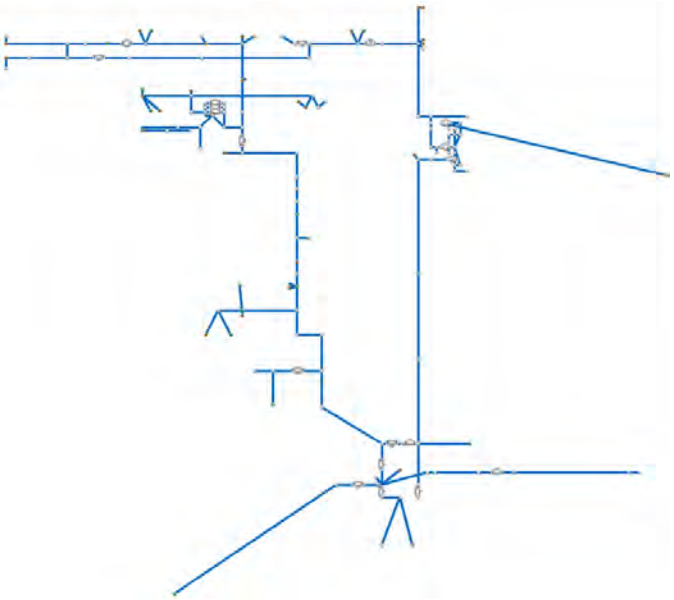
Element	Count
Pipes	136
Compressor groups	3
Resistors	8
Control valves	7
Valves	1
Entries	26
Exits	14

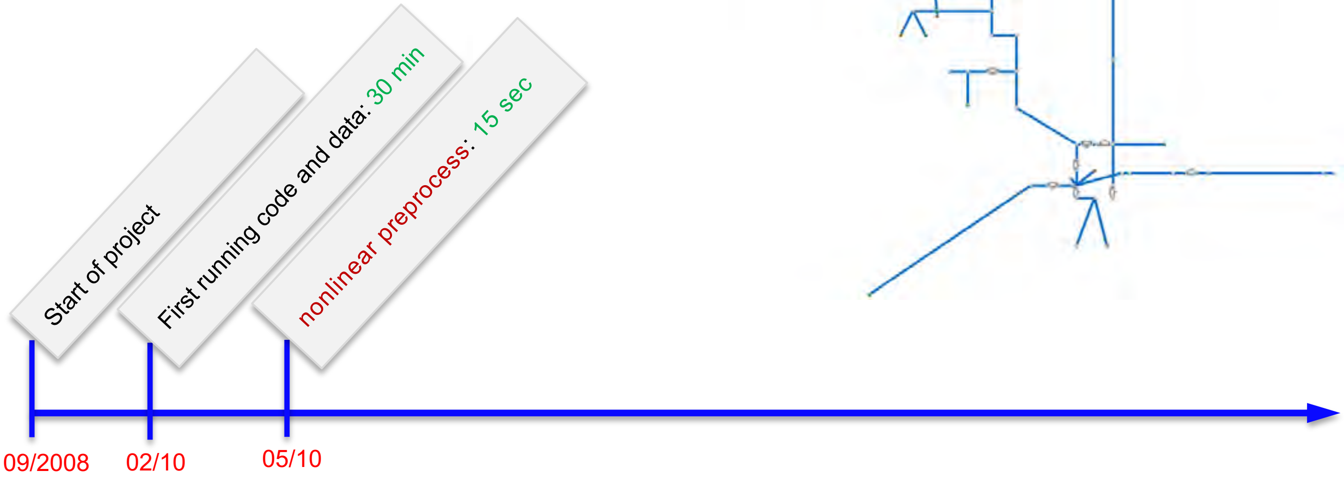




Simplified Subnetwork

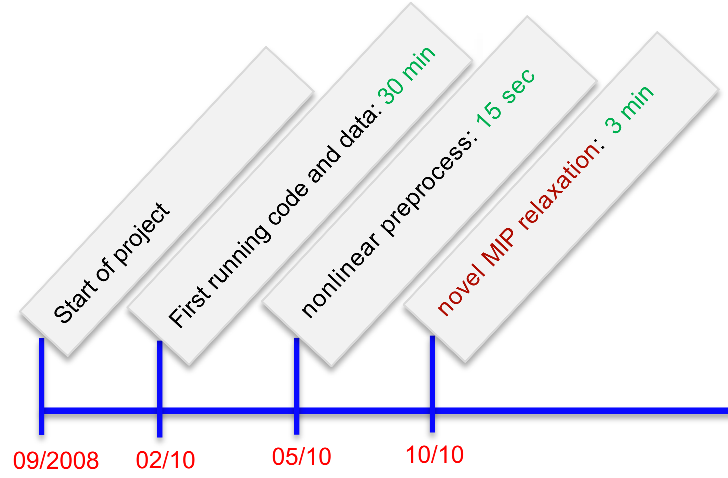
Element	Count
Pipes	136
Compressor groups	3
Resistors	8
Control valves	7
Valves	1
Entries	26
Exits	14

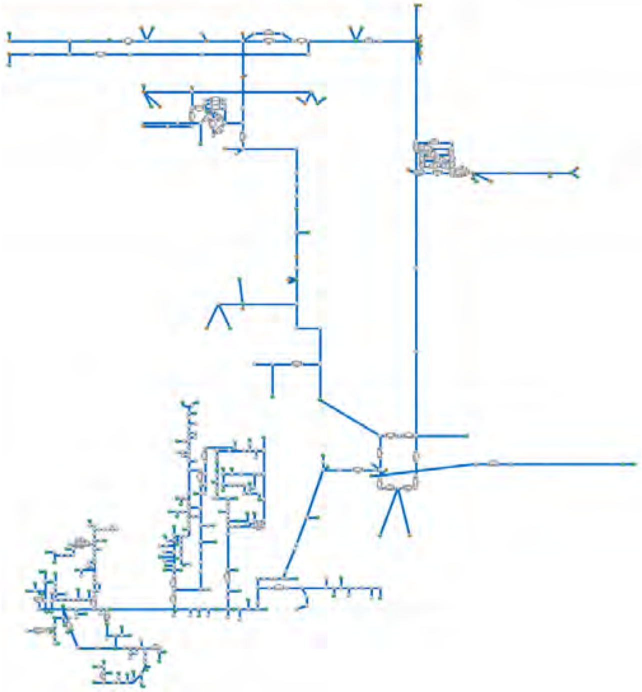




H-Gas Network (north)

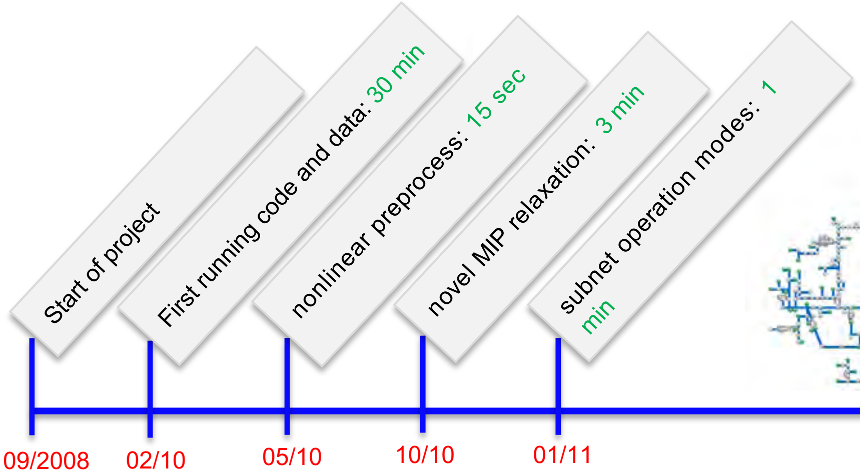
Element	Count
Pipes	470
Compressor groups	6
Resistors	8
Control valves	23
Valves	34
Entries	26
Exits	87

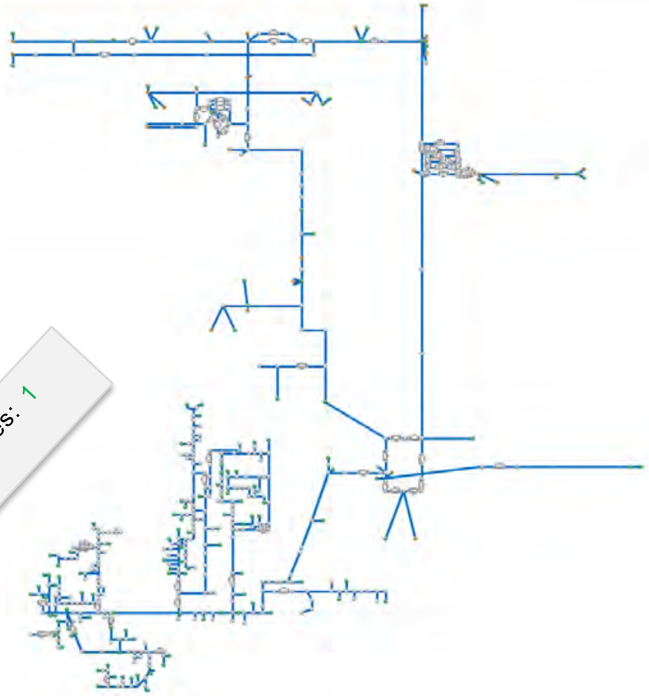




H-Gas Network (north)

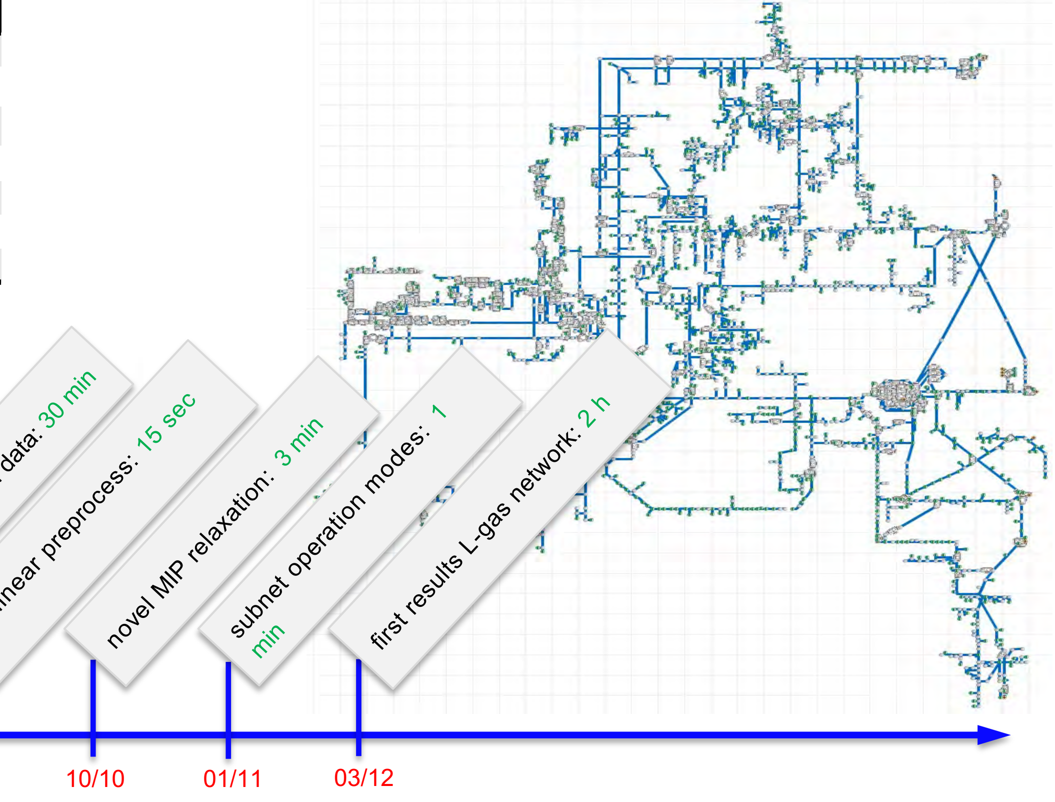
Element	Count
Pipes	470
Compressor groups	6
Resistors	8
Control valves	23
Valves	34
Entries	26
Exits	87





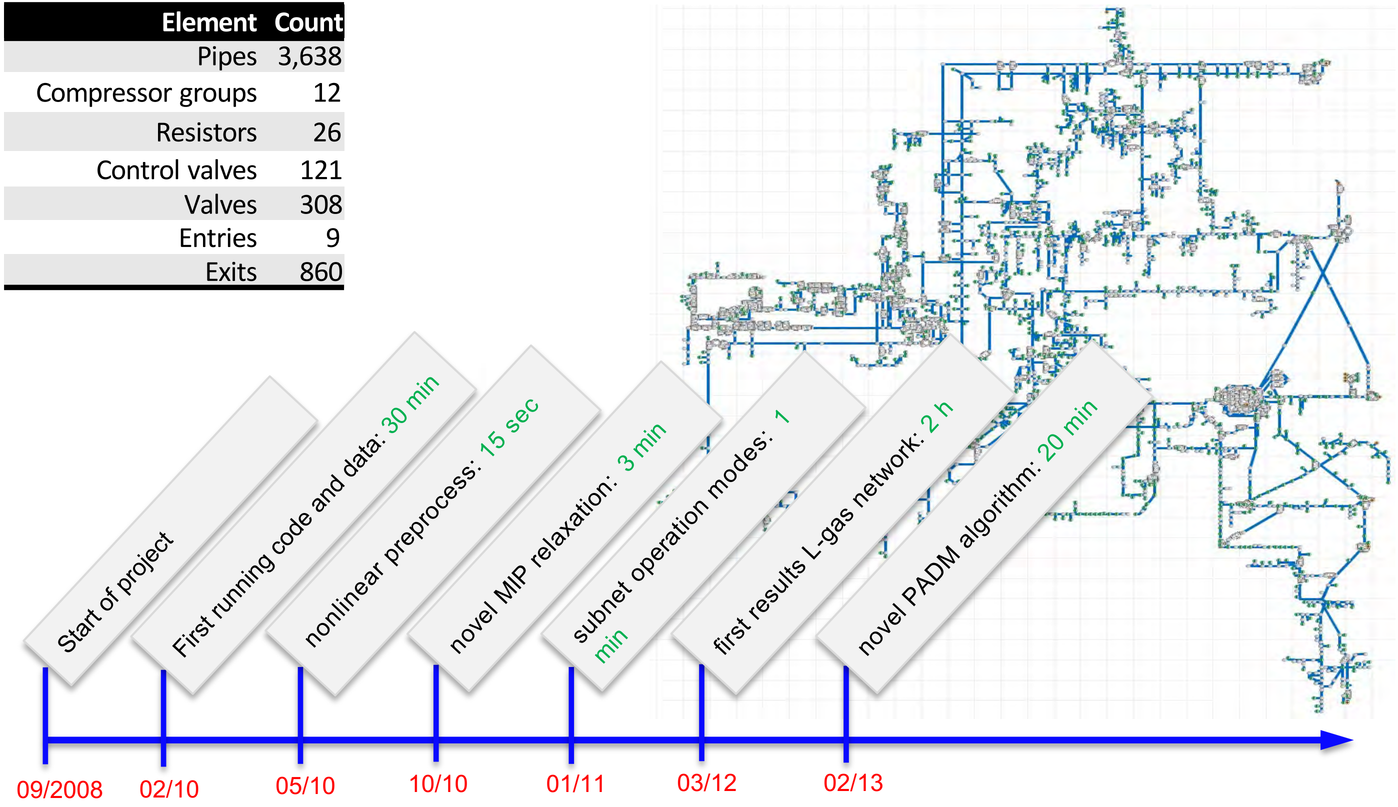
Entire L-Gas Network

Element	Count
Pipes	3,638
Compressor groups	12
Resistors	26
Control valves	121
Valves	308
Entries	9
Exits	860



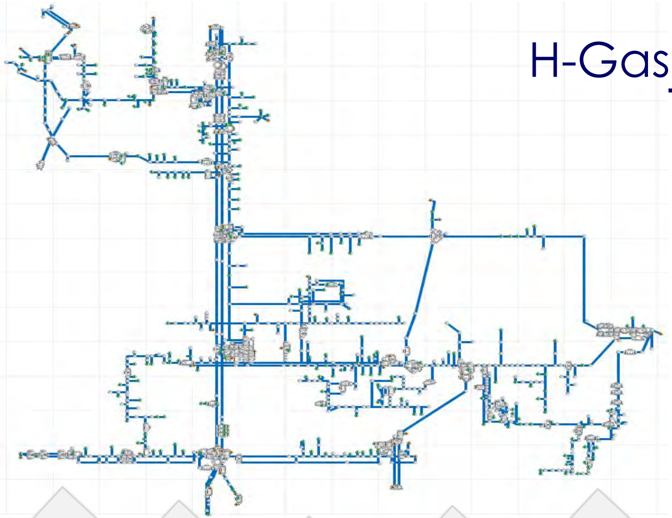
Entire L-Gas Network

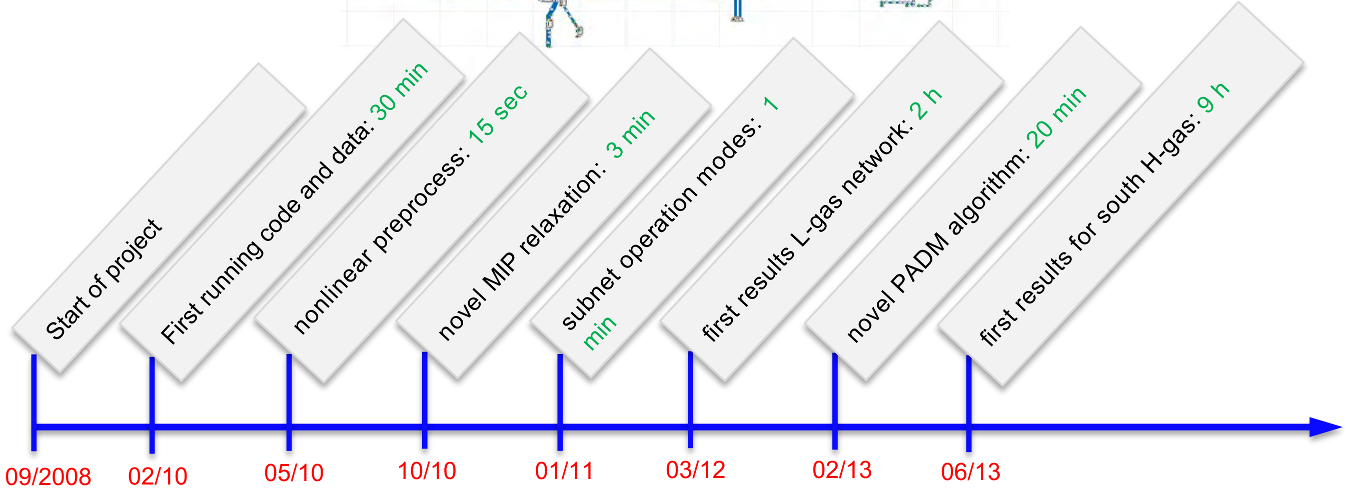
Element	Count
Pipes	3,638
Compressor groups	12
Resistors	26
Control valves	121
Valves	308
Entries	9
Exits	860



H-Gas Network (south)

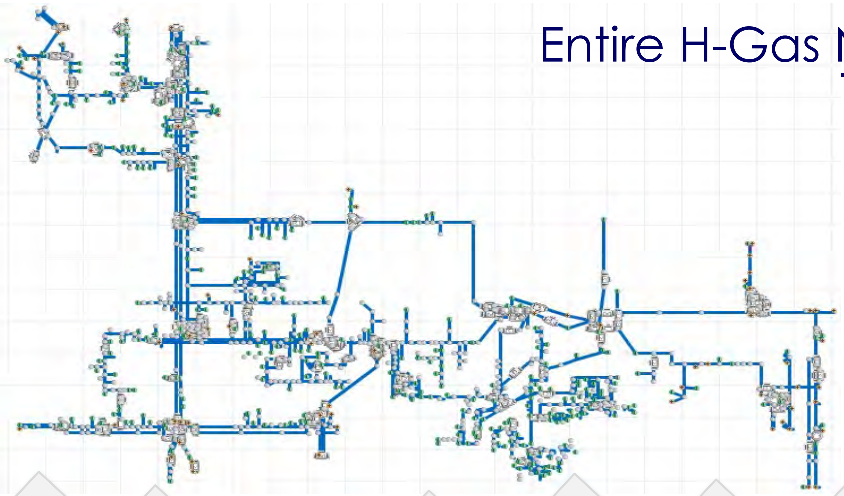
Element	Count
Pipes	1,218
Compressor groups	34
Resistors	47
Control valves	115
Valves	473
Entries	17
Exits	286

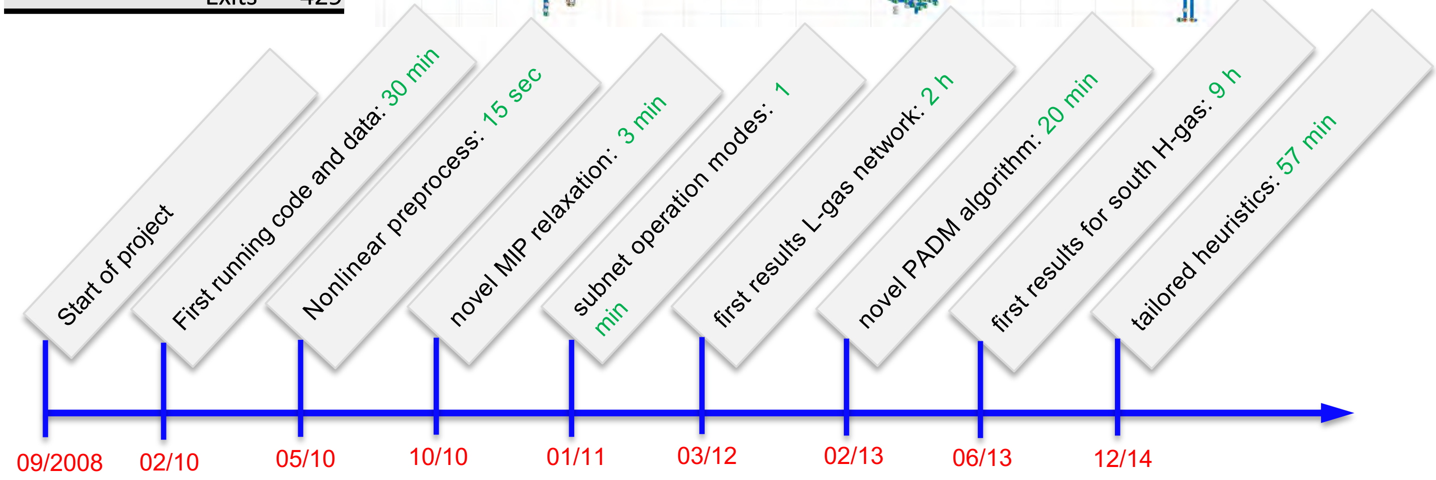


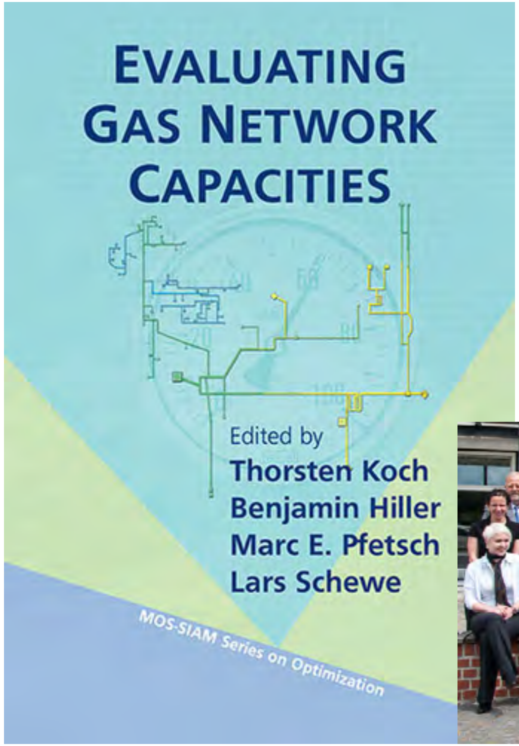


Entire H-Gas Network

Element	Count
Pipes	1,747
Compressor groups	41
Resistors	85
Control valves	145
Valves	545
Entries	45
Exits	429



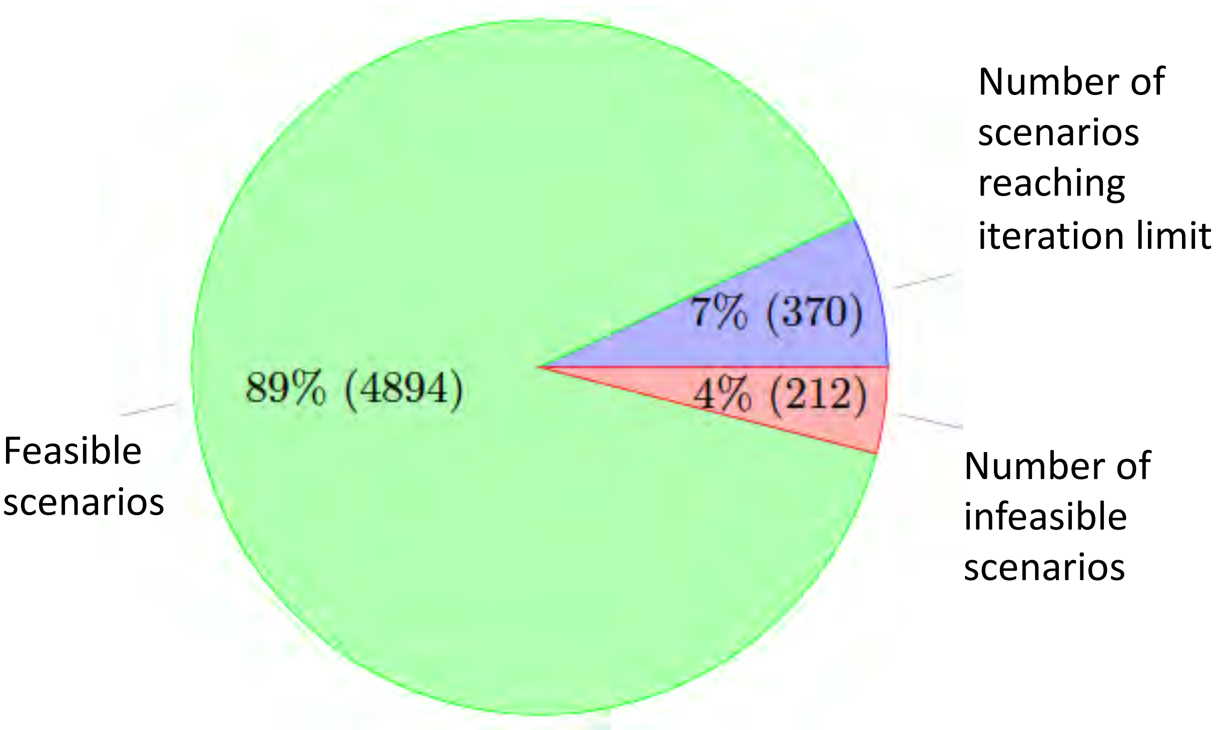




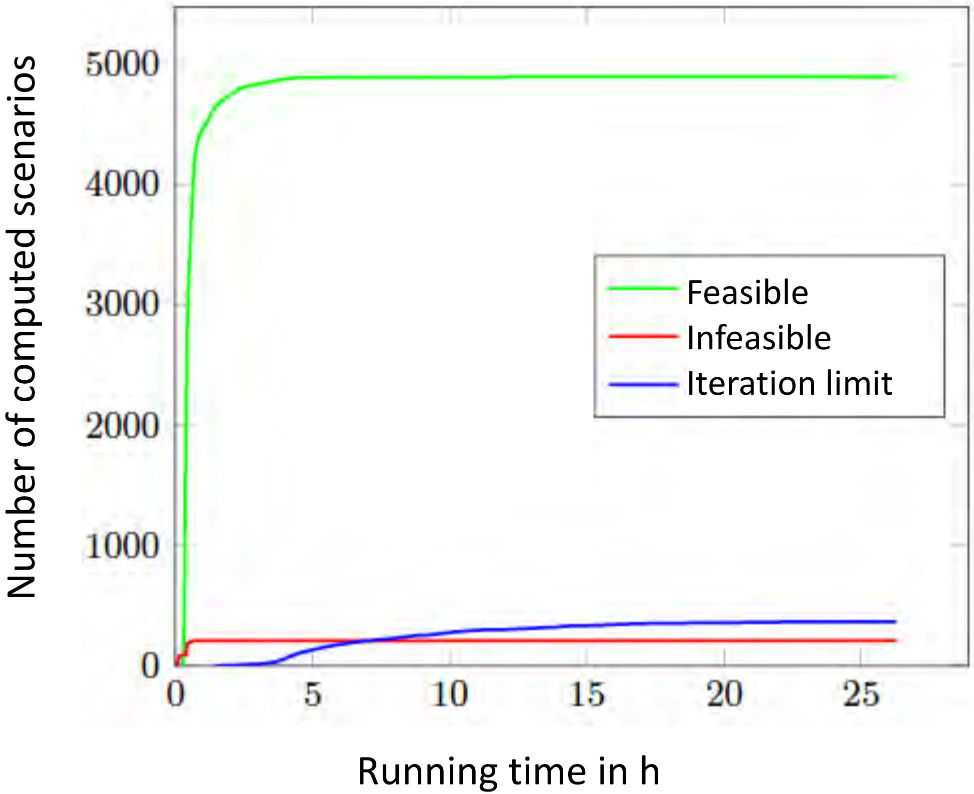
The ***Research Cooperation Network Optimization ForNe*** ran for 6 years and involved more than 30 people from around 10 universities and institutes along with more than 10 employees from Germany's largest gas network system operator OGE.

← Here are the results.

Computational outcome



Time spend


Number of computed scenarios
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
Running time in h
Feasible
Infeasible
Iteration limit

Additional difficulties

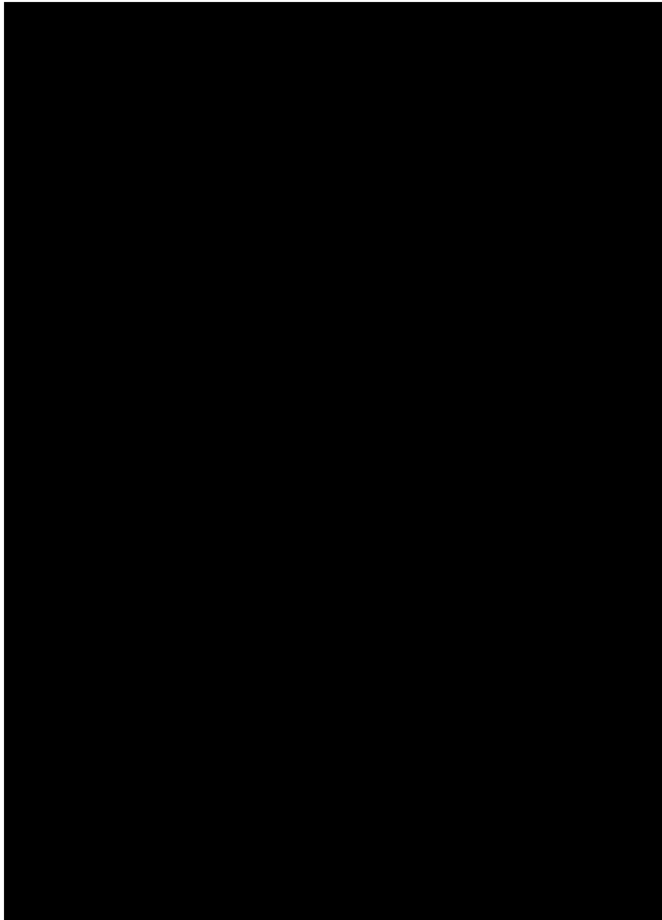
- Technology is changing all the time,
  new systems mix with existing ones

- **Often hard to determine actual system limits**
  (many assumptions are necessary for optimization)

- Optimization drives errors to cluster in one direction

- For larger models/scenarios hard to check against reality
  (also very hard to find data errors/inconsistencies)

- Marketization makes it difficult to predict behavior of participants, since the objectives of the individual players are unknown, and the outcome is result of a game (negotiation).



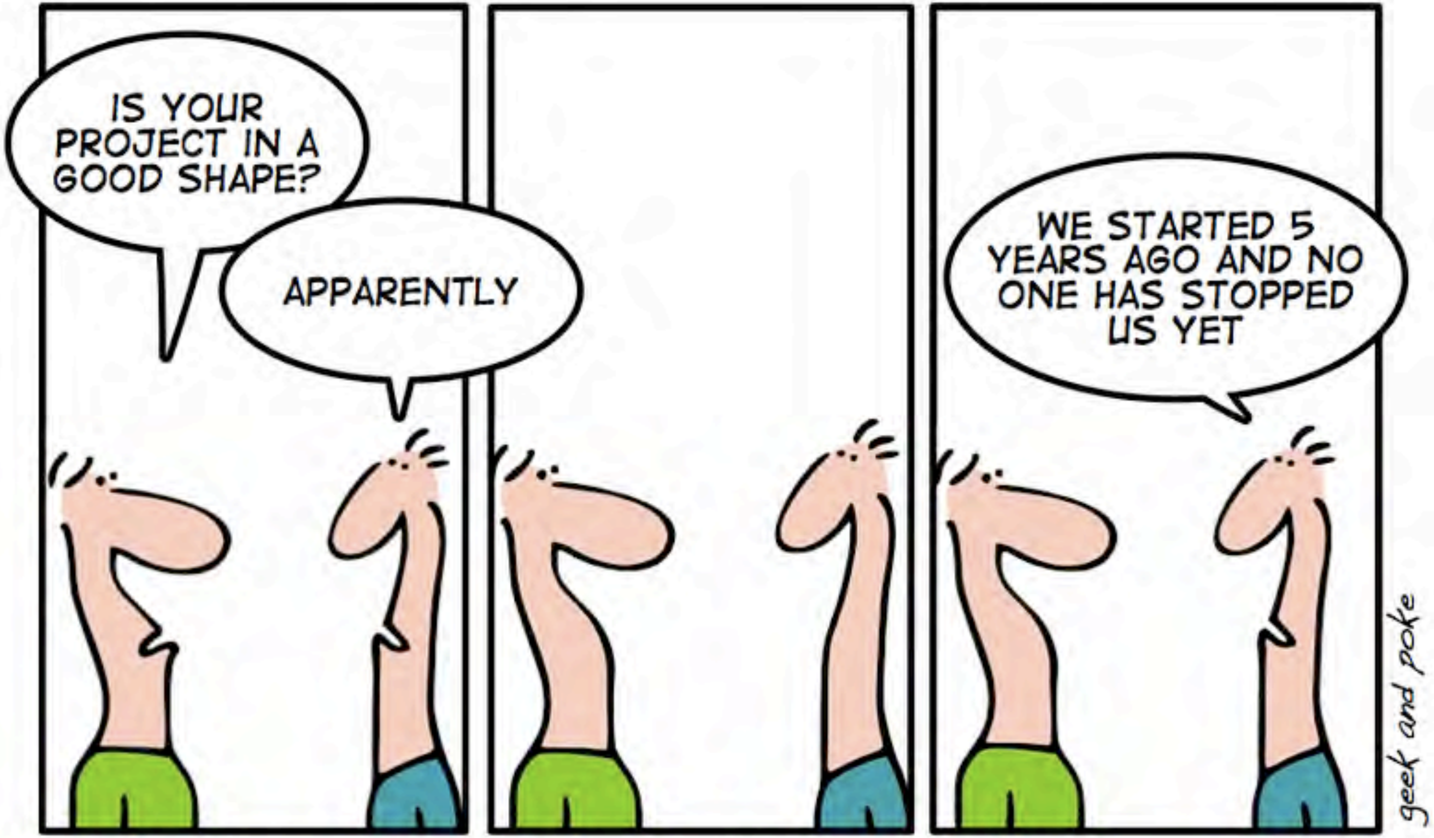
Some insights

Relevant real-world questions can be tackled efficiently with mathematical optimization and algorithmic intelligence.

However,

- a substantial effort is needed to succeed,
- the setup cost is high compared to pure research,
- close cooperation with practitioners is indispensable,
- different disciplines need to collaborate,
- access to and curation of data is essential.

Good luck!


IS YOUR PROJECT IN A GOOD SHAPE?
APPARENTLY
WE STARTED 5 YEARS AGO AND NO ONE HAS STOPPED US YET
geek and poke

Thank you very much

Please continue with the lecture on Gas Network Control