Controlling transient gas flow in complex pipeline intersection areas

Felix Hennings

Mathematical Optimization and Data Analysis Laboratories

MODAL GasLab – Zuse Institute Berlin

4th ISM-ZIB-IMI MODAL Workshop – Tokyo

March 27th, 2019

Research Campus MODAL

MODAL
Mathematical Optimization and Data Analysis Laboratories

FORSCHUNGSCAMPUS
öffentlich-private Partnerschaft für Innovationen

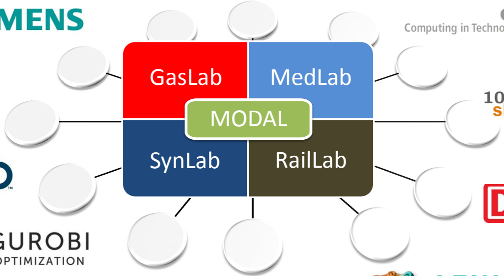
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Open Grid Europe — The Gas Wheel

SAP

SIEMENS

CiT Computing in Technology



1000 shapes

FICO

DB

GUROBI OPTIMIZATION

FIZ Karlsruhe
Leibniz-Institut für Informationsinfrastruktur

GAMS

LBW
Mathematical Optimization Systems in Public Transit

Problem Description

GasLab Project Goal

- Short-term transient gas network optimization on large real-world networks
- "Navigation system" for gas network operators

This figure is omitted due to missing copyrights.

Problem

Given

- Network topology
- Initial network state
- Short-term supply/demand situation, e.g. 12–24 hours

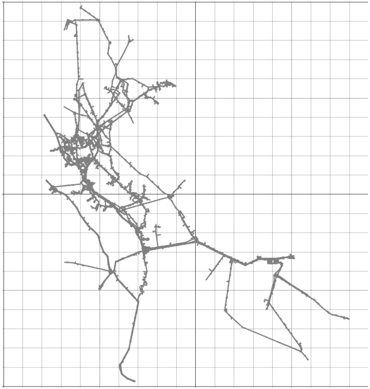
Goal

- Control each element s.t. the network is operated to its "best"

Station Model Description

Subproblem: Solve a single "navi station"

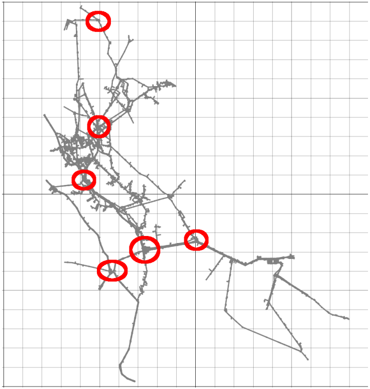
- Assume we already have a solution for the network, using a simplified model at intersection points
- Verify this solution at intersections using the original complex model
- Each such intersection is called "navi station"



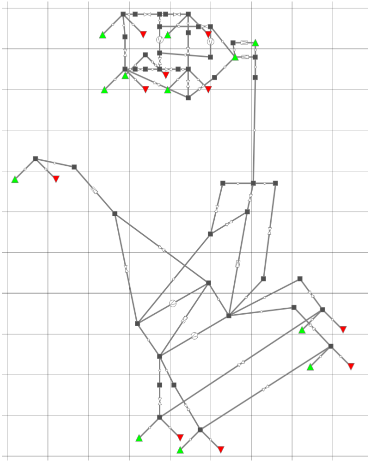
Station Model Description

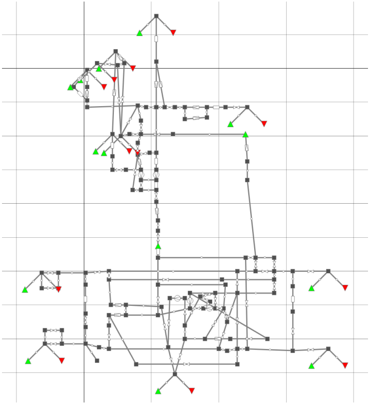
Subproblem: Solve a single “navi station”

- Assume we already have a solution for the network, using a simplified model at intersection points
- Verify this solution at intersections using the original complex model
- Each such intersection is called “navi station”



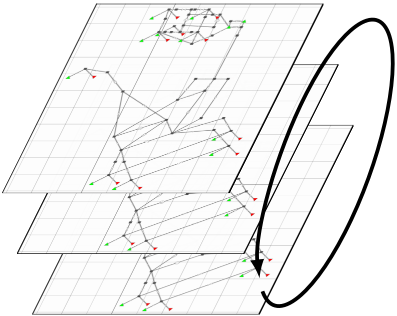
Example Navi Stations





Solution Approach: MIP Model

- Problem can be formulated as MIP model, if some physics are linearized
- Representation as directed time-expanded graph with arcs representing the network elements
- Important variables:
  - p : Pressure at nodes
  - q : Massflow on arcs
- Constraints for each type of element and the overall station
- Assume constant gas temperature and mixture



Pipe

Gas flow in a pipe (L, R) between times t_0 and t_1 can be described by

$$p_{L,t_1} + p_{R,t_1} - p_{L,t_0} - p_{R,t_0} + \frac{2\,R_s\;T\;z\,\Delta_t}{L\,A}\,(q_{R,t_1} - q_{L,t_1}) = 0$$

$$\begin{aligned} &\frac{\lambda\,R_s\;T\;z\,L}{4\,A^2\,D}\left(\frac{|q_{L,t}|\,q_{L,t}}{p_{L,t}} + \frac{|q_{R,t}|\,q_{R,t}}{p_{R,t}}\right) \\ &+ \frac{g\;s\;L}{2\,R_s\;T\;z}\,(p_{L,t} + p_{R,t}) + p_{R,t} - p_{L,t} = 0 \end{aligned}$$

This figure is omitted due to missing copyrights.

Pipe

Gas flow in a pipe (L, R) between times t_0 and t_1 can be described by

$$p_{L,t_1} + p_{R,t_1} - p_{L,t_0} - p_{R,t_0} + \frac{2\,R_s\,T\,z\,\Delta_t}{L\,A}\left(q_{R,t_1} - q_{L,t_1}\right) = 0$$

$$\text{Linearized:}\qquad \frac{\lambda\,L}{4\,A\,D}\left(|v_L|\,q_{L,t} + |v_R|\,q_{R,t}\right) + \frac{g\,s\,L}{2\,R_s\,T\,z}\left(p_{L,t} + p_{R,t}\right) + p_{R,t} - p_{L,t} = 0$$

This figure is omitted due to missing copyrights.

Resistor

- Artificial network element that reduces pressure
- Used to model measurement elements or complex piping

This figure is omitted due to missing copyrights.

Modeled by Darcy-Weisbach formula with drag factor ζ

$$p_{\text{in}} - p_{\text{out}} = \frac{\zeta \, R_s \, T \, z}{2A^2} \left(\frac{q^2}{p_{\text{in}}} \right)$$

Resistor

- Artificial network element that reduces pressure
- Used to model measurement elements or complex piping

This figure is omitted due to missing copyrights.

Modeled by Darcy-Weisbach formula with drag factor ζ

Linearized: $$p_L - p_R = \frac{\zeta\,|v|}{2A} q$$

Valve

- Close valve to separate network parts
- Change network topology

This figure is omitted due to missing copyrights.

Regulator

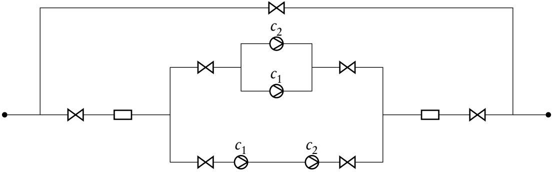
- Valve that can also be partially open
- Used to reduce the pressure in flow direction
- (and potentially change the network topology)

This figure is omitted due to missing copyrights.

Compressor Station

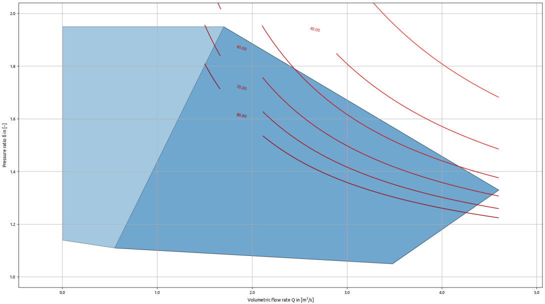
- Increases pressure in flow direction
- Most important element for controlling the gas flow in the network
- Each compressor station has a set of possible configurations
- Parallel (more flow) and/or serial (larger pressure) combinations of single compressors units

This figure is omitted due to missing copyrights.



Compressor Unit

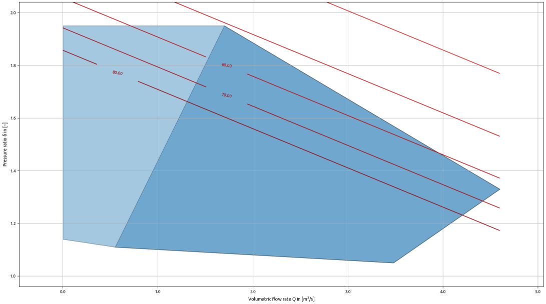
Combination of a compressor and a drive for the necessary power



$$\eta \, P = q \, R_s \, T \, z \, \frac{\kappa}{\kappa - 1} \left[\left(\frac{p_R}{p_L} \right)^{\frac{\kappa-1}{\kappa}} - 1 \right]$$

Compressor Unit

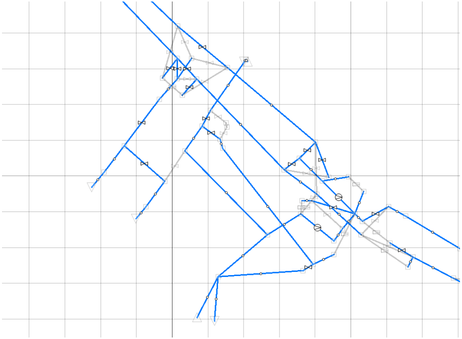
Combination of a compressor and a drive for the necessary power



$$\eta \, P = q \, R_s \, T \, z \, \frac{\kappa}{\kappa - 1} \left[\left(\frac{p_R}{p_L} \right)^{\frac{\kappa-1}{\kappa}} - 1 \right]$$

Navi Station

- Compressor stations are usually located at pipeline crossings and are related to the mode of the surrounding active elements
  $\Rightarrow$ They form a navi station
- A valid combination of element modes is called configuration
- Set of valid configurations is restricted by flow directions and flow amounts at the navi stations boundaries

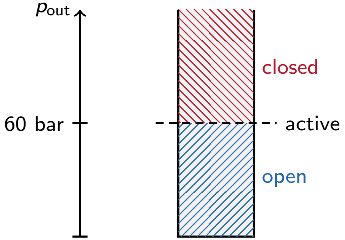


Navi Station

- Compressor stations are usually located at pipeline crossings and are related to the mode of the surrounding active elements
  $\Rightarrow$ They form a navi station
- A valid combination of element modes is called configuration
- Set of valid configurations is restricted by flow directions and flow amounts at the navi stations boundaries

Special Constraints

- Target values for regulators and compressor stations
  - Cannot be controlled directly
- Already fixed behavior for valves or regulators
- Temporary unavailable compressor units
- Flap traps in some regulators, i.e., no backward flow
- Pressure bounds depending on navi station configuration



Objective Function

Different components:

- Try to match the given pressure and flow requirements at the boundaries
  - We allow deviation from these values
- Change navi station configurations, element states and target values as little as possible
- Start compressors as little as possible

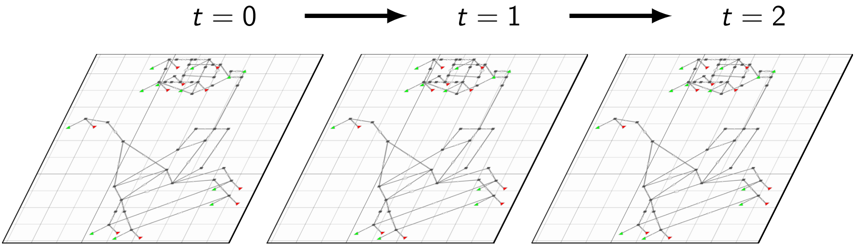
Final MIP Model

$$
\begin{aligned}
\min\ & \text{objective} & \\
\text{s.t. } & \text{flow conservation} & \forall\, \text{nodes} \\
& \text{pipe constraints} & \forall\, \text{pipes} \\
& \text{resistor constraints} & \forall\, \text{resistors} \\
& \text{regulator constraints} & \forall\, \text{regulators} \\
& \text{compressor station constraints} & \forall\, \text{compressor stations} \\
& \text{navi station constraints} &
\end{aligned}
$$

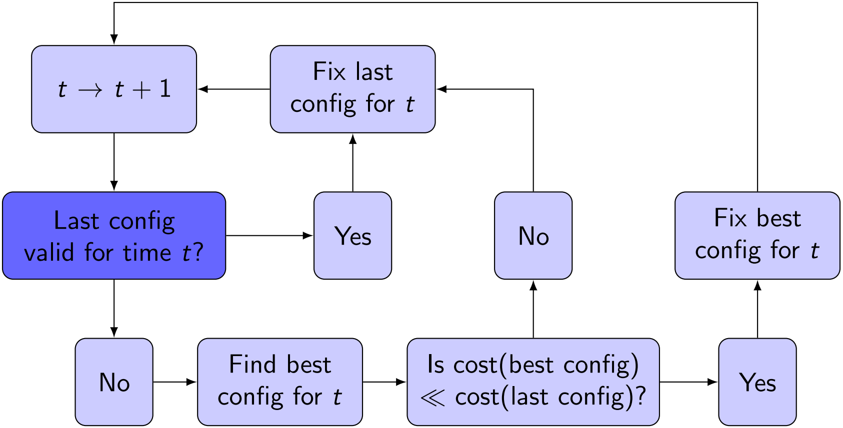
- Model is still challenging for the bigger stations ($\approx$ 170 arcs (50 discrete elements), $\approx$ 1600 configurations)
- Strict solving time limit, need a computationally more robust approach!

Stepwise stationary Idea

- Main decision: Choose a configuration per station and timestep.
- Observation: Pipes in navi stations are very short, no storage capacities
  $\Rightarrow$ We cannot "prepare for the future"
- Solve independent stationary models for each timestep



Algorithm - Initial Solution



Algorithm - Solution Improvement

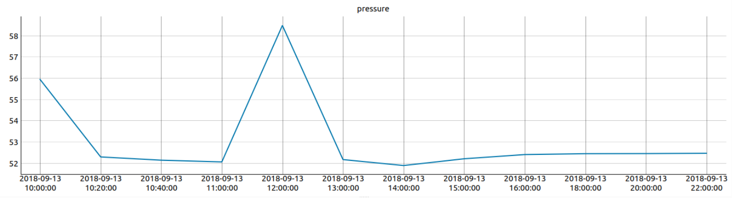
- Problem: Initial solution finds very good configurations for each time step, but only stores one configuration per step!
- It may not find a longer lasting configuration, with slightly worse single step objective value, but better overall objective due to less changes
- We use different improvement heuristics to avoid these kinds of problems.

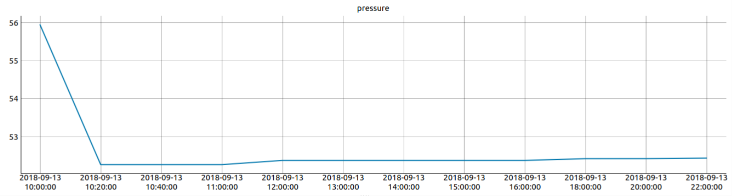
Example:

Time	0	1	2	3	4	5
Initial Solution	C_1	C_1	C_2	C_2	C_3	C_3
Cost	100.0	100.0	50.0	50.0	60.0	60.0
Better Solution	C_1	C_1	C_3	C_3	C_3	C_3
Cost	100.0	100.0	60.0	60.0	60.0	60.0

Algorithm - Solution Smoothing

- Some transient properties are not covered in the algorithm
- Finalize solution by doing a transient calculation with fixed navi station configurations
- Do this in a rolling horizon fashion to speed up long time horizons



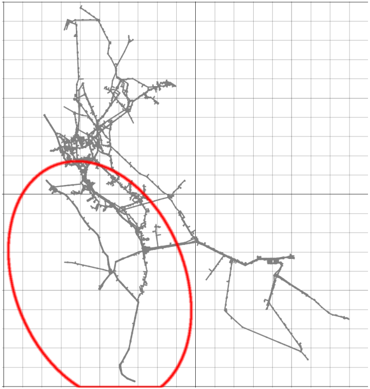


Algorithm Properties

- Very fast
- Scales linearly with number of time steps (no time dependent MIP complexity increase)
- Allows to easily add heuristics based on practitioner advises
- Allows to add not yet covered transient properties outside of the MIP model
  - configuration transition times
  - machine ramp up/cool down
  - minimize running compressor units
  - ...
- High solution quality → Live Solution Viewer

Future Challenges

- Transform solution of linearized problem into non-linear solution
- Add feedback from station model to net model
- Add more realistic element behavior
  - Air temperature dependent compression power bound
  - Semi-fixed elements
  - Single special network elements
  - Reduce simplifications in net model
- Increase network size
- MIP speed up by using more model specific techniques (heuristics, cutting planes etc.)



Mathematical Optimization and Data Analysis Laboratories

Thank you for your attention!