Applying Mathematical Optimization to Germany's Largest Gas Transport Network

— Project "ForNe" —

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Economics · Discrete Optimization · Mathematics

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Background – Gas market unbundling

- Since around 2005, European legislation has forced gas trading and gas transport to be separate operations
- Transport system operators (TSO) are solely responsible for the transportation of gas
- Gas traders only need to specify where they want to inject or extract gas
- Exchange with the corresponding other supplier or consumer is done via a so-called virtual trading point (VTP)
- The VTP can be thought of to be directly connected to any physical *entry* and *exit* of the network

Background – Bookings and Nominations

- For every entry and exit of the network, a TSO has to offer as much as possible independent capacity rights (rights to transfer gas into or out of the network up to a certain maximal amount)
- The acquisition of these rights is called booking
- The use of such a right is called nomination
- For any given time frame, some of the holders of these rights form a *balancing group* trading a *balanced* amount of gas in total
- The resulting load situation (nomination) has to be transported by the TSO during this time frame
- When the rights to participate are sold, the TSO has no knowledge on what particular balancing groups might later team up
- The TSO has to decide which capacity rights to sell, way in advance of the actual nomination.

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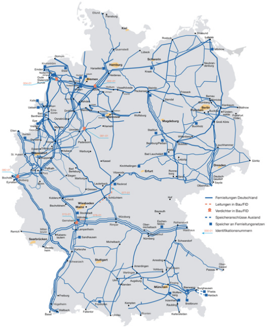
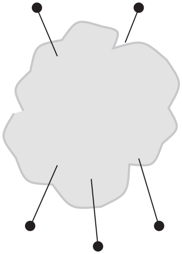


Central question

What is the capacity of a gas network and how can it be computed?

Booking and Nomination (transport customer's view)

entries



exits

Booking and Nomination (transport customer's view)

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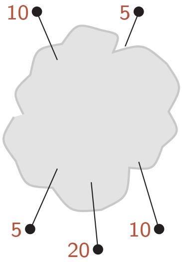

exits

booked capacities

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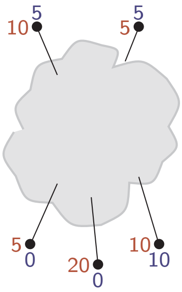

exits

booked capacities

nomination 1

Booking and Nomination (transport customer's view)

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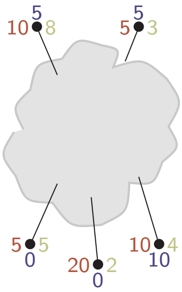
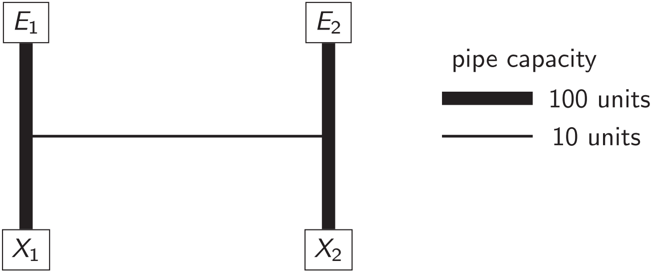


exits

booked capacities
nomination 1
nomination 2

Simple example: The "H"-network (TSO's view)



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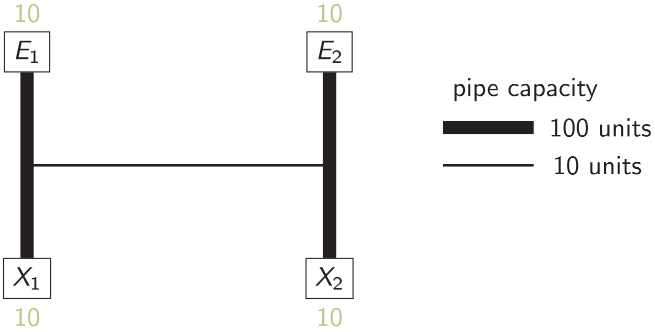

valid booked capacities: all nominations feasible

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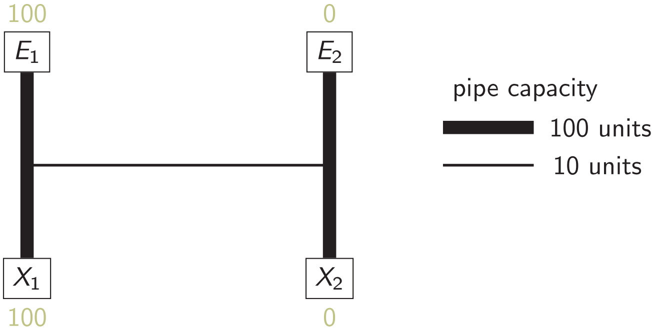

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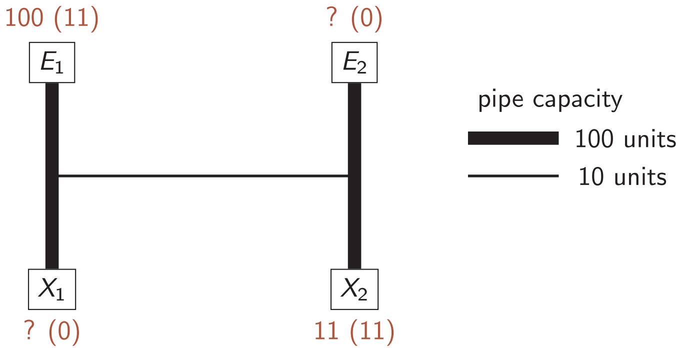

invalid booked capacities: at least one infeasible nomination

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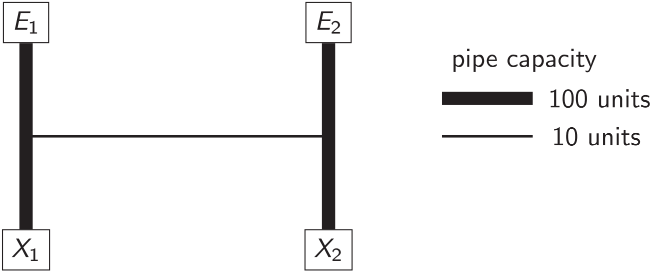

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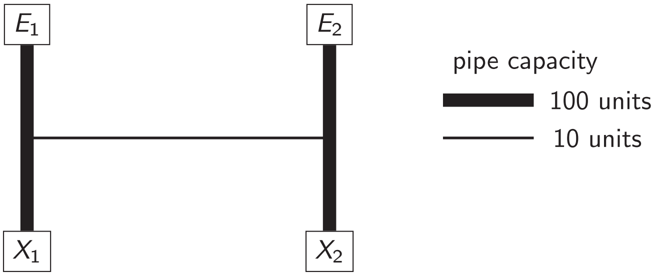

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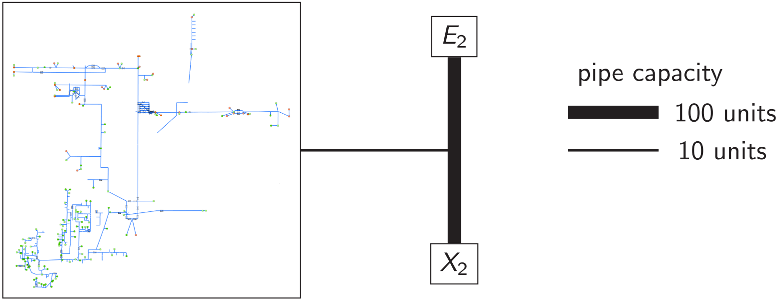

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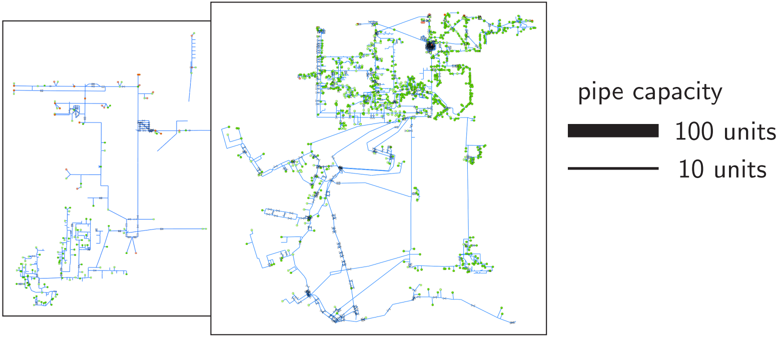

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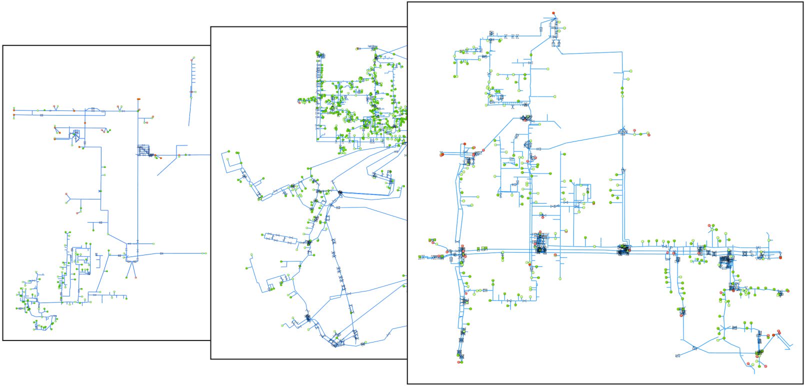

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In the light of that result the problem has been restated:

Verification of booked capacities

"Can all reasonable nominations be transported?"

A nomination is called *reasonable* if it ocurs with at least a certain nonzero probability.

Verification of booked capacities - coarse outline

1. Generate a probability distribution for nominations from historical data
2. Randomly sample nominations $n_1, \ldots, n_k$ with probabilities $p_1, \ldots, p_k$
3. For each nomination n_i check, whether it is technically feasible ($f_i = 1$) or not ($f_i = 0$)
4. If $\sum_i f_i p_i \geq \alpha$ the booking is verfied otherwise not

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There are several problems:

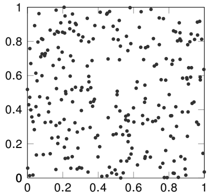
- The dimension is rather high (several hundred entries and exits)
- There are exits without statistical data
- Entries show up a market driven behavior rather than stochastic
- Checking whether a single nomination is technically feasible requires to solve a nonconvex MINLP

Statistical analysis of gas demand data

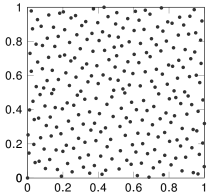
- Gas demand mainly depends on temperature and weekday
- Consider temperature classes seperately (intervals of 2 degrees)
- For each temperature class and each exit automatically fit a univariate distribution (based on the Kolmogorov distance), either normal, shifted normal, log normal, shifted log normal, Dirac, uniform, or shifted uniform
- Establish an overall multivariate distribution for each temperature class by
  - Grouping all exits with normal/lognormal distribution (60% – 90%)
  - Considering all exits with Dirac, shifted or uniform distribution as independent

Scenario sampling

- Apply randomized QMC method based on a Sobol sequence to generate n statistical load scenarios with probability $1/n$
- construct pseudorandom number to perform a digital binary shift of the elements of the Sobol sequence
- Fast convergence $\approx O(1/N)$
- Good equidistribution properties of the generated samples



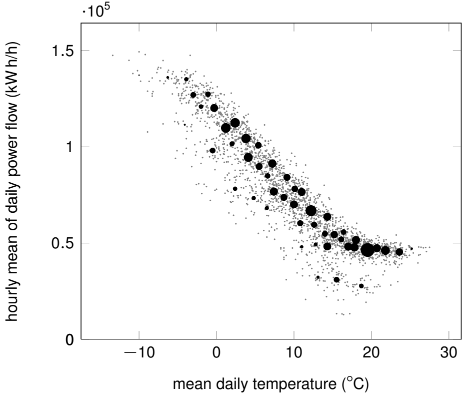
$N = 256$ Monte Carlo Mersenne-Twister samples for $d = 500$, projection $(8, 9)$



$N = 256$ RQMC random digital binary shifted Sobol' points for $d = 500$, projection $(8, 9)$

Scenario reduction

- Replace the n generated statistical load scenarios with probability $1/n$ to $k \ll n$ scenarios $\tilde{s}_1, \ldots \tilde{s}_k$ with probabilities $\tilde{p}_1, \ldots, \tilde{p}_k$



Scenario reduction from $N = 2340$ to $n = 50$.

Nomination generation

We now have a (reduced) set of (not necessarily booking compliant) statistical load scenarios that have to be completed with data for entries and exits w/o statistic data

1. A scenario $\tilde{s}$ that violates a capacity contract gets replaced by a booking compliant scenario s' with minimal L_1-distance
2. To generate *hard* nominations from s', i.e. nominations that are likely to be infeasible
   a. Entries and exits are grouped into sets $V^1, \dots V^N$ of "equivalent" points
   b. A randomized QMC method is used to sample directions from the unit hypersphere in $\mathbb{R}^N$
   c. For each such direction Θ a booking compliant nomination with maximal value for $\sum_{i=1,\dots,N} \Theta_i (\sum_{u \in V^i \cap V^+} P_u - \sum_{u \in V^i \cap V^-} P_u)$ is computed.

Nomination generation (cont.)

- Both tasks (scenario adjustment, scenario completion) can be accomplished by solving an (easy to solve) MIP
- The constraints of these MIPs are a mathematical model for
  1. contractually fixed pressure limits at entries and exits
  2. interconnection agreements between different TSOs
  3. capacity contracts
  4. further special contracts
- Finally, check all nominations for technical feasibility (nomination validation)

Essential Subtask: Validating Nominations

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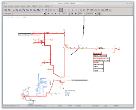

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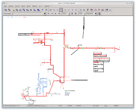

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Issue: How to decide whether a nomination is technically infeasible?

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Optimization

- works on simplified models of gas physics
- automatically finds settings for active devices
- eventually proves infeasibility of an infeasible nomination

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Deciding feasibility of a future nomination requires to test it against

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- all likely start states? infinitely many
- a suitable start state? might be overly optimistic

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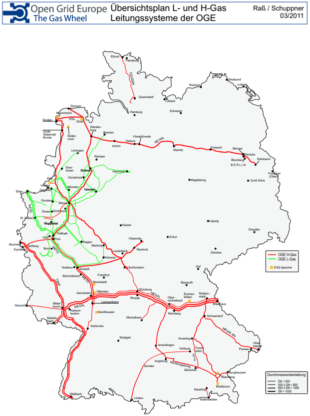
Nevertheless, the better choice for medium and long-term planning.

A model for the valdiation of nominations problem



- Gas network as digraph $G = (V, A)$
- Nodes represent customers (entries and exits)
- Arcs: pipes, valves, control valves, compressors

Pipe model

Euler Equations, Equation of State:

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

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

$$A\rho c_p \left(\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial x} \right) - A \left(1 + \frac{T}{z} \frac{\partial z}{\partial T} \right) \frac{\partial p}{\partial t}$$

$$-Av \frac{T}{z} \frac{\partial z}{\partial T} \frac{\partial p}{\partial x} + Avg\rho \frac{dh}{dx} + Q_E = 0$$

$$\rho - \frac{\rho_0 z_0 T_0}{p_0} \cdot \frac{p}{z(p, T)T} = 0$$

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$$\rho - \frac{\rho_0 z_0 T_0}{p_0} \cdot \frac{p}{z(p,T)T} = 0$$

Stationary, algebraic model (nonlinear, nonconvex, non-smooth):

$$p_j^2 = \left(p_i^2 - \Lambda_a \cdot |q|q\frac{e^{S} - 1}{S_a}\right)e^{-S_a}, \text{ with}$$

$$\Lambda_a = \left(\frac{4}{\pi}\right)^2 \frac{Lp_0 z(p_m, T_m)T_m}{D^5 \rho_0 z_0 T_0}, \quad S_a = 2Lg\frac{dh}{dx}\frac{\rho_0 z_0 T_0}{p_0 z(p_m, T_m)T_m}$$

Valve and control valve model

Valve: open or closed

$$\begin{aligned} \text{closed:} \quad & x_{ij} = 0 \implies q_{ij} = 0 \\ \text{open:} \quad & x_{ij} = 1 \implies p_i = p_j \end{aligned}$$

Control valve: active, bypassed or closed

$$x_{ij}^{\textbf{bypass}} + x_{ij}^{\textbf{active}} \leq 1$$

closed: $x_{ij}^{\textbf{bypass}} = x_{ij}^{\textbf{active}} = 0 \implies q_{ij} = 0$

bypass: $x_{ij}^{\textbf{bypass}} = 1 \implies p_i = p_j$

active: $x_{ij}^{\textbf{active}} = 1 \implies \underline{\Delta} \leq p_i - p_j \leq \overline{\Delta}$

Compressor model

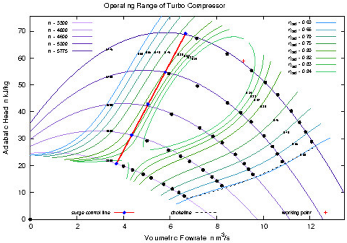
Change in adiabatic enthalpy, volumetric flow rate, and power demand of a compressor machine

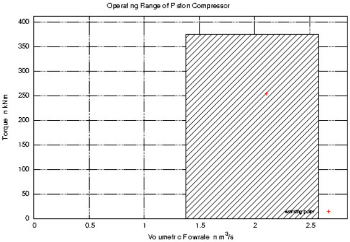
$$H_{ad} = \frac{z_i R_s T_i \kappa}{\kappa - 1}\left(\left(\frac{p_j}{p_i}\right)^{\frac{\kappa - \mathbf{1}}{\kappa}} - 1\right)$$

$$Q = \frac{p_0 z(p_i, T) T}{3.6 z_0 T_0} \frac{q}{p_i}$$

$$P = H_{\text{ad}} Q / \eta$$

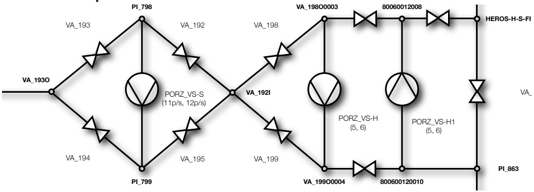
Operating range of a turbo compressor and a piston compressor





Subnetwork Operation Modes

Several network elements cannot be controled independently, e.g., control valve stations or compressor stations



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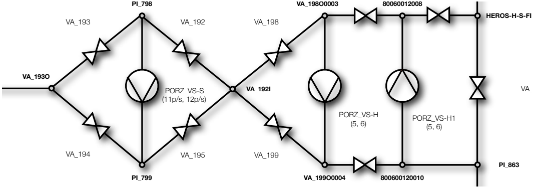

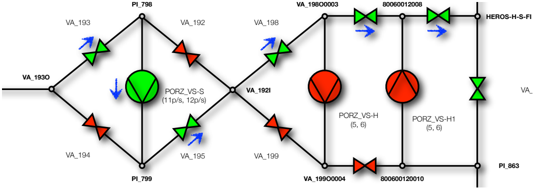

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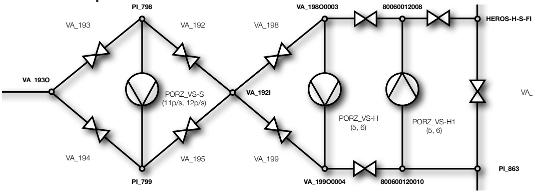

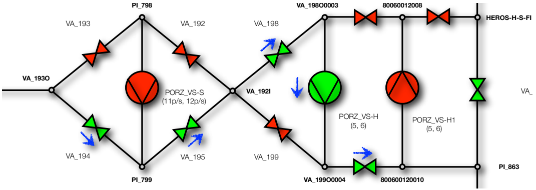

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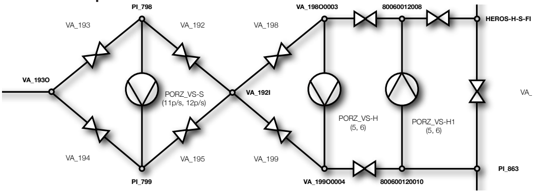
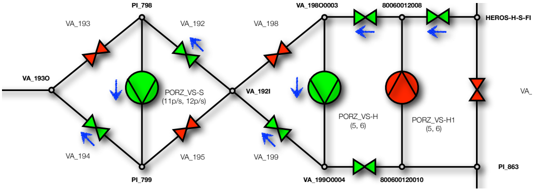
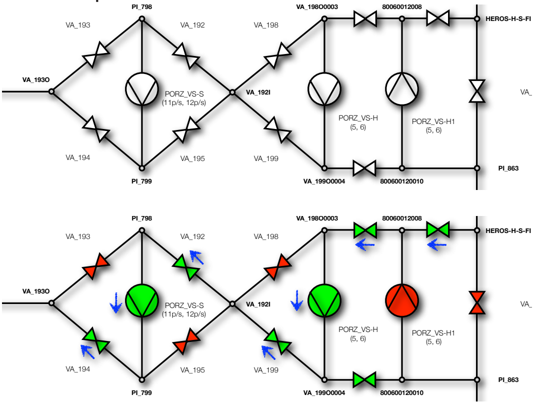




Subnetwork Operation Modes

Several network elements cannot be controled independently, e.g., control valve stations or compressor stations



- each operation mode is described by a binary vector giving the state of each valve and modeled via mixed-0/1 constraints

What does that mean?

What kind of model has to be solved?

To check validity of a single nomination, one has to decide feasibility of a nonlinear, nonconvex, non-smooth MINLP, which is NP-hard.

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The network sizes are up to 4200 nodes and 4500 arcs with more than 500 valves, 150 control valve stations, and more than 40 compressor stations. That leads to models with approximately 70,000 variables (12,000 binaries) and 100,000 constraints.

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How many NoVa problems have to be solved?

To solve the "verification of booked capacities" problem to a meaningful level of accuracy, approximately 120,000 NoVa problems have to be solved.

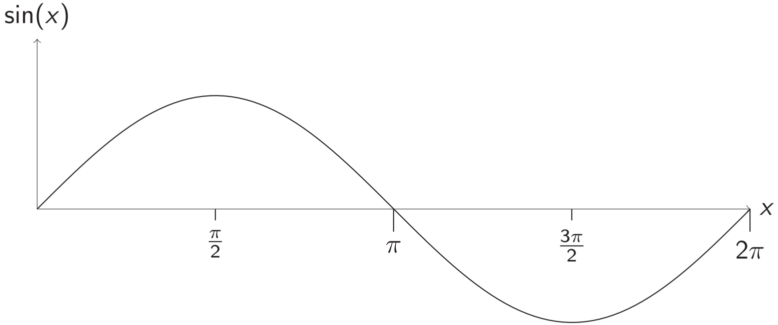
How it can be done

- Checking all possible controls via simulation is too time consuming
- Optimization solvers that compute local optima (pure heuristics, gradient based algorithms) cannot reliably determine infeasibility
- Solvers that rely on global optimization algorithms for MINLP cannot handle problems of that size
- State of the art MIP solvers are very stable and give valid answers about feasibility
- Only problem: Nonlinear constraints

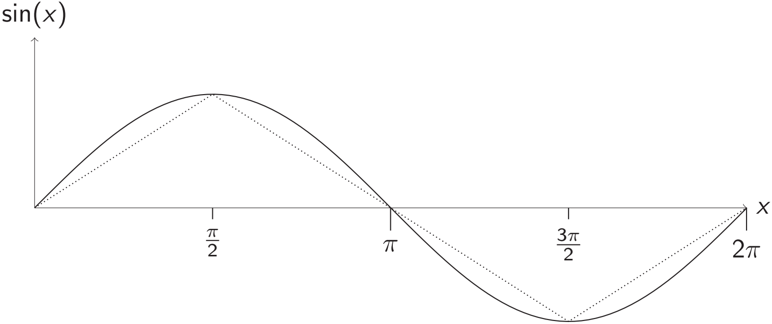
Our approach

Automatically construct an (arbitrarily) tight *relaxation* of the MINLP in terms of mixed-integer linear constraints and solve the MIP-relaxation with a MIP solver.

MIP-relaxations of MINLPs - Idea



MIP-relaxations of MINLPs - Idea



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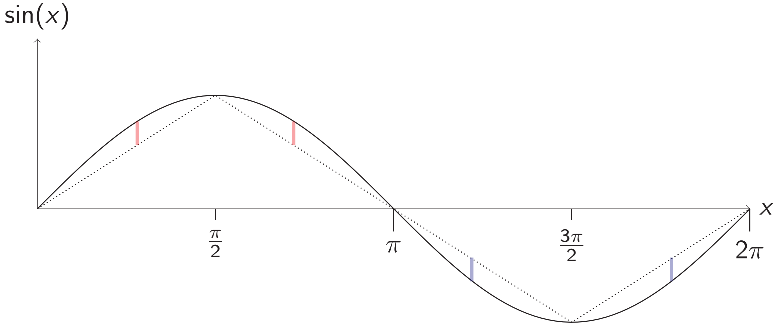

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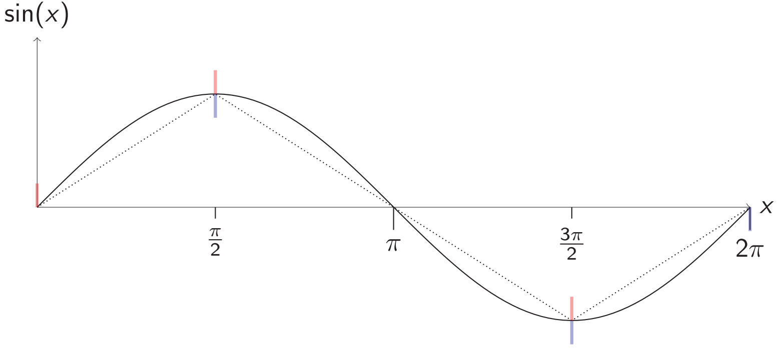
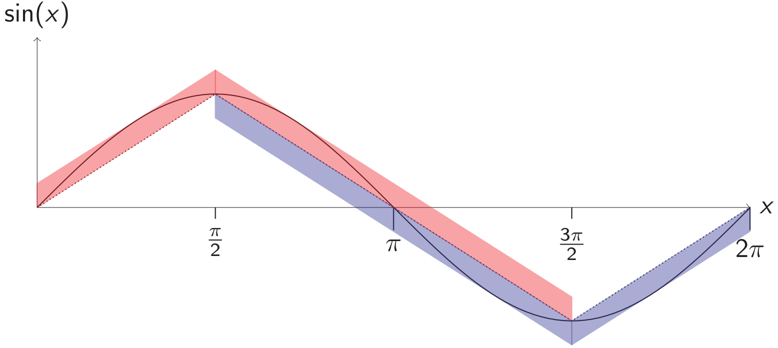
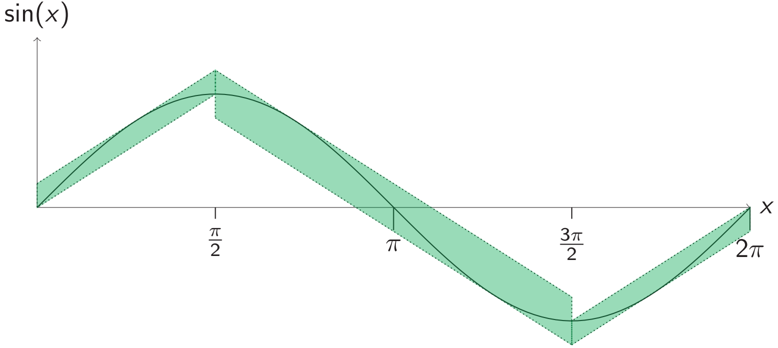


MIP-relaxations of MINLPs - Idea

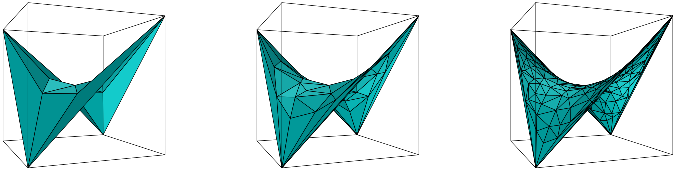


MIP-relaxations of MINLPs - Idea



Constructing MIP-Relaxations

- Decompose nonlinear constraints into univariate and bivariate nonlinear expressions
- Compute a piecewise linear *approximation* of each such expression that satisfies an a priori given error bound (e.g., piecewise minimax approximations, underestimator based interpolation)



- Use the incremental method for piecewise polyhedral envelopes to construct a (piecewise polyhedral) MIP-*relaxation* of the nonlinearity

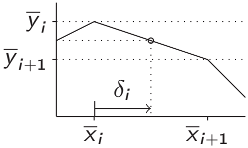
Modeling a piecewise linear function $y = f(x)$

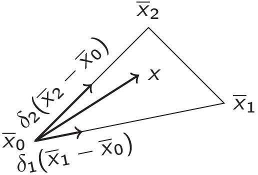
$$x = \overline{x}_0^{S_1} + \sum_{i=1}^{n} \sum_{j=1}^{d} \left(\overline{x}_j^{S_i} - \overline{x}_0^{S_i} \right) \delta_j^{S_i}, \qquad y = \overline{y}_0^{S_1} + \sum_{i=1}^{n} \sum_{j=1}^{d} \left(\overline{y}_j^{S_i} - \overline{y}_0^{S_i} \right) \delta_j^{S_i},$$

$$\sum_{j=1}^{d} \delta_j^{S_i} \leq 1, \qquad \text{for } i = 1, \ldots, n,$$

$$\delta_j^{S_i} \geq 0, \qquad \text{for } i = 1, \ldots, n, \; j = 1, \ldots, d,$$

$$\sum_{j=1}^{d} \delta_j^{S_{i+1}} \leq z_i, \quad z_i \leq \delta_d^{S_i}, \quad z \in \{0,1\}^{n-1}.$$





From approximation to relaxation

$$x = \overline{x}_0^{S_1} + \sum_{i=1}^{n} \sum_{j=1}^{d} \left(\overline{x}_j^{S_i} - \overline{x}_0^{S_i} \right) \delta_j^{S_i}, \qquad y = \overline{y}_0^{S_1} + \sum_{i=1}^{n} \sum_{j=1}^{d} \left(\overline{y}_j^{S_i} - \overline{y}_0^{S_i} \right) \delta_j^{S_i} + e,$$

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$$\delta_j^{S_i} \ge 0, \qquad \text{for } i = 1, \ldots, n,\ j = 1, \ldots, d,$$

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$$\sum_{j=1}^{d} \delta_j^{S_{i+1}} \leq z_i, \quad z_i \leq \delta_d^{S_i}, \quad z \in \{0,1\}^{n-1}.$$

$$\epsilon_u(f, S_1) + \sum_{i=1}^{n-1} z_i(\epsilon_u(f, S_{i+1}) - \epsilon_u(f, S_i)) \geq e,$$

$$-\epsilon_o(f, S_1) - \sum_{i=1}^{n-1} z_i(\epsilon_o(f, S_{i+1}) - \epsilon_o(f, S_i)) \leq e.$$

Solving NoVa

- Read specification of the network, the network elements (pipes, compressors, ...), subnetwork operation modes, nomination data (supplies, demands, gas quality parameters, pressure bounds, ...)
- Setup MINLP model
- Perform variable bound strengthening (flow, pressure, ...)
- Setup MIP-relaxation model
- Solve MIP-relaxation with MIP-solver by branch and bound (+tailored heuristics, separation algorithms)
- Write results to file (control and state of network, working point plots, ...)

Performance

- Problem size
  - 20 temperature intervals
  - 6 time periods
  - network with 4200 nodes and 4500 arcs
  - 50 entries, 450 exits,
  - 500 valves, 150 control valve stations, 40 compressor stations.
  - approximately 4000 capacity contracts
  - 120,000 NoVa problems to solve
- Hardware / Software
  - 256 Cores with 2.5 GHz each on a cluster with 32 nodes á 8 CPUs
  - 128GB main memory per node
  - C++ Software framework Lamatto++
  - MIP-Solver Gurobi 5.6.3 (only one thread per NoVa)
- Runtime: 18 days
- Avg. NoVa runtime 57 minutes
- Human expert + simulation software needs roughly 1 day / NoVa

Validation of bookings - User interface

Input selection

Select the input for Booking Validation:

Comment		User Comment about used data set
Gas Network	2014-09-24_L.net	Network file used for NoVa subproblems.
Compressor Stations	2014-08-21_L.cs	Compressor data file used for NoVa subproblems
Combined Decisions	2014-09-17_L_klein.cdf	Decision group data file used for NoVa subproblems
Contracts	2014-09-04-2-H-Gas.contracts	Contracts file used for generating nominations.
Distribution	2014-09-12_L-Gas_2006_bis_2014.dst	File containing distribution models for exit loads used for sampling load scenarios.
Soil Temperature Map		used for generating nominations
AdversaryModel	optimistic	Adversary model
Objective Function		manually specified adversary objective
ScenarioSamples	10	Number of statistical scenarios sampled from distribution data.
MaxRelativeScenredError	0.2	Maximum deviation from the histogram admissable for scenario reduction.
ScenarioCompletions	2	Number of completions for each statistical scenario.
RandomSeed	42	Random seed for nomination generation.
FeasibilityProbability	0.95	Probability of feasible scenarios needed to consider a booking as valid/feasible.
ContractDate		Contracts valid on this date will be considered. Format: YYYY-MM-DD
DataSetId		Id of the distribution dataset to be used. If empty, the first dataset will be used.
Expert Nominations	1314-SoN-Ey_H_2014-01-15_wegintegral-neu.scn 1314-SoNST-Ey_H_2014-01-15_wegintegral-neu.scn 1314-SoS-OkEyKi_H_2014-01-15_wegintegral-neu.scn	
ExpertNominationProbability	0.0	Probability given for all expert nominations.

Start computation

Validation of bookings - User interface

Input

Instance Hash	330d07fb0b98bf32576d41b88255547e9bbae323
Lamatto Revision	28cfdc5
Online Solver Revision	85b8451
Problem	Booking Validation
Comment	
Gas Network	H-Gas_V3-2014-04-10_Buva.net
Compressor Stations	H-Gas_V3.cs
Combined Decisions	H-Gas04.cdf
Contracts	Changed2a_2014-08-25-H-Gas.contracts
Distribution	H-Gas_2006_2013_Stand_Februar2014.dst
AdversaryModel	optimistic
ScenarioSamples	1500
MaxRelativeScenredError	0.2
ScenarioCompletions	6
RandomSeed	42
FeasibilityProbability	0.95
ContractDate	2015-08-01
DataSetId	DSMultivarWD13
Expert Nominations	
ExpertNominationProbability	0.0

Results

Running Status	done
Solution Status	feasible
Feasibility Probability	0.975333
Log File of the data consistancy ch...	boova_checkData.do.log
Log File of Nomination Generation	buildNominations.do.log
Tabular statistics about objective f...	objStatistics.csv
Scenario Summary	

Scenario	Prob	Status	Nomination / Reason
GasnetzworkdayTC130710	0.00733333	FEASIBLE	GasnetzworkdayTC130710_random0
			GasnetzworkdayTC130710_random1
			GasnetzworkdayTC130710_random2
			GasnetzworkdayTC130710_random3
			GasnetzworkdayTC130710_random4
			GasnetzworkdayTC130710_random5
GasnetzworkdayTC130715	0.00866667	FEASIBLE	GasnetzworkdayTC130715_random0
			GasnetzworkdayTC130715_random1
			GasnetzworkdayTC130715_random2

Validation of bookings - User interface

View Instance

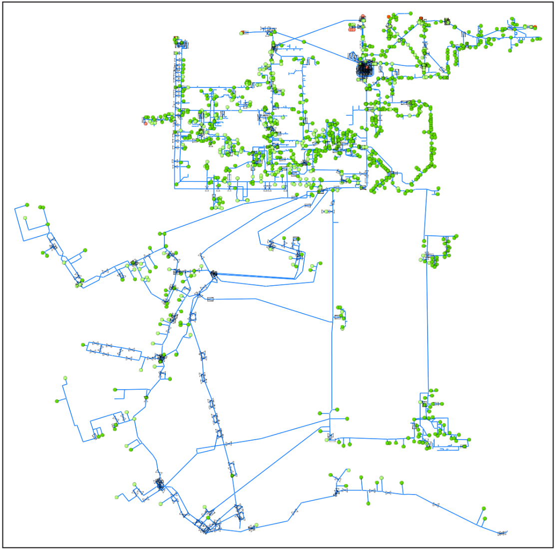
Input

Instance Hash	f49bd7926a5f064b69193f5c3f45d25ea7dd9a76
Lamatto Revision	28cfdc5
Online Solver Revision	85b8451
Problem	Nova First Stage
Gas Network	H-Gas_V3-2014-04-10_Buva.net
Nomination	GasnetzworkdayTC130710_random0.scn
Compressor Stations	H-Gas_V3.cs
Combined Decisions	H-Gas04.cdf
NominationType	Power
ScenarioScaling	1.0
PassiveSubnetPressureBounds	disabled
RealGasFactor	Papay
Model	eta2-Gurobi
TurboCompressorModel	SurgDeact_ChoAct
DriveModel	Idealized

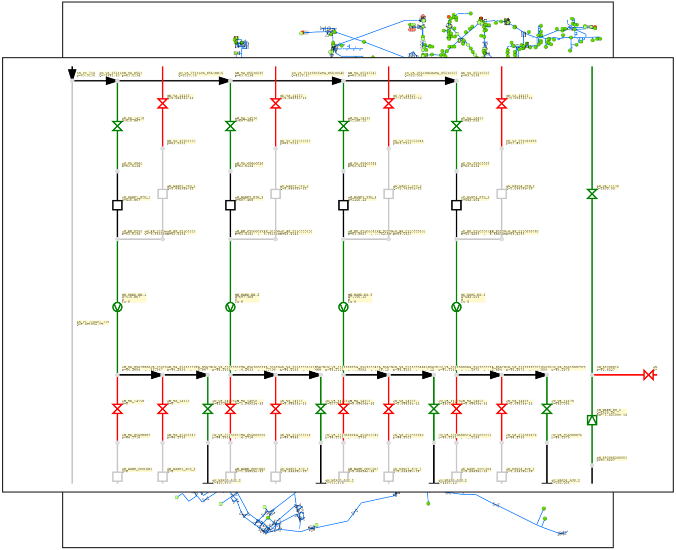
Results

Running Status	done
Solution Status	feasible
Log file of first stage	nomvalid_1_eta.0.do.log
Do file of first stage	nomvalid_1_eta.0.do
Solution of first stage	solution.lsf Store
Scenario with fixed solution values	solution.scn Store
Solution visualization (NView)	solution.nvf
Runtime	0:29:12
ParentLink	330d07fb0b98bf32576d41b88255547e9bbae323
Results as zip archive	Download
Debug information as zip archive	Download

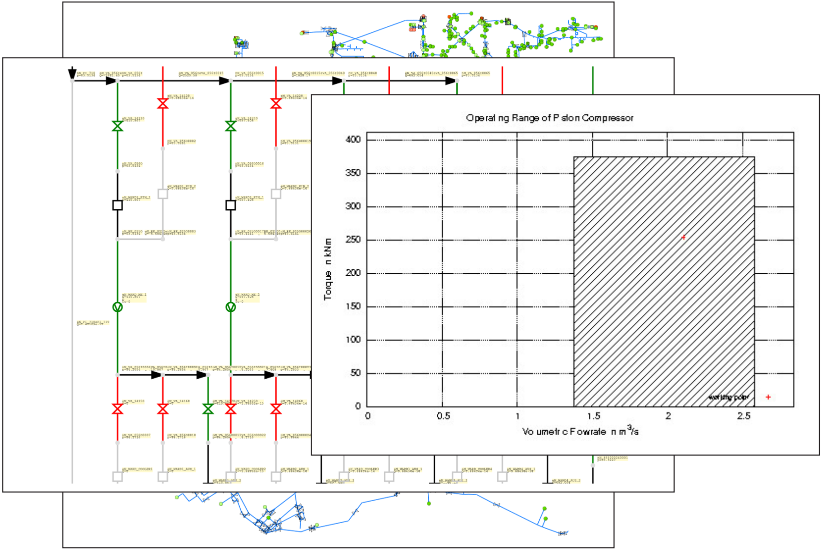
Validation of nominations - Graphics output



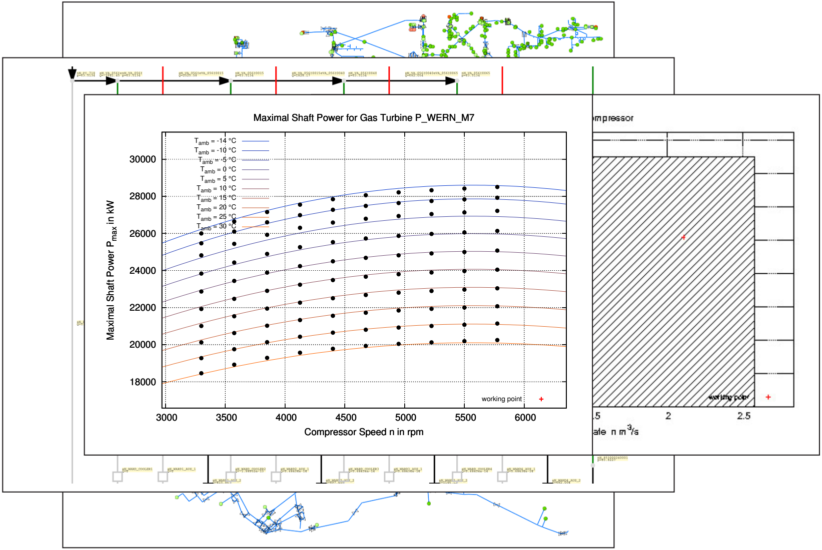
Validation of nominations - Graphics output



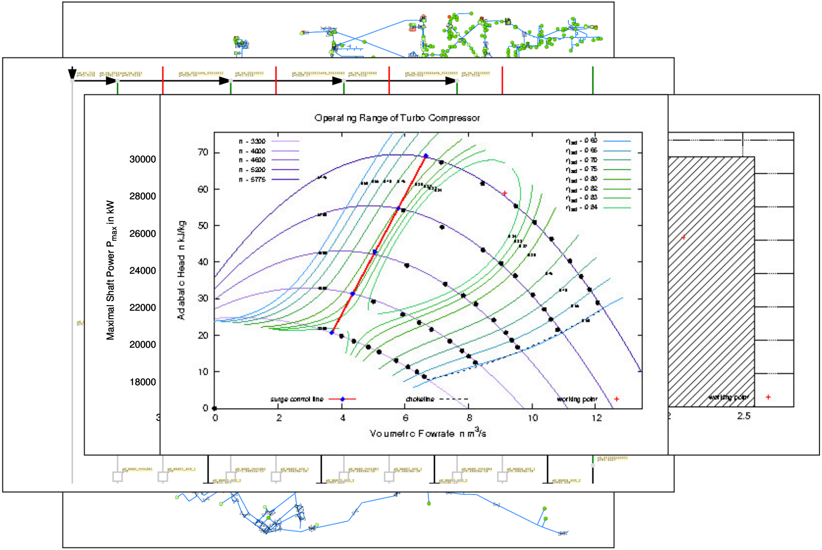
Validation of nominations - Graphics output



Validation of nominations - Graphics output



Validation of nominations - Graphics output

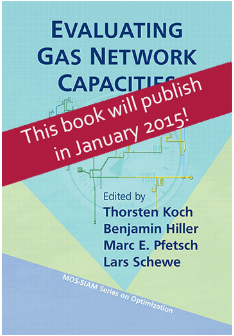


What else can be done?

- Solving NoVa is not only a tool to verify bookings on gas networks
- Other applications:
  - Minimizing operational cost of a gas network
  - Cost minimal gas network topology planning
  - also applied to water networks
  - electricity networks
  - ...
- MIP-relaxations are not even limited to networks, but seem to be promising to all kinds of MINLP with a significant combinatorial complexity

More details

Further details can be found in our book *Evaluating Gas Network Capacities*, which is part of the MOS-SIAM series on Optimization, and the references therein.



http://bookstore.siam.org/mo21/

More research

More research, especially on transient gas network optimization, is done at the Collaborative Research Centre: Transregio TRR 154 "Mathematical modeling, simulation and optimization of gas networks" funded by the German Research Foundation (DFG).

TRR 154 | Mathematische Modellierung, Simulation und Optimierung am Beispiel von Gasnetzwerken

`http://trr154.fau.de/`

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Thank you very much!

Questions?