Globally Convergent Stationary Network Solvers, Modeling of Gas Compressors and Hierarchical Reduction

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

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Globally Convergent Stationary Network Solvers, Modeling of Gas Compressors and Hierarchical Reduction

MYNTS

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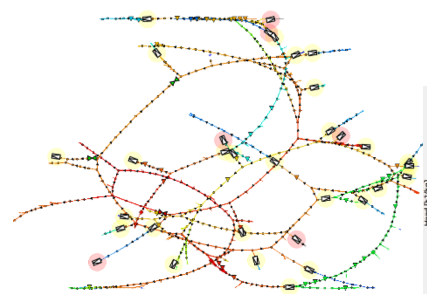

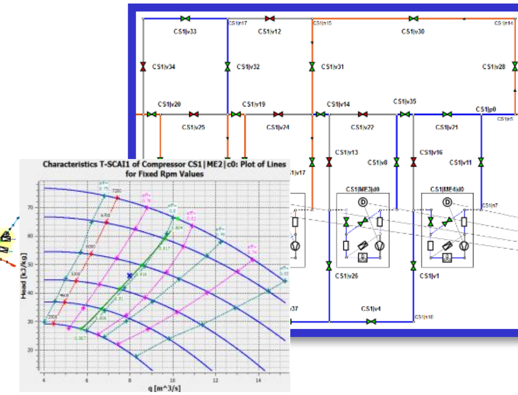

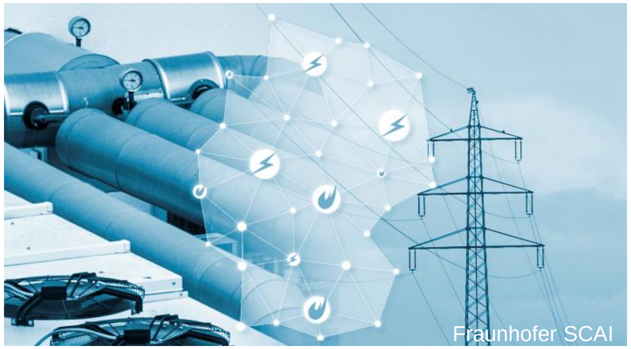

Math Energy

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Introduction

- MYNTS (MultiphYsal NeTwork Simulator), a system for physics-based simulation of energy transport networks, is enhanced by several concepts:

1. Generalized resistivity (GR):
   - GR-conditions provide global convergence of respective solution algorithms, approaching a (then) existing and unique solution from an arbitrary starting point.
   - In previous papers, a theoretical foundation for GR was developed.
   - Modeling of gas compressors is especially complex. Here, an extension of GR to advanced compressors by means of unfolding is explained.
2. Hierarchical topological reduction:
   - For large networks encountered in realistic cases, the newly developed algorithms allow to speed up the solution process significantly.

- For benchmarking both features, a set of realistic test networks is used.

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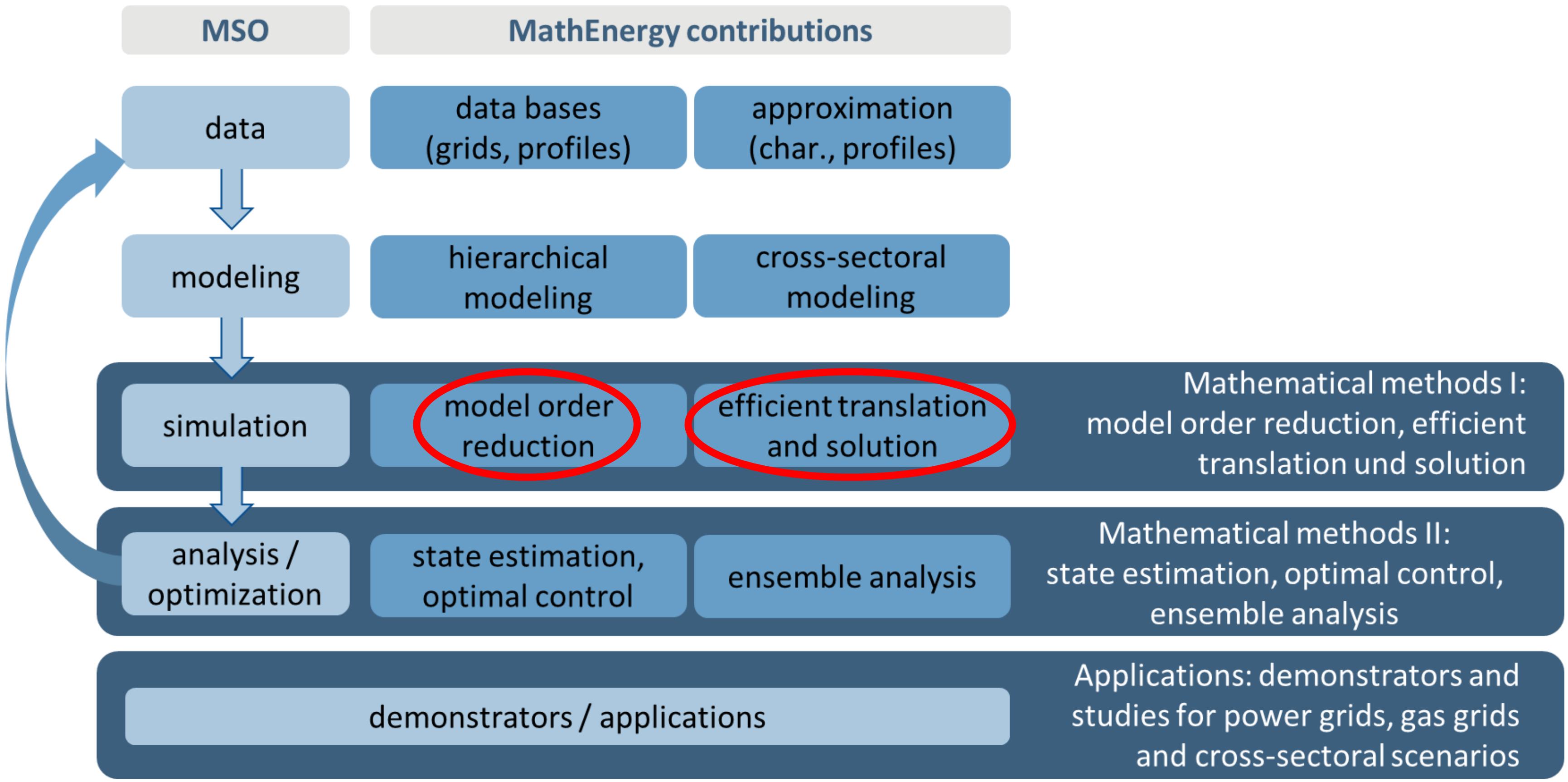
Key Aspects of this Contribution



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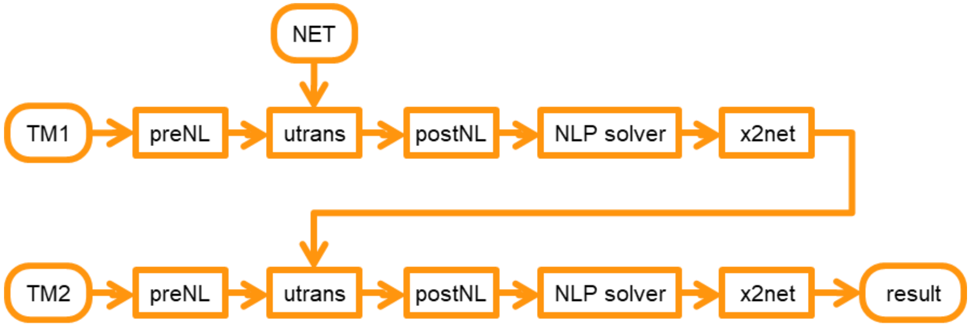
Summary of GR and Exemplary Solver Workflow

- Stability of modeling is addressed by monotonicity of element equations, e.g., m(P1,P2) should increase w.r.t. P1, decrease w.r.t. P2 *
- Stability of the solver is additionally supported by special low level algorithms (Armijo line search)
- IPOPT, as used by previous MYNTS versions as a solver, is replaced by an own SCAI Newton solver, containing these algorithms
- Call to the new kernel (Utrans*) invokes a Python workflow, describing a multiphase solution procedure (e.g., start with forced goals of compressors and regulators; proceed with free compressors; then with advanced; iterate mixing of temperature and gas properties,...)

Example:
2-phase solution process

*) For details on Utrans, see separate set of slides!



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** Ref: T. Clees et al., Making Network Solvers Globally Convergent, Advances in Intelligent Systems and Computing, Springer 2017.*

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Stable Modeling of Advanced Compressors

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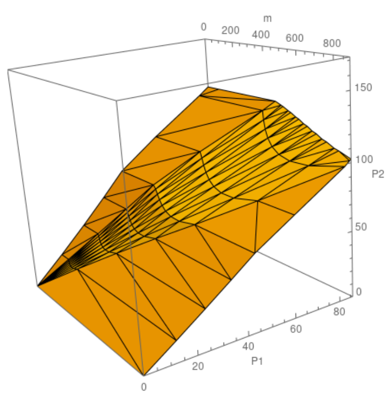
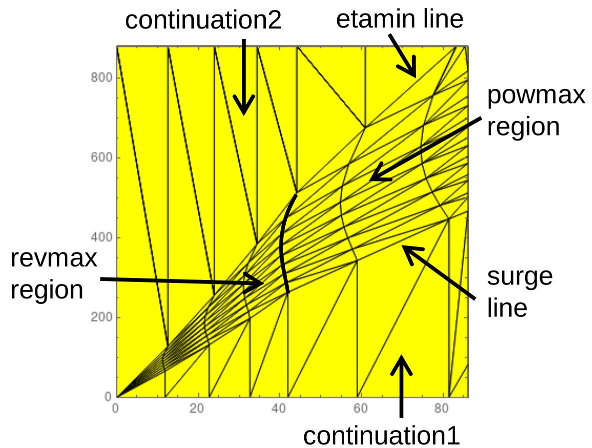
Stable Modeling of Advanced Compressors

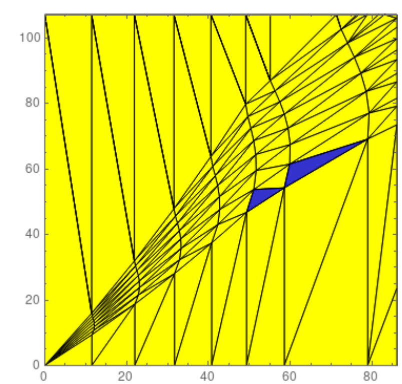
- Strategy: eliminate all intermediate variables (Had,Qvol,rev,Perf,eta,…); represent advanced compressor's equation in the basic form, e.g., P2(P1,m)
- Check monotonicity
- Use a monotone linear continuation outside of the working region *



resulting P2(P1,m) eqn



(P1,m) projection, usually no problem encountered



problems with monotonicity, happen rarely, require a local modification of the diagram

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** Ref: T. Clees et al., Making Network Solvers Globally Convergent, Advances in Intelligent Systems and Computing, Springer 2017.*

Stable Modeling of Advanced Compressors – Results for Benchmark Suite

test networks	total num.	converged old	converged new
H-gas	60	31	60
L-gas	23	23	23

old: internal vars not eliminated, eqs partially unfolded
new: internal vars eliminated, eqs completely unfolded

100% convergence achieved!

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Stable Modeling of Advanced Compressors – Details

- A sequence of non-linear transformations:
  (qvol,rev)→(had,eta,perf)→(rho1,had,m)→(P1,P2,m)
- step1: a usual 1D quadratic and 2D biquadratic models F(qvol,rev) *
- step2: temperature & gasmix independent models
  m=perf/had eta, rho1=m/qvol
- step3: temperature & gasmix dependence
  k=1.29; alp=(k-1)/k; gam=Rgas/mu T;
  P1=EOSinv(rho1) ← inverse equation of state rho=EOS(P), DC92/GERG
  z1=P1/(gam*rho1) ← universal gas law PV=m/mu RTz
  P2=P1(Had alp/(gam z1)+1)^(1/alp) ← Had definition resolved w.r.t. P2
  (watch out for units: W/kW/MW, bar/Pa etc)

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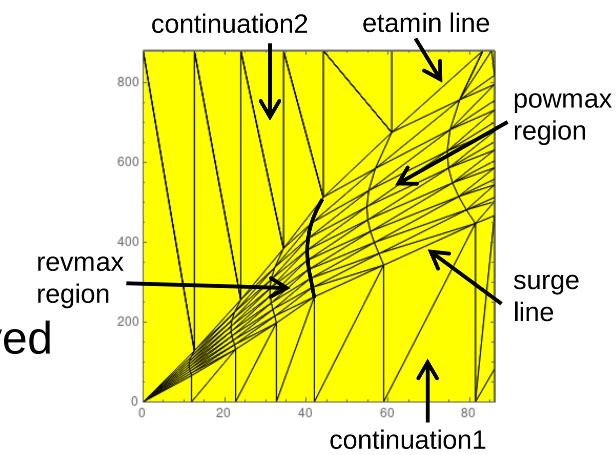
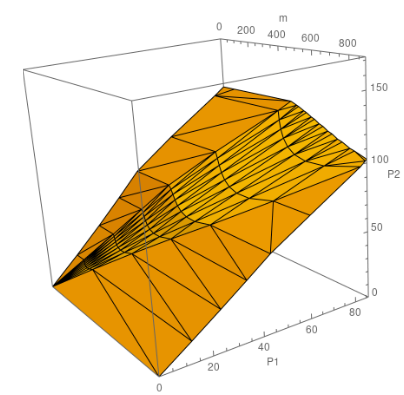
** Ref: T. Clees, I. Nikitin, L. Nikitina, "Advanced Modeling of Gas Compressors for Globally Convergent Stationary Network Solvers", in Proc. INFOCOMP 2017*

Stable Modeling of Advanced Compressors – Details

- powmax region: restricted by revmin/revmax and
- qmin/etamin (aka surge line and choke line)
- revmin/revmax are consts, qmin1(rev) is given as 1D quadratic model, eta(qvolmax,rev)=etamin=const is solved w.r.t. qvolmax(rev)
- qmin2(rev) is defined as argmax_q had(q,rev), qmin=max(qmin1,qmin2,0)
- region between revmin/revmax and qmin/etamin is resampled to Nrev*Neta grid
- revmax region: rev=revmax side, in (rho1,m) projection scaled to the origin
- cont1,2 regions go down/up in (rho1,m) projection
- the obtained 3D surface in (rho1,m,had) or (P1,P2,m) spaces is represented by triangulation



(P1,m) projection



resulting P2(P1,m) eqn

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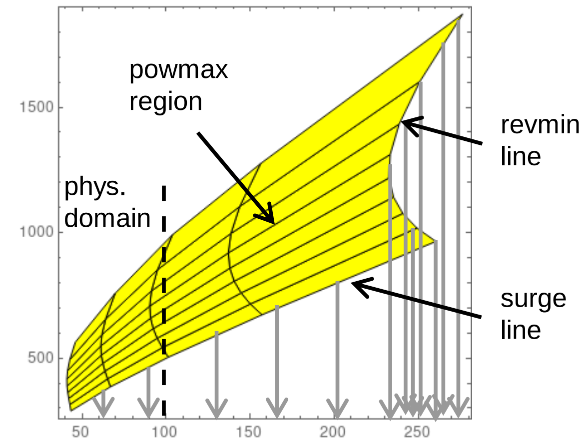
Stable Modeling of Advanced Compressors – Known Challenges (revmin Side)

- revmin side of powmax patch generally has a fold
- m is continued downwards from this line, due to opening bypass regulator, circulating a part of the flow
- this continuation creates the fold, producing multiple solutions, degeneracy of Jacobi matrix…
- fortunately, for most of the cases, this region is located beyond the physical domain of rho1 or P1 and can be safely ignored
- for extra safety, rho1max value is defined, cutting off the fold, and the patch is restricted by this value



(rho1,m) projection

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Stable Modeling of Advanced Compressors – Extended Control equation in Translation Matrix

model=free

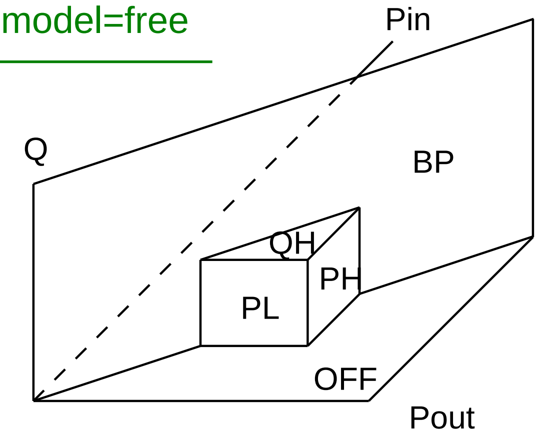
$$
\begin{aligned}
&\max(\min(P_{in} - P_L, -P_{out} + P_H, -Q + Q_H, \\
&-P_{out} + P_{out}^{adv}(\hat{P}_{in}, \hat{m}) \\
&+ \min(P_{in} - P_{in,min}^{adv}, 0) + \max(P_{in} - P_{in,max}^{adv}, 0) \\
&+ \min(-m + m_{max}^{adv}, 0) + \max(-m + m_{min}^{adv}, 0) \\
&), P_{in} - P_{out}, -Q) + \epsilon(P_{in} - P_{out} - Q) = 0,
\end{aligned}
$$

regularization

$$
\begin{aligned}
\hat{P}_{in} &= \min(\max(P_{in}, P_{in,min}^{adv}), P_{in,max}^{adv}), \\
\hat{m} &= \max(\min(m, m_{max}^{adv}), m_{min}^{adv})
\end{aligned}
$$

model=advanced

continuation outside of working reg.



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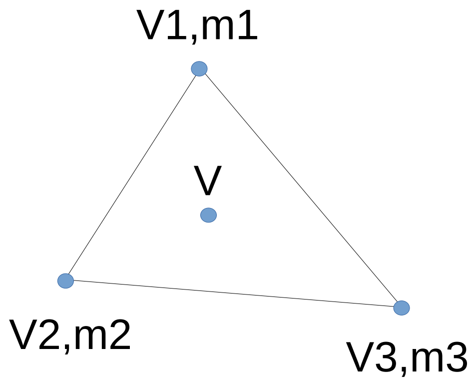
Stable Modeling of Advanced Compressors – Low Level Implementation

- triangulated surface P2(P1,m) represented as follows
- barycentric coordinates on a plane:
  m1*V1+m2*V2+m3*V3=(x,y), m1+m2+m3=1
- can be solved for m123(x,y) by linear formulas, 3 numbers (c0,cx,cy) per m
- one formula can be spared using m3=1-m1-m2
- point belongs to triangle: m1,2,3>=0
- one more linear formula represents z-coord (P2)
- altogether 9 numbers (equivalent to 3 nodes x 3 coords)
- a function is implemented, searching for a triangle and evaluating z-coord and its xy-derivatives
- linked to the solver using a mechanism of user-defined functions



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Stable Modeling of Advanced Compressors – Current Status of Development

- T-, K- & GEN-compressors and P-, E- and S-drives are implemented
- E-drives in the case of strongly increasing Mt(rev) replaced with const Mt
- S-drives implemented as const powmax drives
- procedure of conversion of compressors and drives chars to triangulated surfaces is implemented as an external module in Mathematica
- produces triangle lists in MYNTS_TRIFILE, which can be used in UTrans workflow
- modeling of temperature and gasmix implemented, by non-linear deformation (warping) of precomputed diagrams
- a module for reconstruction of eliminated vars is developed (postprocessing of solution)

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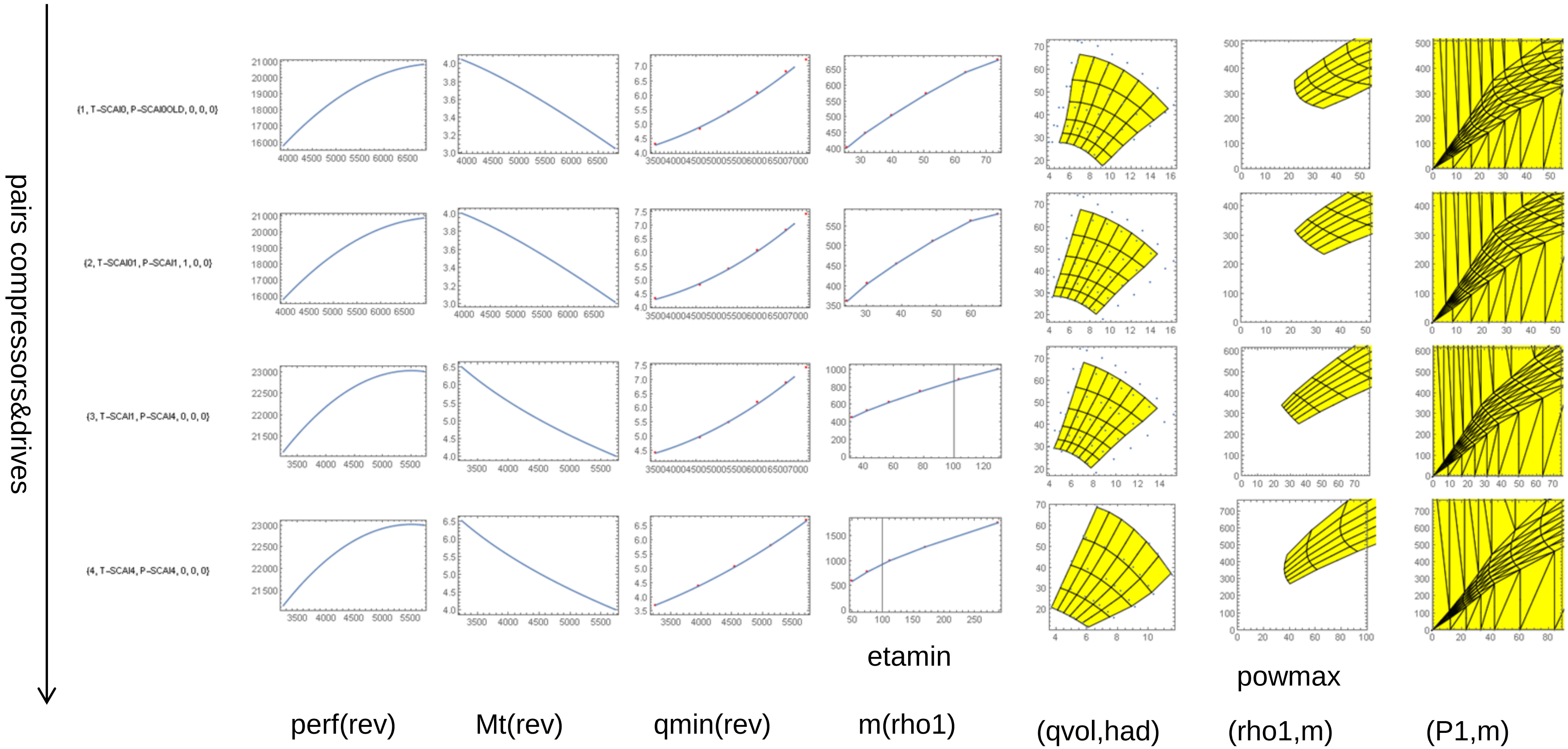
Stable Modeling of Advanced Compressors – Example of Visualization



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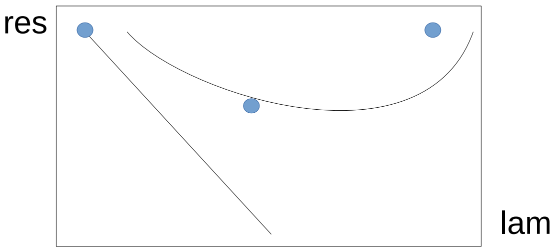
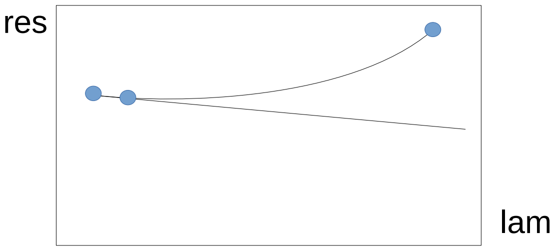
Relaxed Armijo Rule

- standard Armijo rule works as stabilizing line search algorithm for Newton iterations
- ensures that the residual of the system decreases
- theoretically (Kelley 1995) guarantees convergence for $||J^{-1}||<C$
- we are solving nearly degenerate systems (due to marginal signatures of c&r eqs)
- they correspond to nearly plateau behavior of the residual
- small non-linear terms can strongly reduce the step, forcing Newton iterations to stagnate
- we have implemented a relaxed version of Armijo rule





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Relaxed Armijo Rule

- detects plateau situation by estimating of the lowest SVD eigenvalue:
- Jdx=-f, v=dx/|dx|, lam^2<=vT(JTJ)v=|f|^2/|dx|^2
- in plateau situation allow residual to increase not more than a given threshold
- significantly improves convergence of realistic examples (48/60→59/60)
- sometimes (rarely) causes Newton iteration to cycle
- usually those cases can be solved by switching relaxing off (59/60→60/60)
- further, if networks diverge, look at the behavior of residuals
- if almost converged, increase max_iter
- ls=100 – line search failed, a fold or other singularity met
- look at localization of residuals (the nearest c&r are printed out, residuals can be visualized on the networks)
- try to change the local settings to remove the divergence
- (model→free, spo→sm, eliminate shortcircuits if any...)

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Topological Reduction

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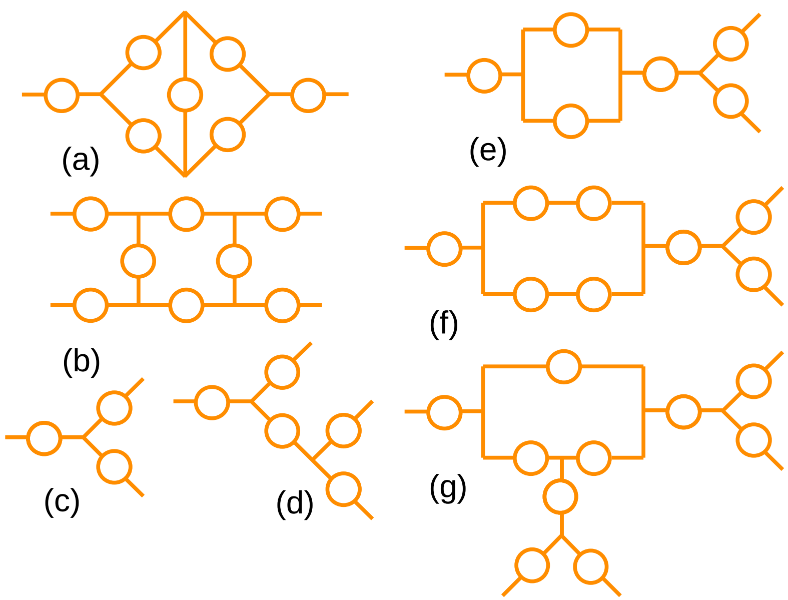
Topological Reduction Algorithms

- series and parallel connections of generic network elements can be reduced *
- in graph theory, the graphs reducible in this way are called series-parallel graphs, SPGs
- additional reduction is an elimination of a leaf (a node of valency 1), for generalized series-parallel graphs, GSPGs
- for transport networks all Qset leafs can be eliminated in this way
- additional reduction is cleaning out „superconductive“ edges, such as shortcuts, open valves, D=1m L=1m pipes, etc; and removing disconnected parts possessing no Psets

Examples of GSPGs



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* Ref: T. Clees et al., Modeling of Gas Compressors and Hierarchical Reduction for Globally Convergent Stationary Network Solvers, Int. J. On Advances in Systems and Measurements, 2018

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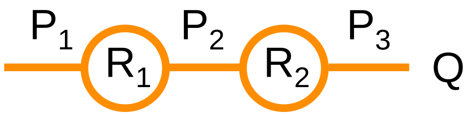
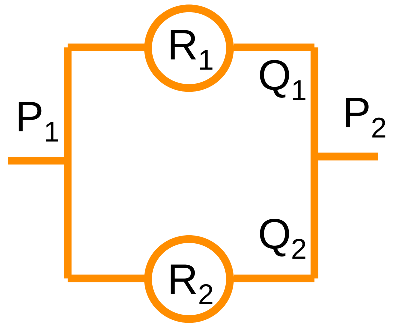
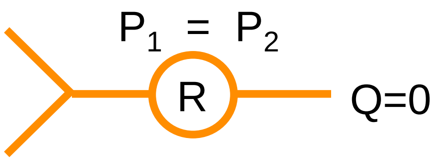
Topological Reduction Filter for Pipes – Implementation

- reduces series, parallel and tree-like connections (Generalized Series Parallel Graph, GSPG)
- implemented for quadratic pipes, generalization for other friction laws is possible







$$P_1|P_1| - P_2|P_2| = R_1 Q|Q|,$$
$$P_2|P_2| - P_3|P_3| = R_2 Q|Q|,$$
$$P_1|P_1| - P_3|P_3| = R^s_{12} Q|Q|,$$
$$\boxed{R^s_{12} = R_1 + R_2}$$

series

$$P_1|P_1| - P_2|P_2| = R_1 Q_1|Q_1|$$
$$= R_2 Q_2|Q_2|, \; Q = Q_1 + Q_2,$$
$$P_1|P_1| - P_2|P_2| = R^p_{12} Q|Q|,$$
$$\boxed{R^p_{12} = \left(R_1^{-1/2} + R_2^{-1/2}\right)^{-2}}$$

parallel

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Ref: A. Baldin et al., Topological Reduction of Gas Transport Networks, in Proc. of INFOCOMP 2019

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Topological Reduction Filter for Pipes – Implementation

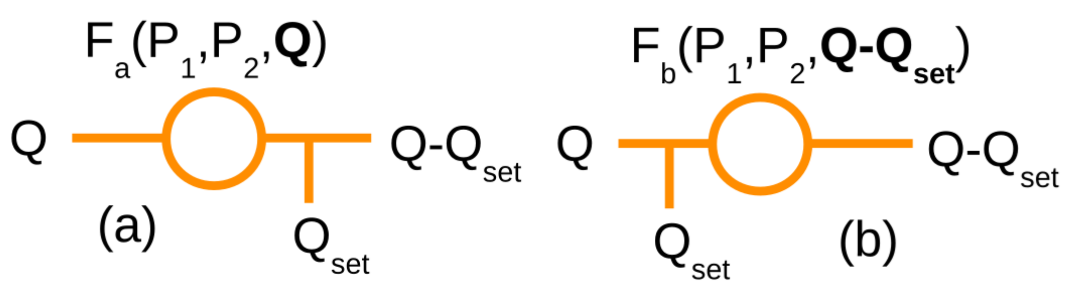
- generalization for other friction laws

$$F(P_1) - F(P_3) = G^s_{12}(Q), \qquad F(P_1) - F(P_2) = G^p_{12}(Q),$$
$$G^s_{12}(Q) = G_1(Q) + G_2(Q) \qquad G^p_{12} = (G_{1,inv} + G_{2,inv})_{inv}$$

where F,G are monotonic 1D-functions (represented by linear interpolation or splines, sampled by N points)

- Qset movement algorithm (level3)

$$F_b(P_1, P_2, Q) := F_a(P_1, P_2, Q + Q_{set}),$$
$$F_a(P_1, P_2, Q) = 0 \;\Rightarrow\; F_b(P_1, P_2, Q - Q_{set}) = 0$$



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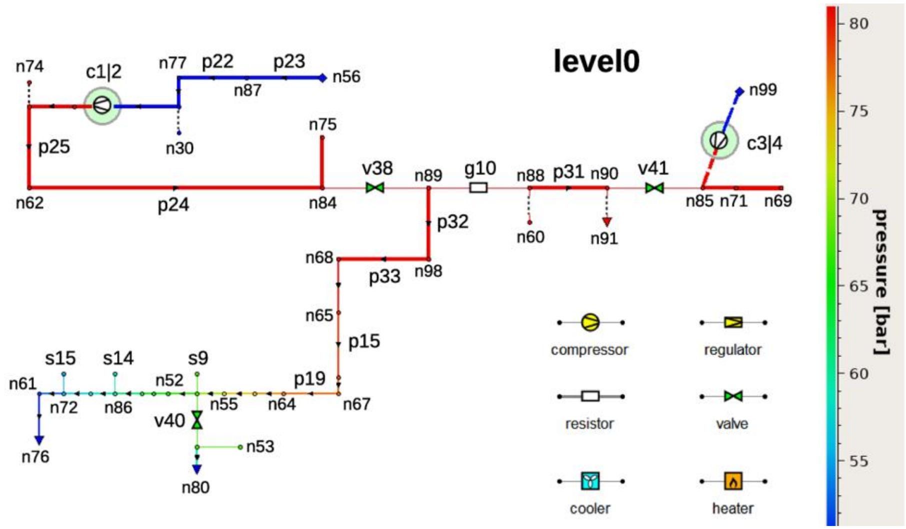
Basic Benchmark Set

network N1



network	compressors	regulators	Psets	nodes:edges:pipes
N1	4	0	2	100:111:34
N2	7	18	4	973:1047:500
N3	25	54	6	4721:5362:1749

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Basic Benchmark Set – Reduction Factors

- tested on realistic networks of different complexity
- reduction factors of 2.4 – 2.9 achieved (level1/level2)

Nodes:Edges:Pipes count for different reduction levels

network	level0	level1	level2	level3
N1	100:111:34	39:40:34	13:14:8	8:9:3
N2	973:1047:500	528:541:479	198:208:146	126:134:72
N3	4721:5362:1749	1723:1814:1666	705:755:607	296:332:184

implemented

(estimation)

level0 = original network

level1 = removing disconnected parts and superconductive elements

level2 = GSPG reduction with fixed Qsets

level3 = GSPG reduction with moving Qsets

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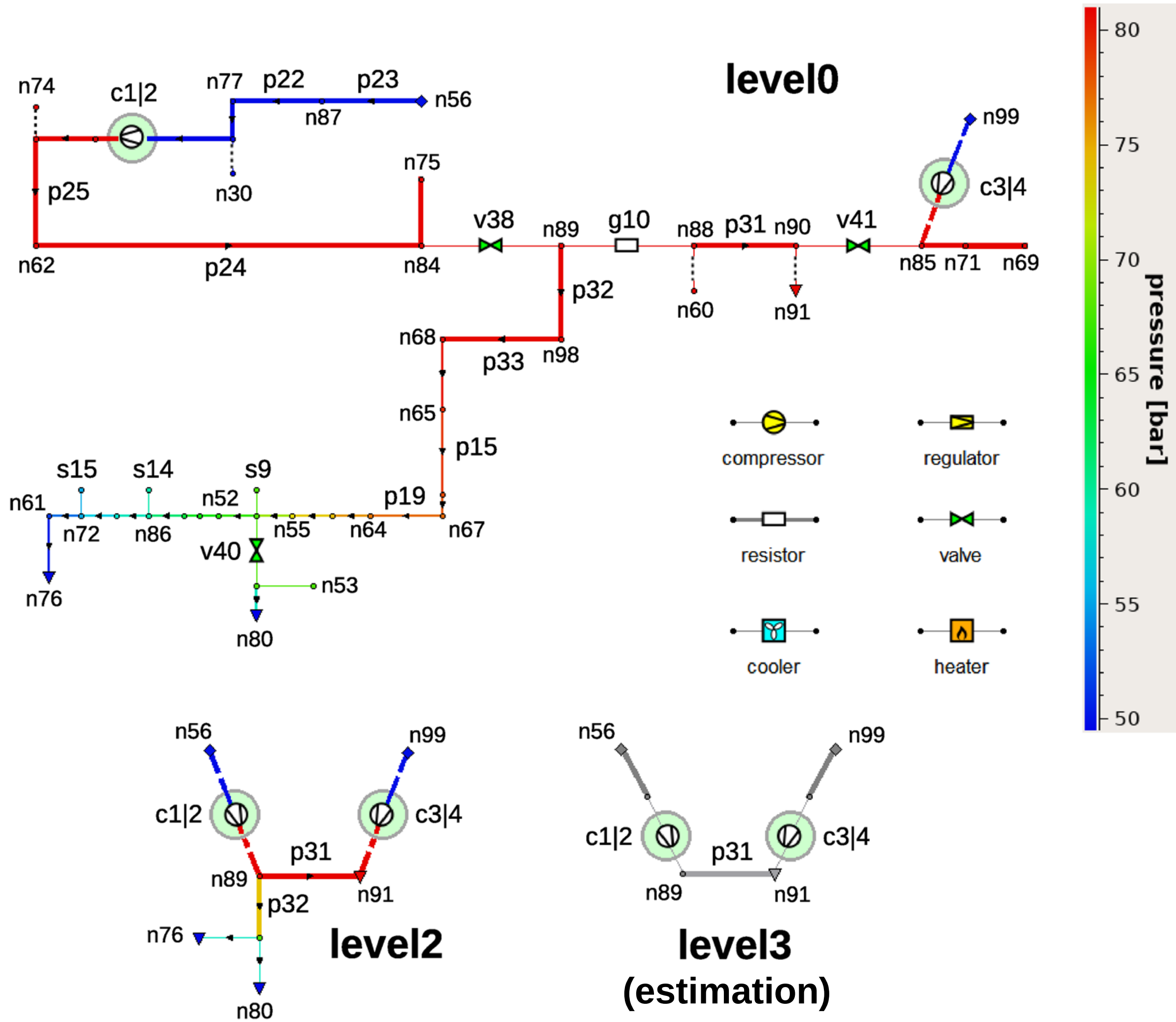
Basic Benchmark Set –
Topological Results for Network N1

level0 = original network

(level1 = removing disconnected parts and superconductive elements, not shown, looks similar to level0)

level2 = GSPG reduction with fixed Qsets

level3 = GSPG reduction with moving Qsets



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Basic Benchmark Set – Run Times and Speedup Factors

- tested on realistic networks of different complexity
- speedup factors of 2.2 – 2.6 achieved (level1/level2):

Run times (2.6GHz Intel i7 CPU)

network	level1		level2	
	filter	solve	filter	solve
N1	0.006	0.044	0.009	0.02
N2	0.063	0.5	0.09	0.196
N3	0.243	2.103	0.371	0.944

level0 = original network

level1 = removing disconnected parts and superconductive elements

level2 = GSPG reduction with fixed Qsets

level3 = GSPG reduction with moving Qsets

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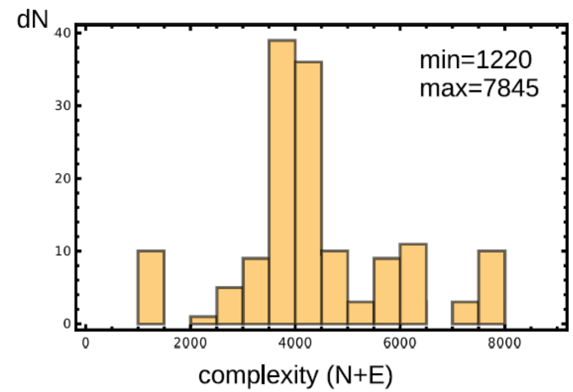
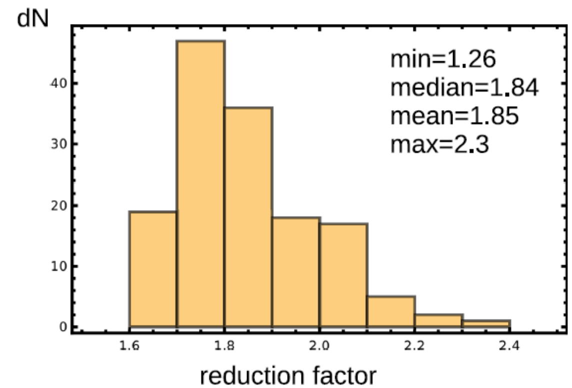
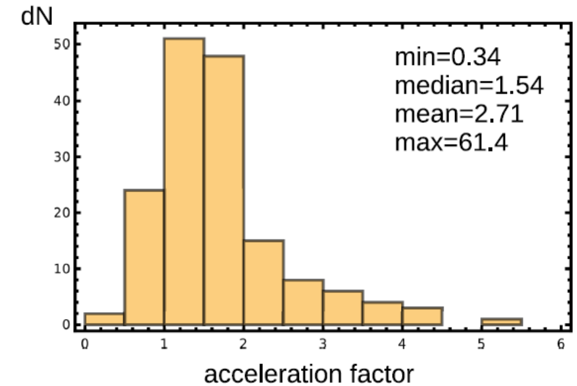
Exemplary Applications (1) – A Large Set of Realistic Examples

- Plots for 146 networks of different complexity:
  - Distribution of complexity (Nodes + Edges) at reduction level 1 (more appropriate for comparisons than level 0!)
  - Reduction factor between level 1 and 2. Shape of the histogram resembles Poisson distribution.
  - Acceleration factor: deceleration up to strong acceleration. Mean important here (ensemble runs!). Outliers related to randomness of the solver path towards solution. Number of compressors influences run times significantly!







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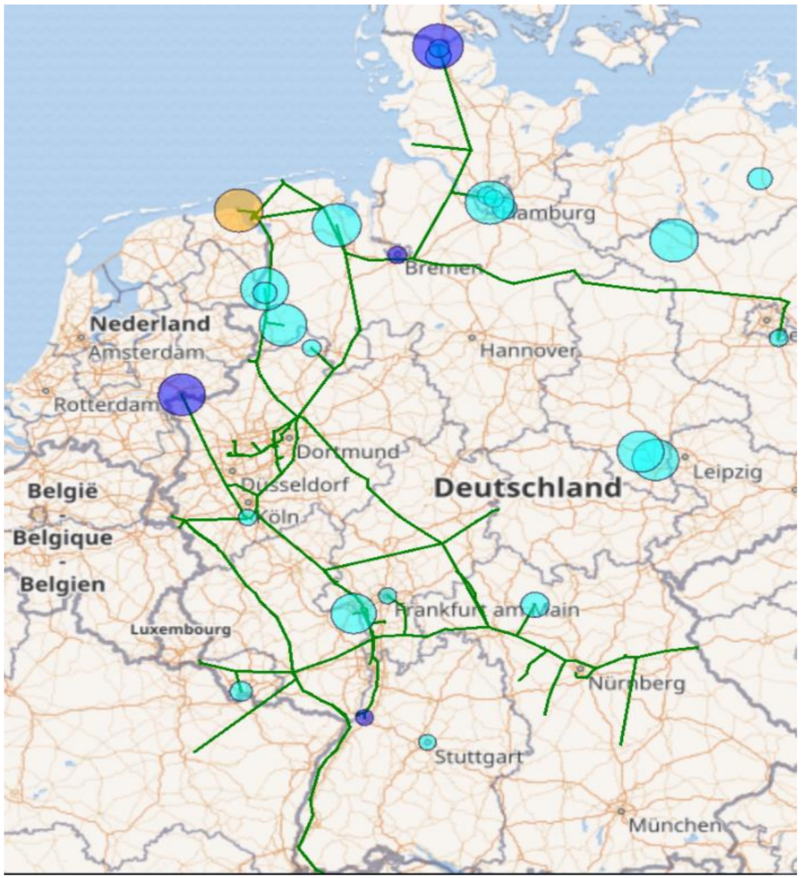
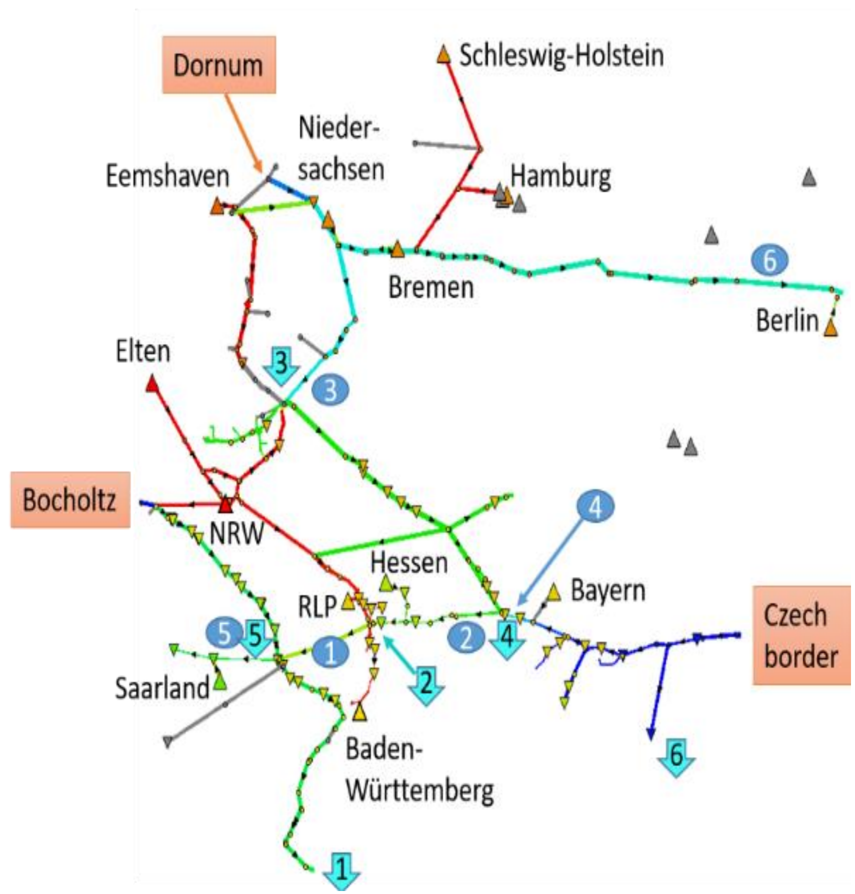
Exemplary Applications (2) – partDE-Hy Demonstrator

- partDE-Hy* v.2 on Open Street Map (left) and in MYNTS (right)





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**) See separate set of slides for more details!*

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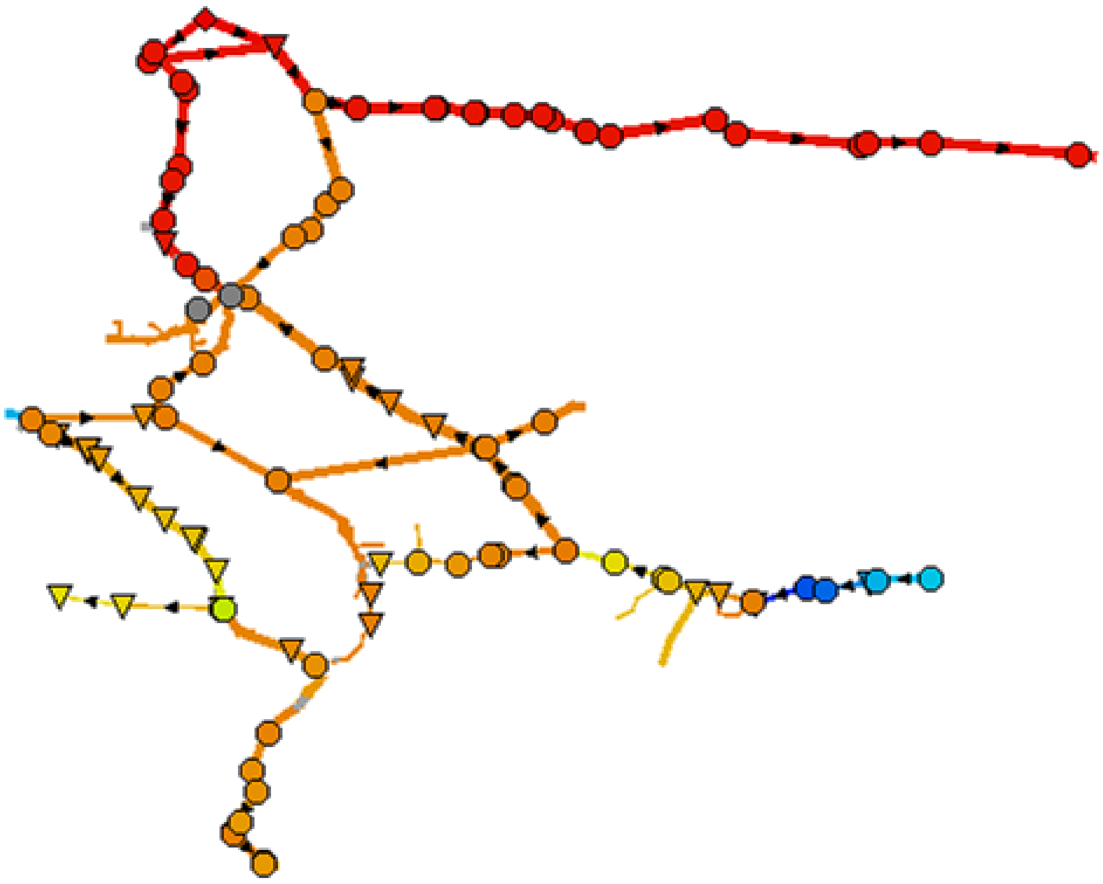
Exemplary Applications (2) – partDE-Hy (v.1)



Input:
437 nodes,
482 edges,
25 compressors

Timings [sec]
free2s 0.8
adv3s 1.5
mix-s 5.4

(timings for 2.6GHz Intel i7 CPU)

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Topological Reduction Filter for Pipes – Discussion

- Novel topological reduction method for gas transport networks developed
- The method uses a contraction of series, parallel and tree-like subgraphs, containing the pipes, described by quadratic friction law.
- Several realistic networks of different complexity have been used for benchmarking of the method.
- Compared with original network, elimination of superconductive elements and disconnected parts (level1) often results in reduction factor of around 2, further GSPG reduction with fixed Qsets (level2) multiplies this by ca. 2, then GSPG reduction with moving Qsets (level3) gives an estimated multiplicative factor of around 2.
- Measured speedup factor (level1 → level2) often around 1.5-3.0.
- Method can be extended to other friction laws and elements.

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