Topics in Gas Network Optimization

Energy Networks Group

Zuse Institute Berlin

- Transmit natural gas to industry and municipal utilities
- Passive elements:
  - Pipelines
  - Resistors
- Active elements:
  - Valves
  - Control valves
  - Compressors

Open Grid Europe, Germany

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▷ Nomination specifying amounts of gas flow at entries and exits

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Validating Nominations

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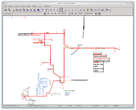

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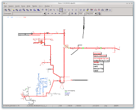

simulation tool

We use mathematical optimization to integrate both steps!

Simulation

- allows very accurate gas physics models
- relies on human experience for control for active devices
- is thus inappropriate to determine infeasibility of a nomination

Using Optimization Rather Than Simulation

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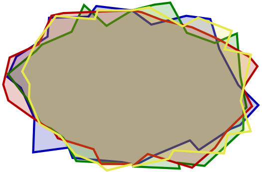
Beware: Different solution spaces due to different modeling

Simulation A

Simulation B



Optimization A

Optimization B

Gas network is modeled as graph $\mathcal{G} = (\mathcal{V}, \mathcal{A})$

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- Flow conservation constraints at nodes
- Model for all kinds of arcs
  - Pipes
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  - Shortcut
  - Valves
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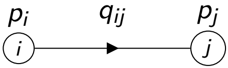
Mixed-Integer Nonlinear Program

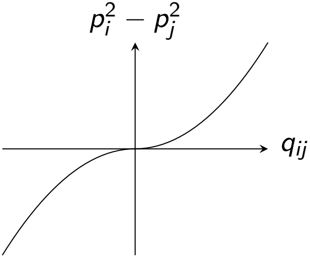
Weymouth equation

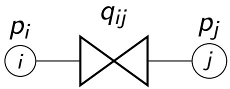
$$\alpha_{ij} \cdot q_{ij} \cdot |q_{ij}| = p_i^2 - \beta_{ij} p_j^2$$



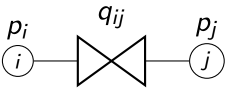
with constants

- α_{ij} diameter, length, temperature
- β_{ij} height difference of vertices





p_i
q_{ij}
p_j
i
j

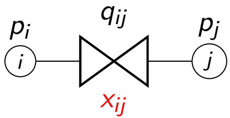


Two states:

Closed

Open

One decision variable: $x_{ij} \in \{0, 1\}$



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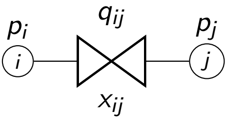

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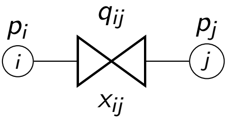

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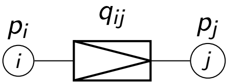
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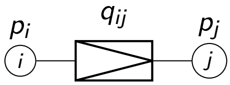

Three states:

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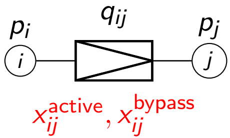
Bypass

Active

Two variables: $x_{ij}^{\text{bypass}} + x_{ij}^{\text{active}} \leq 1$



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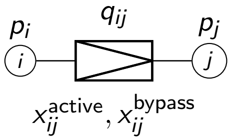

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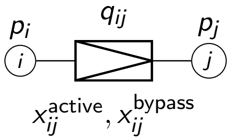

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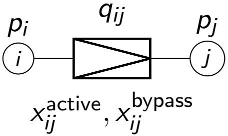

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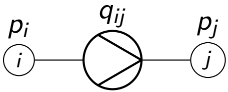
$$

Compressor Station:



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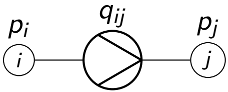

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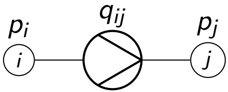

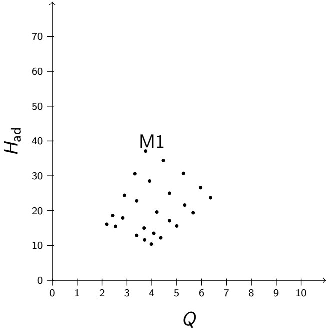

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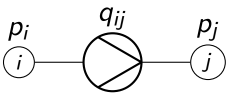

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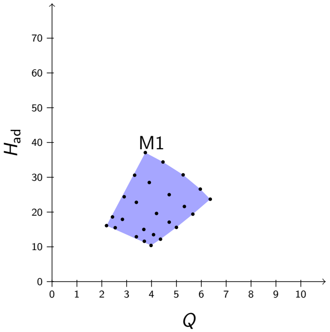

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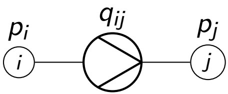

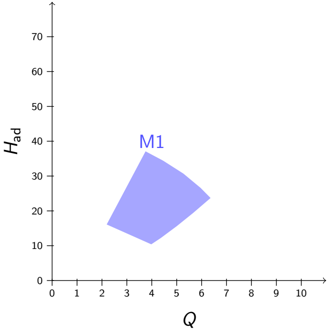

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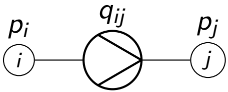

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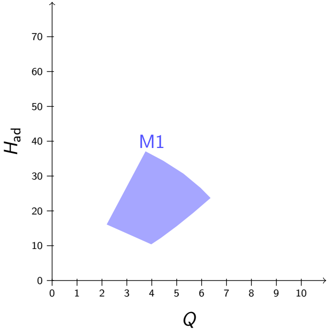

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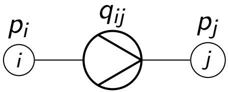

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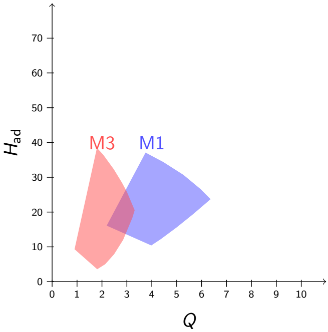

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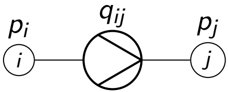

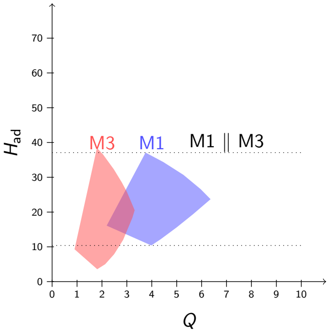

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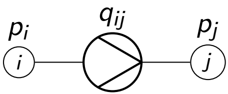

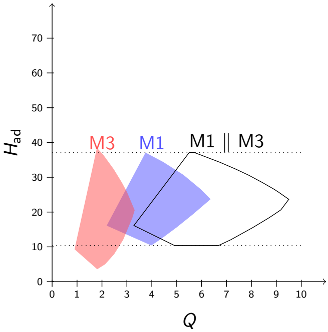

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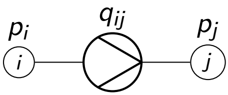

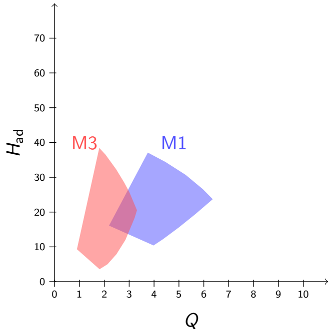

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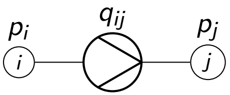

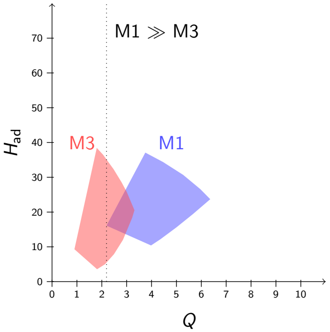

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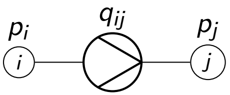

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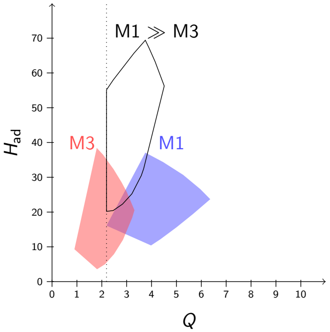

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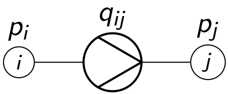

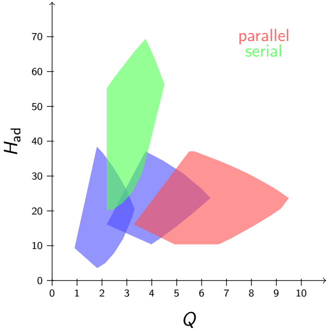

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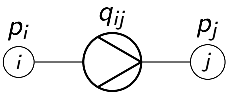

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Modeling approaches:

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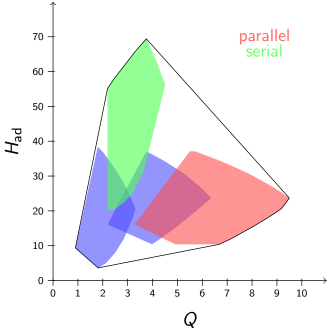

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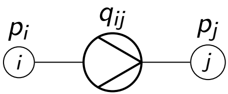

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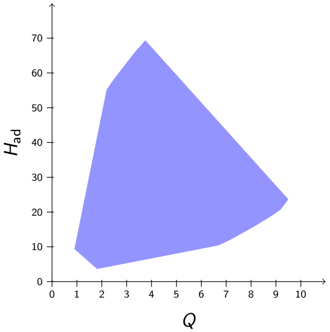

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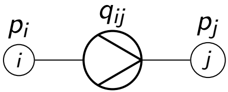
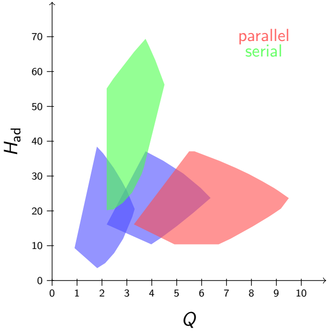
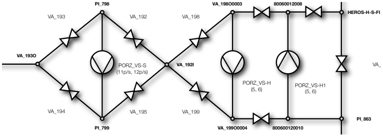




Modeling approaches:

- ▷ Convex hull of all configurations
- ▷ Binary variables per configuration

- Complex subnetworks can be operated only in specific modes, e.g. compressor plants



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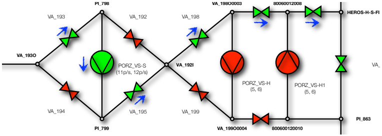

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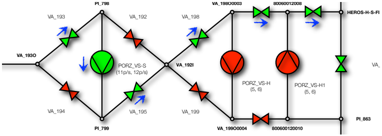

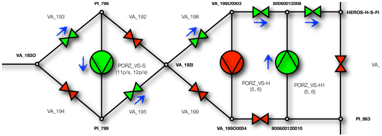

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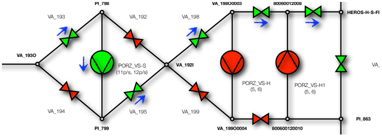

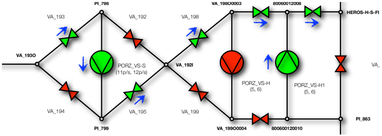

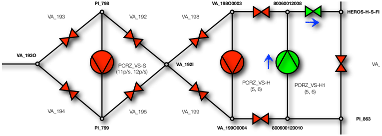

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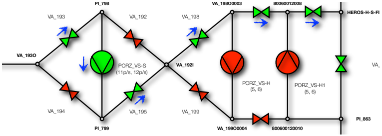
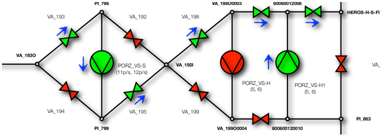
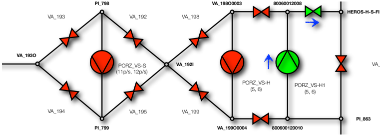
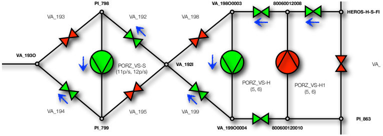
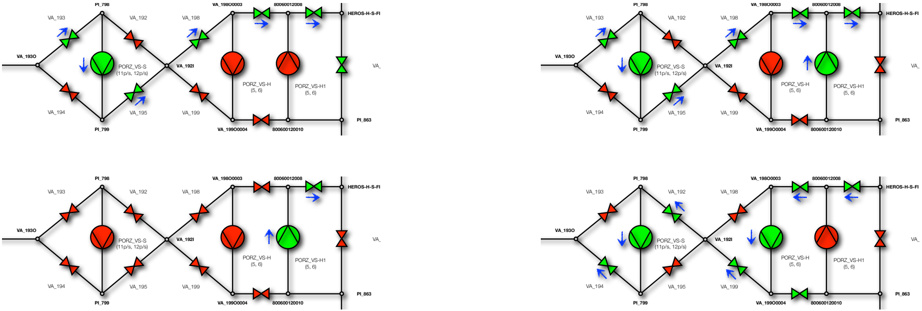






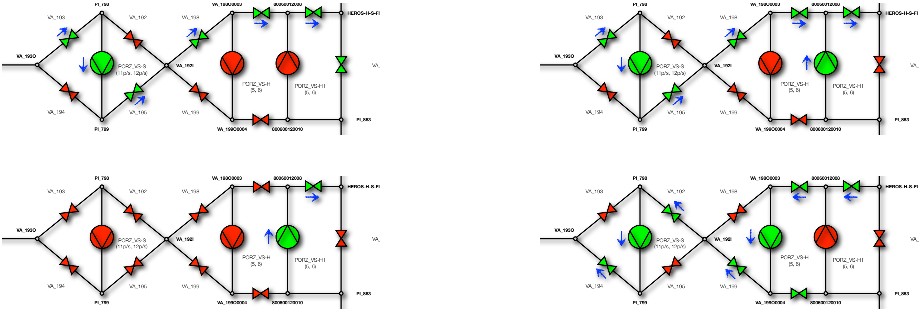


- Complex subnetworks can be operated only in specific modes, e.g. compressor plants



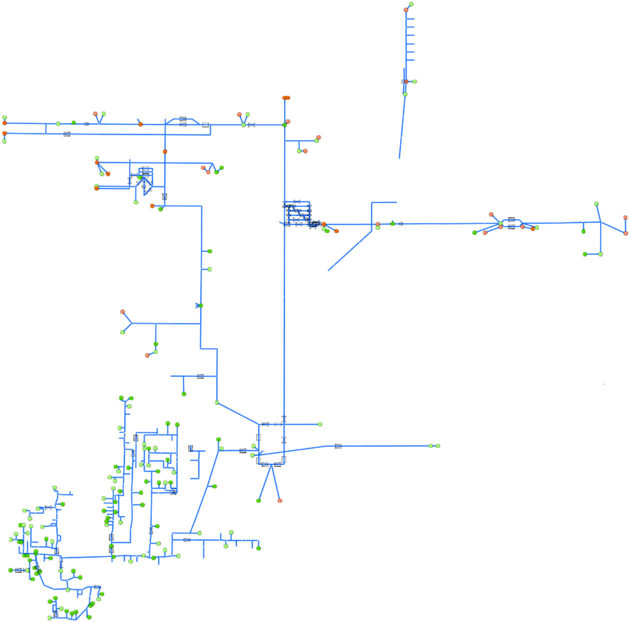
- Choose one of the modes with a binary variable

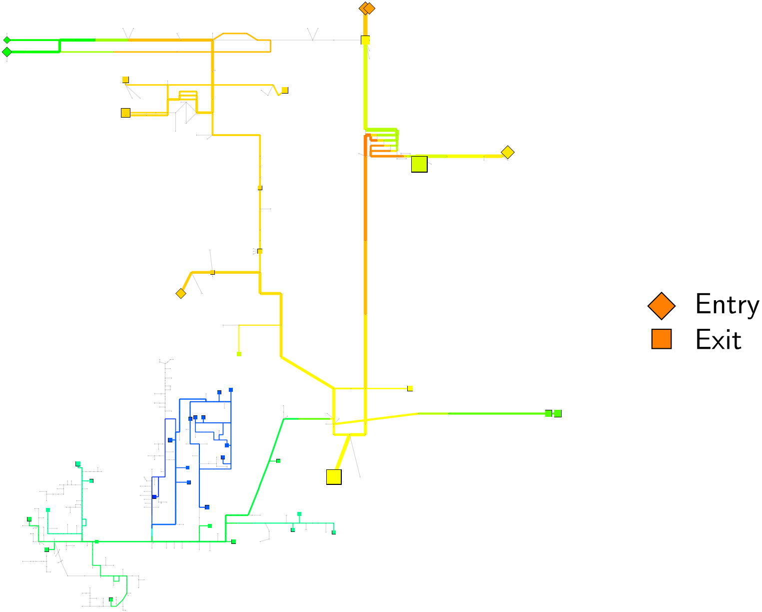
- ▷ Complex subnetworks can be operated only in specific modes, e.g. compressor plants



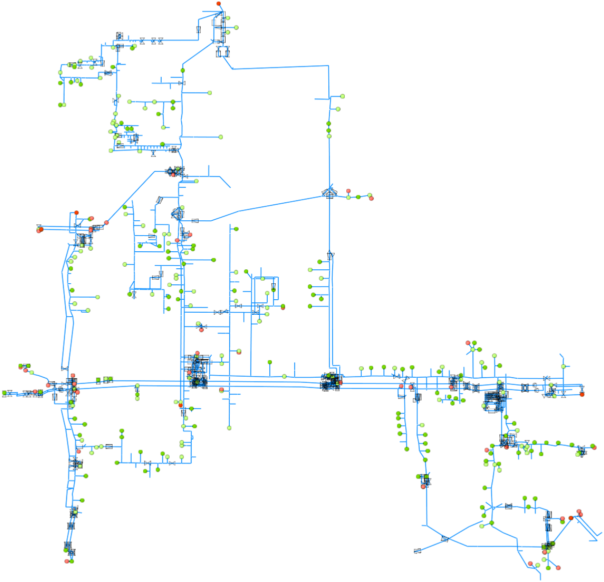
- ▷ Choose one of the modes with a binary variable
- ▷ Couple this variable with the elements' variables via inequalities

- ▷ 661 nodes
  - ▶ 32 entries
  - ▶ 142 exits
- ▷ 498 pipes
  9 resistors
  33 valves
  26 control valves
  7 compressor stations
- ▷ 32 cycles

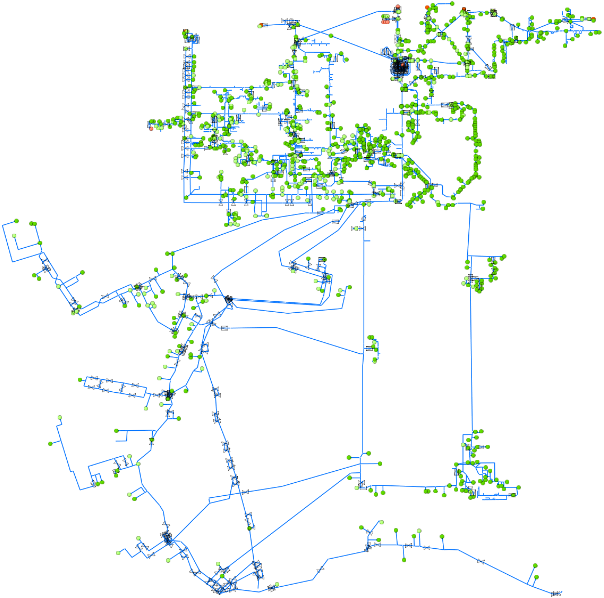



Entry
Exit

- 1662 nodes
  - 47 entries
  - 265 exits
- 1136 pipes
  45 resistors
  224 valves
  78 control valves
  29 compressor stations
- 175 cycles



- 4133 nodes
  - 12 entries
  - 1001 exits
- 3623 pipes
  26 resistors
  300 valves
  118 control valves
  12 compressor stations
- 259 cycles



The issue: tracking of calorific values

- Nomination given in power, not (mass) flow
- Calorific values only known at entry nodes
- Bilinear equations for mixing of calorific values

[1] B. Geißler et al.: "Solving Power-Constrained Gas Transportation Problems using an MIP-based Alternating Direction Method", 2014, Optimization Online

The issue: tracking of calorific values

- Nomination given in power, not (mass) flow
- Calorific values only known at entry nodes
- Bilinear equations for mixing of calorific values

The solution: Iterative approach[1]

- Guess (average) calorific values
- With fixed calorific values: compute target flow values
- Compute solution, minimizing a penalty term for exit demands
- With fixed flows: compute actual calorific values
- Update target flows and penalty weights in objective

[1] B. Geißler et al.: "Solving Power-Constrained Gas Transportation Problems using an MIP-based Alternating Direction Method", 2014, Optimization Online

The issue: Modeling a Stackelberg game

- TSO can use non-technical measures to change nomination (leaders)
- Shippers react to these measures with given preference (followers)

In Practice: Flow Commitments

The issue: Modeling a Stackelberg game

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The solution: Bilevel Optimization

- Model game as Bilevel Optimization Problem
- Leader part is MIP
- Follower part is LP
- Equivalent reformulation as MIP (with complementarity) via KKT optimality conditions

In Practice: Flow Commitments

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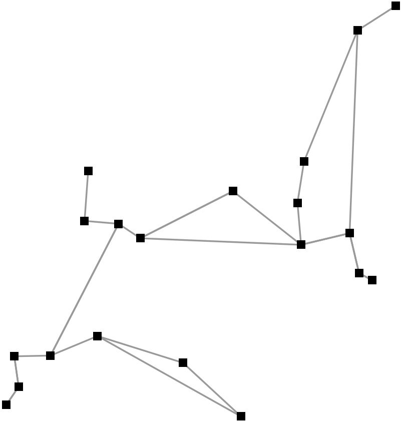
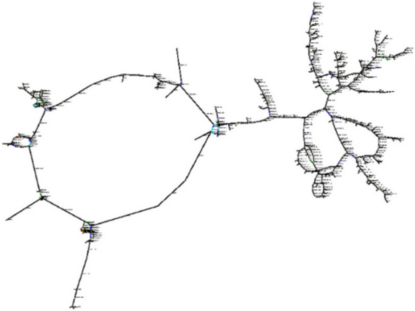
$\rightarrow$ More details later in talk about PPPP!



- almost tree topology
- 20 vertices
- 29 pipes

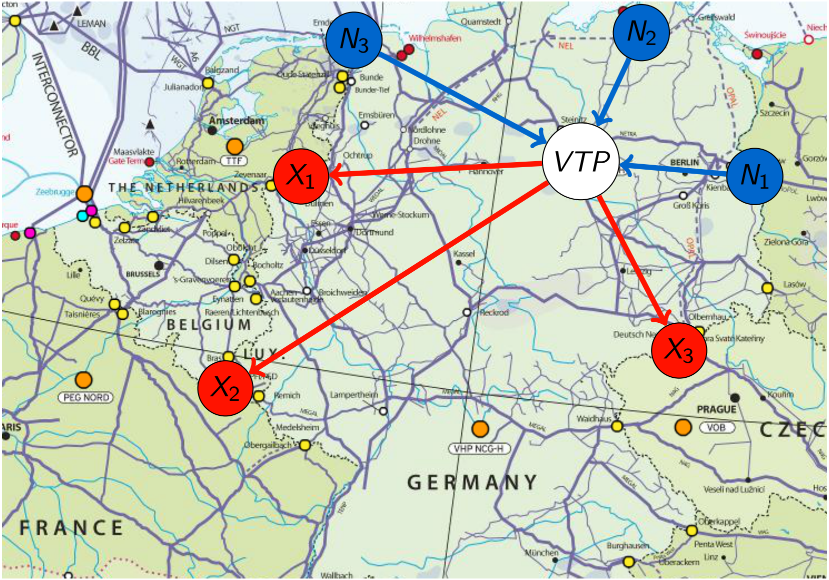
- realistic benchmark instances
- detailed description of gas network
  - 582 nodes
  - 278 pipes, 8 resistors
  - 54 active elements
- thousands of nominations



gaslib.zib.de

- Nomination Validation
- Booking Validation
- PPPP
- Navi


THE NETHERLANDS
BELGIUM
LUX.
FRANCE
GERMANY
TTF
PEG NORD
VHP-GASPOOL-H
VHP NCG-H
VOB
Amsterdam
BRUSSELS
BERLIN
PRAGUE
Rotterdam
Zeebrugge
INTERCONNECTOR
BBL
LEMAN
NGT
NEL
OPAL
Emden
Wilhelmshafen
Bunde
Ochtrup
Zevenaar
Dortmund
Düsseldorf
Essen
Aachen
Hannover
Kassel
Steinitz
Mallnow
Leipzig
Deutsch Neudorf
Waidhaus
Medelsheim
Remich
Lampertheim
München
Burghausen
Oberkappel
Penta West
Linz
Szczecin
Quarnstedt
Greifswald
Julianadorp
Balgzand
Emsbüren
Dülmen
Dilsen
Bocholtz
Eynatten
Raeren/Lichtenbusch
Blaregnies
Quévy
Taisnières
Lille
Zelzate
Poppel
Obbicht
Hilvarenbeek
Bras
Petange
Obergailbach
Reckrod
Kienbaum
Groß Köris
Olbernhau
Lasów
Zielona Góra
Koufim
Veselí nad Lužnicí
Maasvlakte
Gate Terminal
Bunder-Tief
Nordlohne
Drohne
Werne-Stockum
Broichweiden
Winterswijk
Świnoujście
Wallbach
Überackern


N_3
N_2
N_1
VTP
X_1
X_2
X_3
THE NETHERLANDS
BELGIUM
FRANCE
GERMANY
Amsterdam
BERLIN
PRAGUE
BRUSSELS
TTF
PEG NORD
VHP NCG-H
VOB
INTERCONNECTOR
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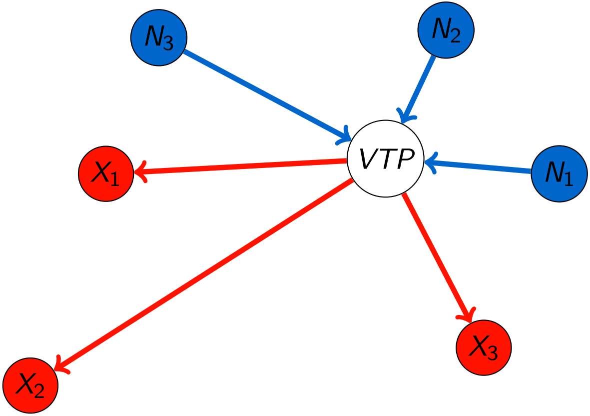
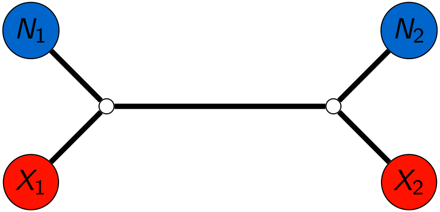
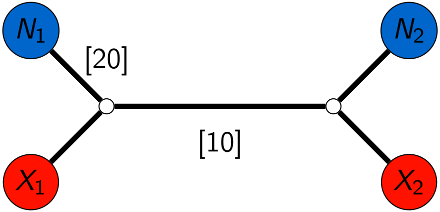
Aachen
München

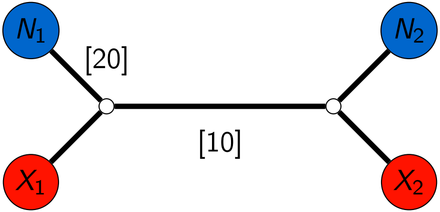


capacity: transport gas from node to VTP,
booked independently for entries and exits


N_1
N_2
X_1
X_2

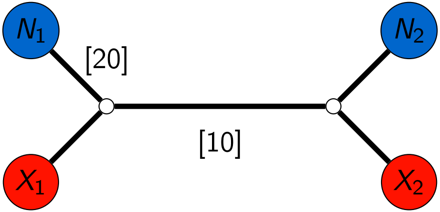


Long pipeline with small capacity



Long pipeline with small capacity

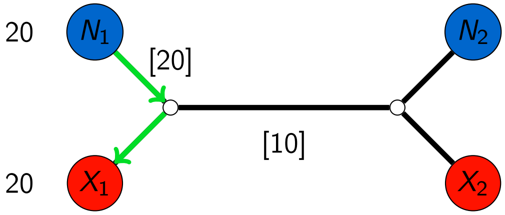
What is the “capacity” of the whole network?

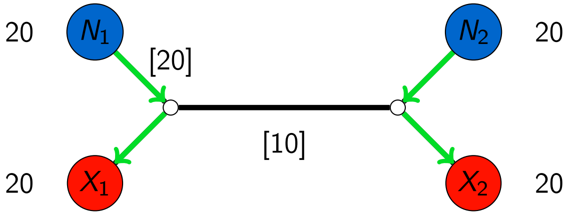


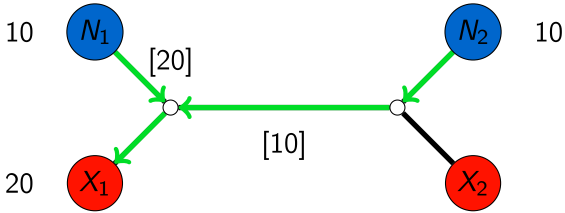
Long pipeline with small capacity

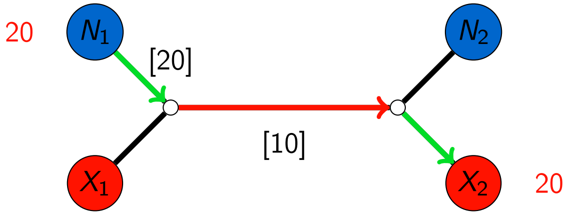
What is the “capacity” of the whole network?

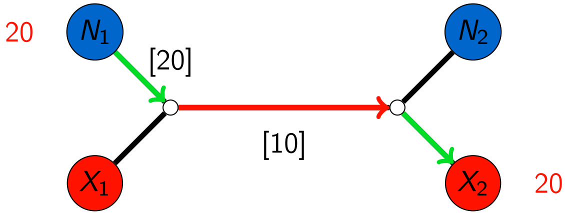
How much capacity can be booked at the nodes?


20
N_1
[20]
N_2
[10]
20
X_1
X_2

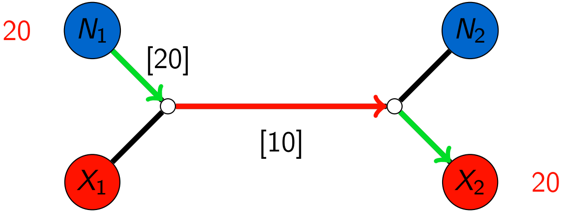

20
N_1
[20]
N_2
20
[10]
20
X_1
X_2
20


10
N_1
[20]
N_2
10
[10]
20
X_1
X_2


20
N_1
[20]
N_2
[10]
X_1
X_2
20

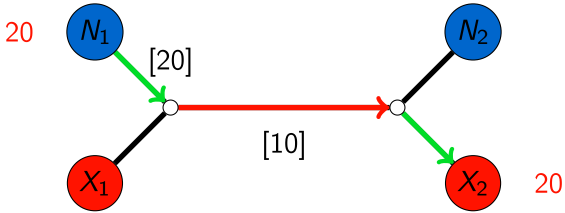


At most 10 units of capacity may be booked at every node!



At most 10 units of capacity may be booked at every node!

But up to 20 units could be transported.



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$\Rightarrow$ Distinguish firm and interruptible capacity!

- TSOs must market as much capacity as (technically) possible

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- Denied requests for more capacity by shippers must be explained

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- Denied requests for more capacity by shippers must be explained
- Need (proven) infeasibility of worst-case scenarios
- Solve Nomination Validation with global solver

Booking contracts for firm capacity at entry/exit (interval $[l, u]$)
- ▷ additional constraints (bounds on group of entries)

Nomination use of capacity (value $v \in [l, u]$)
- ▷ balanced (stationary model)

Example with two entries N_1, N_2 and exit X

▷ Booking		▷ Nomination 1		▷ Nomination 2	
N_1	$[0, 5]$	N_1	3	N_1	0
N_2	$[0, 4]$	N_2	2	N_2	4
X	$[0, 5]$	X	5	X	4

Given

- complete description of network
  - pipes
  - (control) valves
  - compressor stations
- capacity contracts
  - entry/exit nodes or zones
  - valid for specific dates, temperatures
  - pairwise exclusion
- historical measurements
  - hourly demand at exits
  - temperature

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Result

- for several
  - contract dates
  - reference temperatures
- compute
  - feasibility probability
  - (infeasible) nominations

Ideally

- ▷ check feasibility for every realizable nomination

Ideally

- check feasibility for every realizable nomination

Actually

- generate many probable nominations
  - estimate distributions for exit demands
  - sample scenarios from distributions
  - apply scenario reduction
  - worst-case entry completions for each scenario

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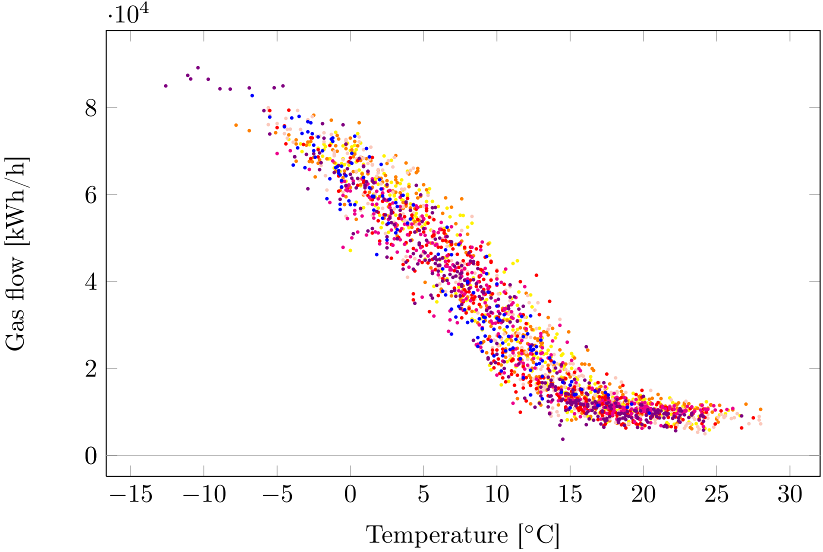
  - compute in parallel

Ideally

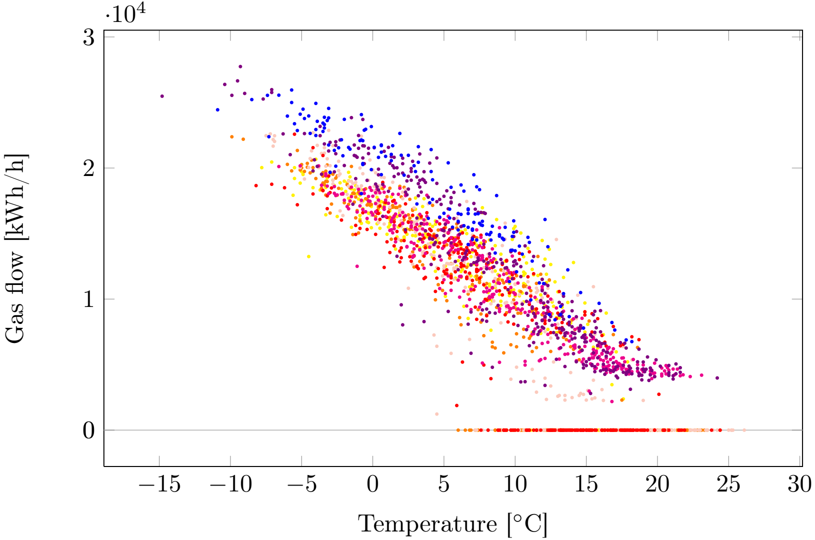
- check feasibility for every realizable nomination

Actually

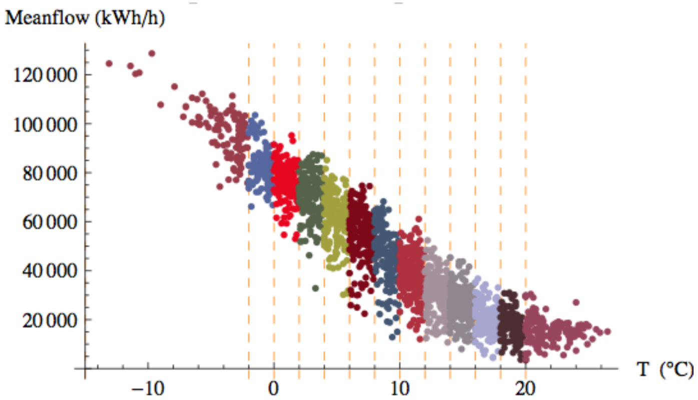
- generate many probable nominations
  - estimate distributions for exit demands
  - sample scenarios from distributions
  - apply scenario reduction
  - worst-case entry completions for each scenario
- check feasibility for each
  - solve Nomination Validation
  - compute in parallel
- aggregate results to estimate feasibility probability



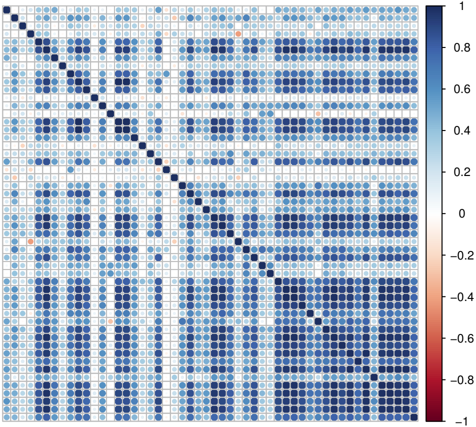
$\cdot 10^4$
8
6
4
2
0
−15
−10
−5
0
5
10
15
20
25
30
Gas flow [kWh/h]
Temperature [°C]

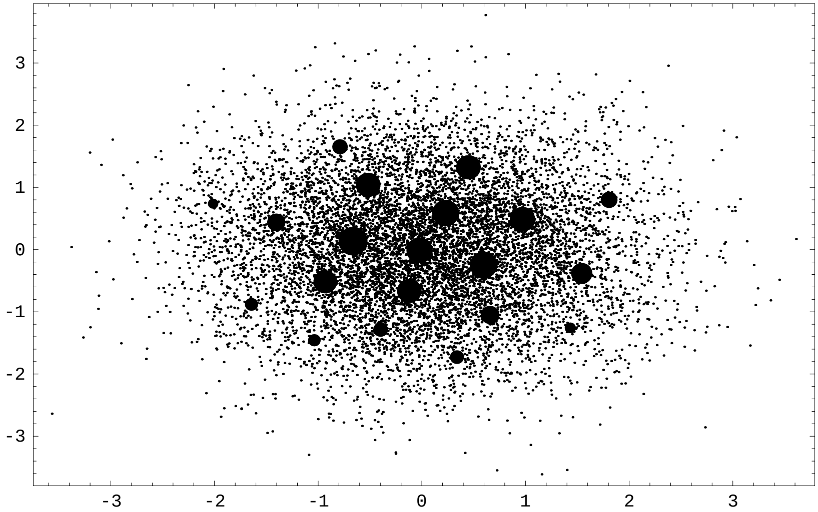

$\cdot 10^4$
3
2
1
0
−15
−10
−5
0
5
10
15
20
25
30
Gas flow [kWh/h]
Temperature [°C]

- separate distribution estimations for
  - temperature classes
  - workday and weekend



- Multivariate Distribution Estimation




3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2
3

$P_n \geq 0$ power at node n

$x_c \in \{0, 1\}$ use of contract c

$P_n^c \geq 0$ power at node n from contract c

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$x_c \in \{0, 1\}$ use of contract c

$P_n^c \geq 0$ power at node n from contract c

$$\sum_{n \in N} P_n = \sum_{n \in X} P_n$$ nomination is balanced

$P_n \geq 0$	power at node n
$x_c \in \{0, 1\}$	use of contract c
$P_n^c \geq 0$	power at node n from contract c
$\sum_{n \in N} P_n = \sum_{n \in X} P_n$	nomination is balanced
$P_n = \sum_{c \ni n} P_n^c$	different contracts contribute at one node

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$x_c \in \{0, 1\}$	use of contract c
$P_n^c \geq 0$	power at node n from contract c

$\sum_{n \in N} P_n = \sum_{n \in X} P_n$	nomination is balanced
$P_n = \sum_{c \ni n} P_n^c$	different contracts contribute at one node
$L_c x_c \leq \sum_{n \in c} P_n^c \leq U_c x_c$	only active when used

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$x_c \in \{0, 1\}$ use of contract c

$P_n^c \geq 0$ power at node n from contract c

$$\sum_{n \in N} P_n = \sum_{n \in X} P_n$$ nomination is balanced

$$P_n = \sum_{c \ni n} P_n^c$$ different contracts contribute at one node

$$L_c x_c \leq \sum_{n \in c} P_n^c \leq U_c x_c$$ only active when used

$$x_{c_1} + x_{c_2} \leq 1$$ pairwise exclusion of contracts

Substitutable capacity

- some contracts $c \in C_s$ are classified substitutable
- predicted behavior according to historical data

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Nonsubstitutable capacity

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- adversial behavior assumed

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Nonsubstitutable capacity

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- adversial behavior assumed

$$P_n = \sum_{c \in C_s} P_n^c + \sum_{c \in C_{ns}} P_n^c$$

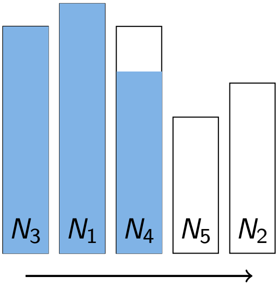
distinguish between contracts

$$S_n = \sum_{c \in C_s} P_n^c$$

substitute value from statistical scenario

- entry supply hard to predict (nonsubstitutable)
- assume extreme behavior

- ▷ entry supply hard to predict (nonsubstitutable)
- ▷ assume extreme behavior
- ▷ entries are filled up in order of (random) preference



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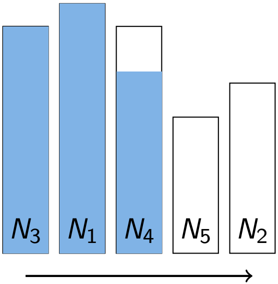
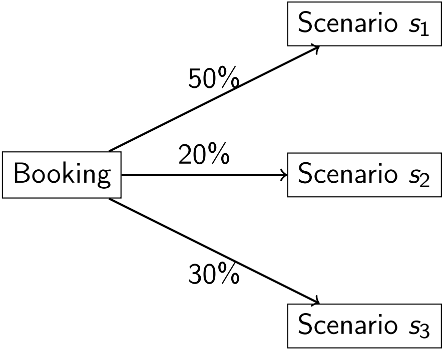
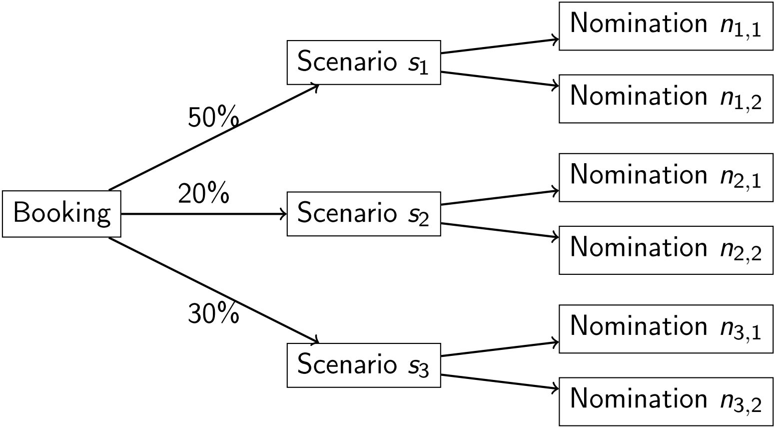


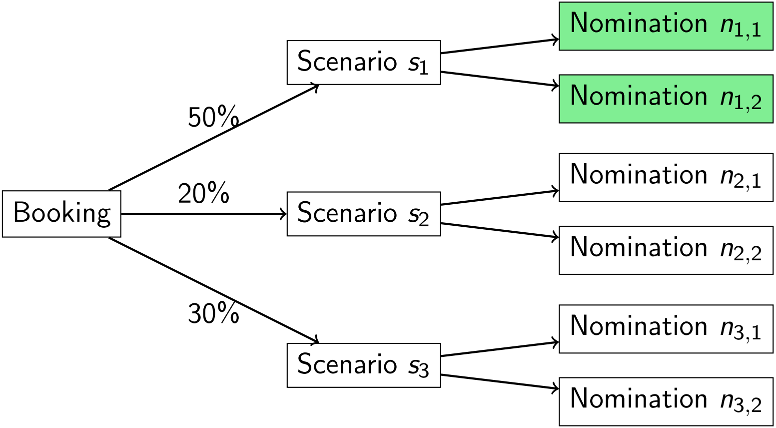
- encode entry order in objective function

$$\max \quad 5P_{N_3} + 4P_{N_1} + 3P_{N_3} + 2P_{N_5} + P_{N_2}$$

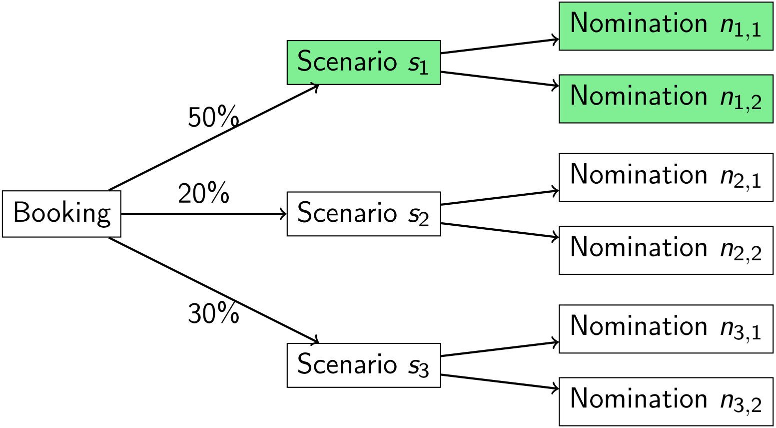
$\boxed{\text{Booking}}$


Booking
50%
20%
30%
Scenario s_1
Scenario s_2
Scenario s_3

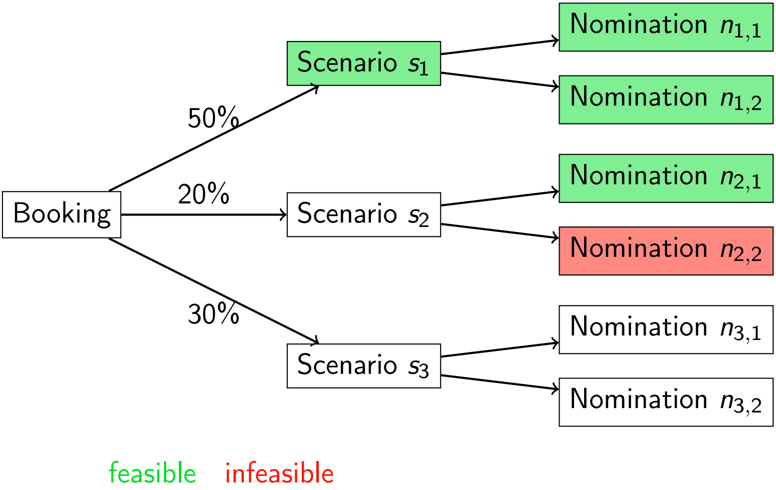

Booking
50%
20%
30%
Scenario s_1
Scenario s_2
Scenario s_3
Nomination $n_{1,1}$
Nomination $n_{1,2}$
Nomination $n_{2,1}$
Nomination $n_{2,2}$
Nomination $n_{3,1}$
Nomination $n_{3,2}$


Booking
50%
20%
30%
Scenario s_1
Scenario s_2
Scenario s_3
Nomination $n_{1,1}$
Nomination $n_{1,2}$
Nomination $n_{2,1}$
Nomination $n_{2,2}$
Nomination $n_{3,1}$
Nomination $n_{3,2}$

feasible


Booking
50%
20%
30%
Scenario s_1
Scenario s_2
Scenario s_3
Nomination $n_{1,1}$
Nomination $n_{1,2}$
Nomination $n_{2,1}$
Nomination $n_{2,2}$
Nomination $n_{3,1}$
Nomination $n_{3,2}$

feasible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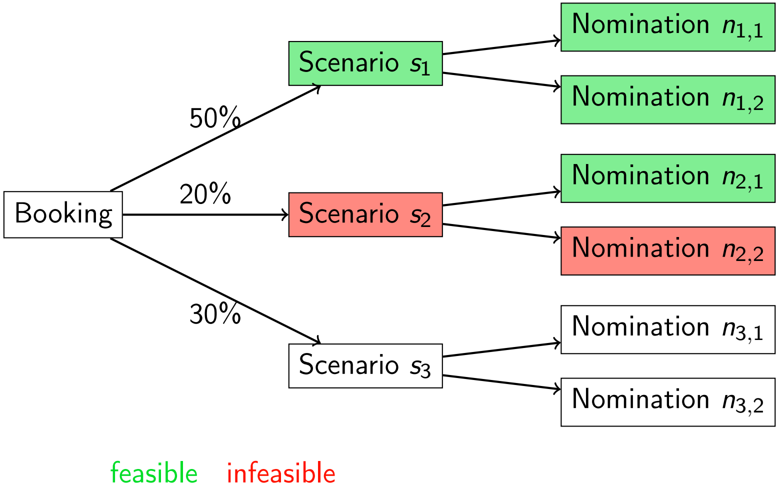
feasible
infeasible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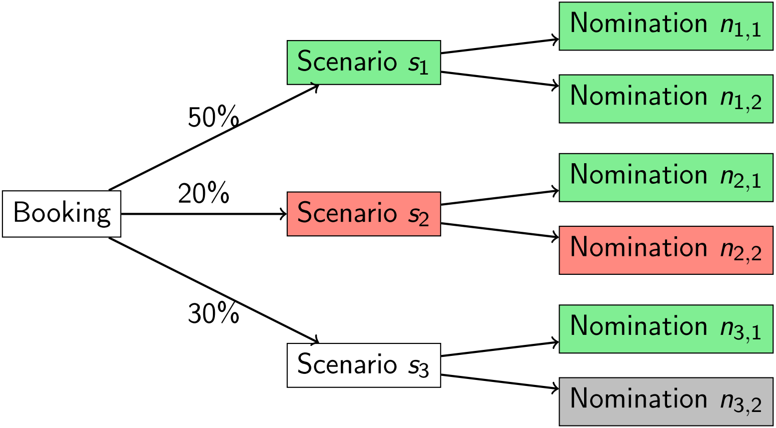
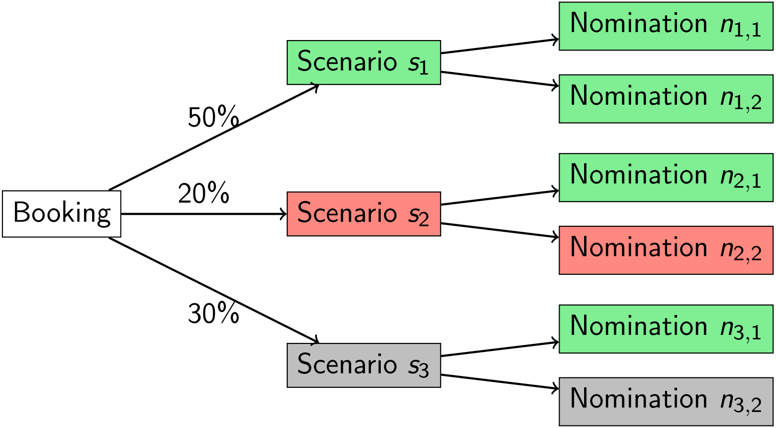
feasible
infeasible



feasible infeasible unknown



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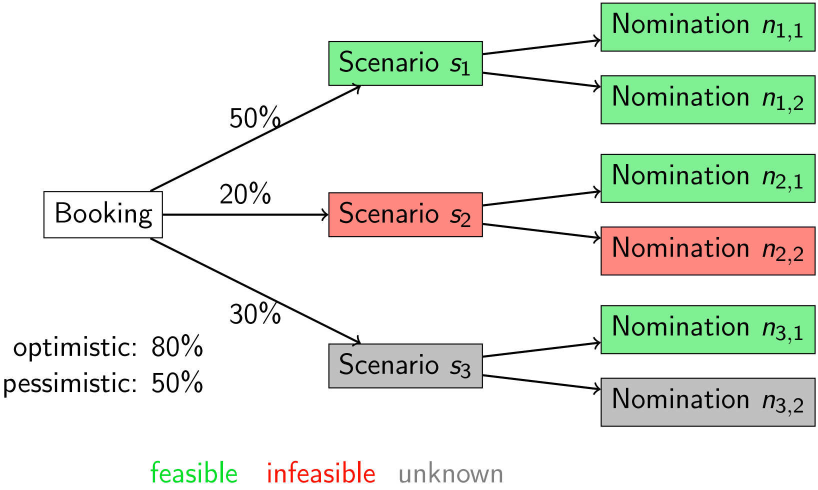
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Scenario s_1
Scenario s_2
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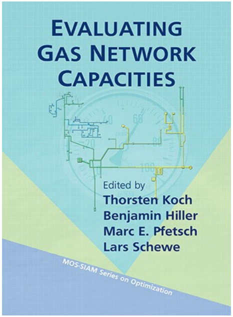
Nomination $n_{1,2}$
Nomination $n_{2,1}$
Nomination $n_{2,2}$
Nomination $n_{3,1}$
Nomination $n_{3,2}$
optimistic: 80%
pessimistic: 50%
feasible
infeasible
unknown

Evaluating Gas Network Capacities

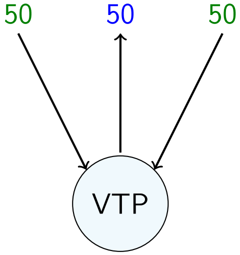
MOS-SIAM Series on Optimization, 2015

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



ForNe team


VTP



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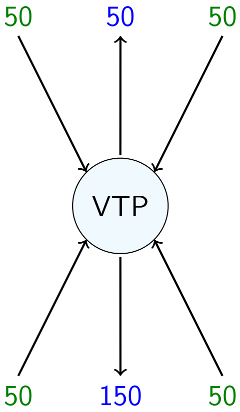

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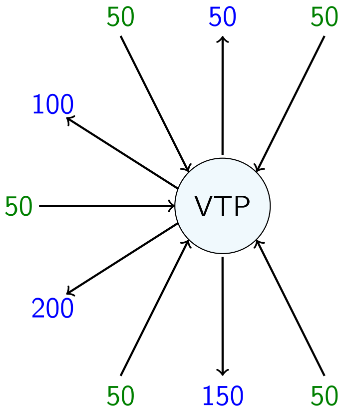

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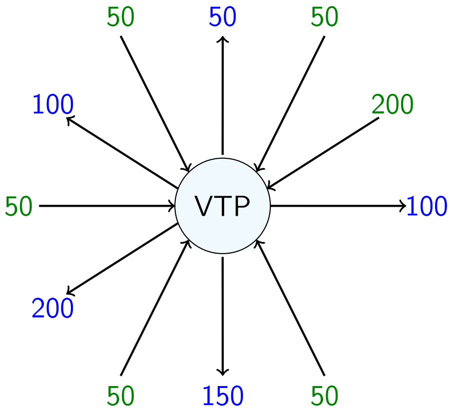

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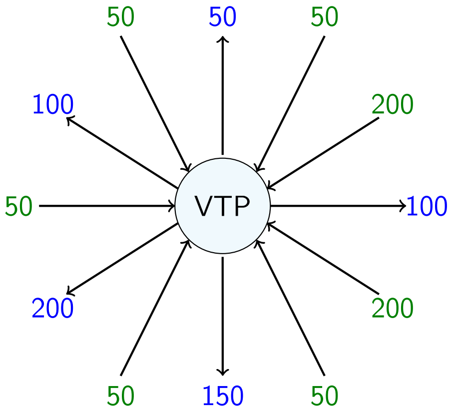

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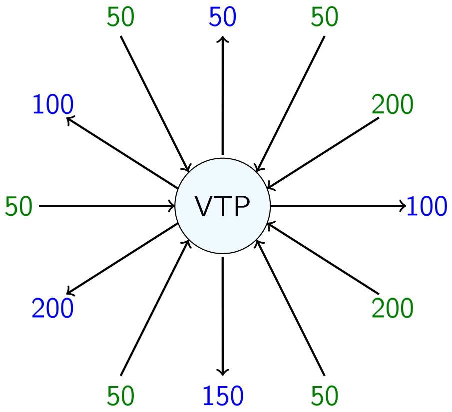

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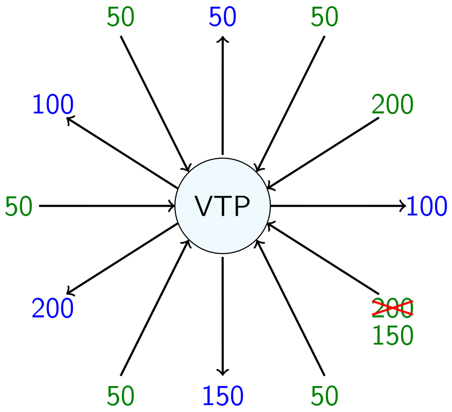

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Basic Non-Technical Network Control Measures of the TSO

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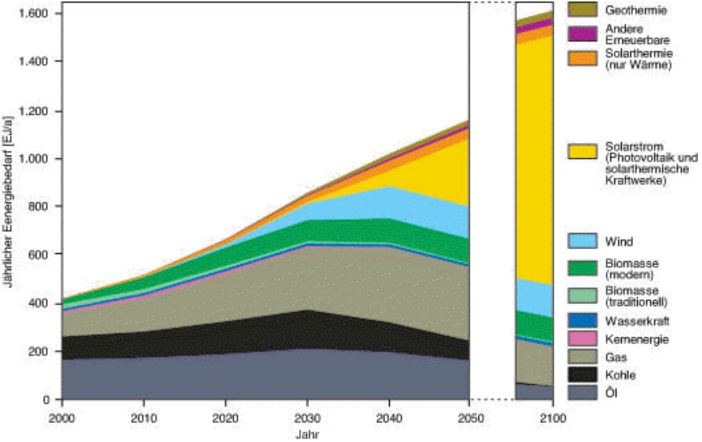
Final demand vector of gas flow is the result of a process of adjustments by the TSO and possible reactions of shippers in terms of renominations.



Source: German Advisory Counsil on Global Change (WBGU).

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- Deployment of new pipes to increase capacity
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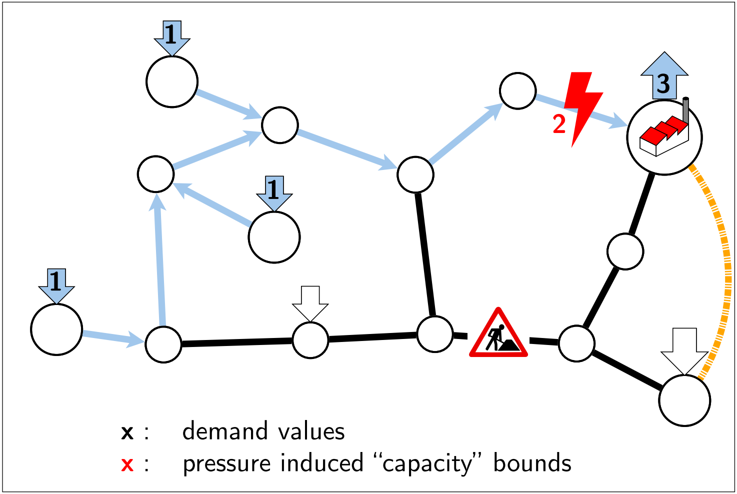
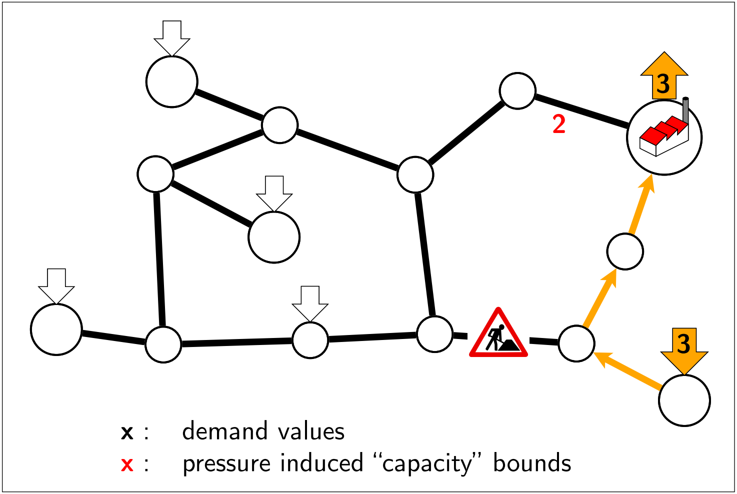
The "smart" way: Extension by Non-Technical Measures

- Design new capacity types and contracts
- Giving the TSO more flexibility and possibilities to act
- Allowing a better distribution of the gas in- and outflow
- Avoiding extreme situations


1
1
1
3
2
x : demand values
x : pressure induced "capacity" bounds


3
2
3
x : demand values
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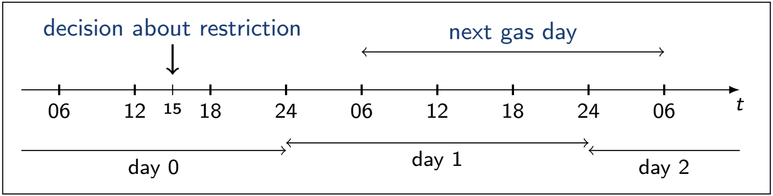
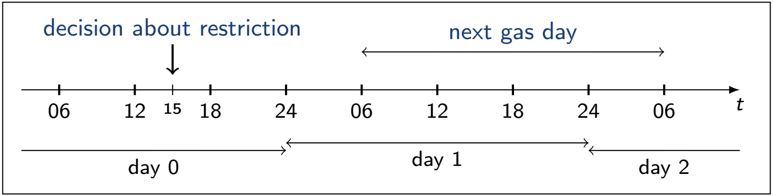


Decide about the restrictions to fallback entries

▷ for all power stations with a fDZK contract,



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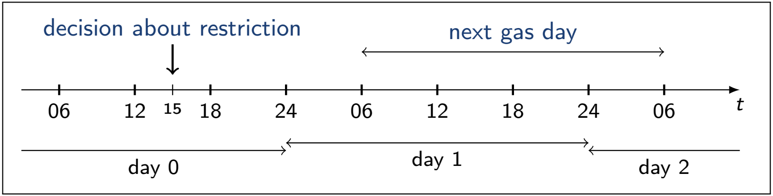

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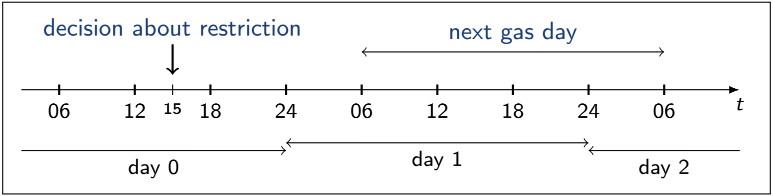
- ▷ in a nondiscriminatory manner,
- ▷ while enabling safe network operation,



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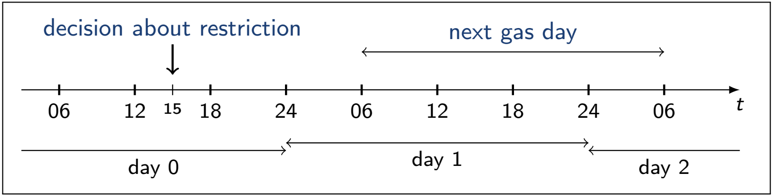

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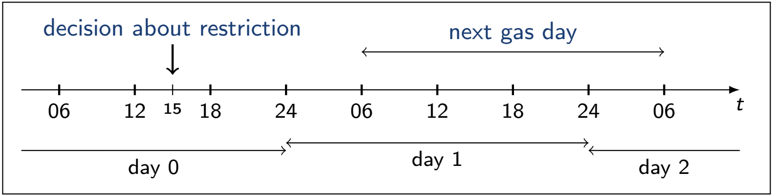
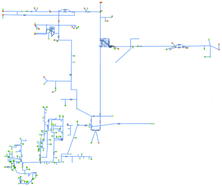


Network topology



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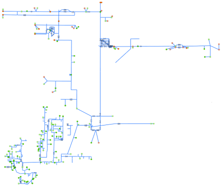
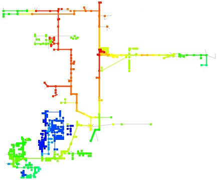


Network state



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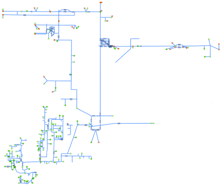

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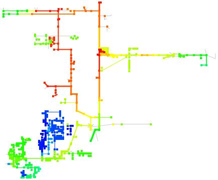
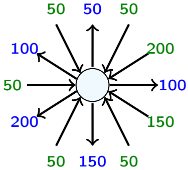
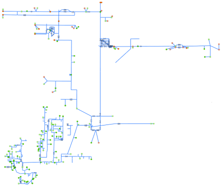


Bookings/Nominations



Base Decision On ...

Network topology



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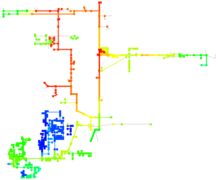

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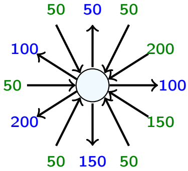
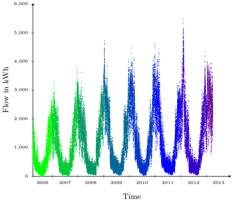


Historical Demands



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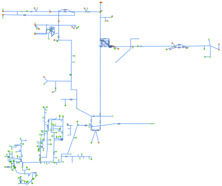

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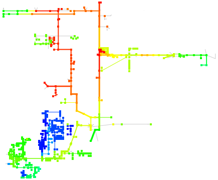

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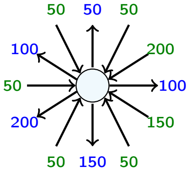

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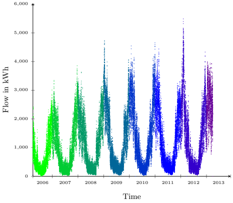
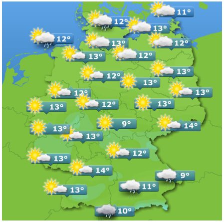


Weather Forecast



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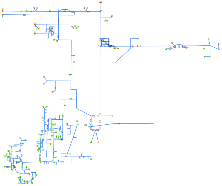

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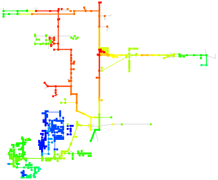

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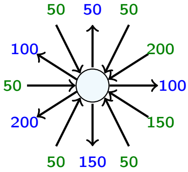

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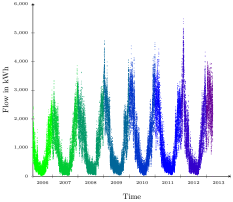

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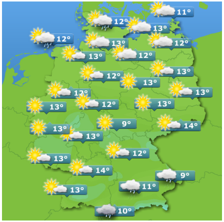

. . .

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- Prognosis
  - $(\mathcal{S}, Pr)$ with
  - $\mathcal{S} := \{S_1, S_2, \ldots, S_n\}$ a finite set of scenarios
  - $Pr : \mathcal{S} \to [0, 1]$ a probability distribution on $\mathcal{S}$
  - $p_i := Pr(S_i)$ for all $S_i \in \mathcal{S}$ with $p_i \in [0, 1]$ and $\sum_{i=1}^{n} p_i = 1$

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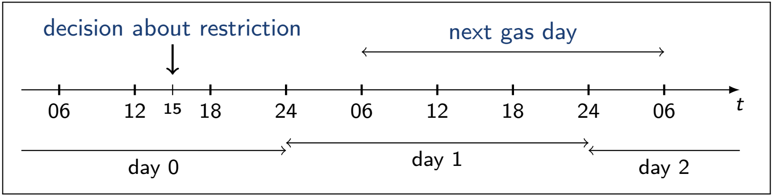

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A subset of powerplants $K \in 2^{\mathcal{K}}$ admits a safe network operation if restricting them to their fallback entries satisfies

$$\sum_{i=1}^{n} p_i \cdot f(G, A, S_i, K) \geq 1 - \epsilon,$$

i.e, it can be operated with probability $(1 - \epsilon)$ assuming prognosis $(\mathcal{S}, Pr)$.

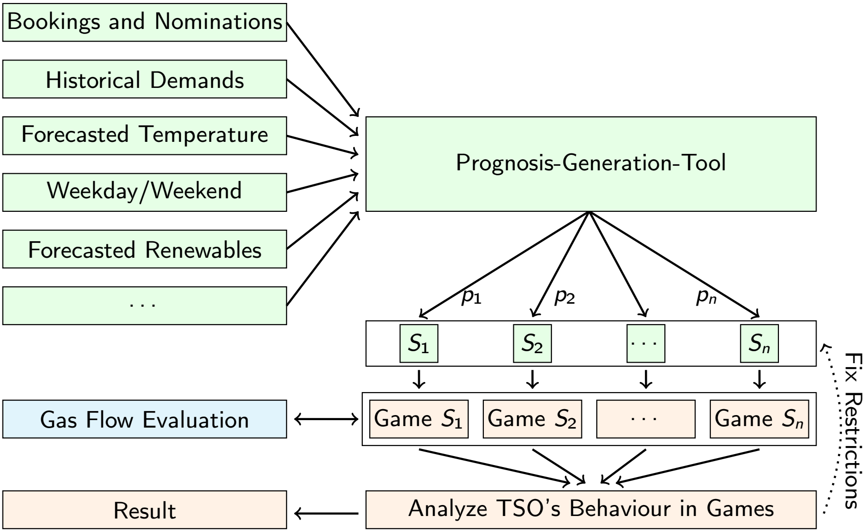
Given a gas network $G = (V, E)$ together with power stations $\mathcal{K} \subseteq V_-$, an initial network state $A \in \mathcal{A}$, a prognosis $(\mathcal{S}, Pr)$, and tolerance value ϵ.

The fDZK Problem is to decide if there exists $K \in 2^{\mathcal{K}}$ admitting a safe network operation

The fDZK Optimization Problem is to find a smallest subset of power stations $K \in 2^{\mathcal{K}}$ w.r.t the cardinality admitting a safe network operation, i.e.,

$$\min_{K \in 2^{\mathcal{K}}} |K|$$
$$\text{s.t. } \sum_{i=1}^{n} p_i \cdot f(G, A, S_i, K) \geq 1 - \epsilon.$$

Remark: The crucial part of this definition is the oracle function f.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Prognosis-Generation-Tool
p_1
p_2
p_n
S_1
S_2
...
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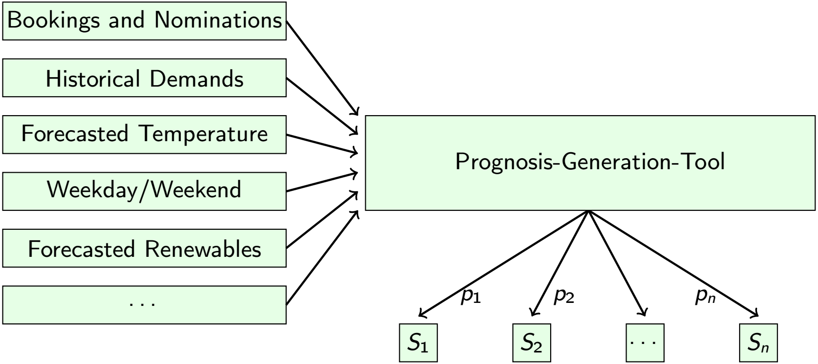
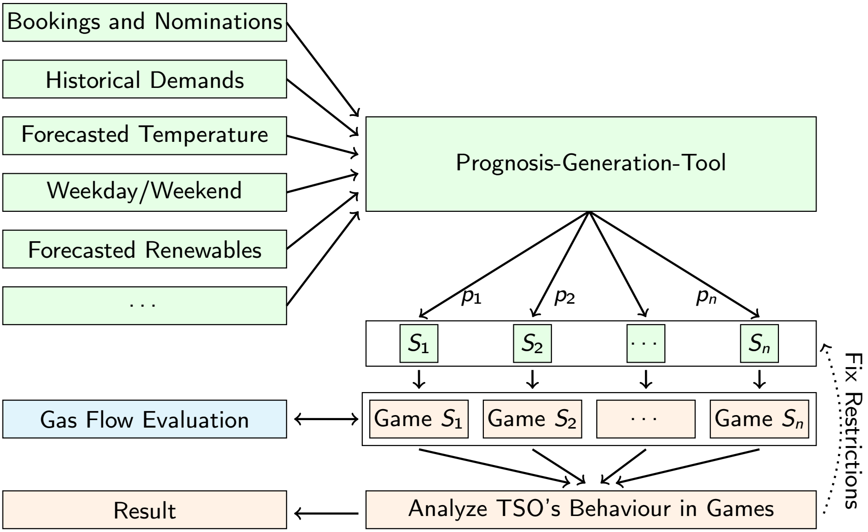
Gas Flow Evaluation
Game S_1
Game S_2
...
Game S_n
Fix Restrictions
Result
Analyze TSO's Behaviour in Games

We need to determine a reasonable prognosis capturing the uncertainty of tomorrow's demands in order to determine a reasonable solution.

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By using contracts (e.g. fDZK) the TSO can change the demand vectors within a scenario. Depending on the type of contract he can

- either increase the amount of flow on some entries (e.g. fDZK) or exits
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But we have to take the reactions of the shippers into account:

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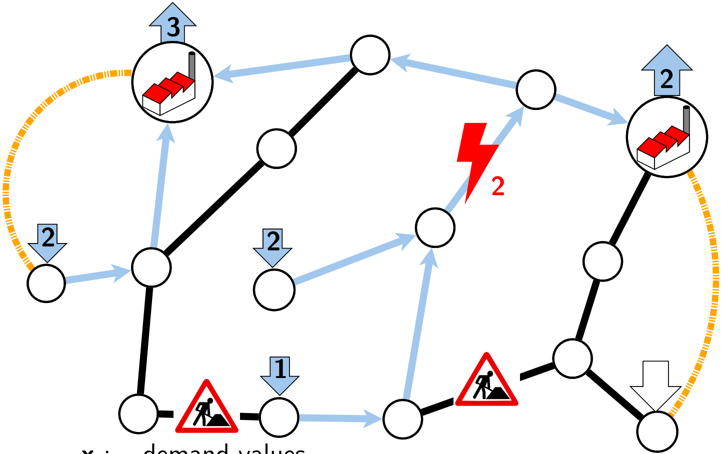
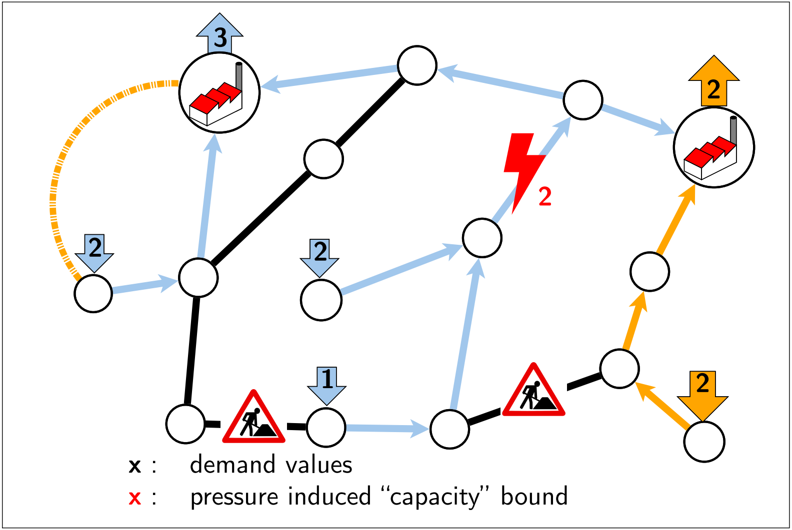
Idea: Model this process as game between TSO and the so-called "shipper's union" (SU) as the antagonist.



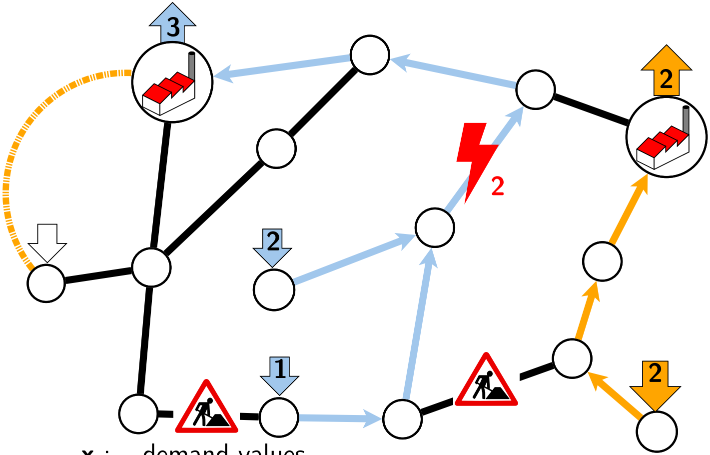
x : demand values

x : pressure induced “capacity” bound

Next turn: TSO



Next turn: SU (Decrease Inflow by 2)



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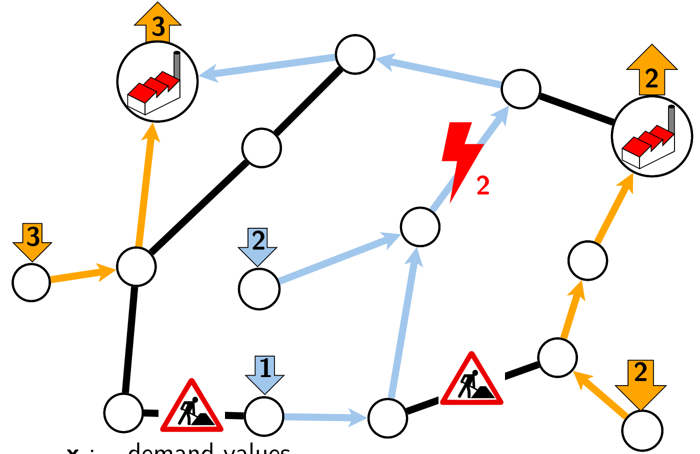

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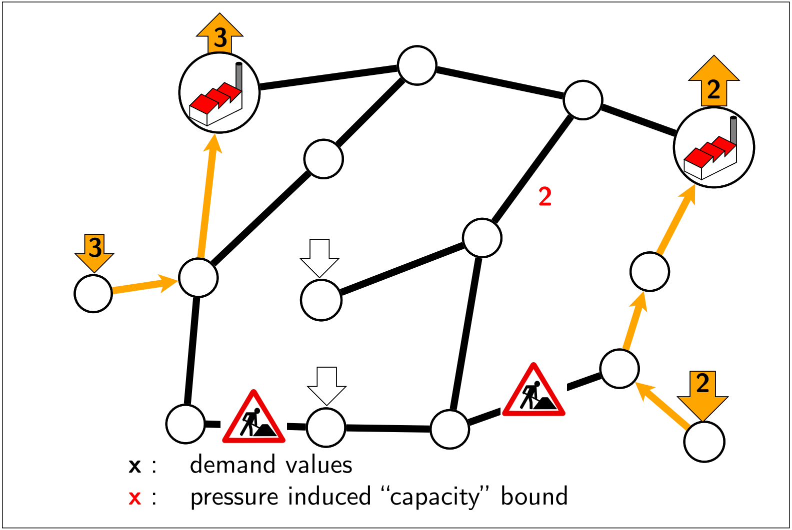
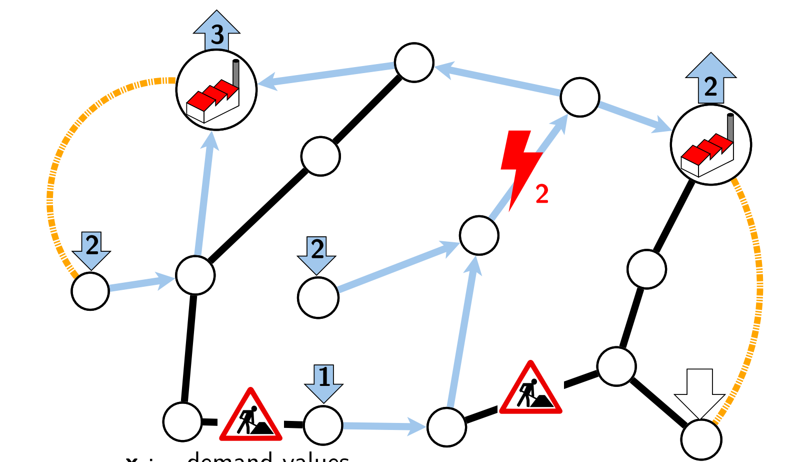
Next turn: SU (Decrease Inflow by 3)



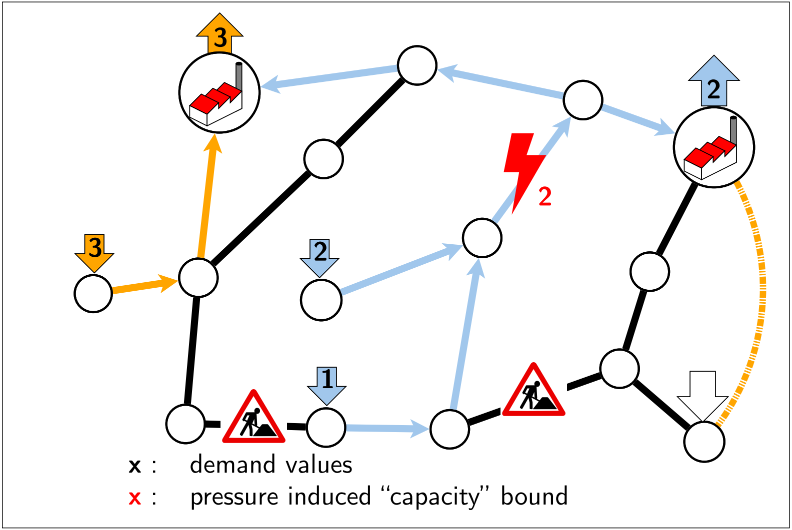
Game Over



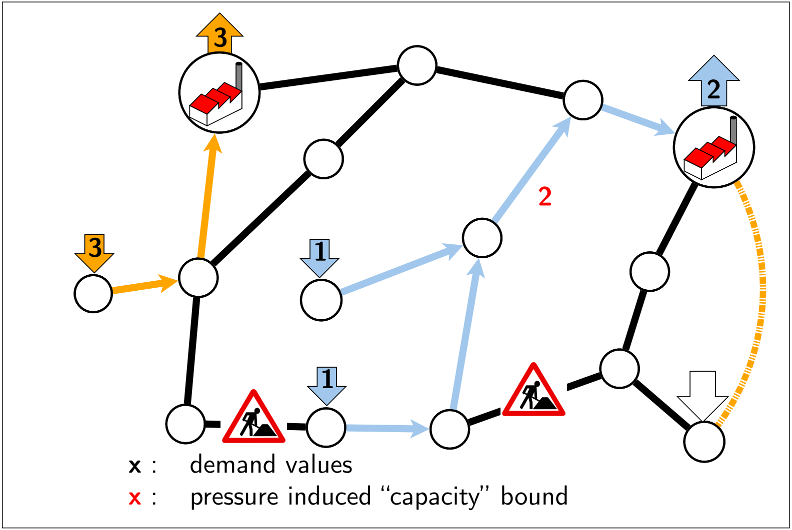
x : demand values

x : pressure induced "capacity" bound

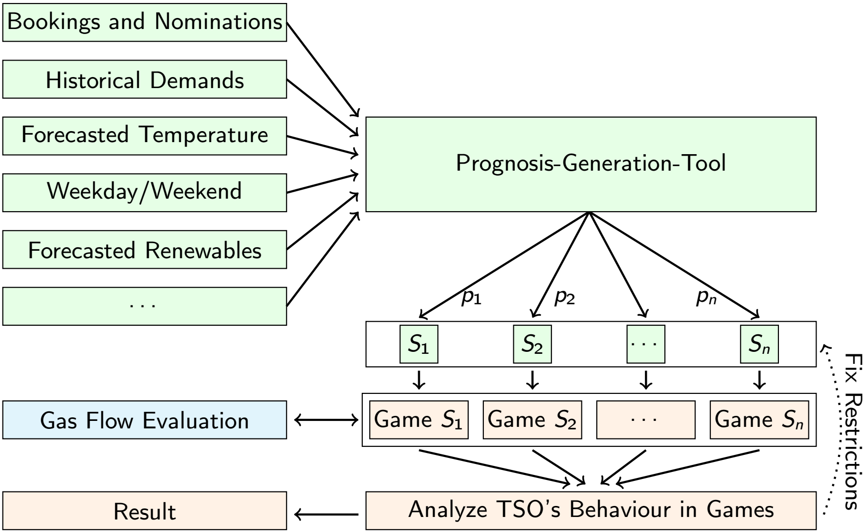
Next turn: TSO



Next turn: SU (Decrease Inflow by 1)



Game Over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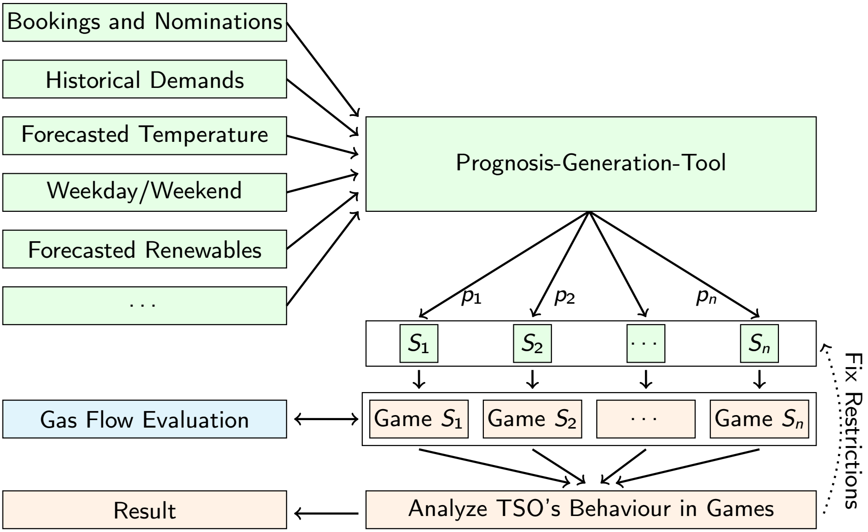
- Needed: A very fast solving model to check many demand situations.
- Plan: Design a coarse, fast solving LP model!

Pipes:	Discretize and approximate Euler PDEs.
Compressors:	Model as single element with max pressure difference.
Valves:	Decide about discrete decisions heuristically.
	Optional: Include discrete decisions into game.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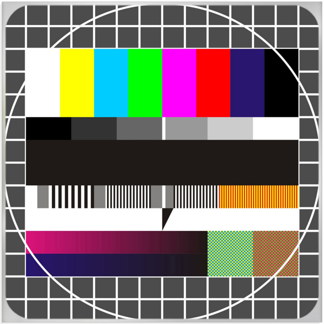
Typical Navi Instructions

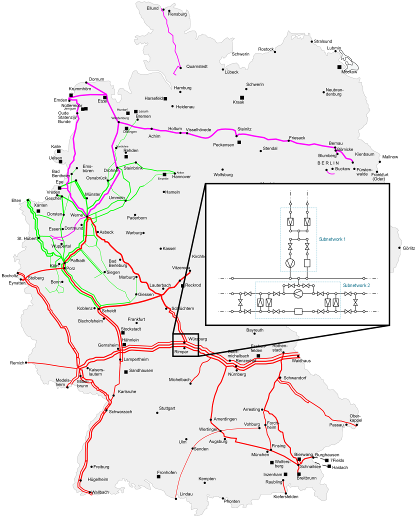
- ▷ Turn left in 400 metres.
- ▷ In 300 metres keep left.
- ▷ Follow the street for 1.4 kilometres.
- ▷ ...

What is a Navigation System for a Dispatcher?



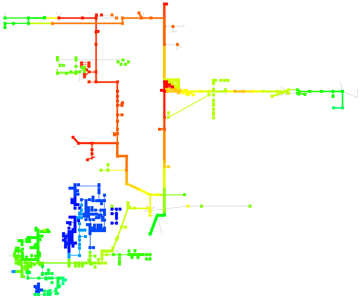
Typical Navi Instructions

- ????????????????
- ????????????????
- ????????????????
- ...



▷ Text to be added

A Second "Idea"



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