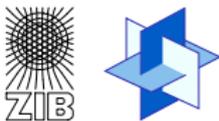


ForNe – Forschungs Kooperation Netzoptimierung

# Optimization of Gas Networks

Martin Grötschel





Zuse-Institut Berlin  
Diskrete Methoden / Optimierung  
Dr. Thorsten Koch (Projektkoordinator)



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



Leibniz-Universität Hannover  
Institut für Angewandte Mathematik  
Prof. Dr. Marc Steinbach



Universität Duisburg-Essen  
Fachbereich Mathematik  
Prof. Dr. Rüdiger Schultz



Technische Universität Braunschweig  
Institut für Mathematische Optimierung  
Prof. Dr. Marc Pfetsch



Humboldt-Universität zu Berlin  
Institut für Mathematik  
Prof. Dr. Werner Römisch



Weierstraß-Institut für Angewandte Analysis und Stochastik (WIAS)  
Dr. Rene Henrion



Open Grid Europe  
Netzplanung und -steuerung / Netzoptimierung  
Dr. Klaus Spreckelsen (Projektleiter)



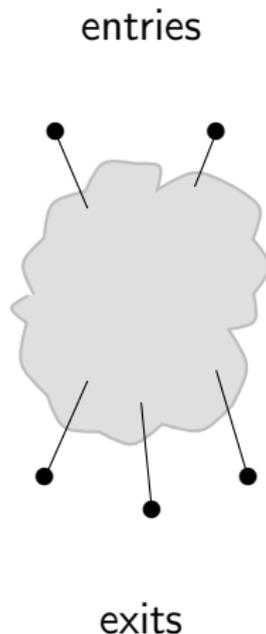
BMWi  
Projekträger Jülich, Geschäftsbereich Energietechnologien  
Christoph Jessen (Projektbetreuer)



T. Berthold, J. Bödecker, M. Ebbers, A. Emgrunt, A. Fügenschuh, G. Gamrath, B. Geißler, N. Geißler, R. Gollmer, U. Gotzes, M. Grötschel, C. Hayn, S. Heinz, R. Henrion, B. Hiller, L. Huke, J. Humpola, J. Hülsewig, I. Joormann, W. Knieschweski, T. Koch, V. Kühl, H. Leövey, F. Malow, D. Mahlke, A. Martin, R. Mirkov, A. Morsi, G. Möhlen, A. Möller, F. Nowosatko, D. Oucherif, M. Pfetsch, W. Römisch, L. Sax, L. Schewe, M. Schmidt, R. Schultz, R. Schwarz, J. Schweiger, K. Spreckelsen, C. Stangl, M. Steckhan, M. Steinbach, A. Steinkamp, J. Szabó, H. Temming, I. Wagner-Specht, B. Willert, S. Vigerske, A. Zelmer

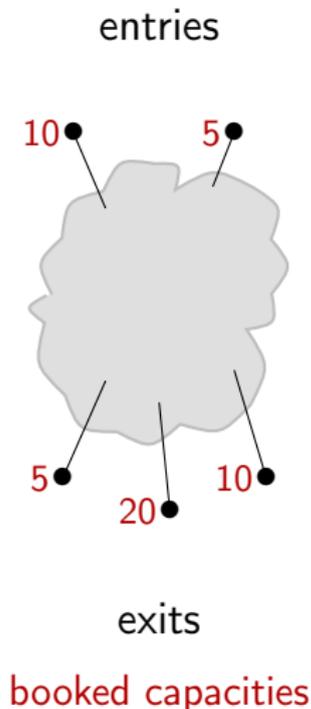
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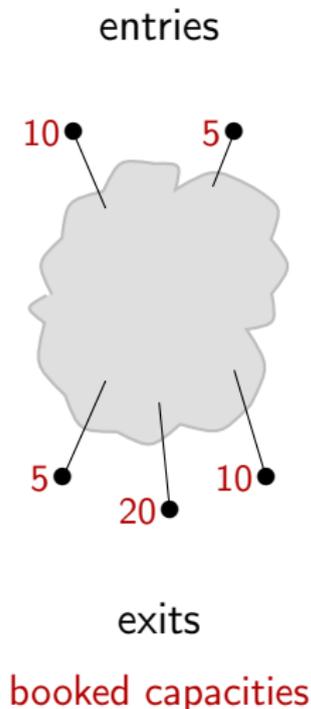
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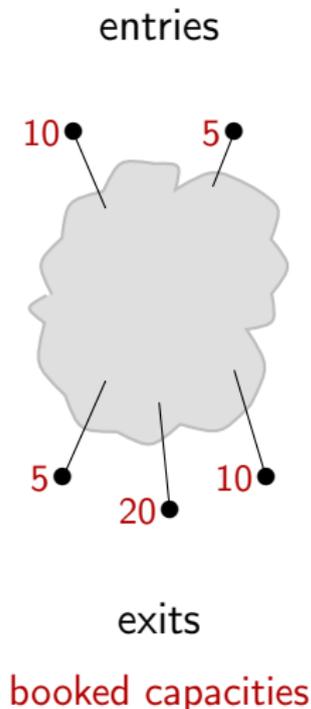
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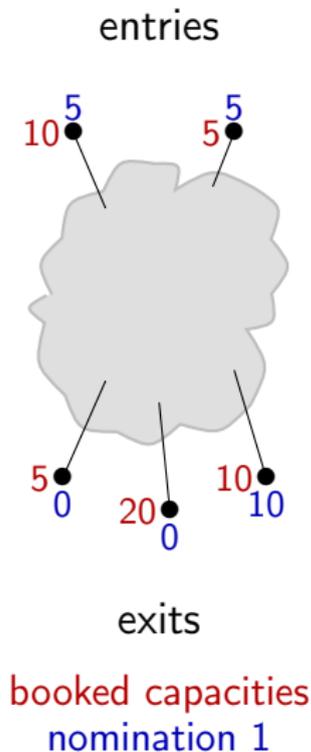
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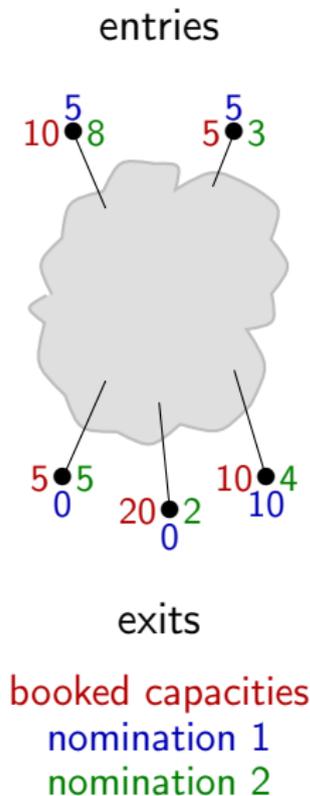
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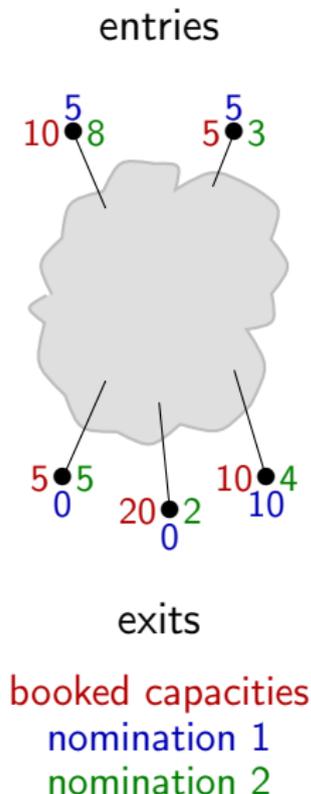
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- ▶ transmission system operator has to ensure that each nomination within the booked capacities can technically be realized



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- ▷ a detailed description of a gas network
  - ▷ a **nomination** specifying amounts of gas flow at entries and exits



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human experience

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simulation tool



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simulation tool



**Issue:** How to decide whether a nomination is technically feasible?

## Simulation

- ▷ allows very accurate gas physics models
- ▷ relies on human experience to decide feasibility
- ▷ is thus inappropriate to determine infeasibility of a nomination

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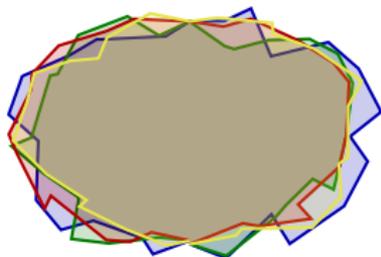
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**Beware:** different solution spaces due to different modeling

simulation A

simulation B



optimization A

optimization B

# Transient Models

Transient models describe the network state evolution over time.

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- ▷ deviations between predicted / physical network state grow over time

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- ▶ transition between nominations cannot be modelled
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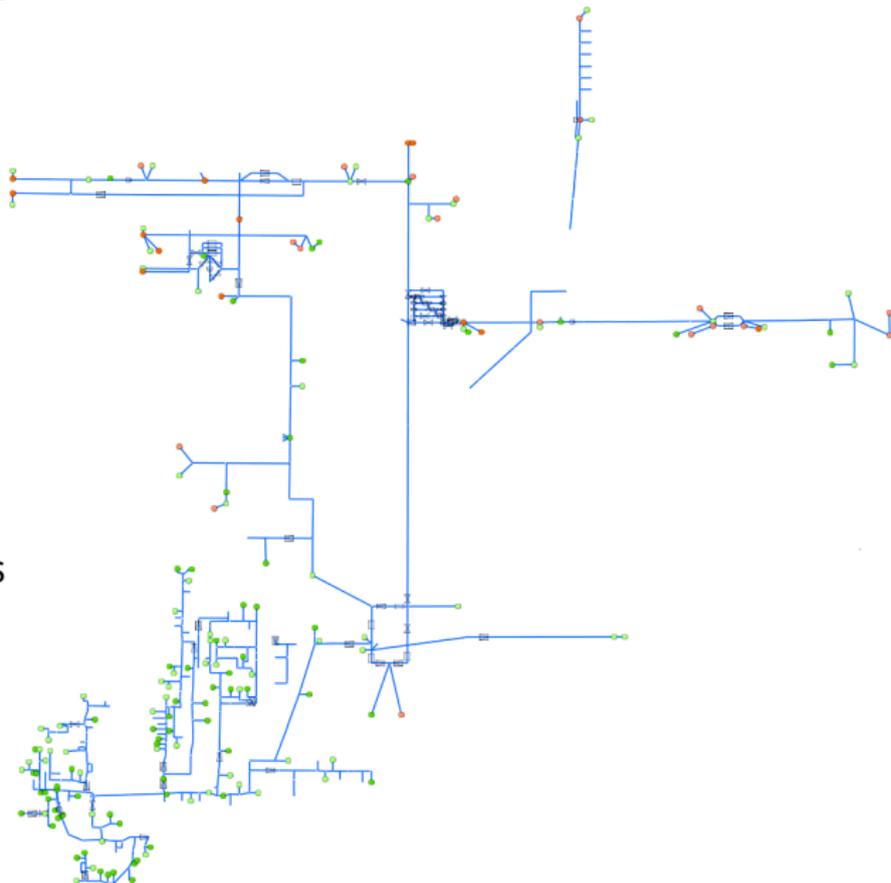
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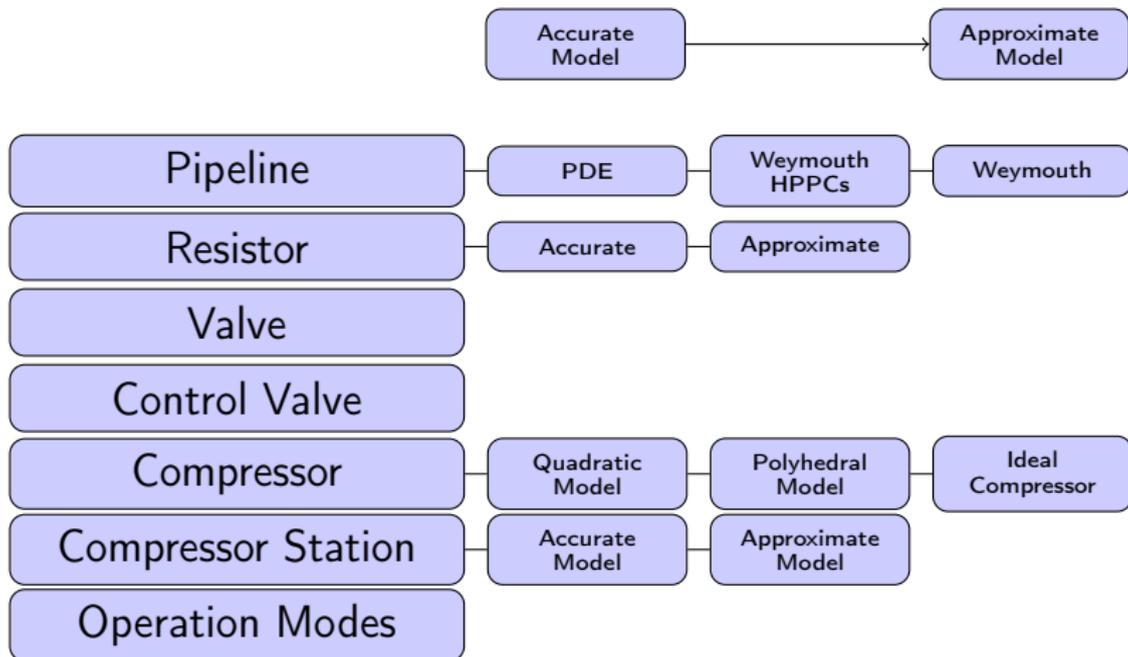
Nevertheless, the better choice for medium and long-term planning.

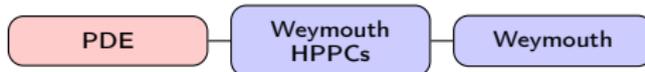
- ▷ 32 entries, 142 exits
- ▷ 498 pipes,  
9 resistors,  
33 valves,  
26 control valves,  
7 compressor stations
- ▷ 32 cycles



Mathematical model description:

- Network:** directed Graph  $G = (V, E)$  with vertices  $V$  and edges  $E$
- Variables:**
- ▷ pressure at node  $i \in V : p_i$
  - ▷ mass flow, volumetric flow rate on edge  $e \in E : q_e, Q_e$
  - ▷ decision for active element  $e_a \in E_a \subset E : x_{e_a}$
  - ▷ temperature at node  $i \in V : T_i$
  - ▷ velocity on edge  $e \in E : v_e$
  - ▷ fuel, power for compressor  $e_{CS} \in E_{CS} \subset E : b_{e_{CS}}, P_{e_{CS}}$
  - ▷ density at node  $i \in V : \rho_i$
  - ▷ real gas factor of gas at node  $i \in V : z_i$
  - ▷ calorific value of gas at node  $i \in V : \hat{B}_i$
  - ▷ speed of compressor  $e_{CS} \in E_{CS} : n_{e_{CS}}$
  - ▷ adiabatic head of compressor  $e_{CS} \in E_{CS} : H_{ad,e_{CS}}$
  - ▷ adiabatic efficiency of compressor  $e_{CS} \in E_{CS} : \eta_{ad,e_{CS}}$





- Pipeline
- Resistor
- Valve
- Control Valve
- Compressor
- Compressor Station
- Operation Modes

Euler-differential equation  
&  
equation of state for real gases:

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

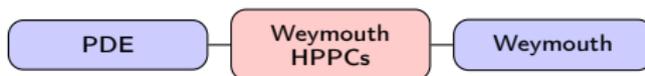
$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho v^2)}{\partial x} + \frac{\partial p}{\partial x} + g\rho \frac{\partial h}{\partial x} + \lambda(q) \frac{|v|v}{2D} \rho = 0$$

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

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

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

# Weymouth Equation of HPPCs Model



Pipeline

Resistor

Valve

Control Valve

Compressor

Compressor Station

Operation Modes

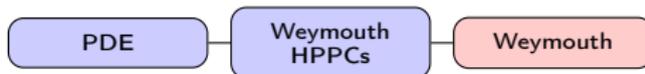
Weymouth-equation  
based on HPPCs-model:

$$p_j^2 = \left( p_i^2 - \Lambda \cdot \phi(q) \frac{e^S - 1}{S} \right) e^{-S}$$

$$\Lambda = \left( \frac{4}{\pi} \right)^2 \frac{L \rho_0 z(p_m, T_m) T_m}{D^5 \rho_0 z_0 T_0}$$

$$S = 2Lg \frac{dh}{dx} \frac{\rho_0 z_0 T_0}{\rho_0 z(p_m, T_m) T_m}$$

# Weymouth Equation



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Simplified Weymouth-equation:

Friction coefficient according to Nikuradze

$$\lambda = \left( 2 \log_{10} \left( \frac{D}{k} \right) + 1.138 \right)^{-2}$$

yields

$$p_j^2 = \left( p_i^2 - \Lambda |q_e| q_e \frac{e^S - 1}{S} \right) e^{-S}$$

Accurate

Approximate

Pipeline

Resistor

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Exact flow dependent resistor equation:

Pressure decrease:

$$p_i - p_j = \frac{8\rho_0 p_0}{\pi^2 z_0 T_0} \frac{\xi T_i |q_e| q_e z(p_i, T_i)}{D^4 p_i}$$

Temperature decrease due to Joule-Thomson effect:

$$T_{e,out} = T_{e,in} + \mu_{JT} (p_j - p_i)$$

Accurate

Approximate

Pipeline

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Operation Modes

## Approximation

of flow dependent resistors:

$$\varepsilon(p_i^2 - p_j^2) = \frac{8\rho_0 p_0}{\pi^2 z_0 T_0} \frac{\xi T}{D^4} |q_e| q_e$$

with

$$\min_{\varepsilon \in \mathbb{R}} \left( \int_I^u \int_I^{p_v} \left( \frac{p_v^2 - p_v \cdot p_w}{1 + \zeta_e \cdot p_v} - \varepsilon \cdot (p_v^2 - p_w^2) \right)^2 dp_w dp_v + \int_I^u \int_I^{p_w} \left( -\frac{p_w^2 - p_v \cdot p_w}{1 + \zeta_e \cdot p_w} - \varepsilon \cdot (p_v^2 - p_w^2) \right)^2 dp_v dp_w \right)^{\frac{1}{2}}$$

Valve: open or closed

Pipeline

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# Valves and Control Valves

Valve: open or closed

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

$$\text{closed:} \quad x_e = 0 \quad \implies \quad q_e = 0$$

$$\text{open:} \quad x_e = 1 \quad \implies \quad p_i = p_j$$

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Valve: open or closed

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$$\text{closed: } x_e = 0 \implies q_e = 0$$

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Control Valve: active, bypassed, or closed

Two decision variables  $x_e^{\text{bypass}}$  and  $x_e^{\text{active}}$ :

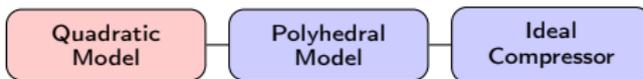
$$x_e^{\text{bypass}} + x_e^{\text{active}} \leq 1$$

$$\text{closed: } x_e^{\text{bypass}} = x_e^{\text{active}} = 0 \implies q_e = 0$$

$$\text{bypass: } x_e^{\text{bypass}} = 1 \implies p_i = p_j$$

$$\text{active: } x_e^{\text{active}} = 1 \implies \underline{\Delta} \leq p_i - p_j \leq \overline{\Delta}$$

# Quadratic Compressor Model



Quadratic approximation  
of turbo-compressor:

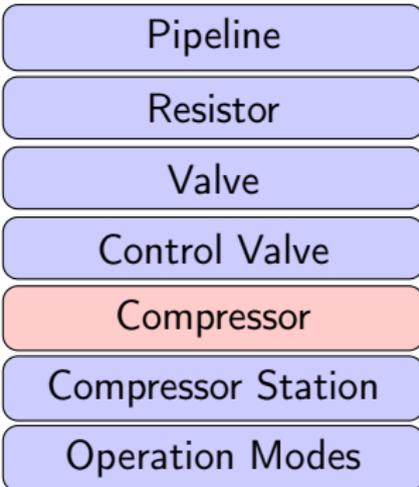
$$H_{\text{ad}}(Q, n) = a_1 + a_2 n + a_3 n^2 + (a_4 + a_5 n + a_6 n^2) Q + (a_7 + a_8 n + a_9 n^2) Q^2$$

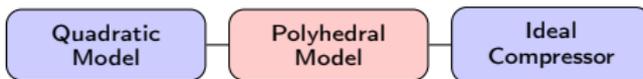
$$\eta(Q, n) = b_1 + b_2 n + b_3 n^2 + (b_4 + b_5 n + b_6 n^2) Q + (b_7 + b_8 n + b_9 n^2) Q^2$$

$$H_{\text{ad}} \leq s_1 + s_2 Q + s_3 Q^2$$

$$H_{\text{ad}} \geq c_1 + c_2 Q + c_3 Q^2$$

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





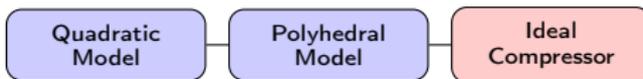
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Polyhedral approximation based on:

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

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

$$\begin{pmatrix} p_i \\ p_j \\ q \end{pmatrix} = p_i \begin{pmatrix} 1 \\ \left( \frac{\kappa-1}{z_i R_s T_i \kappa} H_{ad} + 1 \right)^{\frac{\kappa}{\kappa-1}} \\ \frac{3.6 z_0 T_0}{p_0 z(p_i, T) T} Q \end{pmatrix}$$



Idealized compressor:

$$P_e = \frac{\kappa}{\kappa - 1} \frac{\rho_0 R T_i z(p_i, T_i)}{\eta_{ad} m} \left( \left( \frac{p_j}{p_i} \right)^{\frac{\kappa-1}{\kappa}} - 1 \right) q_e$$

Pipeline

Resistor

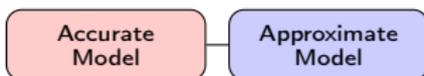
Valve

Control Valve

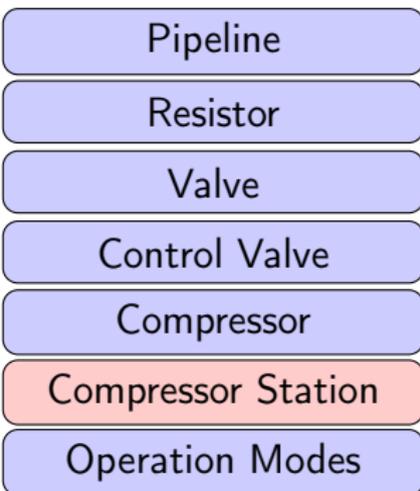
Compressor

Compressor Station

Operation Modes



## Compressor Station:



- ▷ union of single compressor machines
- ▷ compressor station can operate in different configurations
- ▷ configuration: selected compressor machines operate
  - ▶ parallely
  - ▶ sequentially
  - ▶ parallely and sequentially

Accurate Model

Approximate Model

Pipeline

Resistor

Valve

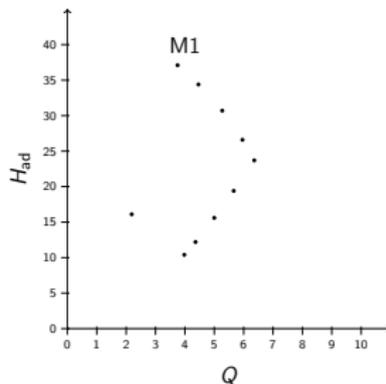
Control Valve

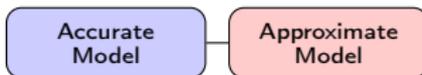
Compressor

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Operation Modes

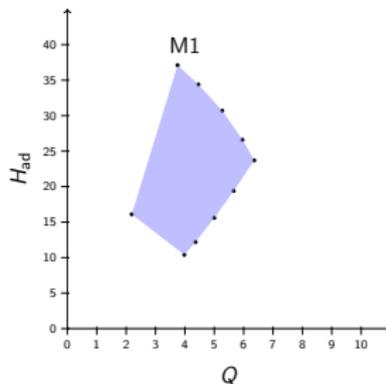
1. The feasible operating range of a compressor machine is mainly described by the characteristic diagram:

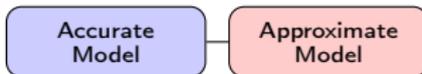




- Pipeline
- Resistor
- Valve
- Control Valve
- Compressor
- Compressor Station
- Operation Modes

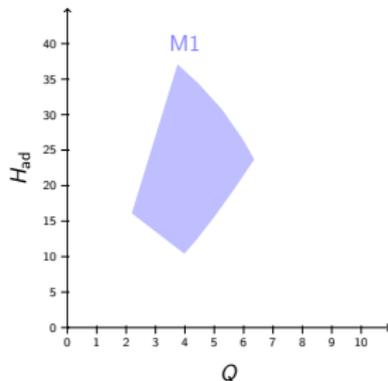
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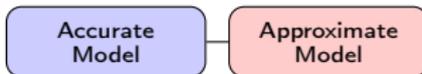




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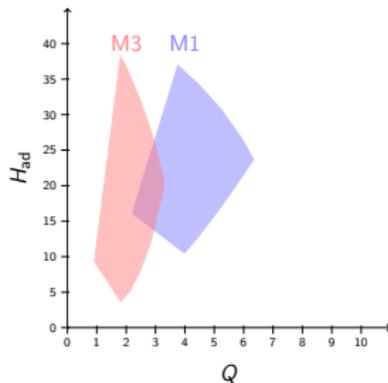
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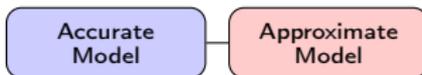


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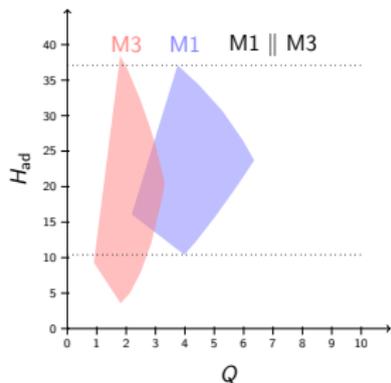


► parallel operation of machines M1 || M3

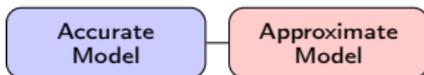


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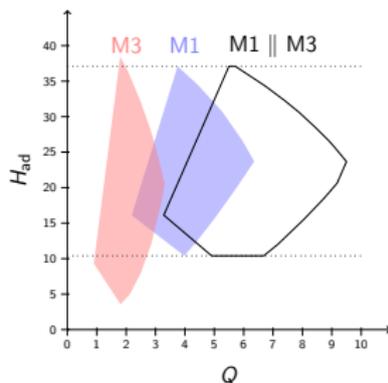


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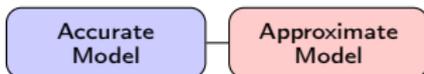


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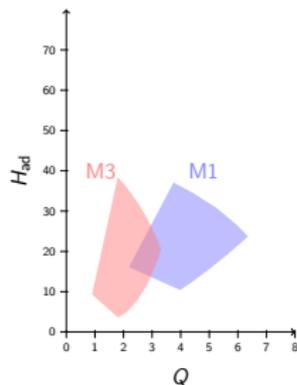


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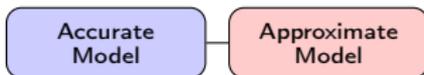


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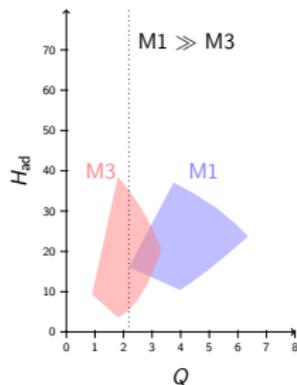


- sequential operation of machines  $M1 \gg M3$

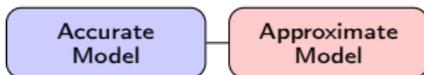


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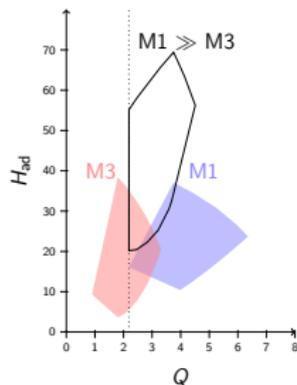


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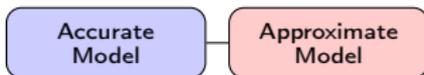


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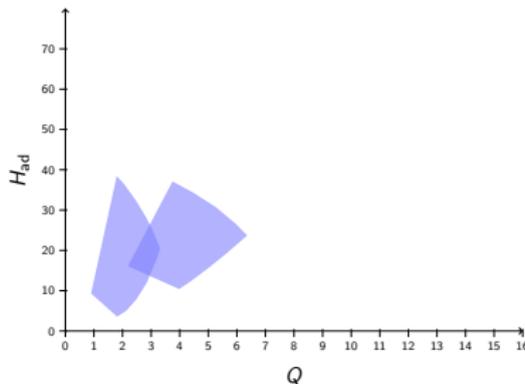


► sequential operation of machines  $M1 \gg M3$



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- Resistor
- Valve
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- Compressor Station
- Operation Modes

3. Convex hull of the union of all configurations yields approximation of the feasible operating range of a compressor station



1. Machines

Accurate Model

Approximate Model

Pipeline

Resistor

Valve

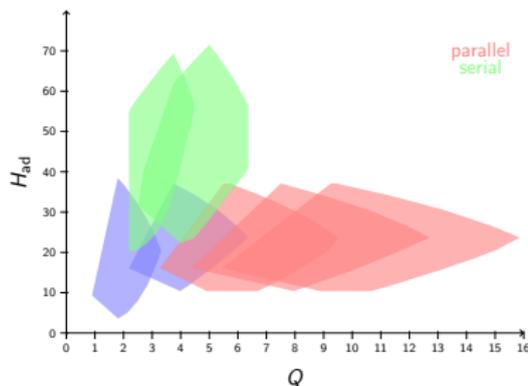
Control Valve

Compressor

Compressor Station

Operation Modes

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1. Machines
2. Configurations

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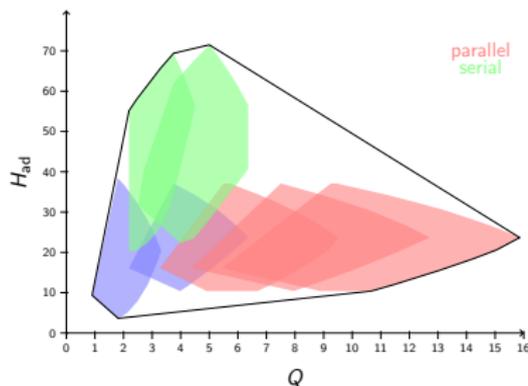
Control Valve

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- 
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1. Machines
2. Configurations
3. Approximation of Compressor Station

# Subnetwork Operation Modes

Pipeline

Resistor

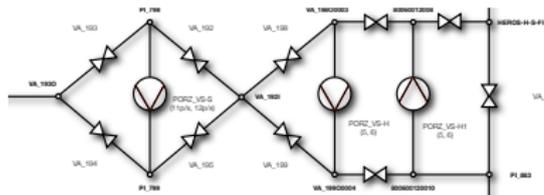
Valve

Control Valve

Compressor

Compressor Station

Operation Modes



# Subnetwork Operation Modes

Pipeline

Resistor

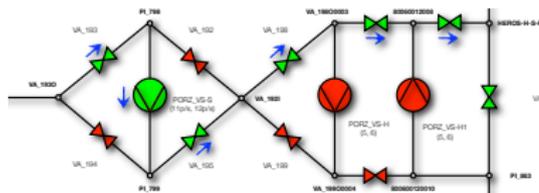
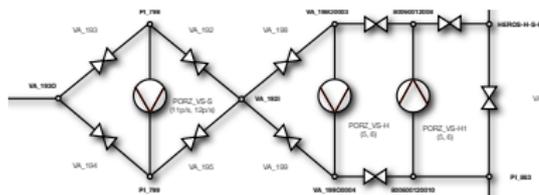
Valve

Control Valve

Compressor

Compressor Station

Operation Modes



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Pipeline

Resistor

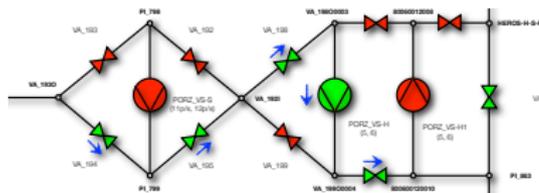
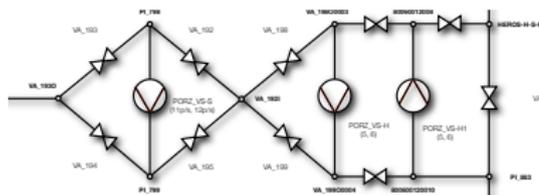
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Operation Modes



# Subnetwork Operation Modes

Pipeline

Resistor

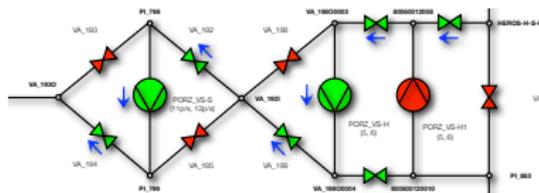
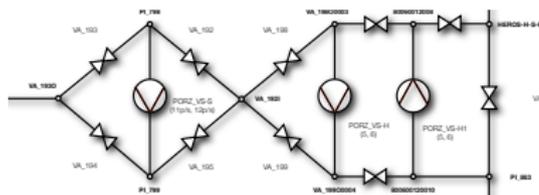
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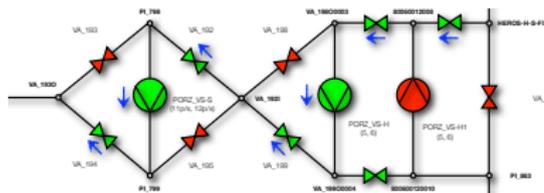
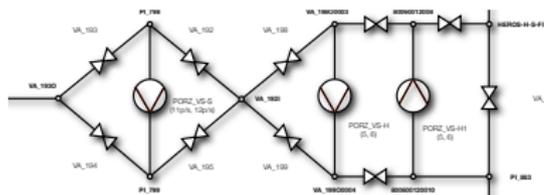
Valve

Control Valve

Compressor

Compressor Station

Operation Modes



- ▷ each operation mode is described by a binary vector giving the state of each valve

# Subnetwork Operation Modes

Pipeline

Resistor

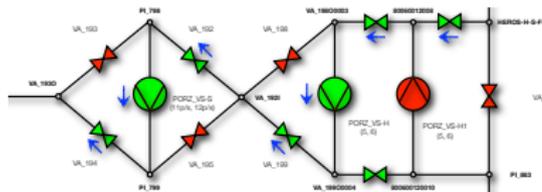
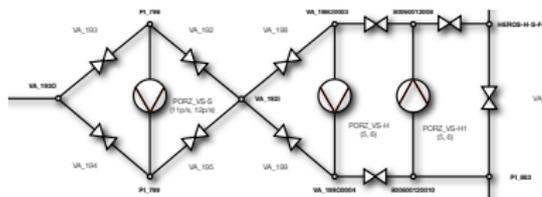
Valve

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Compressor

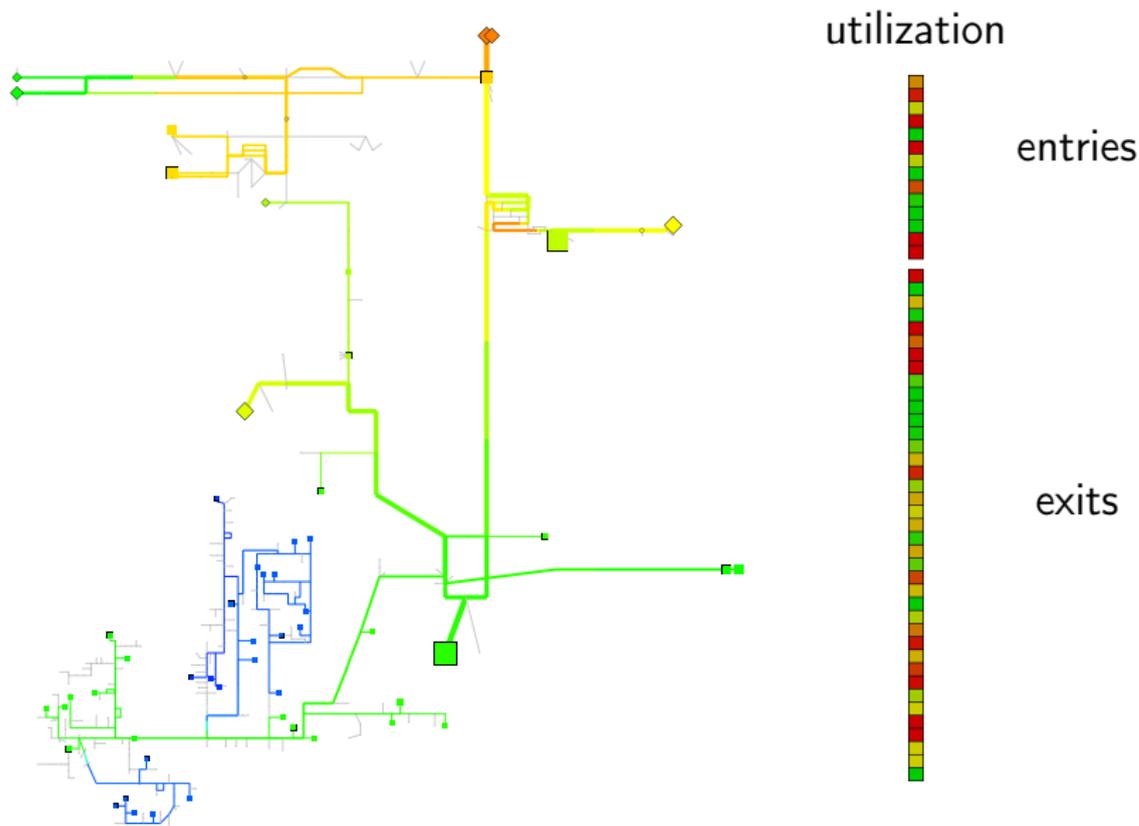
Compressor Station

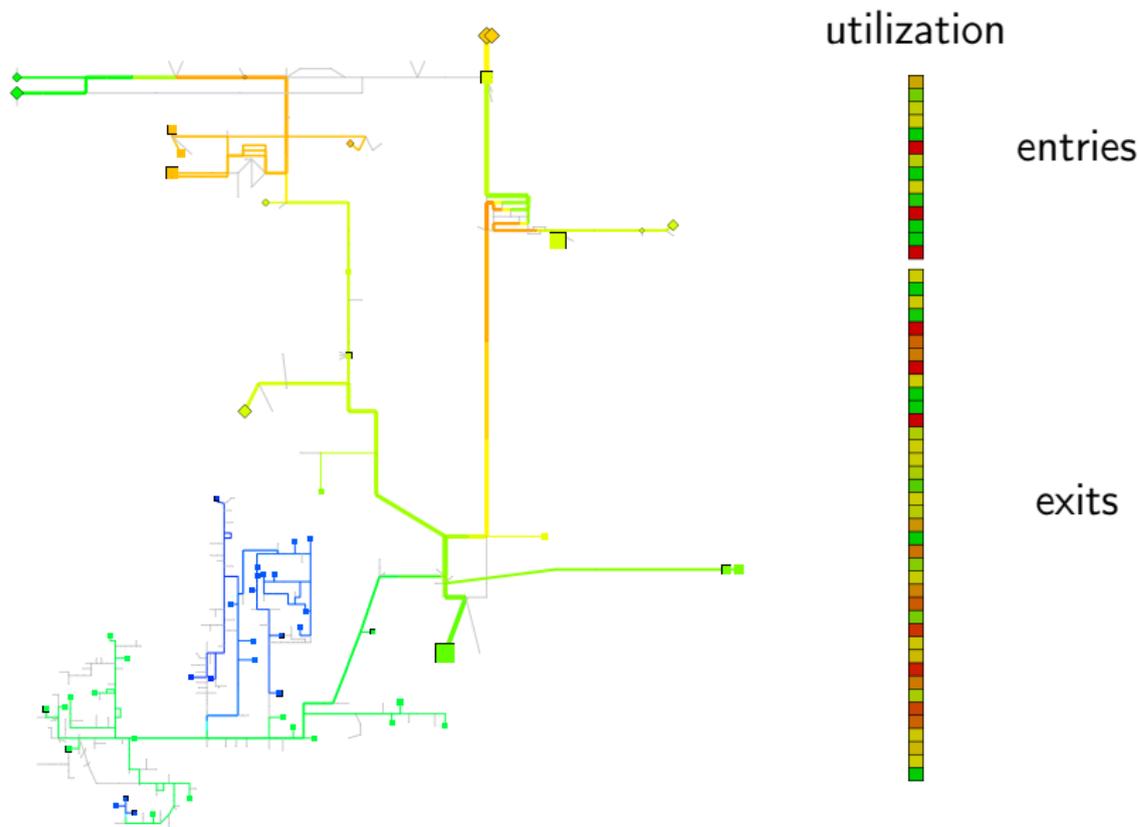
Operation Modes



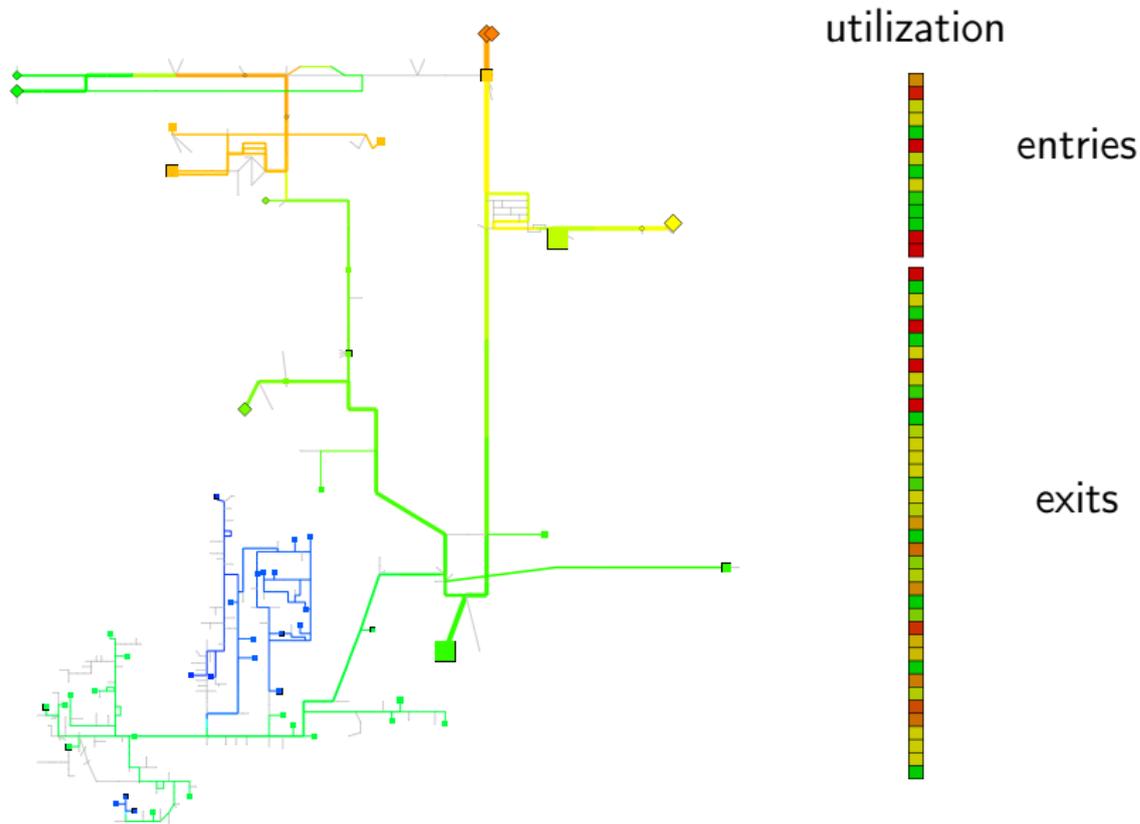
- ▷ each operation mode is described by a binary vector giving the state of each valve
- ▷ we use the convex hull of these binary vectors to include the operation modes in our model

## Visualization of Solutions

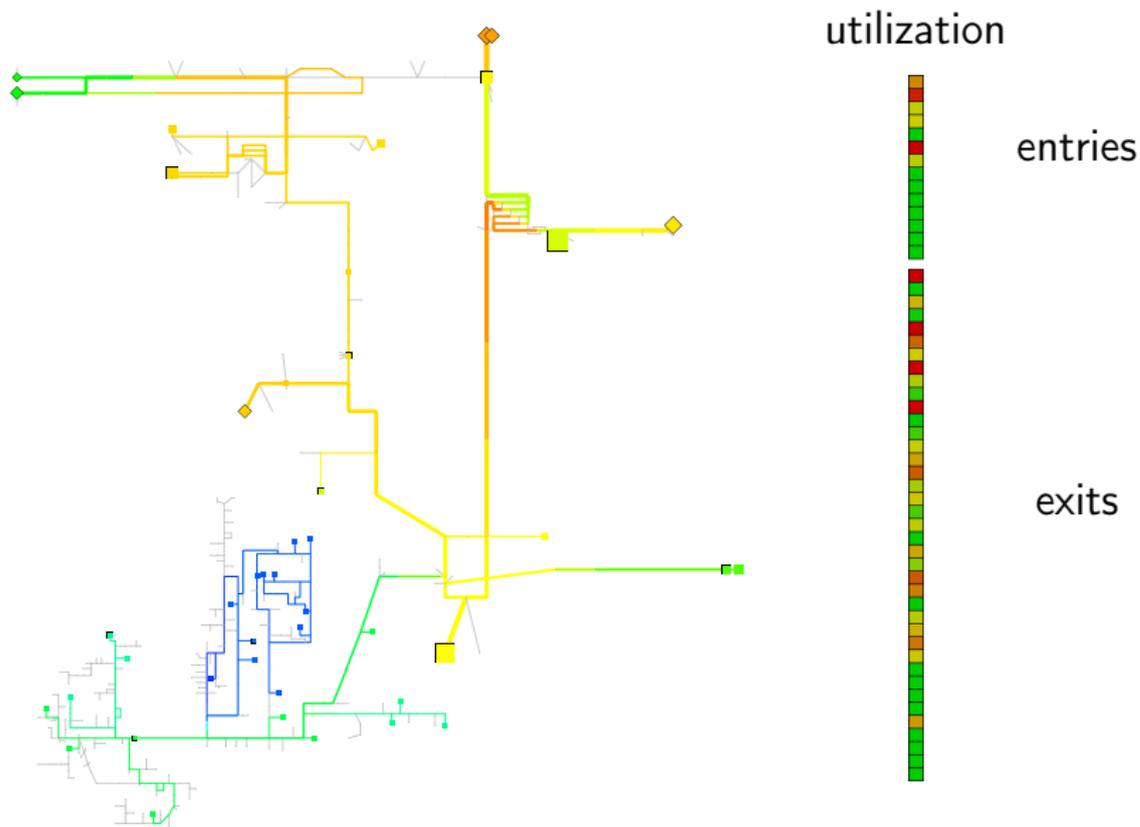


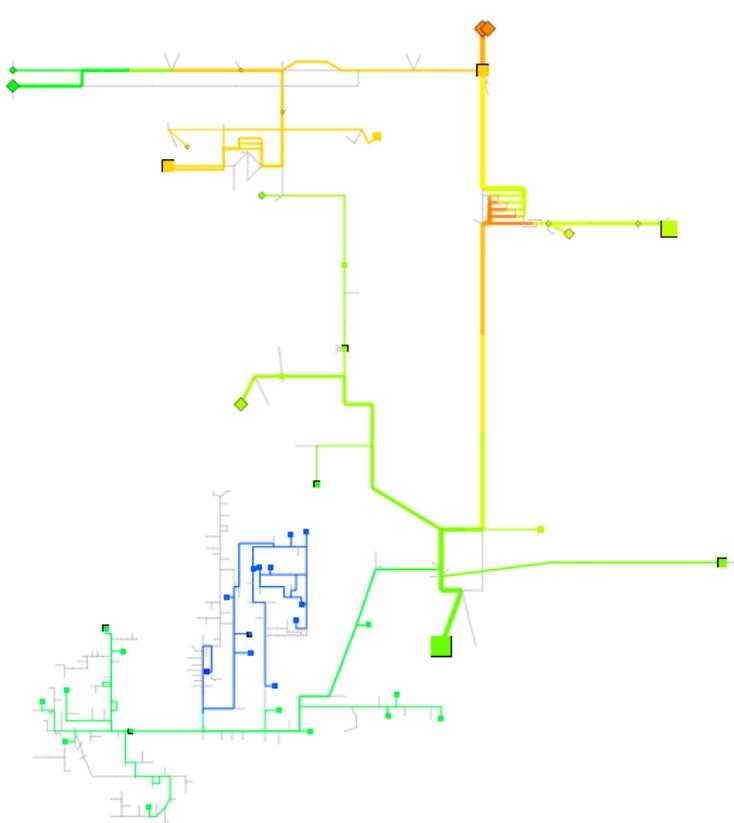


## Visualization of Solutions



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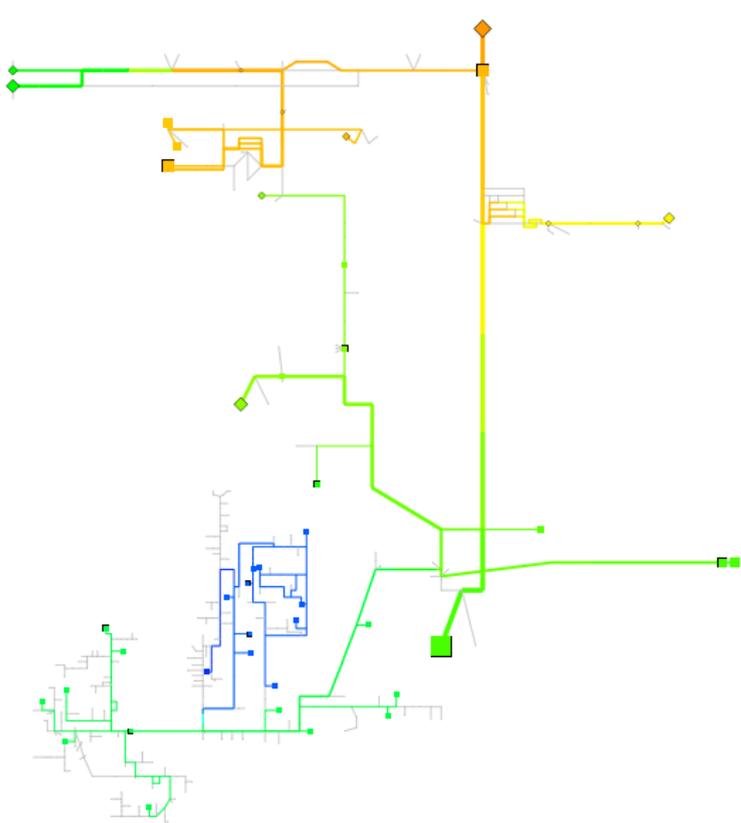


utilization



entries

exits



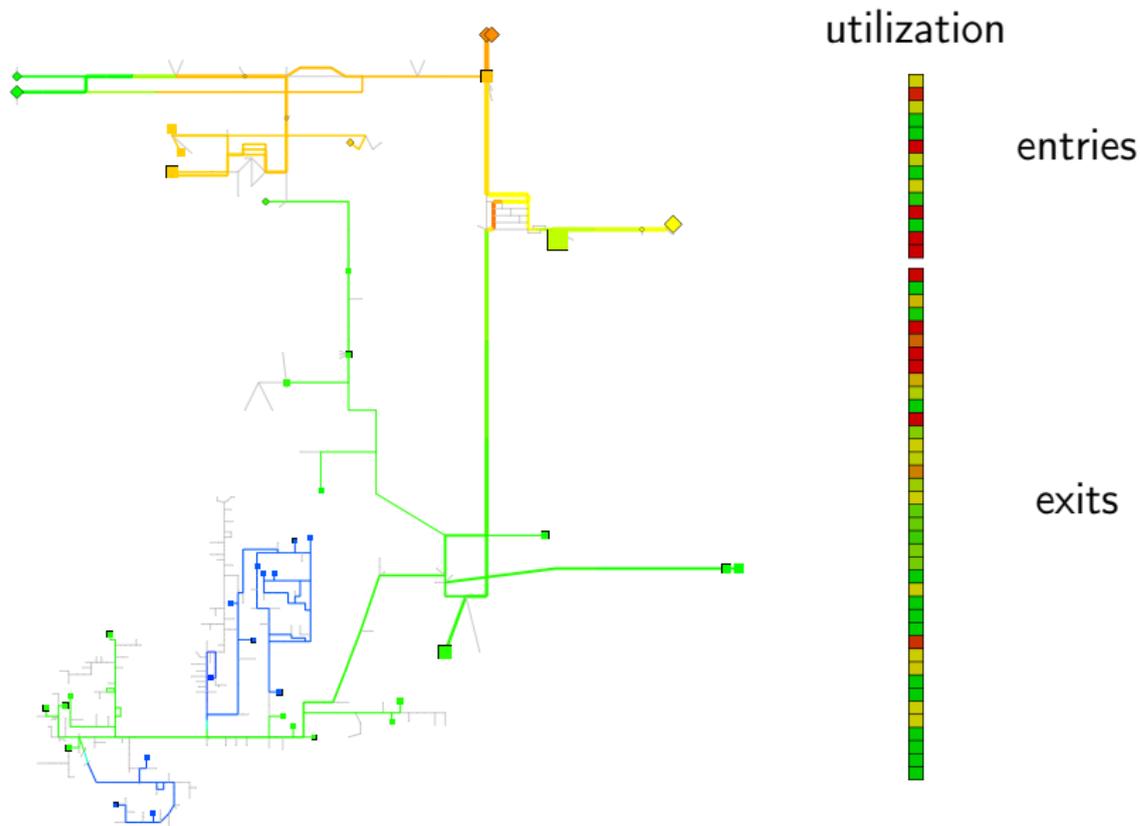
utilization

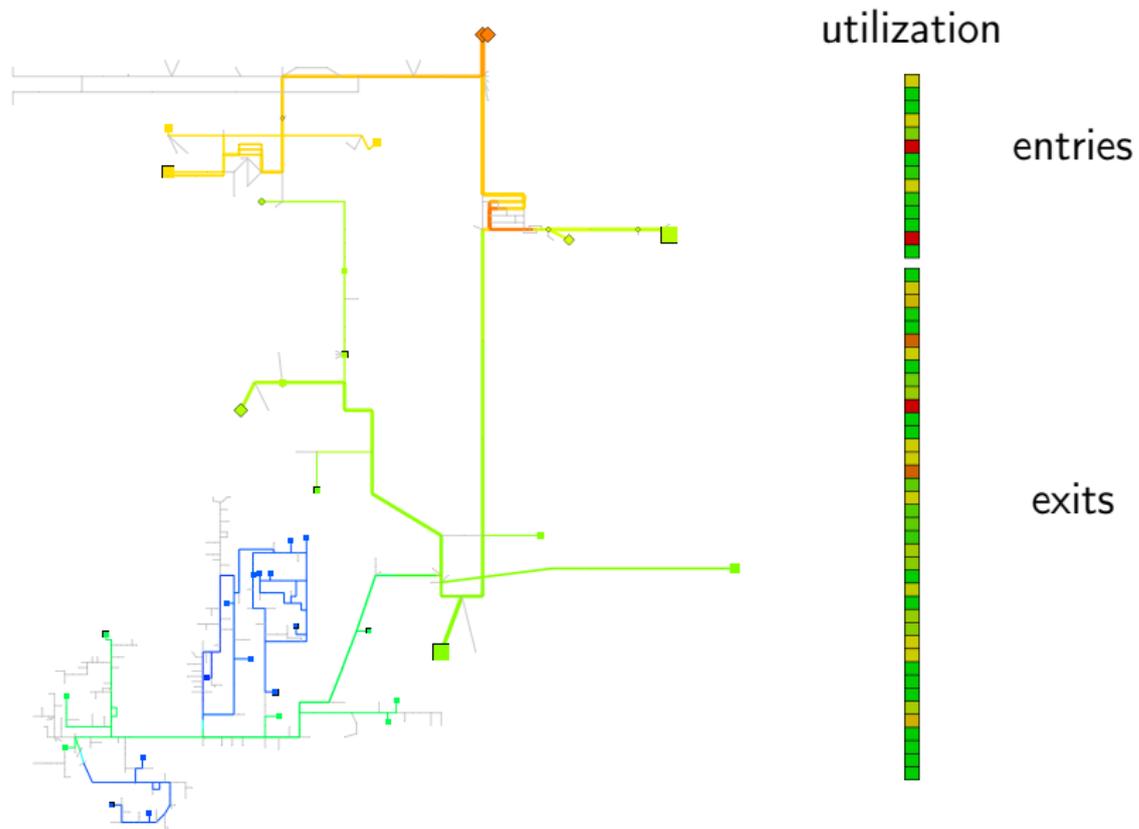


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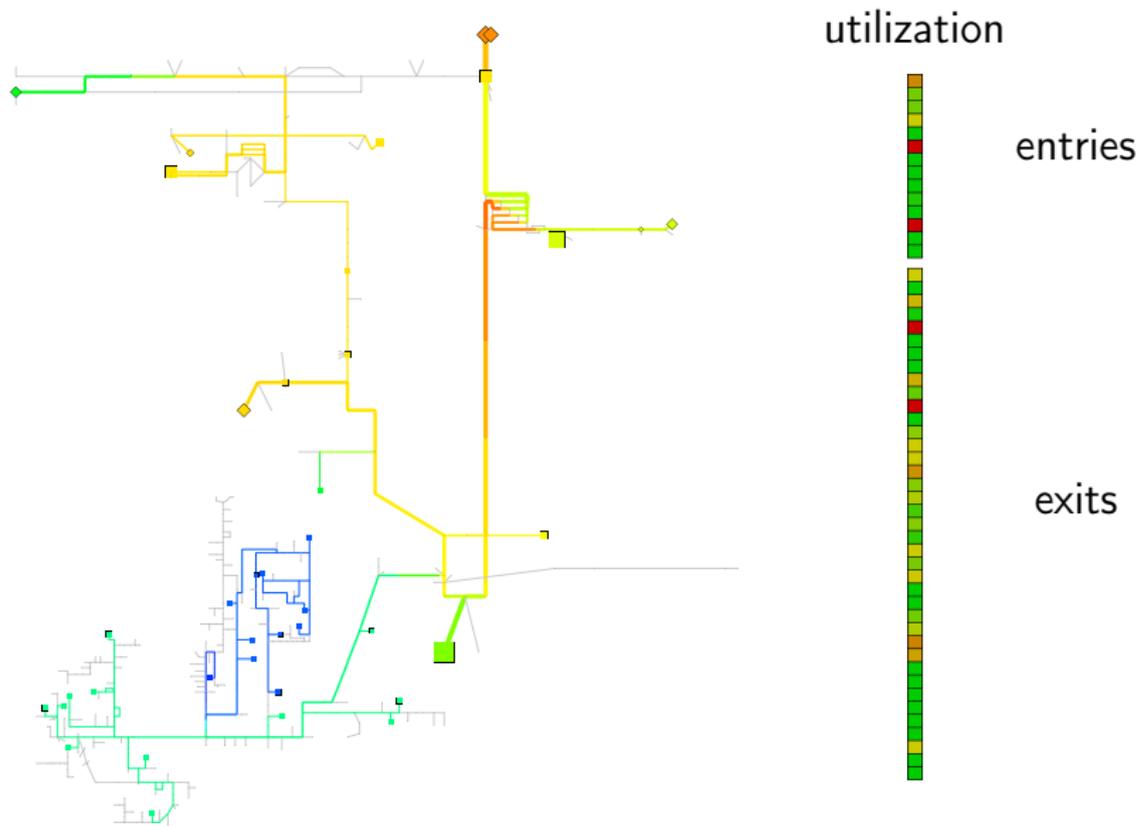
exits

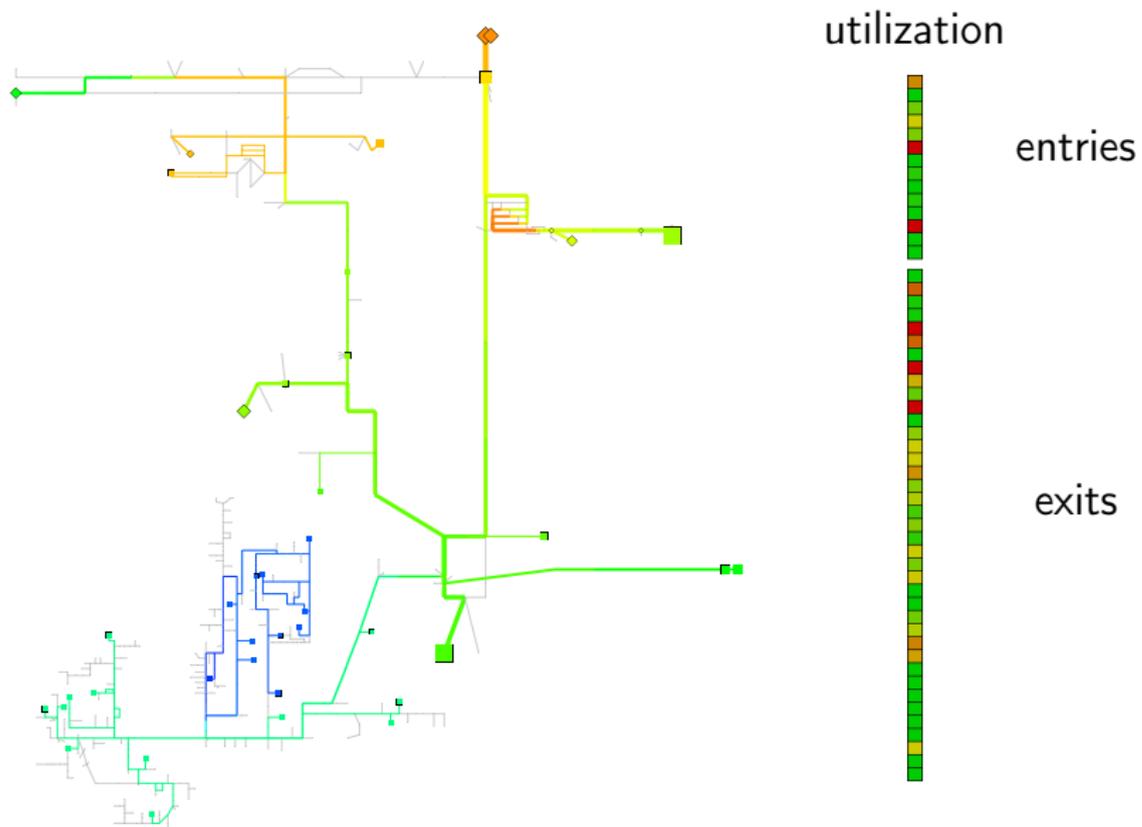
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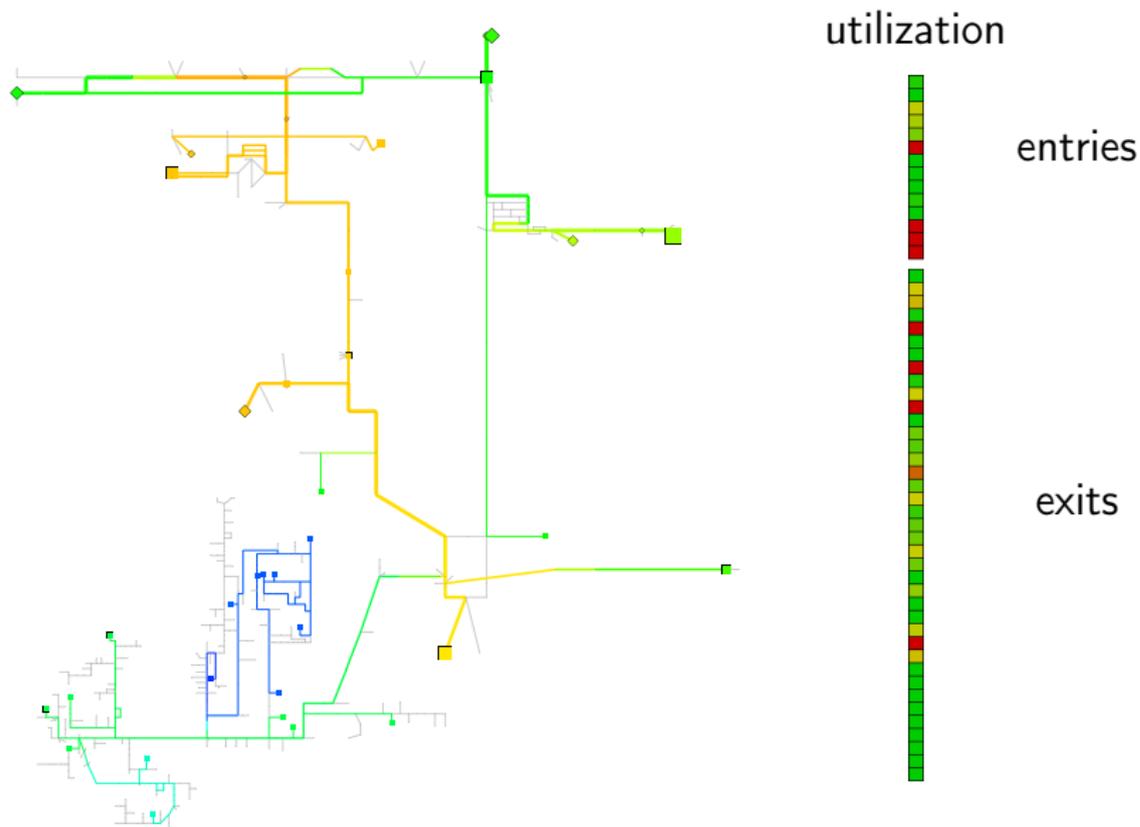


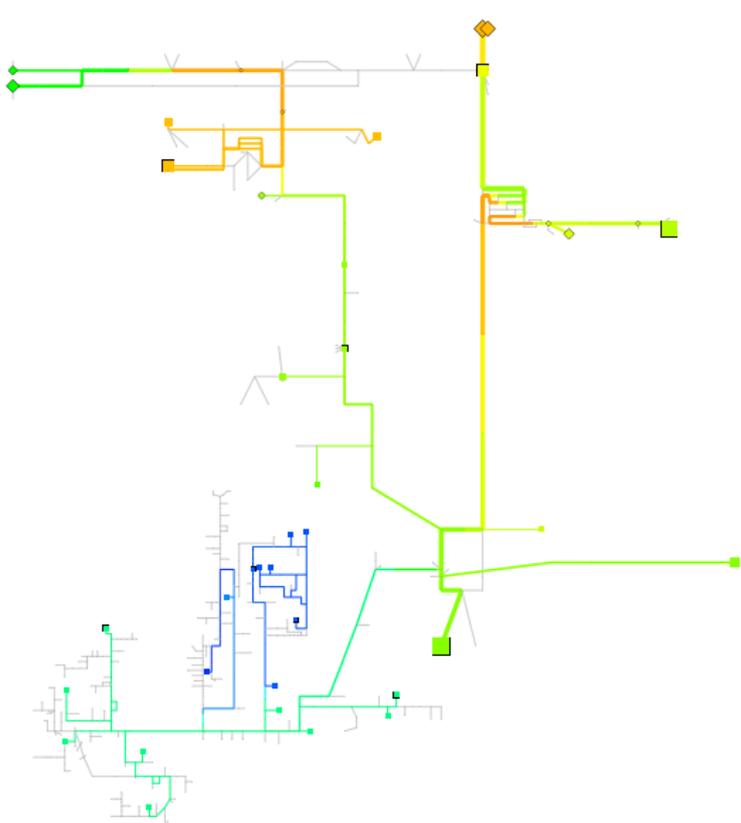


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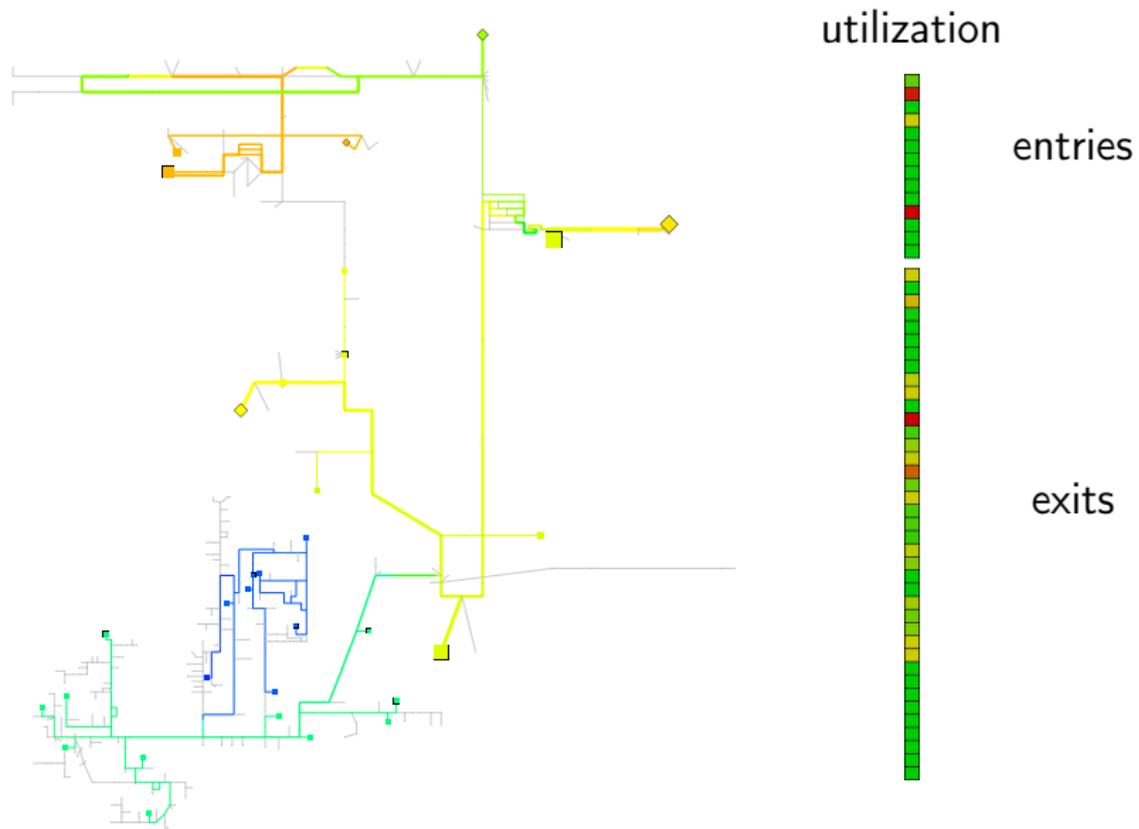


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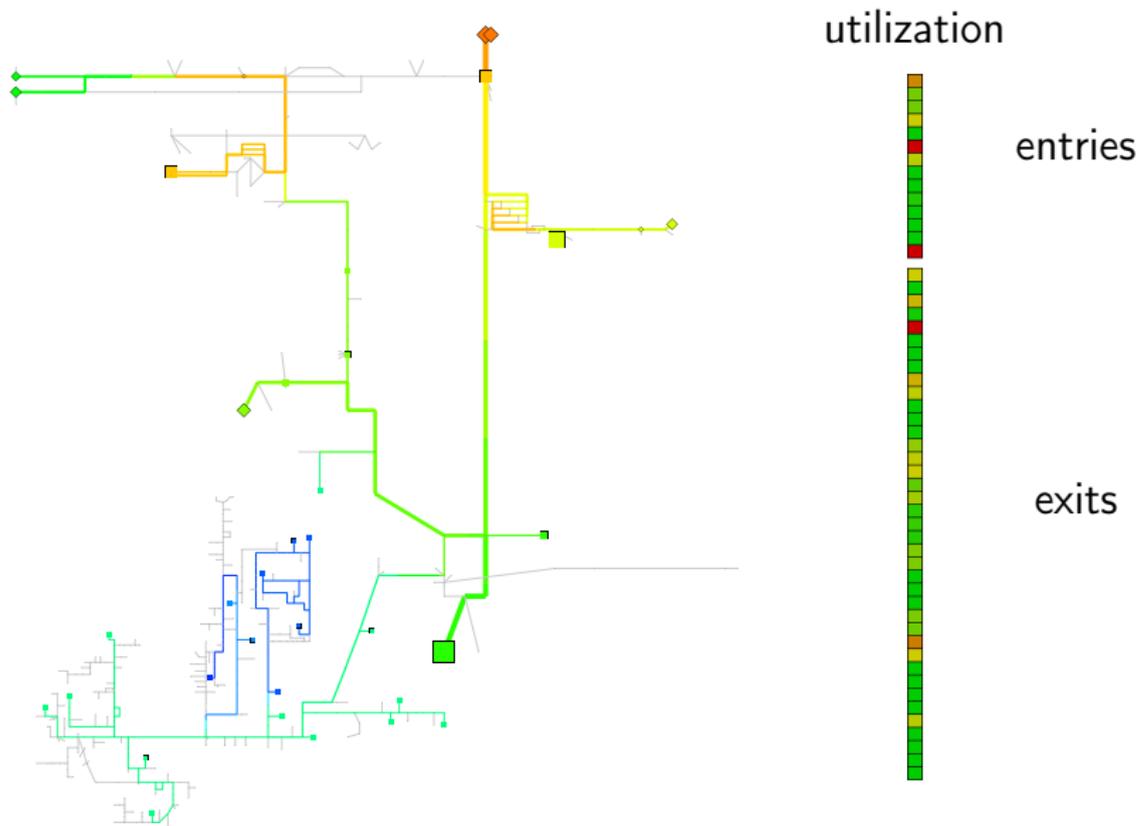


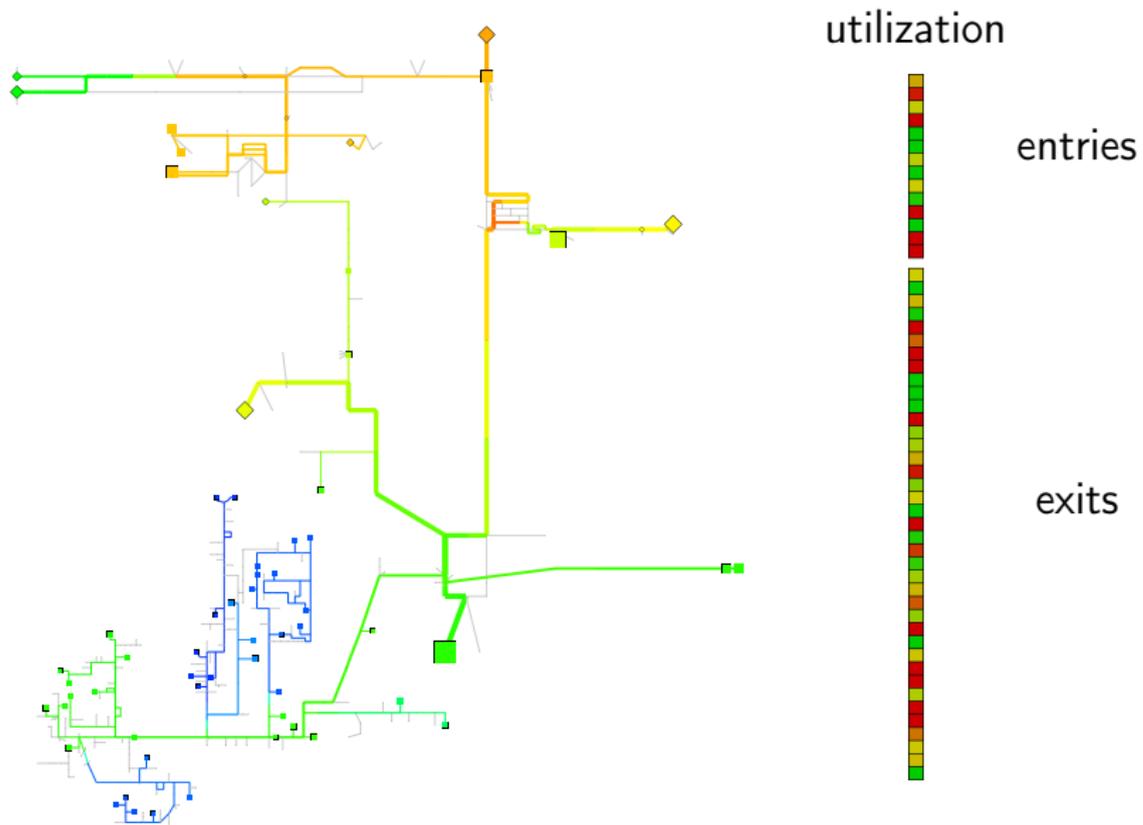
entries

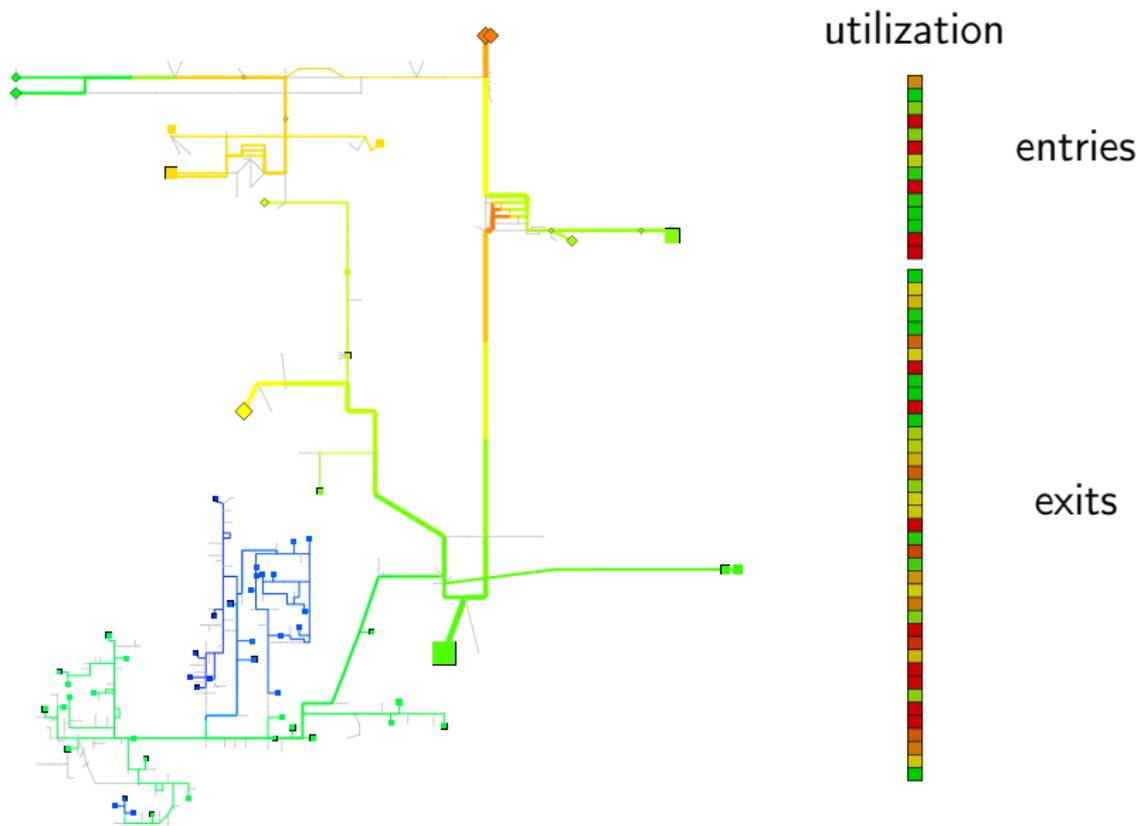
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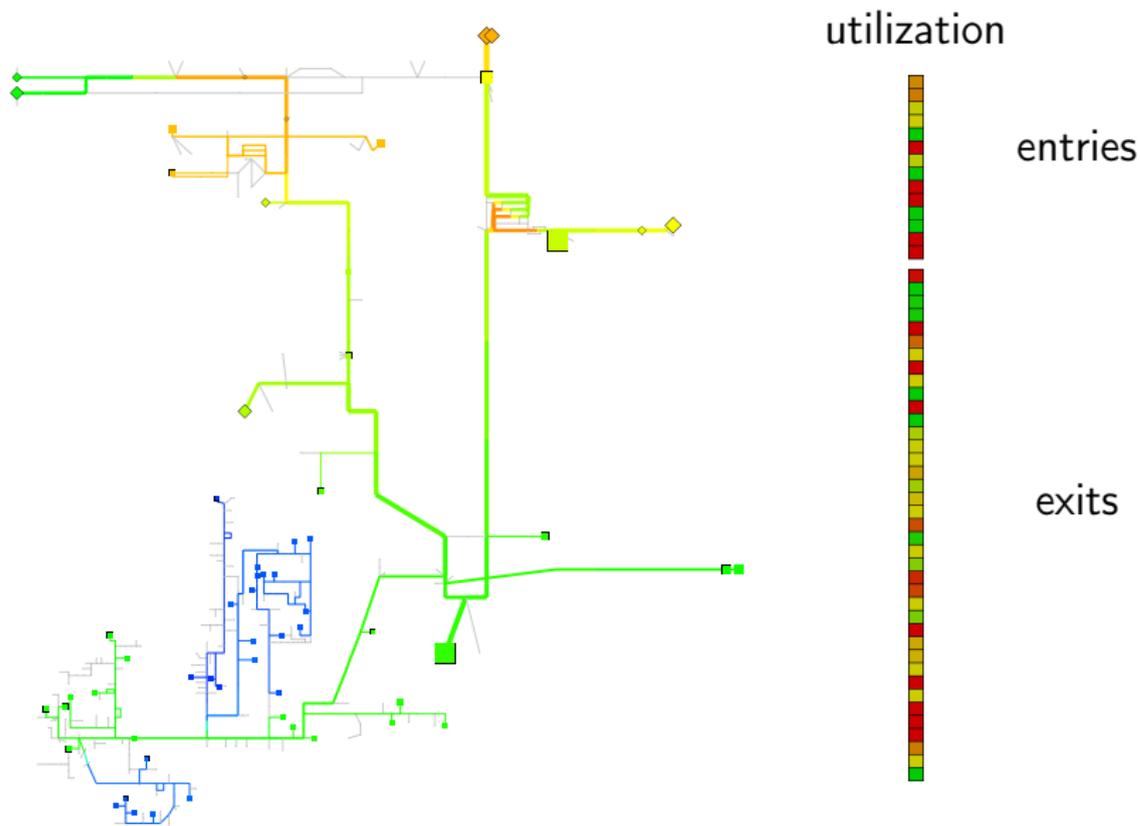


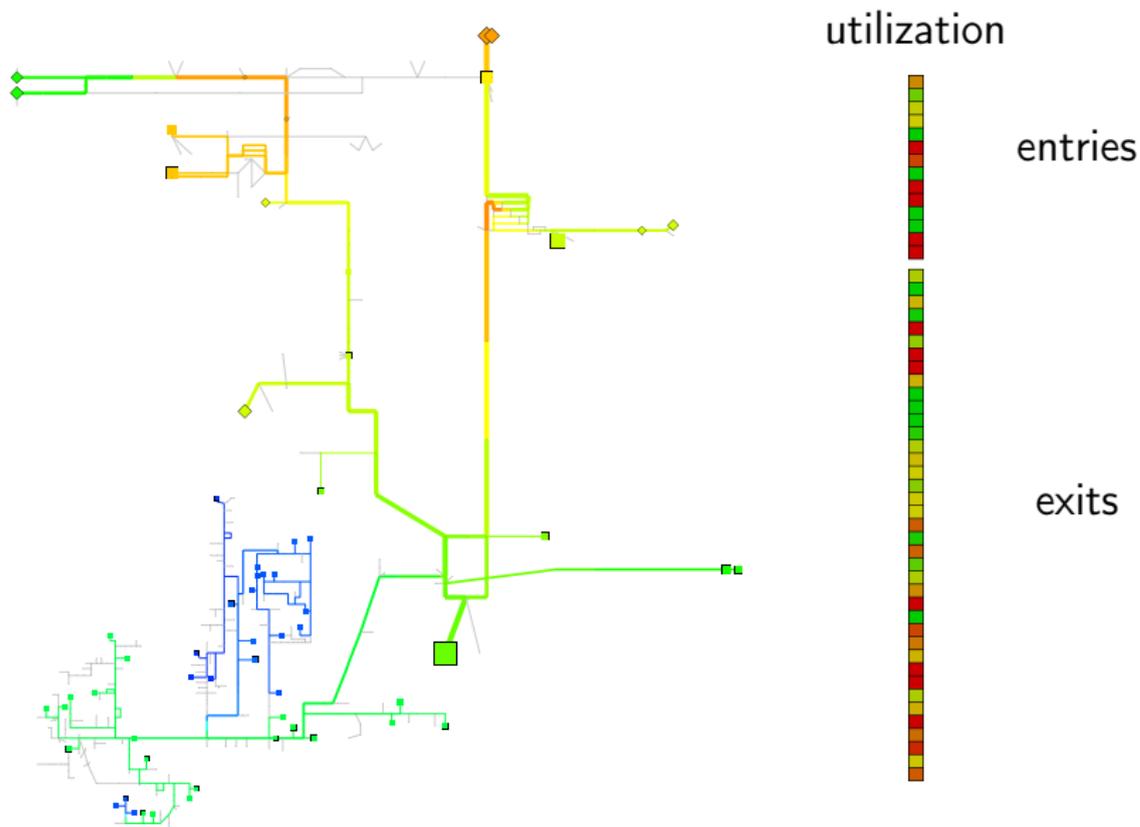
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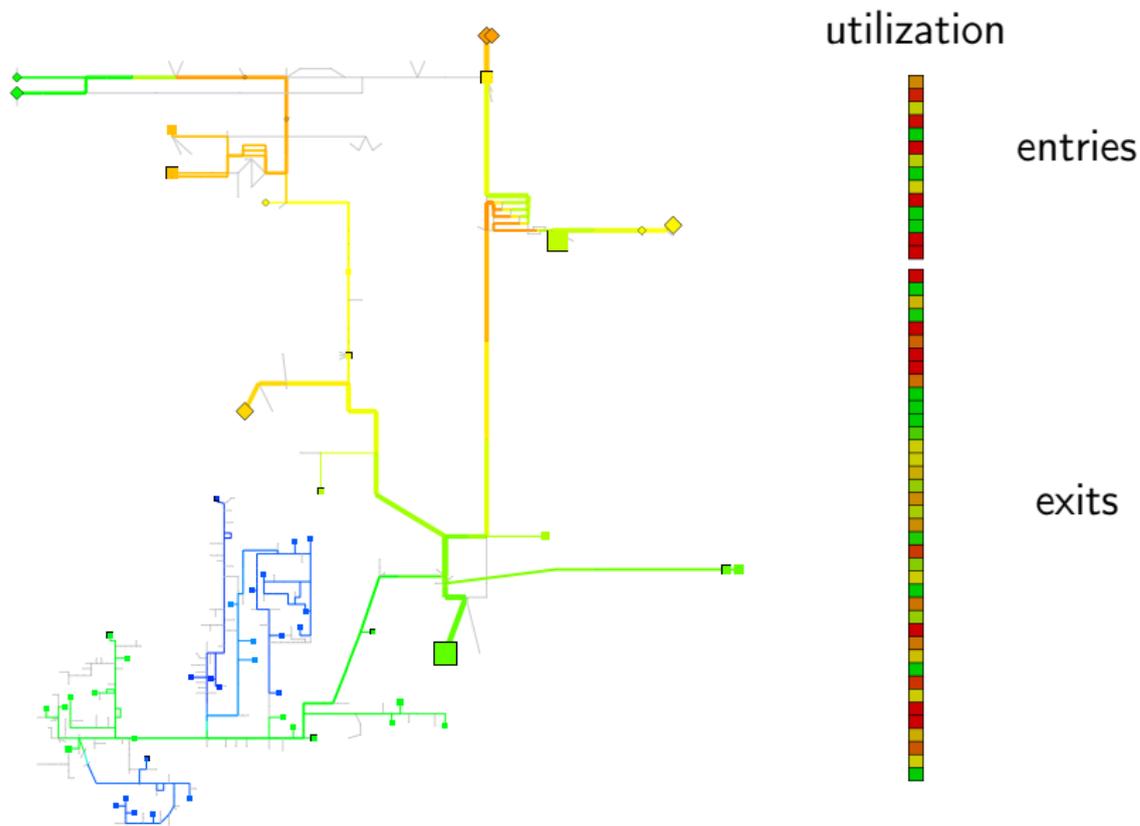


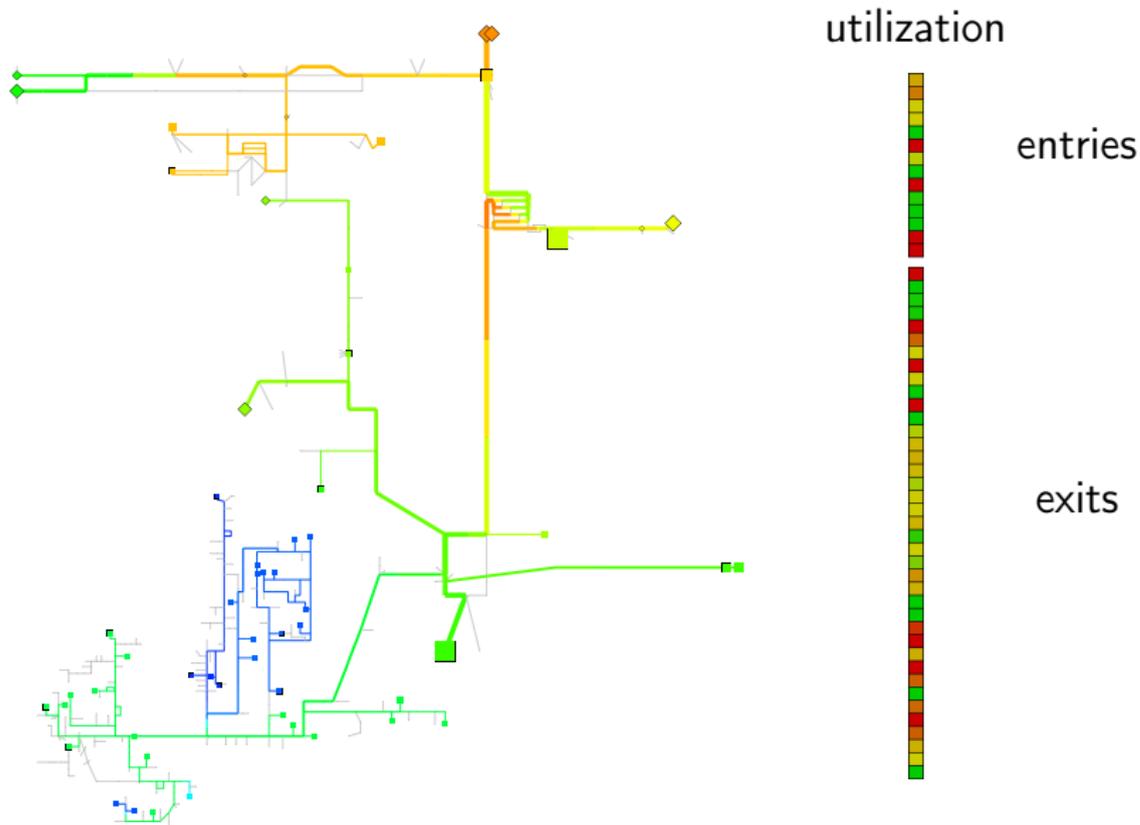


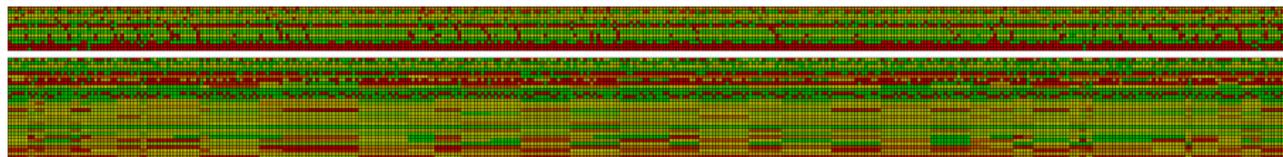
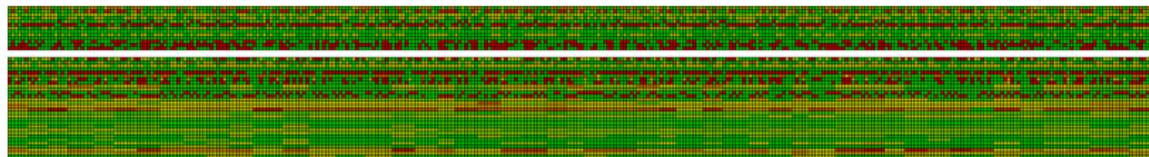












There are mathematically sound methods to reduce a large set of nominations to a much smaller **representative** set.

1 500 000 nominations  $\rightsquigarrow$  ca. 4 000 representative nominations



As usual:

Citius,  
Altius,  
Fortius

bigger networks,  
faster computations,  
higher precision

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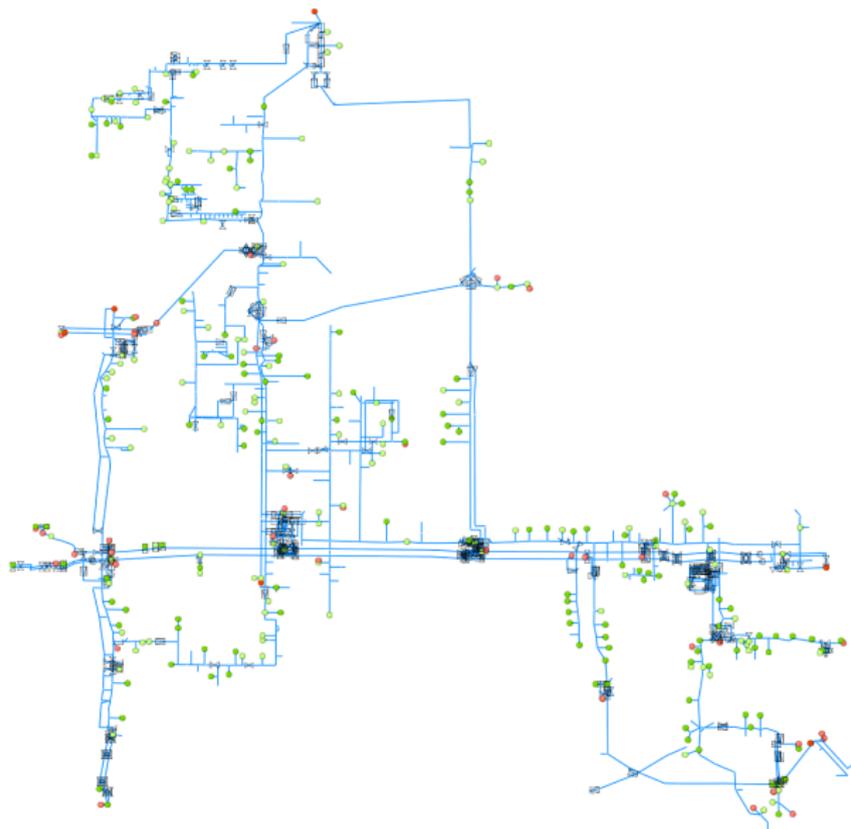
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- ▶ we should be able to handle *multi-scale networks*.

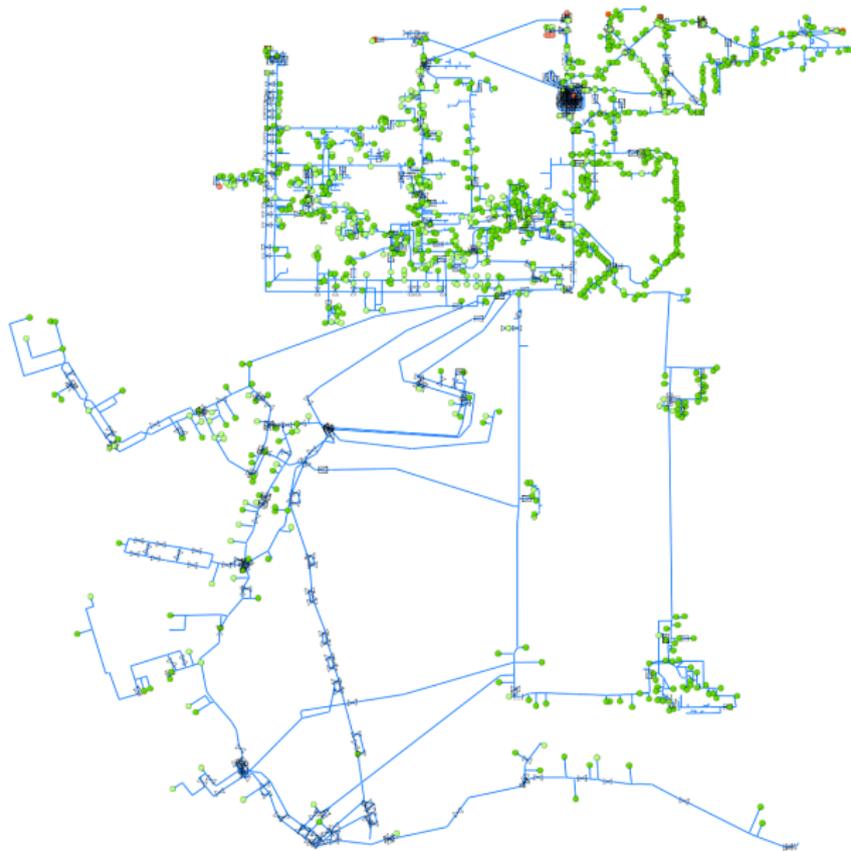
## H-Süd

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



## L-Gas

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





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- ▶ the setup cost is high compared to pure research,
- ▶ close cooperation with practitioners is necessary,
- ▶ different disciplines have to collaborate.

**How can we incorporate transient effects into stationary optimization models?**

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**Research on all levels –from basic theory to practical application– is needed to face future challenges!**

Thank you very much!