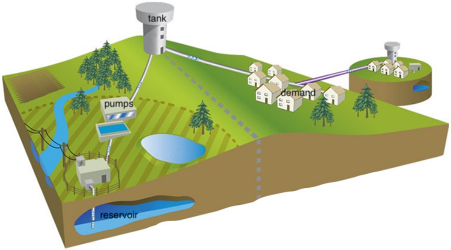
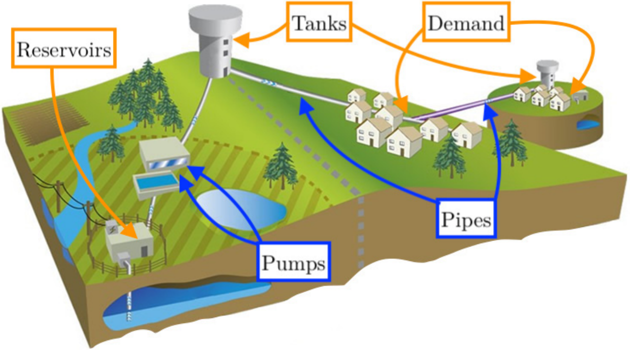
Extended LP formulation for pump scheduling in water distribution networks

Gratien Bonvin and Sophie Demassey (CMA, Mines ParisTech/PSL)



drinking water distribution network



- nodes: reservoirs J_R, tanks J_T, junctions (demand nodes) J_J
- arcs: pipes L, pumps K, valves V

operating water distribution networks

- tanks = storage: dissociate water pumping/supplying times

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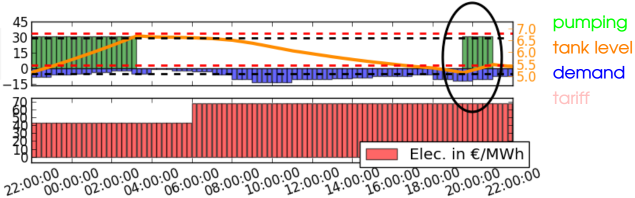

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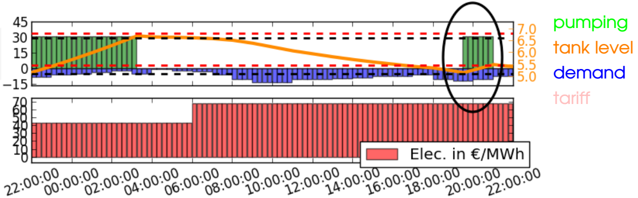

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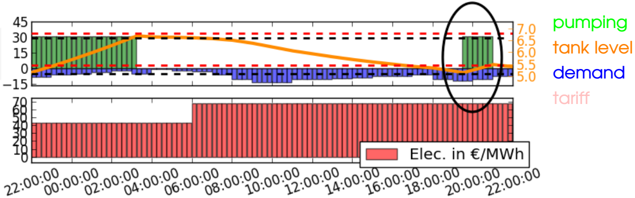

- the historic day/night strategy is not compatible with dynamic tariffs
- a highly **combinatorial** $O(2^{K.T})$, highly **non-convex** scheduling problem

non-convex flow/head relation

- minimum hydraulic head (elevation + pressure) required to supply a node

non-convex flow/head relation

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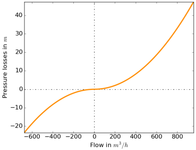
pipe: head loss



$$\Delta h = Aq|q| + Bq$$

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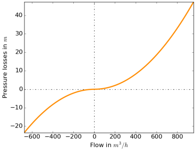

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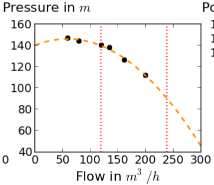

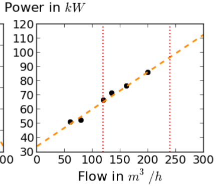

$$\Delta h = -Fq^2 + G, \qquad p = Cq + E$$

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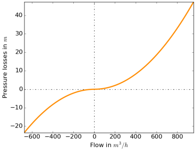

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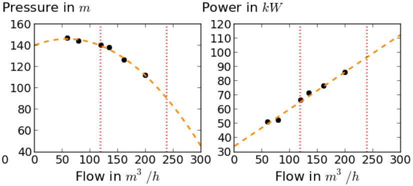

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- good news: at time t and demand $D_t \in \mathbb{R}^{J_J}$, given a pump configuration $X \in \{0,1\}^K$ and tank heads $H \in \mathbb{R}^{J_T}$, there is at most one possible flow/head $(q,h) \in \mathbb{R}^{L\times J}$ solution, which can quickly be computed with the Newton method (Todini-Pilati88).

two main solution approaches

relax the NL part of MINLP

$$
\begin{aligned}
&min \sum_{t\in T}\sum_{k\in K} C_t\Delta_t(C_k q_{kt} + E_k x_{kt}) && \\
&s.t. \sum_{ij\in L} q_{ijt} - \sum_{ji\in L} q_{jit} = D_{jt} && \forall t, j\in J_J \\
&\sum_{ij\in L} q_{ijt} - \sum_{ji\in L} q_{jit} = \frac{S_j}{\Delta_t}(h_{jt} - h_{j(t-1)}) && \forall t, j\in J_T \\
&\boxed{(h_{jt} - h_{it} + F_{ijt}q_{ijt}^2 + G_{ij})x_{ijt} = 0 \qquad \forall t, ij\in K} && \\
&\boxed{h_{it} - h_{jt} = A_{ij}|q_{ijt}|q_{ijt} + B_{ij}q_{ijt} \qquad \forall t, ij\in L_P} && \\
&H_j^{\min} \le h_{jt} \le H_j^{\max} && \forall t, j\in J_T \\
&q_{kt} \le Q_k^{\max} x_{kt} && \forall t, k\in K \\
&x_{kt} \in \{0,1\} && \forall t, k\in K
\end{aligned}
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PWL approximation (MORSI12,MENKE16,...)

convex relaxation (BONVIN17,BONVIN19)

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separate feasibility/optimization

choose configurations

$\downarrow\uparrow$

simulate hydraulics

metaheuristics, ex: GA (MACKLE95,...),

Benders decomposition (NAOUM15),

lagrangian relaxation (GHADDAR15)

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PWL approximation (MORSI12,MENKE16,...)

convex relaxation (BONVIN17,BONVIN19)

- many binaries

separate feasibility/optimization

choose configurations

↓ ↑

simulate hydraulics

metaheuristics, ex: GA (MACKLE95,...),

Benders decomposition (NAOUM15),

lagrangian relaxation (GHADDAR15)

- slow convergence

model decomposition

the compact model

$$\begin{aligned}
& min \sum_{t\in T}\sum_{k\in K} C_t\Delta_t(C_k q_{kt} + E_k x_{kt}) && \\
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\end{aligned}$$

- min pump power consumption
- flow conservation at junctions
- flow conservation at tanks
- head increase by pumps
- head losses in pipes
- tank capacities
- pump capacities
- pumps on/off

model decomposition

the compact model

$$\min \sum_{t \in T} \sum_{k \in K} C_t \Delta_t (C_k q_{kt} + E_k x_{kt})$$

$$\text{s.t.} \sum_{ij \in L} q_{ijt} - \sum_{ji \in L} q_{jit} = D_{jt} \qquad \forall t, j \in J_J$$

$$\boxed{\sum_{ij \in L} q_{ijt} - \sum_{ji \in L} q_{jit} = \frac{S_j}{\Delta_t}(h_{jt} - h_{j(t-1)}) \qquad \forall t, j \in J_T}$$

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- time coupling constraints

- min pump power consumption
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rewrite one-time steps

$$
\begin{aligned}
& min \sum_{t\in T}\sum_{k\in K} C_t\Delta_t(C_k q_{kt} + E_k x_{kt}) & \\
& s.t.\ h_{jt} - h_{j(t-1)} = \frac{\Delta_t}{S_j}(\sum_{ij\in L} q_{ijt} - \sum_{ji\in L} q_{jit}) & \forall t, j \in J_T \\
& (x_t, q_t, h_t) \in \mathcal{S}_t & \forall t
\end{aligned}
$$

- $\mathcal{S}_t$ set of feasible pump/flow/head configurations to supply demand D_t

model decomposition

compact model

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extended model

$$\min \sum_{t\in T}\sum_{s\in\mathcal{S}_t} C_t P^s \Delta_t y_{st}$$

$$\text{s.t. } h_{jt} - h_{j(t-1)} = \sum_{s\in\mathcal{S}_t} R_j^s \Delta_t y_{st} \qquad \forall t, j \in J_T$$

$$h_{jt} = \sum_{s\in\mathcal{S}_t} H_j^s y_{st} \qquad \forall t, j \in J_T$$

$$\sum_{s\in\mathcal{S}_t} y_{st} = 1 \qquad \forall t$$

$$y_{st} \in \{0, 1\} \qquad \forall t, s \in \mathcal{S}_t$$

- $P \in \mathbb{R}$ power consumption, $R \in \mathbb{R}^{J_T}$ tank filling rate, $H \in \mathbb{R}^{J_T}$ tank head
- $|\mathcal{S}_t| = \infty$ but from (Todini&Pilati88):
- (at most) one $s \in \mathcal{S}_t$ for each $x_t \in \{0,1\}^K$ and $h_t \in [H_t^{\min}, H_t^{\max}] \subseteq \mathbb{R}^{J_T}$

proposed approximation

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- relax the integrality constraints

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- relax the integrality constraints
- relax the head/configuration linking constraint

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$$\min \sum_{t \in T} \sum_{s \in \mathcal{S}'_t} C_t P^s \Delta_t y_{st}$$

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- relax the integrality constraints
- relax the head/configuration linking constraint
- restrict to columns $s \in \mathcal{S}'_t \subseteq \mathcal{S}_t$ with $H_j^s = \frac{H_j^{\max} - H_j^{\min}}{2}, \forall j \in J_T$

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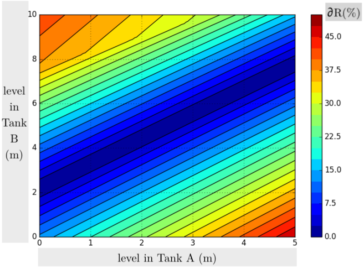
- a reasonable assumption as tanks tend to be equally filled at optimality

ex: relative errors on R and P for ≠ levels in tanks A and B in (Van Zyl)



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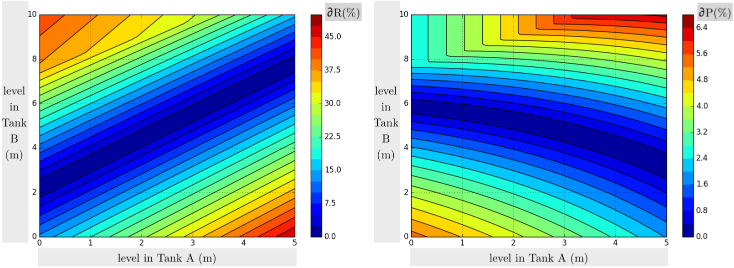

- $|\mathcal{S}'_t| < 2^{|K|}$ AND can be computed **efficiently**

generating $\mathcal{S}'_t$

- apply Newton method: fix $D_t \in \mathbb{R}^{J_J}$ and $H_t \in \mathbb{R}^{J_T}$, then compute Q^s then (P^s, R^s) (if feasible) for all $X^s \in \{0, 1\}^K$

generating S'_t

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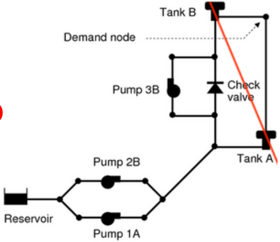
- example: Van Zyl network has 2 components:

$|K \cup V| = 4, |J_J| = 0$



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solve $2^4 + |T|$ flows to generate $2^4.|T|$ columns (max)

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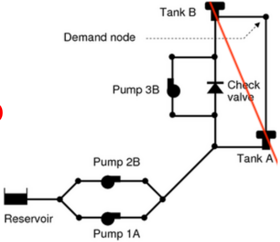

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- symmetry breaking: $D_{t_1} = D_{t_2} \Rightarrow \mathcal{S}'_{t_1} = \mathcal{S}'_{t_2}$

generalization

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- choose the sampling step carefully

$N_k + 1$	2	3	4	5	6	7	8	9	10
$\lvert\mathcal{S}'_t\rvert$	21	52	105	186	301	456	657	910	1221
Z'	244.44	242.15	215.62	215.34	217.50	213.95	211.70	212.97	212.20

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Z'	244.44	242.15	215.62	215.34	217.50	213.95	211.70	212.97	212.20

- also for pressure-reducing valves: either open or pressure reduction $p_v \in [p_v^{\min}, p_v^{\max}]$

approximated solution

- solve the extended LP model and get for each time t the active configurations $C_t^* = \{s \in \mathcal{S}'_t \mid y_{st} > 0\}$ of durations $\delta_s^* = \Delta_t y_{st}$.
  Order each set C_t^* arbitrarily and get an approximated pumping plan:

$$P^* = \underbrace{s_0, s_1, \dots, s_{n_0}}_{C_0^*}, \underbrace{s_{n_0+1}, \dots, s_{n_0+n_1}}_{C_1^*}, \dots, \underbrace{\quad \dots \quad}_{C_{T-1}^*}$$

- start with $i = 0$, apply the Newton method to s_i with $H_i \in \mathbb{R}^{J_T}$ to get the actual flow rates Q_i, then compute the filling rates R_i and update tank heads $H_{i+1} = H_i + \delta_i R_i$.
- plan P^* is *valid* if $H^{\min} \leq H_i \leq H^{\max}$ for all i

to a close feasible solution

- each pump can be switched at any time... not in any old way
- operational constraints to prevent premature aging, e.g
  N max nb of switches on, τ_0/τ_1 max nb of consecutive times off/on

$$
\begin{aligned}
&\sum_{t\in\mathcal{T}} y_{kt} \le N, && \\
&y_{kt} \ge x_{kt} - x_{k(t-1)}, && \forall t \\
&x_{kt'} \ge y_{kt}, && \forall t, t' \in [t, t+\tau_1] \\
&z_{kt} \ge x_{k(t-1)} - x_{kt}, && \forall t \\
&x_{kt'} \le 1 - z_{kt}, && \forall t, t' \in [t, t+\tau_0]
\end{aligned}
$$

- find a **feasible** plan P (with one configuration per time step, satisfying tank capacities and operational constraints) at a close distance of P^*
  i.e. with $\delta_{kt} \approx \delta^*_{kt}$, the activity duration of pump k in time step t

combinatorial Benders local search

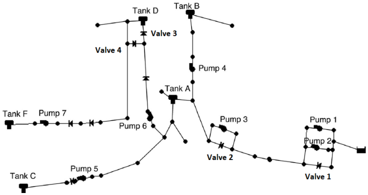
- solve (M) : $\min \sum_k \sum_t (\delta^*_{kt} - x_{kt}\Delta_t)^2 + \sum_{k\in K}(\sum_t \delta^*_{kt} - \sum_t x_{kt}\Delta_t)^2$
  s.t.: (operational constraints), $x \in \{0,1\}^{K\times T}$
- apply Newton method iteratively on each configuration x_t, $t = 0, \dots, T-1$, and get the actual flows-heads (Q, H)
- if some constraint is violated at time $\bar{t}$, add to (M) a no-good constraint

$$\sum_{t=1}^{\bar{t}} \left(\sum_{\substack{k\in K \\ X_{kt}=0}} x_{kt} + \sum_{\substack{k\in K \\ X_{kt}=1}} (1 - x_{kt}) \right) \geq 1$$

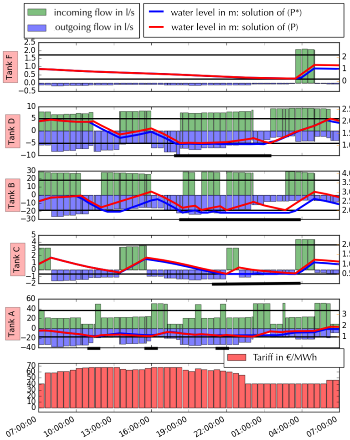
- try to correct the small violations by adjusting the time step durations Δ_t using the matheuristic from (Bonvin-Demassey-Lodi19)

computational results

near-feasible approximated solutions P^*

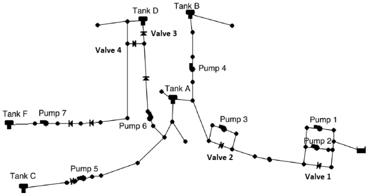


- Poormond instance (GHADDAR15)

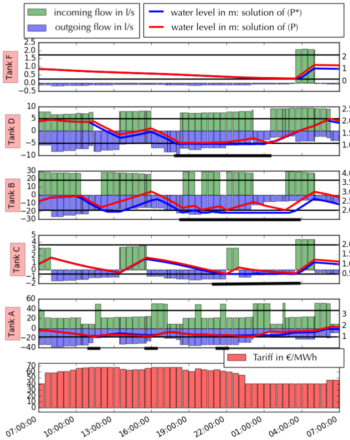


computational results

near-feasible approximated solutions P^*



- Poormond instance (GHADDAR15)
- average relative error on $Q < 1\%$



computational results

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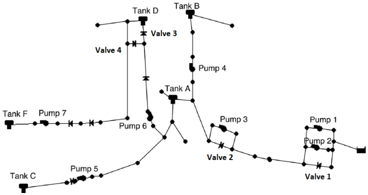
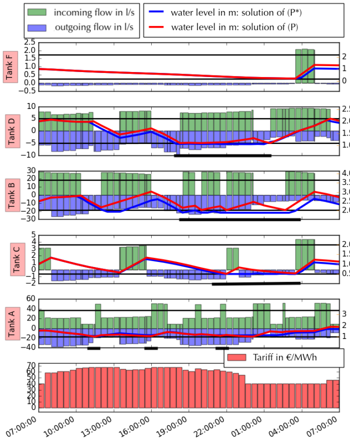
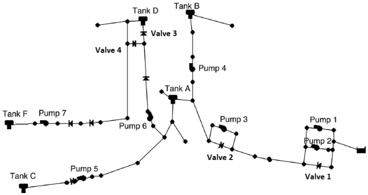


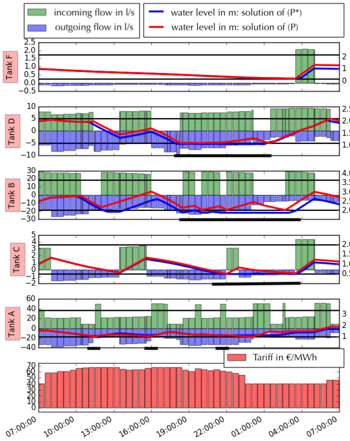


- Poormond instance (Ghaddar15)
- average relative error on $Q < 1\%$
- 3% (104) active columns for $|T| = 48$

computational results

near-feasible approximated solutions P^*

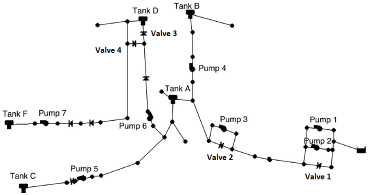


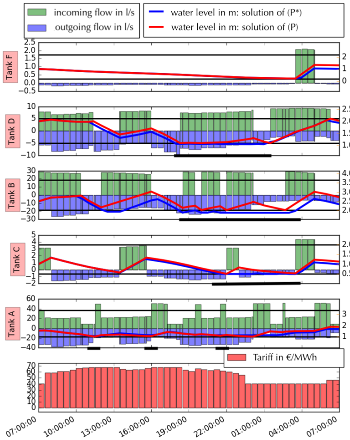


- Poormond instance (GHADDAR15)
- average relative error on $Q < 1\%$
- 3% (104) active columns for $|T| = 48$
- aging constraints are mostly satisfied

computational results

near-feasible approximated solutions P^*





- Poormond instance (GHADDAR15)
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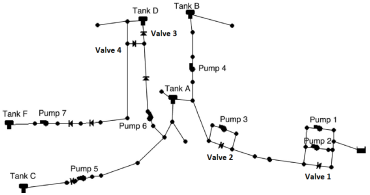
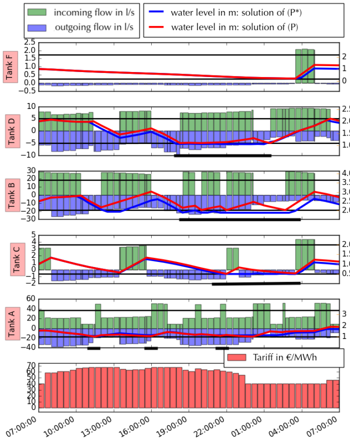
- feasible P in 1 iteration (LS + heuristic)

computational results

near-feasible approximated solutions P^*



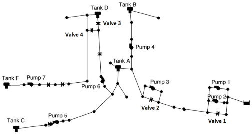


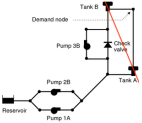
- Poormond instance (GHADDAR15)
- average relative error on $Q < 1\%$
- 3% (104) active columns for $|T| = 48$
- aging constraints are mostly satisfied
- feasible P in 1 iteration (LS + heuristic)
- $Z = 111.03, Z^* = 117.5$ euros

computational results

fast heuristic

	Computation time (s)				Cost (euros)			
Day	S'	LP	LS	Total	LS	best	LS/LB	best/LB
Poormond								
P21	1.6	<0.1	16.3	17.9	117.50	**112.48**	8.2%	4.1%
P22	1.6	<0.1	11.2	12.8	118.55	**116.49**	5.6%	3.9%
P23	1.6	<0.1	8.0	9.6	**120.93**	**120.85**	4.1%	4.0%
P24	1.6	<0.1	10.9	12.5	137.05	**134.99**	4.6%	3.1%
P25	1.6	<0.1	21.2	22.8	98.74	**92.53**	9.8%	3.8%
Van Zyl								
Z21	2.1	<0.1	0.7	2.8	**220.60**	222.66	14.9%	15.7%
Z22	2.1	<0.1	1.7	3.8	**230.07**	**230.69**	14.1%	14.3%
Z23	2.1	<0.1	1.4	3.5	**240.67**	**240.93**	13.7%	13.8%
Z24	2.1	<0.1	0.6	2.6	**267.77**	268.91	14.4%	14.7%
Z25	2.1	<0.1	0.7	2.8	**188.52**	190.29	14.5%	15.3%





- best and LB computed in 1h with LP/NLP branch and check (Bonvin19)
- Van Zyl (sampling 6 speeds/3 pumps, 1 valve, $|T| = 48$)
  - $6^3 \times 2 \times 48 \approx 20,000$ configurations to evaluate
  - network decomposition: $6^3 \times 2 + 48 = 480$ to compute
  - P^*: 50 active configurations
  - get P by solving the compact NLP with fixed X

limits and perspectives

- evaluate the method on bigger networks: where are the instances ?

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limits and perspectives

- evaluate the method on bigger networks: where are the instances ?
- still an exponential number of configurations to compute: could we build $\mathcal{S}'_t$ from historical data ?
- no optimality certificate: how to integrate the approximated model into a global optimization approach ?