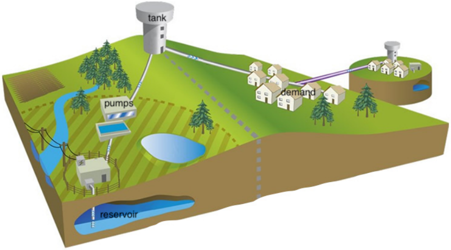
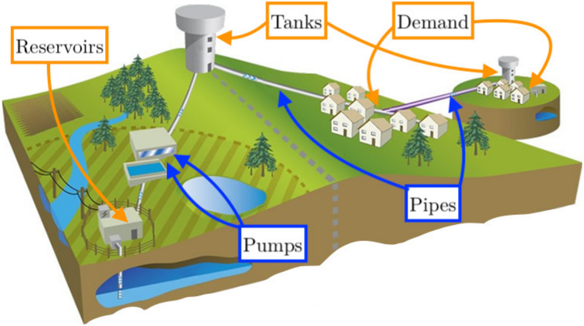
Robust design of pumping stations in water distribution networks

Gratien Bonvin, Sophie Demassey, Welington de Oliveira (CMA, Mines ParisTech/PSL)



drinking water distribution networks



- deliver the water from reservoirs to clients with time-varying demand at minimum hydraulic head (pressure+elevation)

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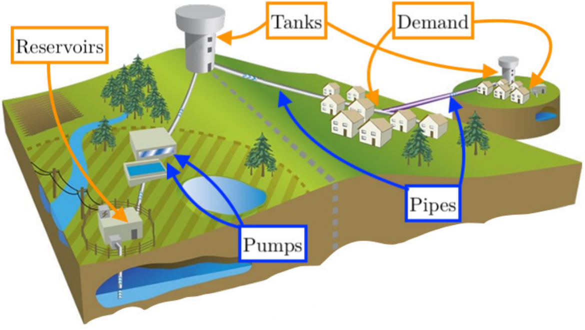

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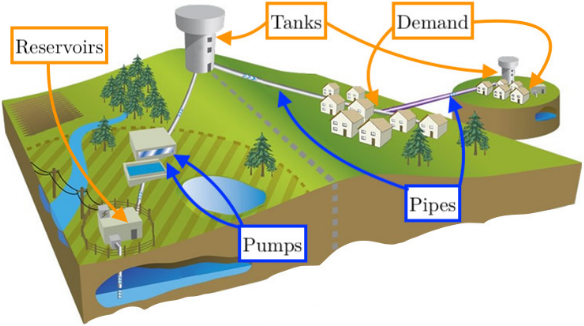

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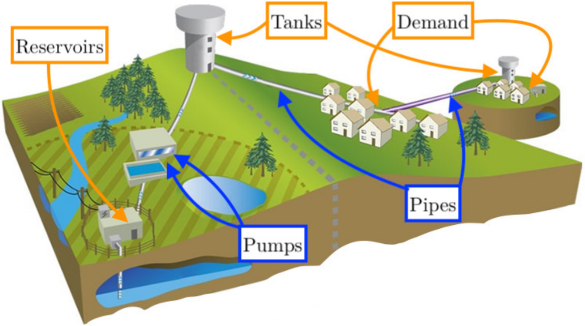

- deliver the water from reservoirs to clients with time-varying demand at minimum hydraulic head (pressure+elevation)
- head increase through pumps and power consumption
- tanks to secure the water supply (e.g. when pumps are off)
- head losses through pipes due to friction

operating water distribution networks

- pump scheduling: given profiles of water demand and electricity tariff on a horizon T (resolution of 1h or 2h), decide when to switch on/off pumps K in order to satisfy the demand and the tank capacities at any time and to minimize energy costs

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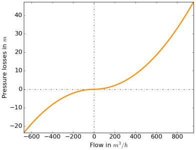

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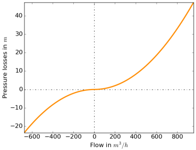

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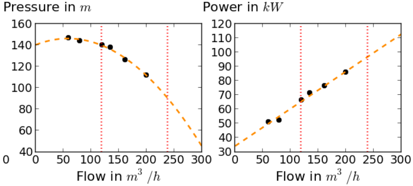
pump: head increase + power



$$\Delta h = -Gq^2 + H, \qquad p = Cq + E$$

designing water distribution networks

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  - **simplifications are required !**

approximated pump scheduling

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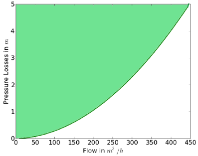
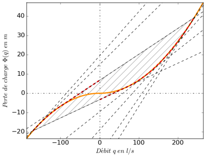
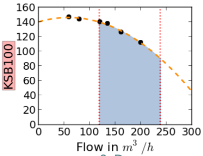
- decompose T: relax the inter-day storage constraints (fix storage at 12PM)
- relax the integrality and non-convex constraints: relax equalities or generate a tight polyhedral outer approximation (Bonvin19)

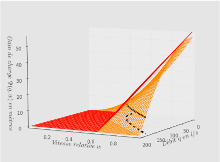
pipes: one-direction / bi-direction





pumps: fixed-speed / variable-speed

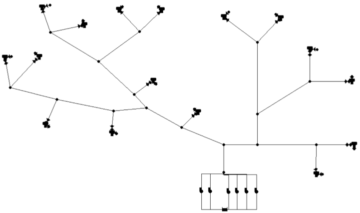




convex continuous relaxation

		T=12			T=24			T=48		
	Day	UB	LB	Gap	UB	LB	Gap	UB	LB	Gap
Simple FSD	21	inf	163.4	-	155.1	146.8	5.4%	150.9	145.9	3.3%
	22	inf	166.9	-	159.1	151.8	4.6%	155.7	150.2	3.5%
	23	inf	180.7	-	172.4	164.6	4.5%	168.5	162.8	3.4%
	24	inf	189.5	-	181.7	171.3	5.7%	176.0	170.3	3.2%
	25	inf	160.4	-	147.8	139.6	5.5%	145.5	139.7	4.0%
AT (M)	21	766.3	718.1	6.3%	733.2	719.0	1.9%	731.8	719.1	1.7%
	22	796.4	708.4	11.0%	732.1	708.5	3.2%	730.6	708.6	3.0%
	23	825.5	739.9	10.4%	761.5	740.6	2.7%	765.0	740.8	3.2%
	24	884.2	800.0	9.5%	822.9	800.8	2.7%	824.0	801.2	2.8%
	25	845.8	654.8	22.6%	690.6	656.3	5.0%	685.6	656.4	4.3%
Poormond	21	111.6	100.8	9.7%	109.0	99.6	8.6%	110.1	99.6	9.5%
	22	113.6	102.1	10.1%	113.0	101.1	10.5%	112.4	101.0	10.1%
	23	126.6	114.2	9.8%	125.2	112.9	9.8%	124.5	112.8	9.4%
	24	138.9	124.7	10.2%	136.3	123.2	9.6%	136.0	123.1	9.5%
	25	113.4	94.2	16.9%	94.2	85.2	9.6%	92.4	85.1	7.9%
Simple VSD	21	148.2	135.0	8.9%	146.8	117.8	19.8%	146.9	108.7	26.0%
	22	154.0	140.0	9.1%	152.4	122.8	19.4%	151.5	113.5	25.1%
	23	167.5	153.0	8.7%	165.1	134.9	18.3%	164.0	124.1	24.3%
	24	173.5	157.8	9.0%	172.2	138.1	19.8%	171.2	127.6	25.5%
	25	145.0	129.9	10.4%	139.8	111.2	20.5%	140.9	103.2	26.8%
DWG	21	3379.3	3263.0	3.4%	-	3228.1	-	-	3230.2	-
	22	3398.2	3274.1	3.7%	3420.6	3229.8	5.6%	-	- 3229.6	-
	23	3555.6	3419.6	3.8%	-	3376.4	-	-	3376.2	-
	24	3689.4	3458.7	3.8%	3737.5	3516.4	5.9%	-	3516.1	-
	25	3477.2	3122.2	10.2%	3312.7	3097.4	6.5%	3360.4	3097.4	7.8%
FRD	29.01				126.2	122.7	2.8%	127.5	122.7	3.8%
	27.03				138.4	132.5	4.3%	137.5	132.5	3.6%
	30.05				103.4	100.6	2.7%	103.9	100.6	3.2%
	26.07				216.4	200.6	7.3%	-	200.5	-
	28.09				105.9	100.5	5.1%	103.9	100.5	3.3%
	24.11				104.4	101.1	3.2%	103.6	101.1	2.4%

- lower bound computed after b&b presolve
- mean gap 9.5% to the best solution known
- for considered benchmark FRD: 4%



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Proposition: for branched networks as FRD, if $Q_k^{\min} = 0$ for each pump class k, then the binary pump operation variables can be aggregated per pump class and their integrality relaxed for the classes of pumps able to exceed the highest allowed head increase.

unfeasibility and dominance

- if a configuration with Y_k pumps in each class k is unfeasible then at least one more pump should be installed: $\sum_k y_{kY_k} \geq 1$ (feasibility cut) with $y_{kn} = 1$ if at least $n + 1$ pumps of class k are installed

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- filtering the initial list: start from a median configuration and check feasibility; if unfeasible proceed as above, otherwise remove all dominating configurations in the upper list

Benders decomposition

1. initialize $\mathcal{F} = \mathcal{F}_0, \mathcal{O} = \emptyset, UB = +\infty$
2. solve the master program, get y^* and $LB = \sum_{k,n} I_k y^*_{kn} + z^*$

$$
\begin{aligned}
& min_{y \in \{0,1\}^{K\bar{N}}, z \geq 0} \sum_{k,n} I_k y_{kn} + z & \\
& s.t.\ y_{kn} \geq y_{kn+1}, & \forall k, n \\
& z \geq c(Y) + s(Y)(y - Y), & \forall Y \in \mathcal{O} \\
& \sum_{k \in K} y_{kY_k} \geq 1, & \forall Y \in \mathcal{F}
\end{aligned}
$$

3. check configuration y^* on the critical days, if unfeasible add to $\mathcal{F}$ with all the identified dominated maximal configurations
4. otherwise, get the operation cost $c(y^*)$ and a subgradient $s(y^*)$ of c at y^* by solving the relaxed daily pump scheduling NLPs and add y^* to $\mathcal{O}$; update $UB = \min(UB, \sum_{k,n} I_k y^*_{kn} + c(y^*))$
5. stop if $UB - LB \leq \epsilon$, otherwise iterate

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- comparison with the configuration currently installed: 5 pumps instead of 6, reference power drops from 127 to 66 kW, optimal operation costs reduced by 25%

conclusion and perspectives

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- the method is generic but some improving features (dominance, relaxation) are specific
- extension to the pump+pipe design ? generalization to wider classes of networks ?