A heuristic approach to the water networks pumping scheduling issue

Gratien Bonvin, Alfredo Samperio, Claude Le Pape, Vincent Mazauric, Sophie Demassey, Nadia Maïzi

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 75 (2015) 2846 – 2851

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

A heuristic approach to the water networks pumping scheduling issue

Gratien Bonvin[a,b]*, Alfredo Samperio[b], Claude Le Pape[b], Vincent Mazauric[b,a], Sophie Demassey[a], Nadia Maïzi[a]

[a]Centre for Applied Mathematics, MINES ParisTech, PSL* Research University, BP 207, 06902 – Sophia Antipolis, France
[b]Schneider Electric, Strategy & Technology, 38TEC, 38050 – Grenoble cedex 9, France

Abstract

In order to improve the efficiency of drinking water networks, we develop a model for branched configurations of pipes, which optimizes pumping scheduling by taking into account electricity tariffs, pumps characteristics and network constraints on a daily basis. We estimate a 10% discount in the energy bill, an amount which depends strongly on the characteristics of the network under study and the quality of the current strategy.

Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: water distribution network, pumping scheduling, mathematical optimization.

1. Introduction

Drinking water networks are linked to two current issues, namely water resources management and the integration of renewable energies.

- According to the World Bank [1], water demand is set to grow in all parts of our world; from 2005 to 2030, the projected increase ranges from 43% in North America to 283% in Sub-Saharan Africa. Thus, because water loss rates can be significant and frequently exceed 30% [2], it will become more and more important to increase the efficiency of the water distribution chain in order to improve the ratio between withdrawals and final consumption.
- The intermittent nature of most renewable energies makes it more complex to equilibrate supply and demand. On the one hand, because of feed-in tariffs, when renewable electricity production is high and

* Corresponding author. Tel.: +33 4 97 15 70 95; fax: +33 4 93 95 74 46.
E-mail address: gratien.bonvin@mines-paristech.fr

Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.569

electricity demand is low, electricity tariffs can fall below zero. On the other hand, electricity peak demand increases continuously [3]. Water tanks can store water and therefore a water network is able to adapt its pumping scheduling [4,5,6] in line with electricity market conditions and bring some flexibility to the electricity market.

In order to improve the efficiency of drinking water networks, we develop a method dedicated to minimizing the electricity costs incurred by pumps on a daily basis. In addition to a direct drop in the energy bill, our tool is designed to take advantage of the increase in intermittent energy production using water storage capacities under operation.

In the next section, we introduce the main physical aspects related to water networks.

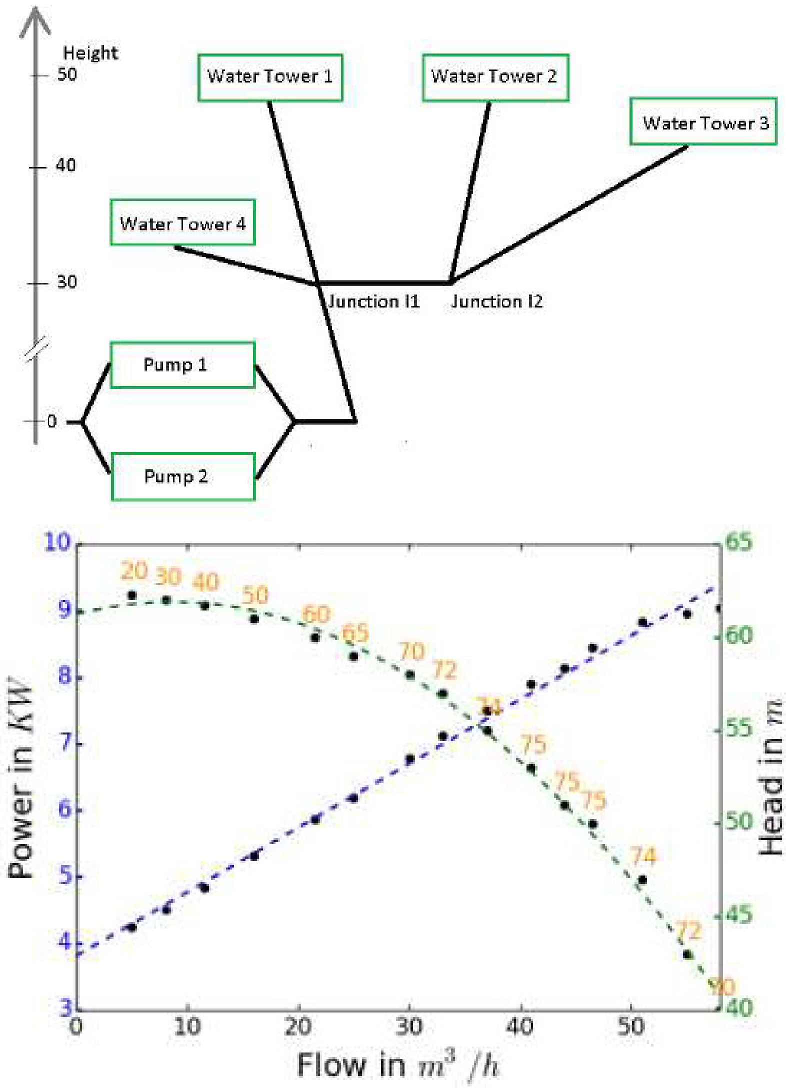

Fig. 1. (top) Drinking network under study; (bottom) Characteristics of the pumps.
Numbers along the curve show the efficiency (in %) of the pump according to the flow.

2. A heuristic approach to the water networks pumping scheduling issue

The goal of the pumping scheduling issue is to manage a set of pumps in a water network in order to minimize the associated total energy costs. As depicted in Fig. 1, the electricity consumption of a pump can easily be well divided into two parts:

- a fixed charge for the pump ignition; and
- an additional charge linear with the pumped flow.

Hence, the total energy cost associated with a set of pumping stations (*i,j*), each of which is equipped with a set of pumps *n*(*i,j*), over the time-horizon $[t_{start}, t_{end}]$ reads:

$$Z = \sum_{t=t_{start}}^{t_{end}} \sum_{(i,j)\in PS} \sum_{n(i,j)\in Pump} \frac{1}{H_{(i,j),n}} \left(\frac{\partial Power_{(i,j),n}(Q)}{\partial Q} q_{(i,j),n,t}^{Pump} \right) C_t^{Elec} \Delta t + \sum_{t=t_{start}}^{t_{end}} \sum_{(i,j)\in PS} \sum_{n(i,j)\in Pump} \frac{1}{H_{(i,j),n}} \left(Power_{(i,j),n}(Q=0) s_{(i,j),n,t}^{Pump} \right) C_t^{Elec} \Delta t \tag{1}$$

where:

- $q_{(i,j),n,t}^{Pump}$ is the flow associated with the pump (*i,j*),*n* during the time interval *t*, in m^3/h;
- $s_{(i,j),n,t}^{Pump}$ is the state (on/off) of the pump (*i,j*),*n* during the time interval *t*;
- $\partial Power_{(i,j),n}(Q)/\partial Q$ is the slope of the power function associated with the pump (*i,j*),*n*, in kWh/m^3;
- $Power_{(i,j),n}(Q=0)$ is the power associated with turning on the pump (*i,j*),*n*, in *kWh*;
- C_t^{Elec} is the electricity tariff, in Euro per *kWh*, during time interval *t*;
- $H_{(i,j),n}$ is the efficiency of the pump's motor (*i,j*),*n*, which we take to be constant for each pump; and
- Δt is the length of a time-step.

In order to satisfy the required water demand, several constraints have to be implemented. Firstly, the pressure in the network depends both on the topology and the flows. Indeed, for each pipe, the downward pressure is equal to the sum of the upward pressure, a hydrostatic component resulting from the height difference between the two points and a dynamic component due to pressure losses. It thus follows:

$$\forall (i,j) \in Pipe, \forall t \in [t_{start}, t_{end}]: \quad p_{j,t} \geq p_{i,t} + \Delta P_{(i,j)}^{Loss}(q_{(i,j),t}^{Pipe}) + \Delta P_{(i,j)}^{Hydro} \tag{2}$$

where:

- $p_{i,t}$ is the pressure at node *i* of the network during the time interval *t*;
- $\Delta P_{(i,j)}^{Loss}$ is a quadratic function of $q_{(i,j),t}^{Pipe}$ that estimates the pressure losses, where $q_{(i,j),t}^{Pipe}$ is the flow in the Pipe (*i,j*) during interval step *t*, in m^3/h;
- $\Delta P_{(i,j)}^{Hydro} = H_j - H_i$ is the hydrostatic component of the pressure and H_i is the altitude of node *i*.

Secondly, inflows match outflows for each node in the network:

$$\forall i \in Node, \forall t \in [t_{start}, t_{end}]: \quad \sum_{j\in Node} \left[q_{(j,i),t}^{Pipe} + \sum_{n(j,i)\in Pump} q_{(j,i),n,t}^{Pump} \right] = \sum_{k\in Node} q_{(i,k),t}^{Pipe} \tag{3}$$

Thirdly, because of the finite size of water towers and supply security constraints, we have to be careful that the stored volume of water constantly remains between a lower and upper threshold V_i^{Min} and V_i^{Max} for a given water tower *i*. Thus, we have to monitor the water volume $v_{i,t}$ stored within the water tower *i* at time *t*, given by the equality

$$\forall i \in WaterTower, \forall t \in [t_{start}, t_{end}]: \quad v_{i,t+\Delta t} = v_{i,t} + \Delta t \, q_{(j,i),t}^{Pipe} - WD_{i,t} \tag{4}$$

where $WD_{i,t}$ is the water demand at water tower *i* during the interval step *t*, in m^3.

Fourthly, we have to ensure that the pump is running ($s_{(i,j),n,t} = 1$) when the pumped flow is non-zero:

$$\forall (i,j), n \in Pump, \forall t \in [t_{start}, t_{end}]: \quad s_{(i,j),n,t} \geq \frac{q_{(i,j),n,t}^{Pump}}{Q_{(i,j),n}^{Max}} \tag{5}$$

where $Q_{(i,j),n}^{Max}$ is an upper threshold on the flows allowed by the pump (*i,j*),*n*. We choose to take the value of the flow when the discharge pressure is equal to the hydrostatic pressure.

Finally, as depicted in Fig. 1a, when we consider pumps with fixed-speed drives, for each discharge pressure, we are allowed to pump only one given flow. Thus, we can write that,

$$\forall (i,j), n \in Pump, \forall t \in [t_{start}, t_{end}]: \quad P_n(q_{(i,j),n,t}^{Pump}) \geq p_{j,t} - M\left(1 - s_{(i,j),n,t}\right) \tag{6}$$

where P_n is the head characteristic of the pump *n*, well-approximated by a quadratic function of $q_{(i,j),n,t}^{Pump}$ and *M* is an upper threshold on $p_{j,t}$.

Our modeling leads to a mixed-integer quadratic constrained program, encoded using Python language and the Gurobi solver [7]. While the time of resolution is acceptable for small networks, it is too long for the real-time instrumentation of a large network, typically a pumping station with 6 pumps and 20 water towers. With the aim of reducing the time of resolution, the full paper will present a heuristic based on a continuation method.

3. Results

This study raises several remarks (see Fig. 2):

- We tend to pump during the night, when electricity is cheaper.
- Looking at Figs. 1 and 2, the solution results in pump operating points that are close to the highest efficiency points (around 43 m^3/h).
- For Water Tower 2, we fill it separately during the first day because the pressure drops are significant at section Junction I2 - Water Tower 2 due to a small pipe diameter. The aim is to obtain a discharge pressure close to the hydrostatic pressure and thus to pump most efficiently during off-peak hours. With this strategy, only one pump is less efficient (Pump 2 between 0:00 am and 2:00 am). On the second day, pumping occurs with a constant and smooth flow into water tower 2 in order to avoid significant pressure losses.
- If we install variable speed drives, the total electricity charges will not be significantly reduced.

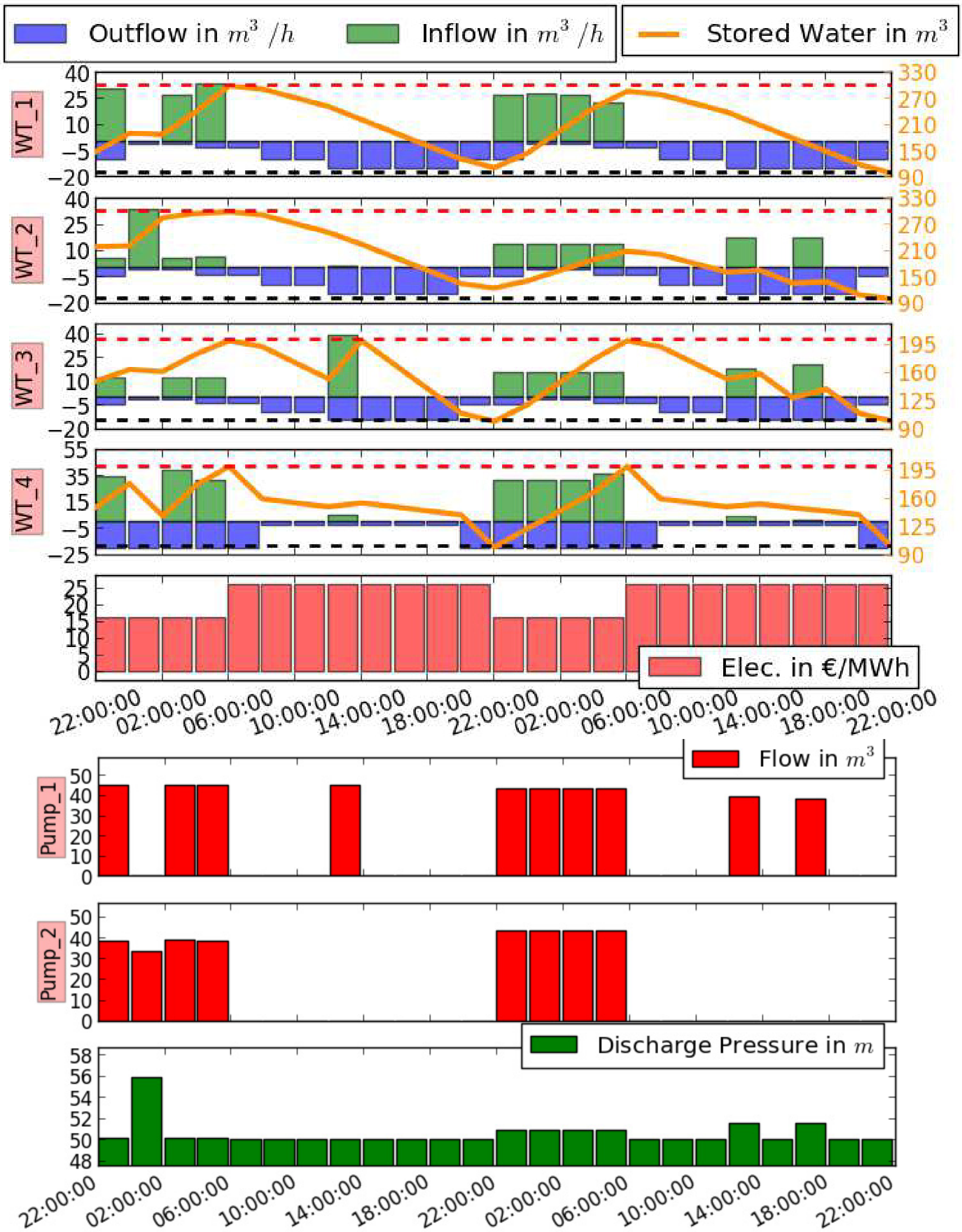

Fig. 2. For a two-day horizon:
(top) Evolution of the stored water volume for each water tower; (bottom) Pumping scheduling for each pump

4. Conclusion

We demonstrate our ability to manage a set of pumps in order to reduce the associated total electricity bill. We observe that, in some cases, variable speed drives do not significantly reduce energy costs if pumping is efficiently scheduled.

Next stage is now to address more complex water distribution networks to validate the relevance of our tool.

Acknowledgements

This work has been partially funded by the Artemis Arrowhead project under grant agreement number 332987 (Artemis/Ecsel Joint Undertaking, supported by the European Commission and French Public Authorities).

References

[1] Jacobsen M, Webster M, Vairavamoorthy K. *The Future of Water in African Cities: Why Waste Water?* Directions in Development, Washington DC: World Bank 2012.

[2] Araujo LS, Ramos H, Coelho ST. Pressure control for leakage minimisation in water distribution systems management. *Water Resources Management* 2006; **20**(1):133-49

[3] Mulder K, Kaijser A. The dynamics of technological systems integration: Water management, electricity supply, railroads and industrialization at the Göta Älv. *Technology in Society* 2014; **39**:88–99.

[4] van Staden AJ, Zhang J, Xia X. A model predictive control strategy for load shifting in a water pumping scheme with maximum demand charges. *Applied Energy* 2011; **88**:4785–94.

[5] Ghaddar B, Naoum-Sawaya J, Kishimoto A, Taheri N, Eck B. A Lagrangian Decomposition Approach for the Pump Scheduling Problem in Water Networks. *European Journal of Operational Research* 2015; **241**(2): 490–501.

[6] Bagirov AM, Barton A, Mala-Jetmarova H, Al Nuaimat A, Ahmed S, Sultanova N, Yearwood J. An algorithm for minimization of pumping costs in water distribution systems using a novel approach to pump scheduling. *Mathematical and Computer Modelling* 2012; **57**(3–4):873–886

[7] Gurobi Optimizer. State of the art Mathematical programming solver (http://www.gurobi.com/products/gurobi-optimizer/gurobi-overview).

Biography

Gratien Bonvin is graduated from Ecole Polytechnique Fédérale de Lausanne (EPFL, Switzerland) and post-graduated from MINES ParisTech (France). He is currently PhD. fellow with the Centre of Applied Mathematics of MINES ParisTech.