On the comparison of numerical methodologies for control optimisation of variable-speed pumps

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INTRODUCTION

The fast expansion of several water supply systems (WSS) due to the population growth and the immediate consumers supply without any planned strategy have led to inefficiently operated systems. In such systems, pumping stations usually represent the main operational costs (Vieira and Ramos, 2008; Van Zyl *et al.*, 2004) revealing an important opportunity for the efficiency improvement of WSS. The operational control optimisation of these systems by a *trial and error process* can present difficulties due to their complexity: multiple pumps, valves and reservoirs, head losses, pressure limitations, several demand loads, etc. For this reason, innovative optimisation techniques are becoming more widely explored in this field (Coelho and Andrade-Campos, 2014).

A numerical methodology to optimise both the rotational speed and the operating time of variable-speed pumps is presented. The proposed methodology differs from other works by not considering the typical fixed 1-hour steps for the pumps operation. Instead, both set of pump speeds and operating times are used as decision variables. Additionally, a technique to reduce the number of variables according to energy price and water demand patterns is introduced.

Results of the proposed methodology using Particle Swarm Optimisation (PSO) and Differential Evolution (DE) are compared to distinct methodologies and optimisation techniques proposed by other authors. The test network introduced by Van Zyl *et al.* (2004) is used for comparison. In addition, a schematic representation of the real Richmond WSS model is also tested.

METHODS

The proposed optimisation problem can be described by the minimisation of a cost function f subject to the bounds of n decision variables ($x_{\min}$ and $x_{\max}$) and also to l equality constraints and m inequality constraints:

$$\begin{aligned} &\min_{\mathbf{x}} && f(\mathbf{x}), && \mathbf{x} = (x_1, x_2, \ldots, x_n); \\ &\text{subject to:} && h_k(\mathbf{x})=0, && k=1,\ldots,l; \\ & && g_j(\mathbf{x}) \leq 0, && j=1,\ldots,m; \\ & && x_{\min} < x < x_{\max}\,. && \end{aligned}$$

Daily pumping costs

Pumps/valves speeds/settings and operating times

Continuity

Pressure,
tank levels,
limits of pump operation

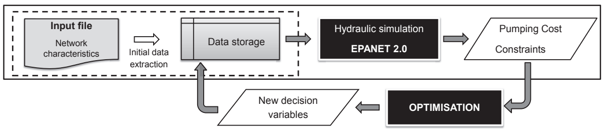
Objective Function:

$$f = \rho g \sum_{p=1}^{n_{\text{pumps}}} \sum_{s=1}^{n_{\text{steps}}} \left(\frac{H_{p,s} Q_{p,s}}{\eta_{p,s}} t_{\text{op},p,s} C_{p,s} \right)$$

Constraints handling:

$$F = f + r_h \sum_{k=1}^{l} (h_k)^2 + r_g \sum_{j=1}^{m} \left(\max\{0, g_j\} \right)^2$$

For the implementation of the proposed methodology, a numerical tool, using C++, was developed. Such tool provides an automatic connexion between the hydraulic simulator EPANET 2.0 and an optimisation module, allowing an easier implementation of distinct optimisation techniques for the energy costs minimisation of any kind of network provided by the user (see Figure 1).



Input file
Network characteristics
Initial data extraction
Data storage
Hydraulic simulation
EPANET 2.0
Pumping Cost
Constraints
OPTIMISATION
New decision variables

Figure 1 – Scheme representing the developed numerical tool.

RESULTS and DISCUSSION

Van Zyl water distribution network

The network represented in figure 2 was proposed by Van Zyl et al. (2004) and, since then, has been tested by several authors (some of them compared in table 1) for the control optimisation of fixed-speed pumps and, more recently, also variable-speed pumps.

The hydraulic simulation of one of the optimal operational solutions obtained by Van Zyl *et al.* (2004) resulted in a daily cost of £345.24, which was used as initial solution.

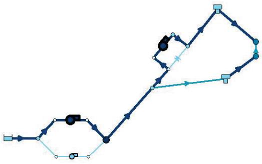


Figure 2 – Representation of the Van Zyl *et al.* (2004) test network.

Table 1 – Resume of the results for the optimisation of the Van Zyl network with distinct methodologies.

Authors	Optimisation algorithm	Method/ Decision variables	Optimal cost (£/day)	OF evaluations / CPU time	Constraints
Van Zyl *et al.*, 2004	GA	Tank level controls (pump on/off)	344.19	100 000	Tank levels and pump switches (cost penalties)
	Hybrid GA + Hillclimber		344.43	6 000	
López-Ibáñez *et al.*, 2011	EA	Level controls	337.20	6 000	Tank levels, pump switches and pressure
		Time controls	315.90	6 000	
Hashemi *et al.*, 2014	ACO	Pump on/off	388.04	400 000	Tank levels and pump switches
		Pump speed	349.43	300 000	Tank levels
Coelho and Andrade-Campos	**PSO**	**Pump speed and time controls**	**231.67**	**50 000 / 140 min(1)**	**Tank levels (cost penalties)**
	DE		**341.40**	**50 000 / 300 min(1)**	
	PSO	**Aggregated pump speed and time controls**	**240.17**	**50 000 / 132 min(1)**	
	DE		**332.93**	**50 000 / 295 min(1)**	

(1)Intel® Core™ i5 processor, 2.53 GHz.

The proposed methodology for the operating costs minimisation using the PSO allowed to obtain the lowest cost results for the Van Zyl water distribution network operation (£231.67). The technique applied for the variables aggregation according to the water demand and the tariffs variation, allowed to slightly reduce the computational effort and, in the DE case, the solution was improved.

Simplified Richmond water distribution network

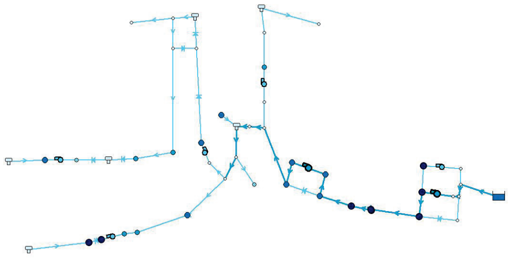


Figure 3 – Simplified representation of the real Richmond network.

The network represented in figure 3 is a simplified model of the Richmond network, which is part of the Yorkshire water supply area in the U.K. Such model is a benchmark of the Centre for Water Systems Resources of the University of Exeter (University of Exeter, 2014). The initial cost for the daily operation of the available network is £12316.79. However, the operation is not fulfilling the constraint for the tanks water levels in the end of the simulation. The network operation was adjusted and, never allowing the water levels in the end of the simulation to be inferior to the levels in the begin, the updated operational cost is £15632.72.

Table 2 – Results for the optimisation of the simplified Richmond network using the proposed methodology.

Optimisation algorithm	Decision variables	Optimal cost (£/day)	Percent of reduction	OF evaluations / CPU time (min) (2)	Constraints	Fulfilled?
PSO	Pump speed and time controls	12541.49 12753.23	19.8 % 18.4 %	100 000 / 430 200 000 / 572	Tank levels (cost penalties)	Yes Yes
DE		13070.24 **12403.09**	16.4 % **20.7 %**	100 000 / 281 200 000 / 434		No Yes
PSO	Aggregated pump speed and time controls	12522.68 12514.70	19.9 % 19.9 %	100 000 / 405 200 000 / 549		Yes Yes
DE		12794.68 12695.79	18.2 % 18.8 %	100 000 / 280 200 000 / 434		Yes Yes

For a reduced number of runs, in this more complex network, the DE provided the best result for the daily operational cost (£12403.09), which was reduced more than 20 %, maintaining the final water levels in tanks always equal or superior to the initial level.

(2)Intel® Core™ i7 processor, 3.40 GHz.

CONCLUSIONS

A computational tool for the efficient control of distinct water distribution networks is presented. This tool is based on a methodology that allies the possibility of control at the same time the pumps speed and the time of operation of both pumps and valves.

Without violating the tanks water levels constraints, the proposed methodology was able to present better results for the operation of both tested networks.

PSO demonstrated a better performance in the Van Zyl network. On the other hand, the DE performed better in the simplified Richmond.

A larger number of runs should be performed due to the probabilistic nature of the selected algorithms which provide distinct solutions in each run and may not always reach the global optimum.

Sensitivity analysis to the parameters of the algorithms must also be performed in order to achieve probable better results.

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