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Interactive comment on "Pump schedules optimisation with pressure aspects in complex large-scale water distribution systems" *by* P. Skworcow et al.

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The Authors would like to thank Referee for a very comprehensive comments. Our replies to each comment are addressed below.

- *14. Are the number and quality of references appropriate? NO! References are almost reduced to author's previous works. In my opinion, it can be OK for a Conference paper, but a good journal paper should have some kind of state-of-the-art, even if a short one.*

The list of additional references to be included in the article is provided below:

- Bentley Systems, Darwin Scheduler, http://www.bentley.com/en-GB/Products/WaterCAD/Darwin-Scheduler.htm, accessed on 17.04.2014.
- Derceto Inc., Derceto Aquadapt, http://www.derceto.com/Products-Services/Derceto-Aquadapt, accessed on 17.04.2014.
- McCormick, G. and Powell, R. (2003). "Optimal Pump Scheduling in Water Supply Systems with Maximum Demand Charges." J. Water Resour. Plann. Manage., 129(5), 372-379.
- Price, E. and Ostfeld, A. (2013). "Iterative Linearization Scheme for Convex Nonlinear Equations: Application to Optimal Operation of Water Distribution Systems." J. Water Resour. Plann. Manage., 139(3), 299-312.
- Salomons, E., Goryashko, A., Shamir, U., Rao, Z. and Alvisi, S. (2007) "Optimizing the operation of the Haifa-A water-distribution network.", Journal of Hydroinformatics, 9(1), 51-64.

And an additional text given below should be inserted in the Introduction section.

"The operational scheduling problem when considering in its full complexity is nonlinear and mixed integer and for large scale systems requires huge computational resources. Known approaches try to obtain a suboptimal solution by using simplifying assumptions. Evolutionary algorithms are the most generic search methods and they work efficiently if a simulator of the considered system is available. The simulator can be called tens of thousands of times during the search and in order to reduce the calculation time simplified simulation models are employed, such approach was used for instance by Solomons et al. (2007) and is used by Bentley System (2014). The approach presented by Derceto Inc. (2014) relies on preparing a highly specialised model of the considered system which is solved using linear and nonlinear programming combined with advanced heuristics, the technical details about the algorithm are not available in the literature. To overcome problems with the nonlinearity of the hydraulic model Price and Ostfeld (2013) proposed the iterative linearization procedure, the approach is quite efficient but it solves only continuous version of the optimisation problem in the current formulation. Additional complexity is added to the scheduling problem when the maximum demand charge is considered, this requires the optimisation problem to be formulated over a long time horizon typically 1 month and application of stochastic methods as illustrated in McCormick and Powell (2003)."

- *1)In the automatic discretization, the first continuous optimization problem to be solved by GAMS/CONPT considers the number of pumps ON at each time step as decision variables. After rounding the continuous number of pumps ON to an integer number, the second continuous optimization problem to be solved by GAMS/CONPT considers the pump speed as decision variables. In the first problem the pump speed is also a decision variable or assumes a fixed value (for example, 100% of the nominal speed)?*

  In the first problem both the number of pumps and the normalised speed are decision variables.

- *The interactive discretization is a procedure involving GAMS/CONOPT solver (continuous solution), EPANET simulator (discrete solution) and an Excel spreadsheet (match discrete and continuous solutions). The text mentions that "For small networks or a short time horizon (24 h) only few iterations are required", but nothing is said about the time it takes to obtain a final solution to be implemented. If we are dealing with real time operation of WDN this can be crucial.*

  The two discretisation methods were presented; automatic and interactive.

The discretization results presented in the paper were obtained from interactive discretisation that involves a user (operator) and cannot be applied in a real time. The automatic discretization in this particular case failed because EPAnet Toolkit was unable to simulate some scenarios.

- *It is well known that EPANET isn't adequate to calculate energy costs from variable speed pumps (it doesn't convert the pump efficiency when changing the pump speed). How did you manage it? Probably you used affinity laws to estimate the pump efficiency. However, affinity laws assume that efficiency remains constant, but in real world variable speed pumps similar operating points don't have similar efficiencies (efficiency reduces when reducing the pump speed). Did you take this in consideration?*

  EPAnet is used only to define the hydraulic data and calculate initial conditions, the optimisation model including energy cost was calculated outside EPAnet using the GAMS language.

- *4) Along the text nothing is mentioned about the leakage level obtained with the optimal pump scheduling, although this was a part of the objective function (minimize energy usage and leakage)? In terms of results, the only reference to leakage is "The automatic discretisation algorithm particularly struggled for scenarios with pressure dependent leakage; for these scenarios the interactive discretisation approach was employed".*

  As mentioned in the paper the current and optimised operations are not compared due to insufficient data. Furthermore, the amount of leakage obtained with the optimal scheduling depends strongly not only on the network, initial tank levels, and pump characteristics, but also on time horizon, cost of water at sources, operational constraints and electricity tariffs. For example, if the night tariff is significantly cheaper than the day tariff, it may be cheaper to pump intensively during the night (if operational constraints allow this and if the pumps' operating points remain close to their peak efficiency) despite an increased leakage. On the other hand, flat tariffs and expensive water at sources tend to results in a more significant leakage reduction, as the optimiser attempts to reduce the total cost by reducing the leakage. Therefore, inclusion of the pressure dependent leakage in the optimisation model enables to take the leakage into account but does not guarantee that the leakage would actually be reduced in all cases.

In our other case study the amount of leakage reduction resulting from optimal pump schedules varied from 1

- *Page 128, Line 12: "For pipes, tanks and pump stations standard equations based on the Hazen–Williams formula are used". I don't understand this sentence! What is the relationship between the Hazen-Williams formula and tanks and pump stations?*

  The sentence should be changed to "Tanks and pump stations are represented by standard models see e.g. Brdys and Ulanicki (1994) and pipes are represented by the Hazen–Williams formula".

- *Page 130, Line 17: "Actual implementation of the control variables in the physical WDN depends on valve construction and is not considered here." The mentioned PRVs and FCVs are physically present in the network or are just an assumption to force the model to achieve a desired set of results (pressures and flows)? We know that real world WDN sometimes have "strange things" (for example, the case study has "...PRVs fed from booster pumps or a booster pump fed from a PRV"), but both PRVs and FCVs introduce head-losses, reducing the system global energy efficiency, and this seems a countersense when we are trying to minimize the energy costs.*

  PRVs in the model represent real valves present in the physical system, the main FCVs were introduced to replace a pipe and a TCV controlled by the rules in the EPAnet model.

- *Page 131, Equation 7: I don't understand the need of that "10^{14}".*

  Equation 7 is a continuous approximation of the sign function and improves performance of the nonlinear solver employed in the method.

- *Page 131, Equation 8: The objective function does not include the power costs, and sometimes these can be quite expressive in the global energy cost.*

  The power is present in Equation 8 by $P_j(k)$, and consider the pump efficiency, pumps on/off and pumps speed as illustrated in Equation 4. This expression is equivalent to considering hydraulic power provided to the water network and pump efficiency but is more accurate if direct power characteristics are provided by a manufacturer.

- *Page 133, Line 7: "...so for example continuous "2.5 pump switched on for 2 h", can be discretised as "3 pumps on for 1 h and then 2 pumps on for another hour". This is correct if it is assumed that the pump flow does not depend on the number of pumps switched on (a simple mass balance equation), but when you have parallel pumps this is not quite true (unless you adjust the pumps speed to compensate). I guess this problem is subsequently solved by the procedure presented in Page 133, Line 23.*

  Yes, according to the procedure described in the paper, the number of pumps ON is assumed during the discretisation and the optimal pump speed is recalculated.

- *Page 136, Line 19: Did this conversion procedure produce a good match even*

when the flow in pipes was low (for example, when some pumps were OFF during the night)?
And
Page 138, Line 2: I guess that this can be the answer to some of the previous questions.

Indeed, the conversion procedure from D-W to H-W is less accurate for low flows and it was the most significant source of errors in the reduced model. However the model reduction procedure was carried out at the operating point when at least one of major pumps was ON and the obtained reduced model was sufficiently accurate for all operating condition present in the considered system.

- *Page 136, Line 11: A screenshot of the case study WDN would help, even if it was a simple print screen of the EPANET model.*

  A schematic of the network with fictitious names will be provided to the editor to be included in the final version of the paper.

- *Page 137, Line 2: When using the Darcy-Weisbach formula, it is easy to replace a fixed opening TCV with a pipe of equivalent resistance (they both have the same exponent = 2), but with the Hazen-Williams formula that is not straightforward. How did you manage it?*

  Head losses at these fixed open valves were minimal and the valves could simply be removed, however in the study they were replaced by pipes which gave the same head loss at the representative operating point.

- *Page 137, Line 4: Why did you replace the TCVs by FCVs? Was it to reduce the number of different control elements in the model or is it an imposition of the automatic model reduction algorithm applied?*

  The conversion was carried out so the flow going through the valve could be an additional decision variable in the optimisation problem.

- *Page 137, Line 6: I don't understand the physical meaning of "A pipe to which an open-close control rule was assigned...".*

  This is a construct used by EPAnet and the original model provided by a water company included such elements.

- *Page 137, Line 13: Table 1 refers 10 tanks in the original model and 9 in the reduced model, but section 5.1 refers 9 tanks in the WDN and section 5.2 refers that two of them were merged into one (there should be 8 in the reduced model). There is some disagreement in these numbers.*

  It is a mistake and section 5.1 should refer to 10 tanks.

- *Page 138, Line 18: "Subsequently, it was decided to extend the boundaries of the model and include an additional pump station and a tank." Is this another case study (based on the original one), or these changes were necessary to attain good results with the methodology?*

  These changes were necessary to attain good results and were introduced on the request from a water company.

- *Page 138, Line 22: "Optimisation for 24 h horizon with 1 h timestep and for 7 days horizon with 2 h time-step took around 5 min and 1 h, respectively, on a standard office PC." Do these execution times correspond to the methodology with automatic discretization?*

  These are times to obtain respective continuous solutions.

- *Page 140, Line 13: Eliminate the "s" in "heuristics".*

  It will be corrected.

- *Page 140, Line 19: Introduce an "a" in the middle of "for variety".*

  It will be corrected.

- *Page 148, Figure 5: Looking at these results we can see that there are always 5 pumps ON, and sometimes with a normalized speed of 0.7. Is this a limitation of the methodology (the number of the pumps ON is always the same)? At first look I would say that 4 pumps ON with higher normalized speed would do the same with a better efficiency.*

  It is not a limitation of the methodology, generally it produces time dependent schedules for ON/OFF pump operation however in this case 5 pumps ON was the optimal solution. It can results from the two factors: 1) efficiency of one local pump may not be at its maximum but it is still the best solution if the entire interlinked water system is considered 2) power of a pump depends on the speed cubed and linearly on the number of pumps ON.

- *Page 149, Figure 6: For the 7 days horizon results, the low levels of the tanks at the middle of the week can be a consequence of the leakage (higher level increase the pressure and, consequently, leakage). If leakage was not considered, perhaps the solutions would lead to a "better use" of the tank capacity.*

  No, this is a characteristic profile for weekly tank storage in a system where pumps pump to a tank, if the tank level is lower the pumping is against lower head and hence energy and cost savings. At the end of the week the level is brought back to the initial level due to the imposed tank level constraints.