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Optimization of pump operation using rule-based controls in EPANET2: a new ETTAR toolkit and correction of energy computation

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Abstract

The optimization of pump operations has the potential to reduce operational costs, while still maintaining the high level of reliability required of water distribution systems. The hydraulic software EPANET2 toolkit has been frequently linked to evolutionary algorithms for this purpose, however, only time-based controls and simple controls based on one single condition, e.g. the tank level, could be automatically changed during the optimization. This paper introduces a modification to the original EPANET2 toolkit library, so that the operation of pumps can be optimized taking into account simultaneously several conditions (e.g. the time of the day and the tank level). A problem in the original toolkit associated with computing pump energy and costs using rule-based controls has also been solved. The new ETTAR toolkit has been tested on a case study, in which a genetic algorithm has been used to optimize different types of controls. Results show that it is possible to find more cost-effective solutions compared to simple controls and, although with longer computational times, let the algorithm create the entire pump control rules. The robustness of the optimized controls found has also been tested.

Keywords: pump operation; optimization; water distribution system; EPANET, rule-based controls, evolutionary algorithms.

Introduction

Pump operations are the major source of energy consumption in water distribution systems (Boulos et al. 2001), and many researchers have focused on their optimization. A large part of the research has studied the minimization of operational costs (e.g. Ormsbee and Lansey, 1994; Mackle et al. 1995; Kazantzis et al. 2002; van Zyl et al. 2004; López-Ibáñez et al. 2008; Behandisha and Wu, 2014, Ibarra and Arnal 2014) and, more recently, the reduction of greenhouse gas emissions in order to reduce the environmental impact caused by the energy production (Wu et al. 2012a, 2012b; Sadatiyan Abkenar et al. 2014; Stokes et al. 2014). The optimization of pump operation has also been studied in conjunction with water quality (Mala-Jetmarova et al. 2015) and network leakage (Price and Ostfeld, 2014). Other researchers have focused on the optimization of pump efficiency (Wu et al. 2015). Recent forecasts in population growth (Vörösmarty et al. 2000) and increased energy costs (The Brattle Group, 2006; ESAA, 2012) make the optimization of pump operation an actual and important problem.

Pump operations are usually controlled in three possible ways: (i) using scheduling, i.e. the status of the pumps is based only on the time; (ii) using tank trigger levels, i.e. a pump is switched on when the water level in a tank reaches the lower trigger and is switched off when the water level in the tank reaches the upper trigger; and (iii) a combination of both. Scheduling has proved to be successful in many papers (e. g. McCormick and Powell, 2003; López-Ibáñez et al. 2008; Giacomello et al. 2013; Reca et al. 2014) and it is usually more cost-effective than using tank trigger levels: in fact, it can better exploit the off-peak tariff period and pump in the peak tariff period only when it is strictly necessary (Kazantzis et al. 2002). However, scheduling requires a good knowledge of the water demands, and given their uncertainty, often tank trigger level controls are preferred in order to guarantee a higher reliability of the system. Note that, to adapt the pump operations to the variability of the demands, it is also possible to optimize their control in near-real time (Martinez et al. 2007; Salomons et al. 2007; Shamir and Salomons, 2008; Pasha et al. 2014, Odan et al. 2015), but this option requires a good automatic control system, where tank levels, pump operations and a decision system tool are all linked together.

Tank trigger levels are more robust and require a less accurate estimate of a forecast of demands: in case an abnormally large demand occurs, the pumps will be switched on to avoid the tanks emptying so that the users will not experience a service interruption. The clear disadvantage of tank trigger levels is the fact that they are a passive control and they only respond to the hydraulics of the network: pumps may pump more than necessary in the peak tariff period and not as much as they could in the off-peak period. As there is usually a big difference between the electricity cost in the off-peak period and the peak period, excessive pumping in the high cost tariff period has a large impact on the operational costs. Because of operational costs and system reliability requirements, a mix of scheduling and tank trigger levels is often used, with the objective of exploiting the off-peak tariff period where possible, while still allowing the pumps to be controlled by the demands in the network. Note that, even when the electricity tariff structure is not based on times, it could still be useful to control the pumps based on several conditions, as this could allow, for example, the reduction of peak demand charges by avoiding the simultaneous operation of all pumps. Multiple conditions can also be useful in complex systems where the pump operation needs to be defined based on the water level of multiple tanks.

Hydraulic software packages can usually implement all the three types of pump controls described. For example, EPANET2 (Rossman, 2000), one of the most commonly used software packages in the research of the optimization of water distribution system, can represent the pump scheduling using 'patterns', the tank trigger levels with 'simple rules' and the combination of scheduling and tank trigger levels using 'rule-based controls'. One of the reasons EPANET2 has been widely used in the research field is that it can be easily linked to an optimization program by using the toolkit: system characteristics (e.g. pipe sizes) can be easily changed and hydraulic variables (e.g. pressures and velocities) easily retrieved for each time step of the simulation. However, EPANET2 does not allow the modification of rule-based controls during the optimization process. This is a limitation that has impacted the application of the results of the optimization in real systems or forced researchers to find elaborate solutions to the problem. In fact, simply rewriting the EPANET input file for each solution that needs to be simulated would generally result in excessively long computational times.

This paper introduces a modification to the EPANET2 toolkit, called EPANET2-ETTAR (EPANET2 Toolkit To Alter Rules) that allows rule-based controls to be changed directly by an optimization algorithm. The paper is divided in two main sections. The next section describes (i) the problem that EPANET2 has in computing energy and costs when rule-based controls are used and (ii) rule-based controls and how they can be changed using the new functions of the ETTAR toolkit. The second part of the paper describes the case study and some of the possibilities for the optimization of pump operations introduced by the new ETTAR toolkit. The analysis of the results tests the optimal controls found for a 24 hours optimization then applied to longer periods of times. Conclusions on the potential uses of the new toolkit are summarised at the end. For space reasons, the modifications to the original EPANET2 toolkit are introduced only as supplemental material. Note that the supplemental material does not contain the correction of pump efficiency and hence energy computation for variable speed pumps, which can be found in Marchi and Simpson (2013).

EPANET2 correction of energy computation

In the current version of EPANET2 (2.00.12) and in the previous version as well (2.00.11), there is a problem in computing the energy when rule-based controls are used to define pump operations. In particular, while for patterns and simple controls the pump status is updated after having computed the energy consumption for the current time-step, rule-based controls update the pump status before the energy computation. This results in an underestimation (sometimes significantly) of the energy consumption and electricity costs associated with the pump operation. For example, let us assume that pump 1 is switched on at the current time step and, according to the current rules, it needs to stay switched on for a time step Δt (e.g. one hour). After this time step, the pump needs to be switched off: EPANET2 directly updates the pump status to be CLOSED (i.e. the pump is switched off) and, in the energy computation that follows, the energy consumption of pump 1 is ignored as its status is set to be closed. Appendix A of the supplemental material shows how to correct this problem so as to correctly compute energy and costs associated with pumping when using rule-based controls.

EPANET2 rule-based controls

A typical example of rule-based controls for a system that has a peak – off peak electricity tariff is defining two sets of trigger levels (one for the off-peak tariff period and one for the peak tariff period) so that the tank level is maintained high when the pumping has the lowest cost electricity and, during the peak tariff period, if the pumps need to be switched on, they pump only the minimum volume required. As an example, rule-based controls in EPANET2 in the off-peak tariff period may look like:

```
RULE 1
IF SYSTEM CLOCKTIME > 0:00:00 AM
AND SYSTEM CLOCKTIME <= 7:00:00 AM
AND TANK 1 LEVEL <9.0000
THEN PUMP 1 STATUS IS OPEN

RULE 2
IF SYSTEM CLOCKTIME > 0:00:00 AM
AND SYSTEM CLOCKTIME <= 7:00:00 AM
AND TANK 1 LEVEL >9.7
THEN PUMP 1 STATUS IS CLOSED
```

Rule 1 and Rule 2 above represent one set of trigger levels for the off peak tariff period (shaded area in Figure 1). When the tank level reaches the upper trigger level (9.7 m) the pump is switched off and when the tank level reaches the lower trigger level (9 m) the pump is switched on. An additional set of rules would be required to define the pump operation in the peak tariff period: while in the off-peak tariff period the tank level is maintained as high as possible (so as to guarantee that the tank is nearly full at the start of the peak tariff period), in the peak tariff period the tank level is maintained as low as possible, so as to decrease the static head and to avoid pumping that could be delayed to the off peak period. In Figure 1, this is represented by the dotted lines: without a reduced upper trigger level, the pump would have filled up the tank during the most expensive period of the day.

The New Toolkit - EPANET2-ETTAR capabilities

As shown by the previous example, the use of rule-based controls can be beneficial as it can combine the advantages of tank trigger levels in terms of control robustness with the advantages of scheduling in terms of cost savings. However, the original EPANET2 toolkit does not allow any modification to the existing rules in the input file and the existing modification of the EPANET2 toolkit by Lopez-Ibanez (2009), available at http://iridia.ulb.ac.be/~manuel/epanetlinux.html , allows only tank trigger levels to be changed in rules where the off-peak and peak tariff periods are fixed. In order to be able to optimize all of the components of rule-based controls, the existing EPANET2 code has been modified and eleven new functions have been introduced (the modification to the original EPANET2 code can be found in Appendix B in the supplemental material). The aim of this section is to show what these new functions can do and how they can be used in an optimization program. A more detailed description on how to use these functions can be found in the manual provided in Appendix C available as supplemental material.

Table 1 lists the new functions introduced: following the naming convention of the existing EPANET2 functions, the new functions can be divided in functions aimed at retrieving an existing part of the rule, i.e. "ENget" functions, and in functions aimed at setting a new value in a rule, i.e. "ENset" functions. As shown in Figure 2, a rule is in general composed of four terms: a set of conditions (or premises), a set of actions to be performed if the conditions are met (true actions), a set of actions to be performed when the conditions are not met (false actions) and the priority of the rule compared to other rules. Premises and actions are numbered consecutively starting from one as shown in Figure 2 by the grey numbers on the left: for example the second true action in the example in Figure 2 would switch pump 2 on.

The functions introduced in the new toolkit EPANET2-ETTAR refer to one of these components, i.e. premises, true actions, false actions and priority. In order to understand how they work, it is necessary to understand how rules are formalized in EPANET. Figure 3 shows the format of the conditions and of true and false actions in a rule. The conditions start with a logic operator (LogOp), followed by the type of Object which the condition refers to (e.g. a tank), the index of the object and the Variable (e.g. level) which will be checked. The conditions then need to specify the relationship operator (RelOp) and the Status or the Value of the variable. Possible values for LogOp, Object, Variable, RelOp and Status are coded as integer numbers, as shown in Figure 3 (a full list is available in Appendix C). Note that the new functions require the specification of the rule index, i.e. the position of the rule in the rule list, and the index of the condition or action, i.e. the position of the condition/action in the premise/action lists. For example, using the ENgetpremise function to retrieve the third condition of the rule in Figure 2 (ENgetpremise(1, 3, &LogOp, &Object, &Index, &Variable, &RelOp, &Status, &Value) would result in LogOp=2 (“AND”), Object=2 (“TANK”), Index=16 (if, for example, tank t6 is the 16^{th} element in the list of network nodes), Variable=3 (“LEVEL”); RelOp=4 (“BELOW”), Status=0 and Value=5.5. Note also that the Status and Value are always present in the conditions/actions, but the Value overwrites the Status. In a similar way, the command ENgettrueaction(1, 2, &Index, &Status, &Value) would retrieve the second action in the list of true actions in Rule 1: Index refers to the link index (for example 13 if Pump2 is the 13^{th} element in the link list), Status would be equal to 1, which corresponds to “OPEN” and Value would be equal to zero as it is not used. Note that Index in the top row and in the last row of Figure 3 does not have a set of options but depends on the network.

The functions ENsetpremise and ENsettrueaction (or ENsetfalseaction) work in a similar way, but instead of retrieving the current values in the rule, they set new values. Figure 4 shows how the original Rule 1 shown in Figure 4a) can be changed to the Rule 1 shown on the right side (Figure 4b) using the new ETTAR toolkit functions. A sample of the function format and their scope is given in Figure 4c), while Figure 4d) shows how the functions would be implemented in order to obtain the new rule in Figure 4b). For example, assuming the index 1 corresponds to node 1 in the network, the command ENsetpremise (1, 2, 3, 6, 1, 4, 5, 0, 25) would change the second condition of the old Rule 1 in Figure 4a) from “AND SYSTEM CLOCKTIME <=

7:00:00 AM” to be “OR NODE 1 PRESSURE ABOVE 25”. Therefore, with the ENsetpremise command, it is possible to completely change a condition in a rule.

As in most cases only the value in a condition (for example the tank trigger level) needs to be optimized, the command “ENsetpremisevalue” is also available: this command will change only the value of the corresponding object for a specific condition in a rule. The command ENsetpremisevalue (1,3,8.5000) changes the tank trigger level in the third condition of Rule 1 in Figure 4a) from 9 m to 8.5m. The ENsetpremisevalue can also be used to change the time value in a condition, as shown in the first condition of the new Rule 1 (Figure 4b). Note that the time values need to be inserted in seconds.

Although it is probably less common, the object that a certain condition refers to could also be optimized: the “ENsetpremiseindex” command changes only the index of an object. For example, if the water distribution system has multiple tanks, and which tank controls the pump needs to be defined, the optimization could change “TANK 3” in the fourth condition of Figure 4a) to become “TANK 2” (Figure 4b).

Case Study

The case study used in this paper was first introduced by van Zyl et al. (2004), where additional information and the input file of the network can be found. The network, shown in Figure 5, consists of two parallel pumps and a booster pump, but it is representative of real systems, e.g. the real network optimized by Odan et al. (2015) has only three pumps. The network has also two tanks, tank t6 being the highest one. Both tanks can be filled by the pumps, but, when all pumps are switched off, tank t6 can provide water to the lower tank t5. In case Pumps 1 and 2 are both switched off, the booster Pump 3 can transfer water from the lowest tank t5 to the highest tank t6. The only constraints of the problem are the maximum number of pump switches for each pump (three, as in López-Ibáñez et al. 2008) and the final water level in the tanks that needs to be higher or equal to the initial one. The minimization of the daily pumping costs (£/day) was the objective selected in the previous papers and it has been adopted also in this work in order to compare the results.

For reference, the best solution found by van Zyl et al. (2004) was £344.19/day while the best solution found by López-Ibáñez et al. (2008) was £326.5/day. As López-Ibáñez et al. (2008) controlled the pump operations based on time, results will be compared with van Zyl et al. (2004) that used tank trigger level controls. In fact, although time-based controls usually results in less expensive solutions, tank trigger level controls are more robust. The comparison therefore aims at assessing the savings when both time and tank trigger levels can be used to create robust and economical pump controls.

The optimization algorithm chosen for the optimization in this paper is a single objective genetic algorithm (GA). Although the new toolkit EPANET2-ETTAR could be linked to any optimization algorithm that requires an external hydraulic software to simulate the solutions, GAs have been selected as they have been extensively applied to water distribution system problems (Goldberg and Kuo, 1987; Savic et al. 1997; Kazantzis et al. 2002; Sadatiyan Abkenar et al. 2014). Here it is important to note that, as with many other evolutionary algorithms, GAs require a set of parameters (population size, *Pop.Size*, maximum number of iterations, *No.Gen*, probability of crossover, P_c, and probability of mutation, P_m) and the specification of the type of selection, crossover and mutation operators. Additional details on GAs can be found in Nicklow et al. (2010).

Note that the version of GA used in this algorithm uses an integer representation of the decision variables, so possible trigger level values are selected from a list of discrete values. In particular, the tank trigger levels for tank t6 are chosen to vary from 0.2 m to 10 m with an increment step of 0.1 m, while the tank trigger levels for tank t5 are chosen to vary from 0.2 m and 5 m with an increment step of 0.1 m. In addition, in order to avoid the creation of unrealistic solutions, the upper trigger level is forced to be above or equal to the lower trigger level. Results presented in the following sections are the best results obtained in ten trials with different seeds of the random number generator. Note that all results are obtained using the new toolkit EPANET2-ETTAR as it is not possible to modify rule-based controls with the original EPANET2 toolkit.

Results

Despite the relatively simplicity of the network, this case study offers many opportunities for different types of optimization using rule-based controls. In the following, different versions of the controls will be optimized, including: (1) all of the three pumps are controlled by the same tank and the same trigger levels; (2) each pump its controlled by the water level of its own tank as in the original description of the network; (2a) Pumps 1 and 2 are forced to operate simultaneously; (3) the tank trigger levels and which tank they refer to are optimized by the algorithm; (4) the entire operational pumping rules are decided by the algorithm.

The best results of each case are discussed in the following subsections. Table 2 reports the algorithm parameters used in the optimization and the statistics of the ten optimization trials for each case. As can be seen, the average cost of the best solutions generally decreases from Case 1 to 4, due to the larger flexibility given to the algorithm in deciding the pump controls. The exception for the results of Case 3 can be explained by the larger probability of the algorithm being trapped in a local optimal solution, as the trigger levels are limited by the choice of the tank. Note that it would be more difficult to implement the controls of Cases 3 and 4 in practice (especially in real-time control), because of the possible changes in the input variables to be considered.

Case 1: All pumps are controlled by the same tank trigger levels

The first option considers that all of the three pumps are controlled by the same rules, and, in particular, are controlled by the same tank (tank t6 has been chosen because it has the highest water elevation). The problem so formulated has four decision variables, i.e. the trigger levels to switch the pumps on and off in the peak and off-peak tariff period.

For this problem, it has been possible to enumerate all 92,236,816 solutions: only 22,591,009 solutions have lower trigger levels below the higher trigger levels and only 106,792 solutions (less than 0.2% of the possible combinations) comply with the constraints. The lowest cost of these feasible solutions is £370.22/day. As shown in Table 3, the optimization algorithm always found a solution with a cost of £370.22/day (note that there are 20,425 solutions with the same best cost).

It should be mentioned that the solutions obtained by van Zyl et al. (2004) and López-Ibáñez et al. (2008) are about 7.6% (£344.19/day) and 14.3% (£326.5/day) less expensive than the best solution of Case 1. This is because, in these previous studies, pumps have been controlled independently from each other, resulting in an increased flexibility of the operations and lower costs (as it will be shown by the results of Case 2).

Figure 6 shows the tank level of tank t6 for one of the best solution obtained (£370.22/day): it can be noted that tank trigger levels during the off-peak period (shaded area) are higher than the tank trigger levels in the peak tariff period. Note also that the lower tank trigger level in the off-peak tariff period and the higher trigger level of the peak tariff period do not influence the pump operation in this case, as the pumps would be switched on and off, respectively, in any case.

Case 2: Each pump has different tank trigger levels

The second option of controlling the pumps is as the one described in the original paper (van Zyl et al. 2004): Pump 1 is controlled by the tank t5 level and Pumps 2 and 6 are controlled by the level of tank t6. Given that, depending on demand conditions, tank levels and pump operations, Pumps 1 and 2 could fill tank t6 even without the use of the booster Pump 6, the tank trigger levels for Pump 6 are defined independently from the tank trigger levels of Pump 2. This results in having 12 decision variables: the upper and lower trigger level in the peak and off-peak tariff period (four decision variables) for each of the three pumps.

Figure 7 shows the hydraulic behaviour of the best solution obtained, which has a cost equal to £337.66/day. Figure 7 shows that the off-peak tariff period is exploited by all three pumps, but, while for Pump 1 it is possible to work mainly in the off-peak-tariff period, Pumps 2 and 6 operate for a significant period of time also in the peak-tariff period. The solution also highlights that there are times in which Pump 2 is used to fill tank t6 without the use of the booster Pump 6 (as shown by the increase of tank t6 level at about 1 pm, when Pump 6 is switched off). Note also that the operation point of Pump 1 is influenced by the operation of Pump 2. The water level in Tank t5 triggers the operation of Pump 1 just before midnight. As Pump 2 is not operating, Pump 1 is able to deliver about 182 L/s (with 63% efficiency). Thirty minutes later Pump 2 is switched on by the lower tank trigger level in the off-peak tariff period: Pump 1 is now delivering only 127 L/s with a much higher efficiency (74%).

Given that when Pump 1 and 2 work in parallel they have a higher efficiency, the case when these two pumps are controlled by the same trigger levels (based on tank t6) has been tested (Case 2a in Table 3). As shown in Table 3, the cost of the least expensive solution has now decreased to £329.91/day. This result highlights that the operating efficiency of the pumps is an important factor to take into account when deciding how the pumps will be controlled, i.e. will they always work in parallel or will they have separate controls? From a practical point of view, however, it is also important to remember that having Pump 1 and 2 working in parallel is more cost effective for the 24 hours tested, but it could result in too frequent and short pump switches in another period of the year, as it will be shown in the following section.

Case 3: tank and tank trigger levels are decided by the algorithm

In this case, the algorithm can decide which tank will be used to control the operation of the pumps (if tank t6 or tank t5) and at which water level the pump will switch on or off. As the possible water level depends on the chosen tank, the genetic algorithm has been modified so that crossover can only separate the solution, which is a sequence of tank indexes followed by the corresponding trigger level value, after the tank trigger level value. During the mutation phase, a check is made to ensure that the choice of the variables' values is still feasible, i.e. that tank t5 does not have a trigger level set above its maximum height (5 m).

Despite the larger computational effort, the best solution obtained (£337.44/day) is only slightly less expensive than the solution of Case 2 (while it is more expensive than the best solution of Case 2a). The hydraulic behaviour of this solution is similar to Case 2, where all pumps exploit the off-peak tariff period (see Figure D1 of Appendix D provided as supplemental material). However, Pump 6 now operates for a longer time than in Case 2 and the algorithm clearly prefers to pump water from tank t5 to tank t6 from about 3:00 to 7:00 PM instead of using Pump 1 and 2 to withdraw water from the reservoir. The likely reason for this is that Pump 6 has a much higher and constant efficiency (85%) than Pump 2, which operates between 64% and 76% efficiency. Although not optimal, this solution highlights that another way to reduce the pumping costs is to prefer the use of Pump 6 when possible.

As specified in Table 3, the three pumps are not controlled by the same tank in the off-peak and peak-tariff period. Although pump controls based on multiple tanks may not be easily implemented from a practical point of view (and for this case study it would not be the most cost effective option), there are few aspects of this solution that is worth noting. In particular, the algorithm choice of selecting tank t5 for some of the lower trigger levels in the peak tariff period is justified by the fact that this tank can supply the network demands even if tank t6 is almost empty. Contrary to the expectations, the controls for the off-peak tariff period are not based on tank t6, which could have guaranteed that as much water as possible was stored in the network, but are based on tank t5. However, even if tank t5 is chosen to control the pumps, both tanks get refilled at the end of the simulation period.

Case 4: the entire rule is decided by the algorithm

In this case, the optimization algorithm is free to decide the entire rule. The EPANET2 input file is set up with 12 rule-based controls in order to ideally define the status of the pumps for the off-peak and peak tariff periods. Each rule-based control contains four conditions: two of them are meant to define the time period, one is meant to define the tank trigger level and the last one has been added in order to increase the flexibility of the algorithm.

In addition to deciding the tank and the tank trigger levels, the algorithm will select also the logic operator ("AND" or "OR" for each condition, excluding the first condition that is set to be "IF"), the "object" (if the condition is about the time or the tank level), the relationship operator (e.g. if the tank level is "ABOVE" or "BELOW" a certain value) and the value of the object. Note that, in order to allow the algorithm to use fewer conditions than the four available, the reservoir has been added among the choices of the possible "objects". In this case, choosing an object equal to the reservoir will create a condition that is always true and therefore will not impact on the pump operations. Note that, in this case, the constraint related to the fact that the upper trigger level needs to be below the lower trigger level has not been inserted, as checking and correcting the rules during the optimization would have been too complex and time-requiring.

Each solution is represented using 288 integer numbers, although, depending on the selection of the object, less numbers may be required. Table 4 shows the controls of the best solution found (£312.41/day) once the rules have been cleaned from the always-true conditions and the redundant settings. Conditions have been classified in three categories according to the type of rule used: time control only, tank trigger level only and a combination of the two. It can be seen that all three types of rules are present in the optimized controls and that the algorithm introduces time-based conditions in order to fit the pump operation to the specific demand condition modelled. These controls could have been written in EPANET2 also using simple controls or a pattern for pump scheduling. For example, Pump 2 is entirely controlled by time: this pump is operational from 0:00 AM to 9:12 AM and switched off in the other time periods. Note that, as Rule 2 is written before Rule 5, Rule 2 has a higher priority. An example of rules that could have been written using simple controls is Rule 9, which controls Pump 1 using only the level of tank t6.

Rules 3, 4 and 12 need rule-based controls as they have multiple conditions. Rule 4 represents a typical control, where the pump is controlled based on the time of the day and the tank level. Rule 12 is based only on the water levels of the two tanks: in particular, Pump 1 is switched off when tank 6 is not full and there is not much water left in t5. As switching a pump off when the storage level is low does not make much sense from a practical point of view, it is likely that the algorithm is using the tank levels as a surrogate for time controls. Note also that, in this case, Rule 3 could have been rewritten using only the time, as the water level in t6 is always higher than 1.1 m.

Most of the final rules found by the algorithm still take advantage of the scheduling: this results in a final solution that is 9.23% and 4.31% less expensive than the solutions found by van Zyl et al. (2004) and Lopez-Ibanez et al. (2008), respectively.

Note also that Rules 1, 6, 8, 10 and 11 are not necessary: the conditions of Rule 1 are never true, as tank t6 never reaches the lower trigger level of 0.9 m required to switch on Pump 6. Also Rule 6 has a set of complex conditions that never occur and therefore this Rule is not used to switch off Pump 1. Rule 8 would switch on Pump 2 after 9:24 AM, but this rule conflicts with Rule 5, which has a higher priority. Because of the higher priority of Rules 7 and 5, also Rule 10, which would switch Pump 6 off if the level of tank t5 is above 1.7 m, and Rule 11, which would switch Pump 2 off based on the time and the water levels of tank t5 and t6, are never used.

The hydraulic behaviour of the system (shown in Figure D2 of Appendix D provided as supplemental material) is still similar to the previous cases, where the rules exploit the off-peak tariff period as much as possible (all of the three pumps are switched on). Pumps are also switched on in similar period of times and the minimum water level in the tanks also occurs at similar times, but, in terms of costs, there is a significant difference. We believe that the possibility of optimizing different types of rule-based controls can be beneficial and it could offer some insight in the network characteristics. However, we would also like to highlight that the optimized controls still need to be analyzed and reviewed by an expert before being implemented in the network.

Analysis on the robustness of pump controls

In this section the pump controls of the best solutions found by optimizing over a period of 24-hours for the case study (shown in Table 3) will be tested taking into account the variations of the demands for an entire year. Note that the input files of the optimal solutions with the 24-hour demand pattern and the one-year demand pattern can be downloaded as supplemental material (Appendix E). In order to extrapolate the demand pattern for this longer simulation time, the 24-hours of the demand pattern included in the original network file are considered to be the demands of the peak day, i.e. the volume of water delivered to the users in the 24h optimized is considered to be the maximum volume of water delivered in one day. However, none of the daily demand patterns exactly matches the demand pattern that has been optimized, so as to take into account the uncertainty in the demand. Seasonal variations of the demands are estimated using the Behavioural End-use Stochastic Simulator (BESS) (Thyer et al. 2011) for Adelaide (South Australia) (see Arbon et al. 2014). Figure 8 shows the annual demand pattern considered, which still has an hourly time step. As can be seen, each day has a similar pattern, with peak demands at about 8am and 6pm. However, it can also be noted that each day is slightly different from another, thus the seasonal variability of the demand and its uncertainty are taken into account.

Figure 9 shows the water level in tank t6 in the simulated year for each optimization case. As can be seen, all controls avoid the emptying of this tank: this guarantees the satisfaction of demands for the entire year, as tank t6 is the highest one and can satisfy the demands and fill tank t5. The controls also allow tank t6 to be completely filled on a daily basis, but different controls will result in different minimum tank water levels. In particular, while case 1 allows the minimum tank water level to reach about 1m each day, the other controls result in a much higher minimum tank water level (~4m for Cases 2 and 2a, ~5m for Case 3 and between 5m and 8 m for Case 4). For this last case, it is evident that the controls result in a higher tank water level in the winter period. This is in contrast with what a water utility usually does, as the lower water consumption usually allows for lower minimum levels in the tanks.

Figure 9 also shows the operation of Pump 2 on the days of maximum and minimum consumption (11 January and 30 July, respectively, in the annual pattern considered). The reason for choosing this pump is because Cases 1, 2 and 2a directly link the operation of this pump to tank t6. Figure 9 shows that all controls still exploit the off-peak tariff period in the day of maximum consumption. However, in Cases 2a and 3 the number of pump switches exceeds the maximum number allowed during the optimization. This problem is more frequent in the day of minimum consumption. In particular, Case 2 has several pump switches in the peak tariff period, caused by the fact that, due to the small demand, the upper trigger level is reached in a very short time. The analysis of the peak-day controls used in the day of minimum consumption also highlights that some of the controls (e.g. Cases 1 and 2a) do not perform as desirable, as most of the pumping that occurs in the peak tariff period could have been deferred to the off-peak period.

Interestingly, for this case study, the simplest optimization case where all pumps operate simultaneously seems to guarantee better behaviour, in terms of pump switches and annual pumping costs. In fact, as shown in Table 5, Case 1 has the lowest annual operational costs, in spite of having the largest costs in the optimized peak-day-demand. Note that Case 4 is the only case where the simulation in EPANET generates warnings during the annual simulation, thus the estimate of the annual cost in not considered reliable. The warnings are due to the fact that the controls of Case 4, which has been selected based on the demand of the 24 hours optimized and are mostly based on time, try to switch Pumps 1 and 2 on when the two tanks are full.

This analysis highlights the importance of testing the pump controls for different demand cases. Moreover, as some pumping could be deferred to the off-peak tariff period, the operational costs could be further decreased if pump controls could be optimized in near-real time or, potentially, if the pump controls could be optimized considering a longer period of time in the simulation. This option will be explored in future research, where several factors need to be taken into account (e.g. the uncertainty in demands and the behaviour of the system during pipe bursts, fire emergencies or power outage). In this work, we assume that the functionality of the system in abnormal operations is guaranteed if the emergency water volumes in the tanks, which are not specified for the case study, are maintained.

Conclusions

This paper introduced a modification of the EPANET2 toolkit, EPANET2-ETTAR, for changing rule-based controls in an automatic way and also corrected the way energy and costs are computed when rule-based controls are used. The new toolkit opens new possibilities to the optimization of pump operations, which is not limited anymore to either time controls or tank trigger levels. Being able to optimize pump controls that depend on more than one condition can be useful in complex distribution systems, where the pumping could be based on the level of multiple tanks or node pressures in the network. The definition of this type of controls is likely to be case specific and was not considered in this paper. However, it is worth noting that if the pump controls can be written as rule-based controls, they could be optimized using the new ETTAR toolkit.

The new EPANET2-ETTAR toolkit has been applied to the optimization of pump operations of a small water distribution system. Different types of controls, including the case in which the algorithm can choose both tank and trigger levels and the case in which the entire rule is decided by the optimization, have been tested. Results showed that usually less expensive solutions can be found compared to use of simple controls that only use tank trigger levels. The results also showed that the optimization of pump operation using rule-based controls can be useful to gain some insight on the system and pump efficiency. The analysis performed by applying the pump controls optimized for 24 hours to a one-year demand pattern generally confirmed the robustness of tank trigger levels, but highlights the necessity of testing longer simulation times for the optimization of pump controls.

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APPENIDX A: Correction to the EPANET2 code to correctly computing pump energy and cost when using rule-based controls

This appendix is provided as supplemental material.

APPENIDX B: Modifications to the EPANET2 code to modify rule-based controls (EPANET2-ETTAR)

This appendix is provided as supplemental material.

APPENDIX C: Guide for the new rule-based controls in EPANET2-ETTAR

This appendix is provided as supplemental material.

APPENDIX D: Additional Figures

This appendix is provided as supplemental material.

APPENDIX E: EPANET2 input files of the best solutions found

This appendix is provided as supplemental material.

Table 1: Short description of the new functions available in EPANET2-ETTAR toolkit for rule-based controls. More details can be found in Appendix C provided as supplemental material.

Function in ETTAR toolkit	Description
ENgetrule	To retrieve the number of conditions, the number of actions to be performed if the conditions are met or not and the priority of a rule.
ENgetpremise	To retrieve a specific condition in a rule (e.g. which tank level and what trigger level are set in the condition)
ENgettrueaction	To retrieve a specific action in a rule if the conditions are met (e.g. switch pump 1 on)
ENgetfalseaction	To retrieve a specific action in a rule if the conditions are not met (e.g. switch pump 1 off)
ENsetrulepriority	To set the priority in a rule
ENsetpremise	To set a specific condition in a rule (e.g. a condition about a tank trigger level could be changed into a condition about the time)
ENsetpremiseindex	To set the index of the object in a condition (e.g. a condition about the level in tank 1 could be changed to the level in tank 2)
ENsetpremisestatus	To set the status of an object in a condition (e.g. "if pipe 3 status is closed" can be changed to "if pipe 3 status is open")
ENsetpremisevalue	To set the value of an object in a condition (e.g. "if tank 1 level is above 4 m" could be changed to "if tank 1 level is above 3.5 m")
ENsettrueaction	To set the action in a specific rule if the conditions are met
ENsetfalseaction	To set the action in a specific rule if the conditions are not met

Table 2: Parameters and statistics of the best solutions obtained in the ten optimization trials.

Case	Pop. Size	No. Gen.	P_c	P_m	Average cost of best solutions (£/day)	Standard deviation (£/day)

1	100	1000	0.8	0.25	370.22	0.00
2	100	1000	0.8	0.10	345.97	6.90
2a	100	1000	0.8	0.10	343.95	11.38
3	500	1000	0.8	0.08	347.36	6.92
4	500	1000	0.8	0.02	323.33	4.73

Table 3: Best results of the optimization for the different types of pump controls

Case	Cost (£/day)	Cost difference compared to van Zyl et al. (344.19 £/day) (%)	Pump	Lower trigger level 0:00-7:00 - tank	Upper trigger level 0:00-7:00 - tank	Lower trigger level 7:00-24:00 - tank	Upper trigger level 7:00-24:00 - tank
				OFF_PEAK		PEAK	
1	370.22	+13.4	Pumps 1, 2, 6	9.7* – t6	9.8 – t6	0.9 – t6	9.2* – t6
2	337.66	-1.90	Pump 1	1.6* – t5	4.7 – t5	0.3 – t5	4.6 – t5
			Pump 2	9.8* – t6	10.0 – t6	5.3 – t6	5.5 – t6
			Pump 6	6.5* – t6	9.7 – t6	4.2 – t6	9.1* – t6
2a	329.91	-4.15	Pumps 1,2	9.5* – t6	9.6 – t6	4.5 – t6	9.8 – t6
			Pump 6	4.0* – t6	10.0 – t6	5.5 – t6	9.4 – t6
3	337.44	-1.96	Pump 1	4.7 – t5	8.9 – t6	5.5 – t6	9.7 – t6
			Pump 2	4.7 – t5	5.4 – t6	5.0 – t6	5.0 – t5
			Pump 6	5.5*– t6	5.0 – t5	4.7 – t5	4.8 – t5
4	312.41	-9.23	A summary of the controls is shown in Table 4				

* this value does not influence the operation of the pump.

Table 4. Optimal controls found for Case 4: the algorithm optimizes the entire rule. Controls in grey are not used in the simulation.

Type of Rule	Pump 1	Pump 2	Pump 6
Time-based		RULE 2 * IF SYST CLOCKTIME < 9:12:00 AM THEN LINK pmp2 STATUS IS OPEN RULE 5* IF SYST CLOCKTIME >= 0:00:00 AM THEN LINK pmp2 STATUS IS CLOSED (RULE 8 IF SYST CLOCKTIME > 9:24:00 AM THEN LINK pmp2 STATUS IS OPEN)	RULE 7* IF SYST CLOCKTIME >= 0:00:00 AM THEN LINK pmp6 STATUS IS OPEN
Tank trigger level	RULE 9** IF Tank t6 LEVEL < 5.9000 THEN LINK pmp1 STATUS IS OPEN		(RULE 10 IF Tank t5 LEVEL > 1.7000 THEN LINK pmp6 STATUS IS CLOSED
Combination	RULE 3*** IF Tank t6 LEVEL > 1.1000 AND SYST CLOCKTIME < 2:12:00 PM THEN LINK pmp1 STATUS IS OPEN RULE 12*** IF Tank t5 LEVEL > 0.7000 AND Tank t6 LEVEL < 9.7000 THEN LINK pmp1 STATUS IS CLOSED (RULE 6 IF Tank t5 LEVEL < 1.8000 AND Tank t5 LEVEL > 0.2000 AND (SYST CLOCKTIME <= 3:48:00 PM OR Tank t6 LEVEL < 4.8000) THEN LINK pmp1 STATUS IS CLOSED)	(RULE 11 IF SYST CLOCKTIME >= 0:36:00 PM AND Tank t5 LEVEL >= 1.9000 AND Tank t6 LEVEL > 9.2000 THEN LINK pmp2 STATUS IS CLOSED)	RULE 4*** IF SYST CLOCKTIME > 7:12:00 AM AND SYST CLOCKTIME < 4:48:00 PMAND Tank t5 LEVEL > 2.3000 THEN LINK pmp6 STATUS IS CLOSED (RULE 1 IF SYST CLOCKTIME > 4:24:00 AM AND Tank t6 LEVEL <= 0.9000 AND Tank t5 LEVEL <= 1.0000 THEN LINK pmp6 STATUS IS OPEN)

* this rule could have been represented also using simple controls in EPANET or using scheduling with an appropriate time discretization.

** this rule could have been represented also using simple controls in EPANET

*** this rule can only be written using rule-based controls.

Table 5: Annual pumping cost of the simulated year compared to the cost of the 24 hours optimized.

Case	Cost of 24h optimized (£/day)	Annual cost of the simulated year (£/year)	Average daily cost (£/day)
1	370.22	89523	245.27
2	337.66	91162	249.76
2a	329.91	111461	305.37
3	337.44	110376	302.40
4	312.41	82539*	226.14*

*EPANET warnings are generated during the simulation

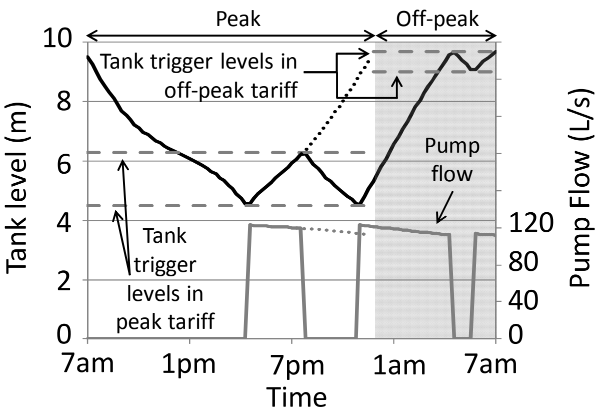

Figure 1: Example of pump operation with two sets of tank trigger levels: when the tank level (black line) reaches the lower trigger level (dashed lines) the pump is switched on; when the tank level reaches the upper trigger level, the pump is switched off.

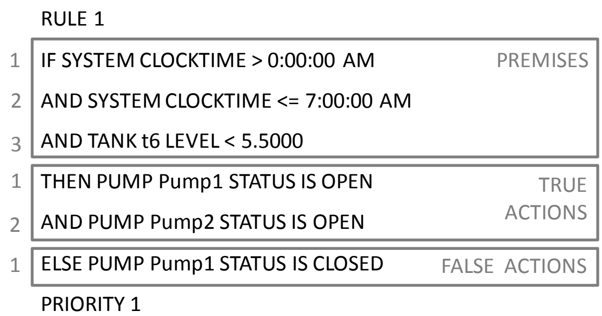

Figure 2: Components of rule-based controls: premises, true actions, false actions and priority.

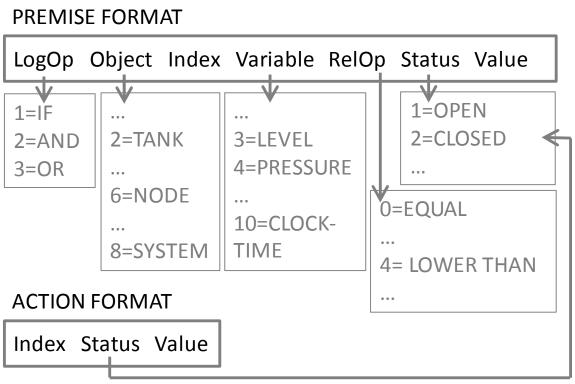

Figure 3: Format of premises and actions of rule-based controls in EPANET2 and example of codes used to represent logic operators, objects, variables, relationship operators and statuses.

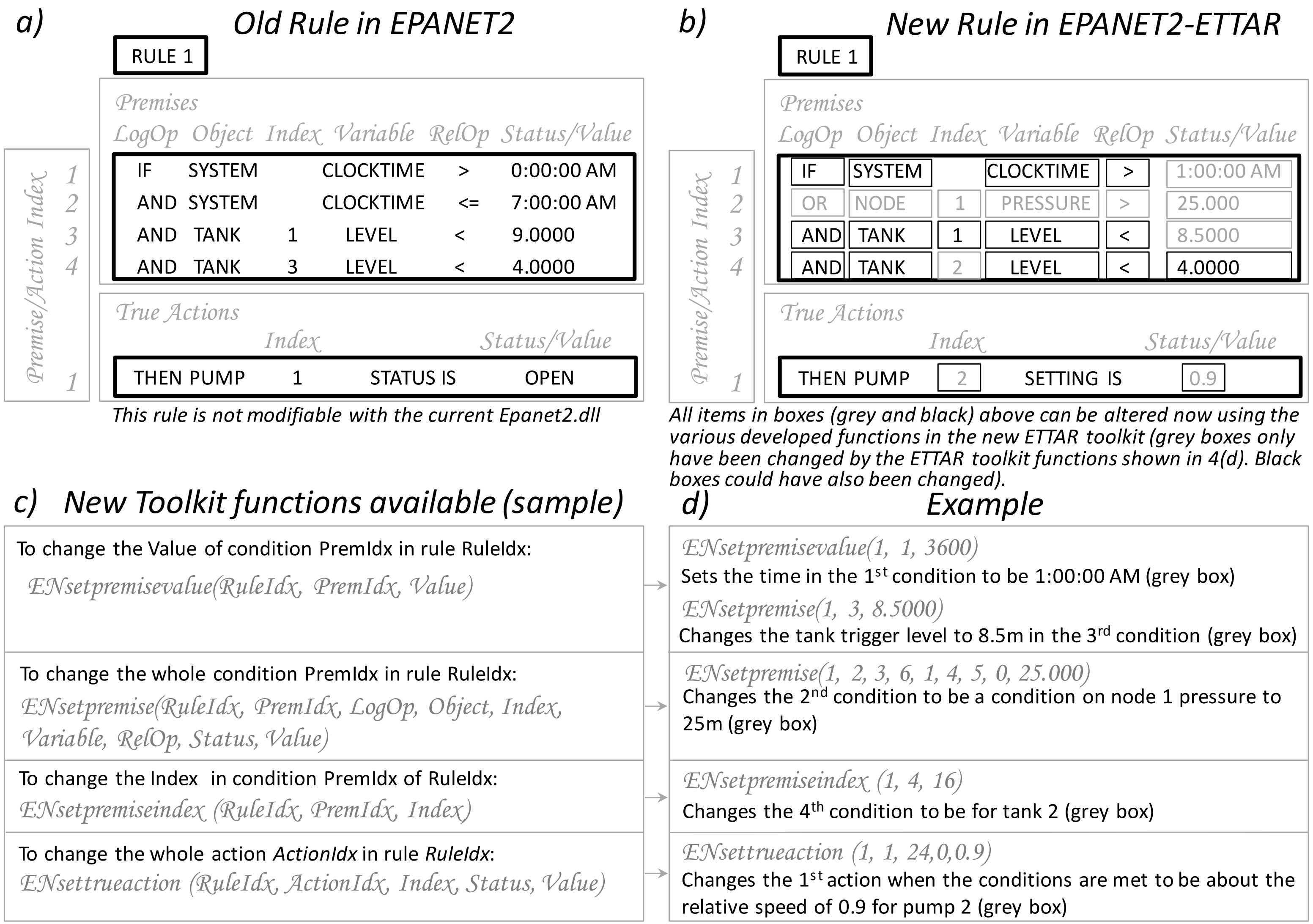

Figure 4: a) Existing rule (in black boxes); b) new rule after the functions shown in d) have been executed (changes are highlighted in grey); c) sample of functions in the new EPANET2-ETTAR toolkit to modify rule-based controls; d) example applied to the rule in a) assuming Rule 1 has RuleIdx equal to 1, that tank 2 has Index 16 and pump 2 has Index 24.

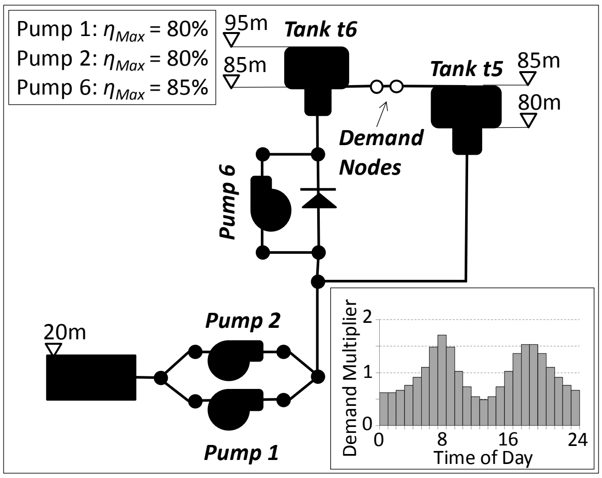

Figure 5: Layout of van Zyl case study network and demand pattern. η_{max} refers to the maximum efficiency of the pump.

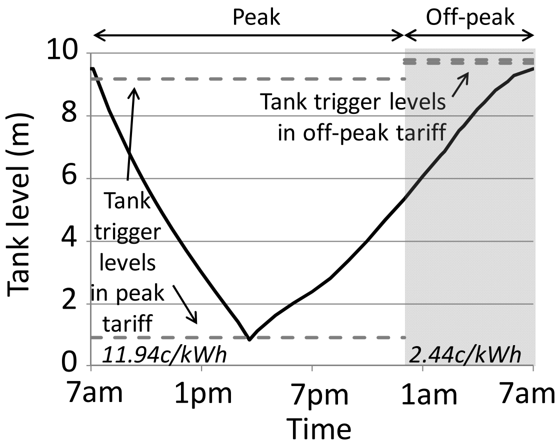

Figure 6: Tank trigger levels and water level in tank t6 for the best solution obtained for Case 1: all pumps are controlled by the same trigger levels.

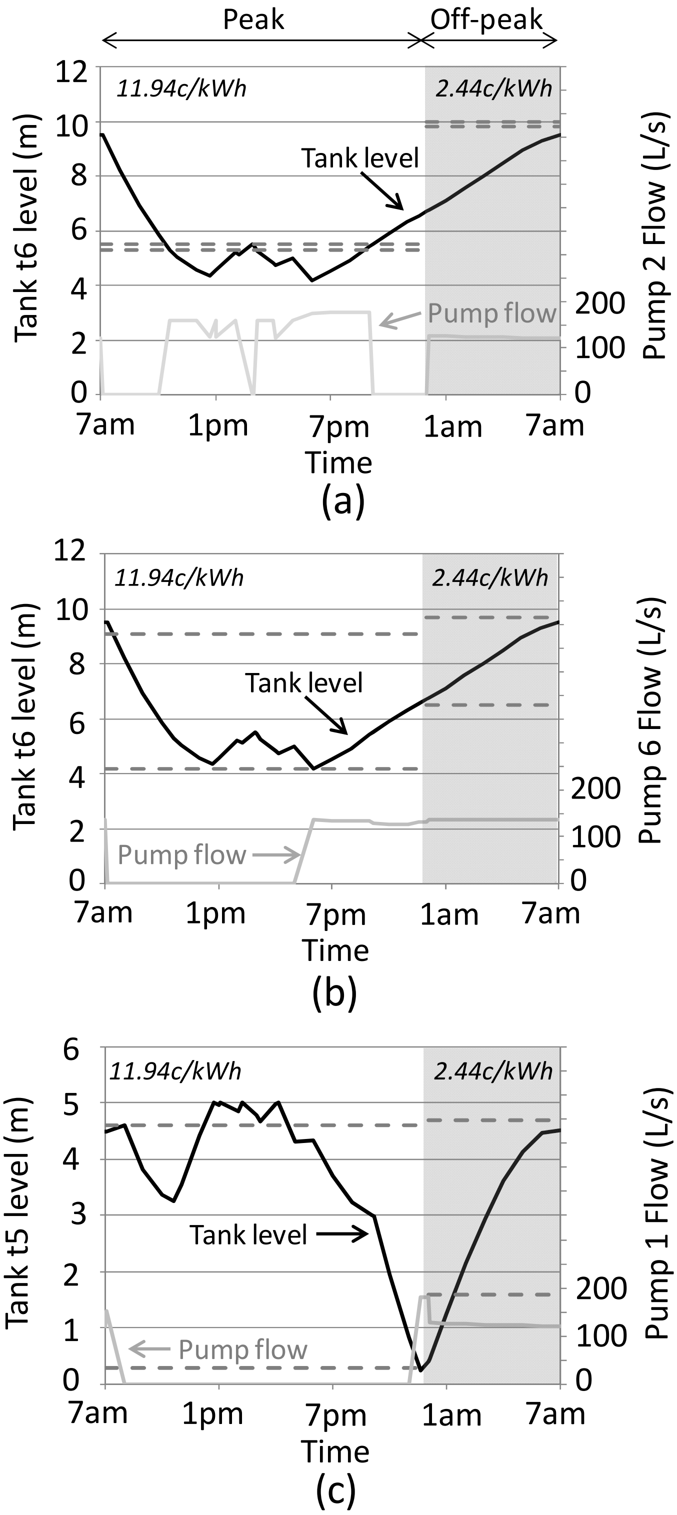

Figure 7: Results of Case 2: each pump has its own set of trigger levels. a) Tank t6 levels and Pump 2 flow, b) Tank t6 level and Pump 6 flow; c) Tank t5 level and Pump 1 flow. Tank levels are shown in black, pump flows are shown with the grey continuous line and tank trigger levels with the grey dashed horizontal lines.

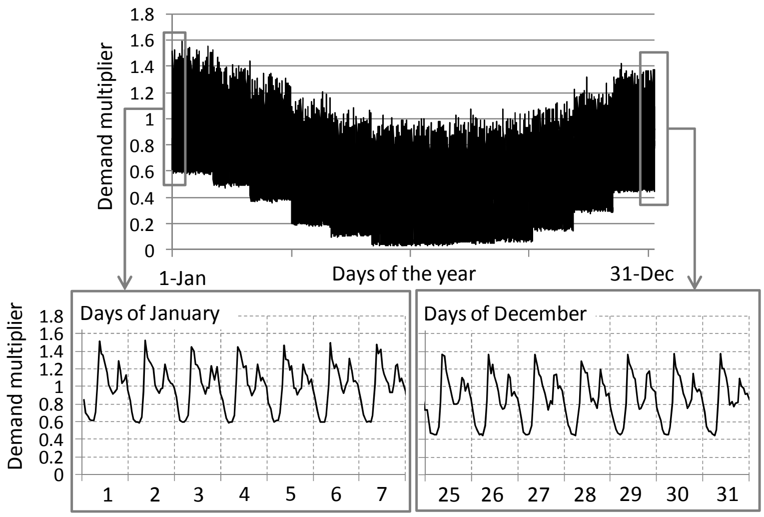

Figure 8: Annual demand pattern considered for testing the robustness of the optimal pump controls found.

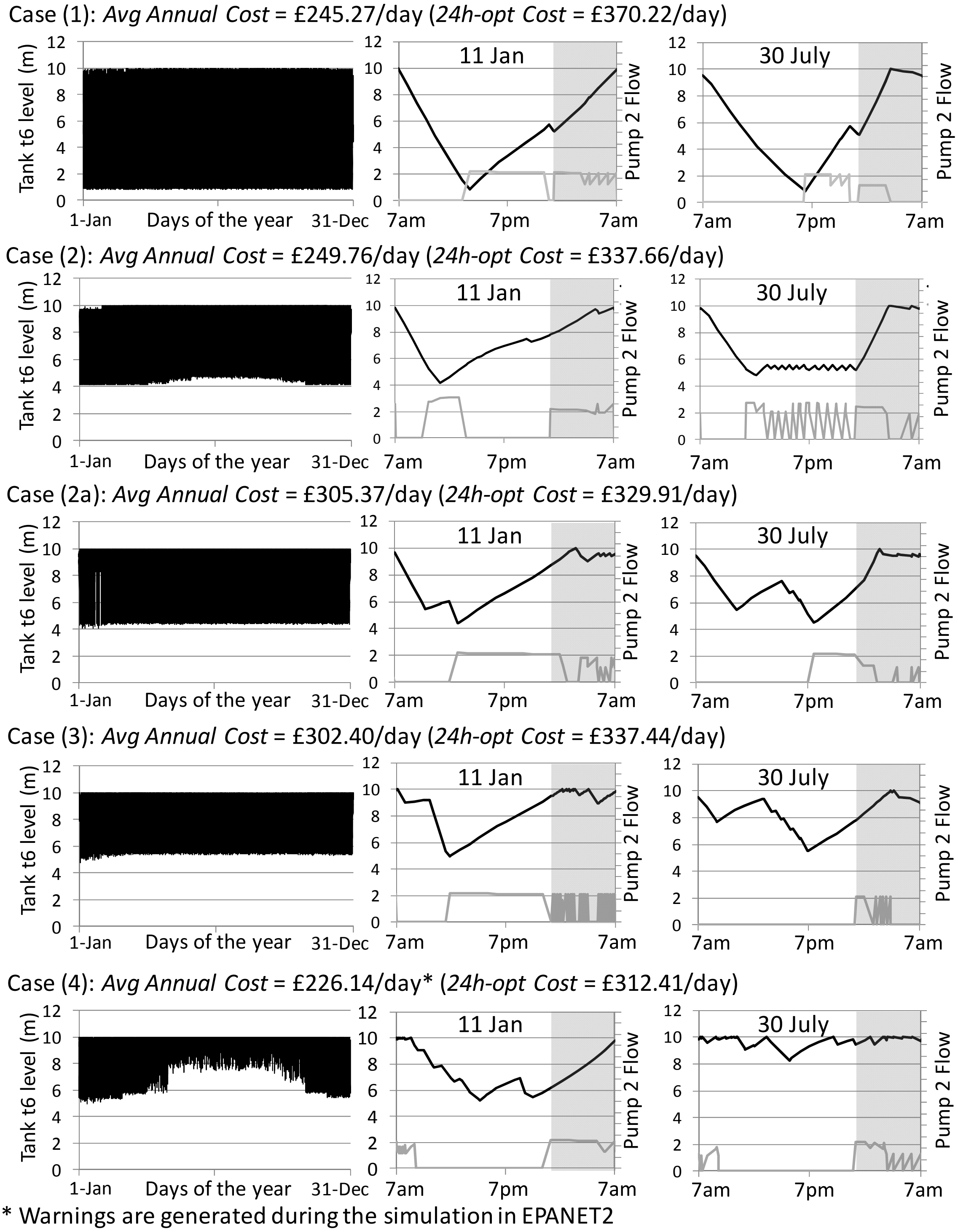

Figure 9: Hydraulic behaviour of the optimal pump controls tested with an annual demand pattern: water level in tank t6 and operation of Pump 2 for the day of maximum consumption (11 January) and minimum consumption (30 July). *Avg Annual Cost* is the average daily cost of the solution; *24h-opt Cost* is the cost of the solution optimized for the 24 hours.