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Improving energy efficiency of pumping systems through real-time scheduling systems

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ABSTRACT: Optimisation of water supply systems has been the subject of many papers over the past 20 years of CCWI conferences. Most papers have proposed various methods for off-line optimisation of complex networks to take advantage of low-priced energy tariffs, whereby the cost saving is achieved by rescheduling as much of the pumping load as possible to occur at night when the energy tariff is lowest. Whilst cost saving through time-of-use scheduling is an attractive opportunity for water companies, it does not save actual energy, it simply redistributes its use; consequently, there is no saving in carbon emissions. The only way the system can be operated more efficiently and hence save carbon as well as energy cost, is if the pumps themselves can be operated more efficiently.

The paper presents results following implementation of a closed-loop, real-time optimiser to four actual water supply systems in US. The data shows that by measuring the efficiency of each pump in real-time and ensuring that each pump in the system is positioned as close as possible to its best-efficiency point, significant improvements in average efficiency of between 6–9% can be made in addition to the 10% time of use savings. This in turn translates into real reductions of the carbon footprint.

1 INTRODUCTION

1.1 *Energy use in water supply*

The UK water industry uses approximately 3% of the total electricity consumption, or 4,400 GWh annually costing some £200 million. This energy causes around 1.9 million tones of carbon dioxide to be emitted to the atmosphere. The majority of the energy use is for lifting water from river and groundwater sources (26%) into the treatment plant (30%) and then pumping it to service reservoirs (43%) so that the water company can supply its customers.

Historically, whilst energy has been recognised as a major operating cost, the efficiency of the pumping operation has been accepted as a given and apart from addressing efficiency during pump selection and pump station design, the overall operational energy efficiency has not been of great concern.

This situation is changing very rapidly, the need to efficiently manage energy is of particular importance to society as we embark on a low carbon economy. Even a relatively small percentage of energy saved, by pumping systems, as part of fine tuning of water supply operations can have a significant impact on green house gas emissions, energy costs, and the organisations' bottom line profits.

1.2 *Water supply optimisation*

There has been a large amount of work done within the academic community to develop a wide range of different optimisation methods for water supply systems. Ever since the first UK CCWI conference in the mid eighties, many different techniques have been presented claiming impressive theoretical potential in terms of speed or financial savings. Unfortunately, few have ever been implemented in practice for a variety of reasons:

a) Robustness: There has been a perception that whilst the algorithms may find an optimal solution, they are not robust to the practicalities of real plant failures and changes in customer demand.
b) Speed: in order to meet changing demand and equipment availability, decisions need to be made quickly to adapt to new conditions.
c) Reliability: the models which have been developed require measurements from the actual sensors and output signals to actuators in the field carried over many different forms of telemetry media. The data and signals received are noisy and unreliable, any errors in the field measurements will result in inaccurate forecasts of demand or status and hence wrong decisions.

d) Accuracy: The underlying models have to capture the exact form of the real system and all its configurations. This requires a systematic and detailed analysis and representation of the real-system in the model. There is no room for approximations or simplification.
e) Confidence: there has been a reluctance to close-the-loop, i.e. take the human operator out of the loop, because of the critical importance of the water supply system. As a result, where open-loop scheduling systems have been applied, the operator is applying his own understanding of the risk of how the system should be operating as a filter of the outputs of the optimized schedules. Inevitably, this filter is unpredictable and changes the performance of the model.

Most of the academic approaches have focused on improving the speed of the algorithm and recently have adopted GA techniques because of the long solve times and huge dimensions of the possible options.

Figure 1 shows a solution which has been able to close the loop and provide real-time optimisation of large and complex water supply systems. Aquadapt has taken a different approach, it has focused on techniques to improve the robustness of the solution by ensuring that the interface between the model and the real-world is engineered to be robust and presents a simple intuitive interface to the operator. It connects directly to telemetry and reads key information on the state of the water supply system. The output is in the form of start/stop and open/close commands which are routed directly via the telemetry or SCADA system to the PLC or RTUs controlling the pumps and valves in the field. An absolutely critical aspect is the automation of staggered starts and gradual changes of state which ensures robust plant control. By solving the optimisation problem quickly($<$5mins), it can be run many times during the day, which enables it to adapt quickly to changing demand and availability of plant and equipment.

In a typical installation, the optimizer runs every half hour and produces an optimal pump and valve schedule for up to 48 hours ahead. The system can handle several hundreds of pumps and control-valves, multiple water treatment plant and many demand zones.

2 PUMPS AND PUMP EFFICIENCY

2.1 *Theory of pumps*

Most pumps used for municipal water supply are of the centrifugal type driven by electric motors. They have complex and unique head/flow characteristics and associated energy efficiency curves.

Every pump is designed and manufactured to operate most efficiently at a specific "duty point." The duty point is the point at which the pump produces the required flow (Q) at the required head (H) which it has to overcome.

Pump performance is subject to fixed and transient head/pressures that the pump encounters in the pumping pipe network in which it operates. The impact of all these fixed and transient head/pressures, present a complex and challenging case for designers, of pumping systems, to arrive at an optimal and energy efficient outcome, over the entire range of pump/pumps operation.

The analysis of pump performance and operational outcomes is undertaken by utilizing pump characteristic curves. These curves are generated by pump manufacturers for each specific pump type.

Figure 2 shows an idealized set of pump curves plotted on a common X-axis representing flow. In an ideal situation, the duty point is arranged to be exactly the point where the energy efficiency of the pump is at its maximum, in this way the efficiency of the pump operation will be maximized.

In practice, however, the duty point is hardly ever located at the best efficiency point for a number of practical reasons:

a) The water demand changes throughout the day and hence the pump moves up and down the flow-axis.
b) The system pressure will also change, more users will reduce the back pressure in the network causing the pump to move along the head-axis. (The flow

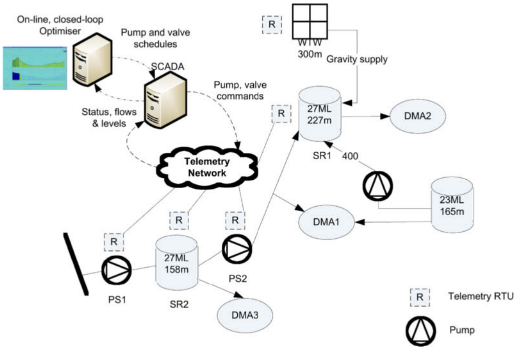

Figure 1. Schematic of a real-time, closed-loop water network optimiser.

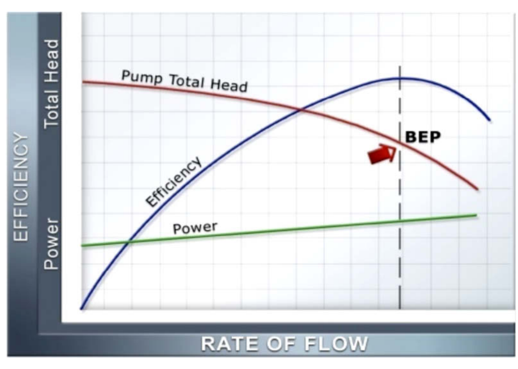

Figure 2. Idealised set of pump curves. Best Efficiency Point ideally at Duty Point.

and pressure relationship is known as the system curve.)

c) The design duty has to allow for growth in demand over say a 20 year period and therefore a larger duty is specified than will be seen when first commissioned, this moves the duty point to the left and lowers the efficiency.
d) The motor is usually over-sized for the pump, this will cause it to operate at a lower efficiency.
e) The pump is installed in pipe-work in the station which will throttle the flow and create additional headloss in the delivery system. The actual pump curve of the installed pump will be different to the curve of the pump as it was tested in the factory.
f) There will usually be more than 1 pump installed in a station to achieve the required range of flow duty. Multiple pumps will be connected into a common manifold and will interact with each other.
g) The net positive suction head (NPSH) will have a major influence on the duty and efficiency curve of each pump.
h) Pumps wear as they get older, various studies have been performed but a reliable study (Ref2) has shown that as a rule of thumb a pump will lose 5% of its new efficiency over the first 5 years and then stabilise thereafter.
i) The pump station will often be operating together with other pumps delivering into the same network. Whilst it might be possible to arrange one or other pump station to operate at its most efficient if operating alone, it will be difficult to get all stations operating at their most efficient point when operating together.

In summary, selecting and designing the right pump and pipe-work is a compromise between cost and performance which is not often performed effectively, with the result that most pumps usually run a long way away from their BEP.

3 AQUADAPT CALCULATES PUMP EFFICIENCY IN REAL-TIME

3.1 *How Aquadapt saves money*

Aquadapt Optimisation software saves costs in five main areas:

a) Time-of-use (TOU) load shifting, this is the movement of pumping operations from daytime into night-time when the energy is lower cost. Most pump scheduling systems do this in some form.
b) Peak charges avoidance (TRIAD); a natural result of TOU optimisation. The software will naturally chose to avoid running pumps during high tariff periods which is when peak charges such as triads[1] occur.
c) Selecting lowest cost sources of water. The software holds the marginal cost of production for each of the water treatment plants in the system, it selects the plant with the lowest production cost for each half-hour period.
d) Shortest path through the trunk distribution network. The software has a hydraulic model at its core and is able to find the path through the network with the lowest total headloss.
e) Pump efficiency improvement. Because the software holds the actual pump operating curve which is calibrated from flow and pressure measurements read from telemetry, and from the monthly energy bill, it is able to balance the complex problem of selecting the combination of pump settings which delivers the overall lowest operating cost and highest possible efficiency. Each pump will be positioned as close as possible to its Best-efficiency-point (BEP).

3.2 *Calculating pump efficiency improvements*

Aquadapt has been installed in four major water supplies in US. It has proven itself in independently audited measurements to reduce energy consumption per ML delivered by operating pumps and pump stations at higher points on their efficiency curve. It holds pump and efficiency curve information in the internal database and uses this to predict where each pump or combination of pumps is likely to operate on its curve if run, and does this for each half hour period for the next 24 hours. It then uses the resulting calculations of kWh per ML delivered to determine the lowest cost solution. In fact in any energy tariff market where the differential between peak and off peak rates is low the optimiser typically determines that the lowest cost strategy is to run pumps efficiently even in peak periods rather than inefficiently in off-peak periods, if this is the overall lowest cost solution.

Unfortunately likely efficiency gains are hard to predict in a system planning an Aquadapt installation. It has always been easier to measure "before" and "after" kWh per ML delivered figures for Aquadapt systems, then try and predict the results beforehand. What is surprising is that the efficiency figures are quite consistent in all Aquadapt installations. In all four systems in the US measurements were made which verified efficiency improvements of between 6% and 8.8% overall; with some individual pump stations demonstrating gains of over 20%. Three of these four systems were independently audited.

3.3 *Characteristics of the US water supply systems*

In order to predict energy efficiency improvements for a new client, the pumping stations were categorised using the efficiency improvement. It has been observed that where a pump operates over a wide range of its pump curve, or where variable speed drives are used, there can be quite considerable efficiency gains.

[1] In UK energy market, a triad is one of the 3 highest half-hour demand periods in a year. It is calculated at year end and the charge is applied retrospectively. It can account for up to 5% of the annual electricity bill if it is not minimised.

Table 1. Reference sites in US.

Undertaking	Pop^{n}.K	SR	Pumps	Demand (ML)
E. Bay MUD, Calif.	660	28	66	480
Washington Maryland	1600	57	81	900
WaterOne, Kansas	570	25	84	400
EMWD, Calif.	630	68	149	450

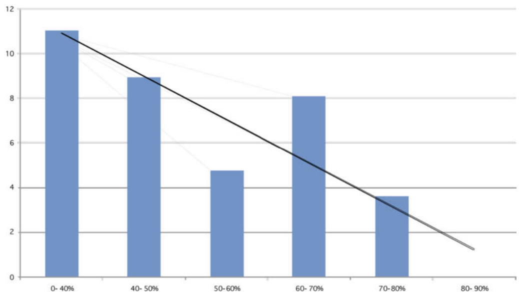

Figure 3. Direct relationship between efficiency gap and potential for improvement.

Account is also taken of the current performance of the pump station, i.e. newer pumps tend to operate better than older pumps and may already be operating well on their curve. On the other hand, older pump stations have worn pumps and may have system curves quite different to those envisaged when they were built. Figure 3 shows the relationship between efficiency of a pump before Aquadapt to the efficiency afterwards, with pumps divided into efficiency bands.

In Figure 3 above we have categorised the original pump efficiency into ranges, the first group is all pumps that were running at less than 40% original efficiency, then all pumps between 40% and 50%, 50%–60%, 70% to 80% and above 80%. The Y Axis shows the efficiency GAIN after Aquadapt and as can be seen, there is a close to linear relationship. Pumps that were running at lower efficiencies made the most efficiency improvements (about 11% on average gain in the first group for example) whereas pumps that were relatively new and performing well, i.e. in the 70% to 80% range only showed a ~4% improvement after Aquadapt.

Figure 4 shows similar data obtained for East Bay Municipal Utility District (EBMUD) in Oakland California. This is based on 6 years of data, two years prior to Aquadapt and four years post Aquadapt. This dataset contains over 600 accurately measured monthly energy and flow data points.

Figure 4 shows a big improvement in the least efficient pumps, after the optimizer was commissioned, no pump runs below 65% efficiency whereas before Aquadapt there were many pumps operating between 55% and 65% and more running between 65% and 75% efficiency. None were running at better than 75% yet now 80% of pumps and pump stations are achieving this outcome, all done purely through the optimiser

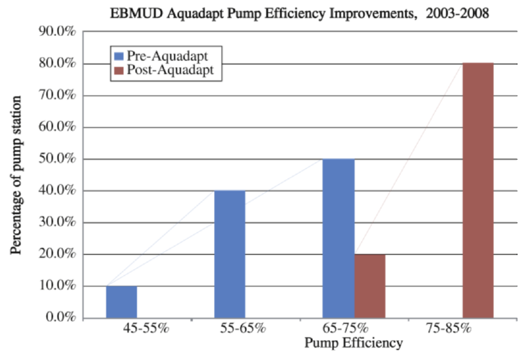

Figure 4. Efficiency improvement in pumps at EBMUD before and after introduction of Aquadapt.

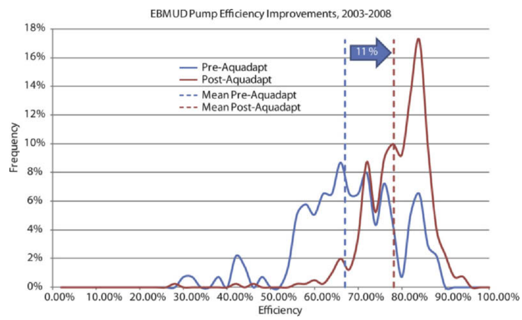

Figure 5. Average 11% improvement in mean of average pump efficiency over 4 years.

software selecting the right pump or pumps at the right time. This is made possible by Aquadapt's real-time optimiser being able to deduce the moving system curve responding to changing diurnal water demand.

In Figure 5, the performance improvement at EBMUD is even more pronounced. Recall that this is based on 2 years worth of accurate energy accounts for the "pre-Aquadapt" figures and 4.5 years worth of 'post-Aquadapt" energy bills from over 40 pumps. These figures were scrutinised by EBMUD in a very detailed review process as part of a performance payment scheme and are accepted as correct. In fact measuring these benefits is very simple; they are simply the monthly water volumes that flowed through the pump station divided by the kWh recorded by the electricity meter.

3.4 *Variable speed drives*

Many utilities incorporate variable speed drives into their pumping stations to improve energy efficiency. These pumps can operate over a wide range of flows and pressures. The operating points of these pumps taken from telemetry have been plotted to create a 'cloud' of operating points. Figure 6 shows the manufacturers pump efficiency curve adjusted for different shaft speeds using the affinity laws and which intersect the data cloud. The dots along the pump curve line

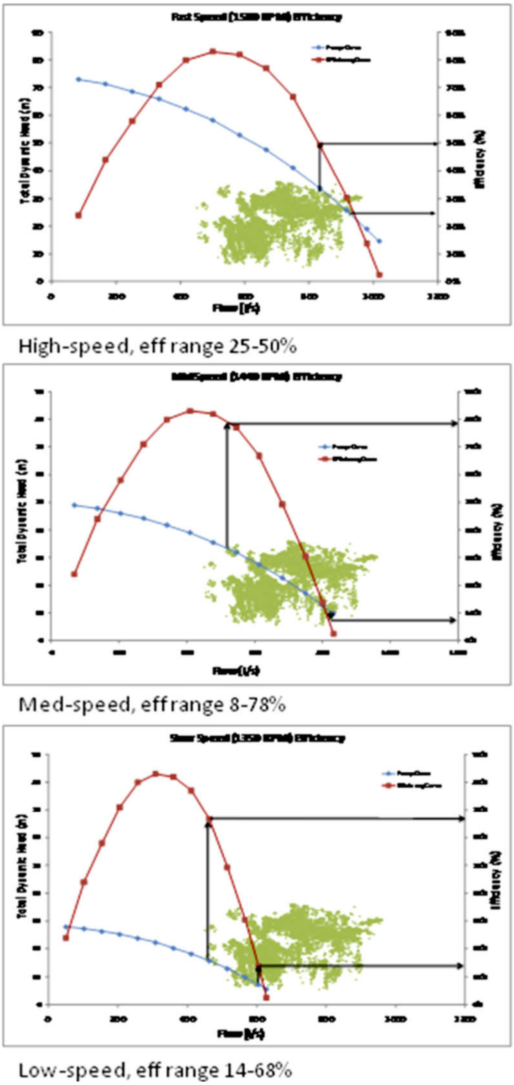

Figure 6. Variation of operating efficiency for range of pump speeds.

indicate that at any particular fixed pump speed there is a range of head and flow operating points and hence a range of efficiencies that the pump is operating over.

Figures 6 shows that the variable speed drive operates over a very wide range of efficiency from 8% to 78% efficiency with an average of 47%. If this were a fixed speed pump we would expect a gain of 14% after Aquadapt as per the chart for EBMUD. However, because this is a variable speed drive, the potential savings potential will be much greater.

The optimiser knows exactly how to set the speed, pressure or flow setpoint of the pump to have it operate at much more efficient ranges of the curve. Figure 7 shows the curve of Optimum efficiency (Red-line) is nearly vertical, and compares with a fixed head

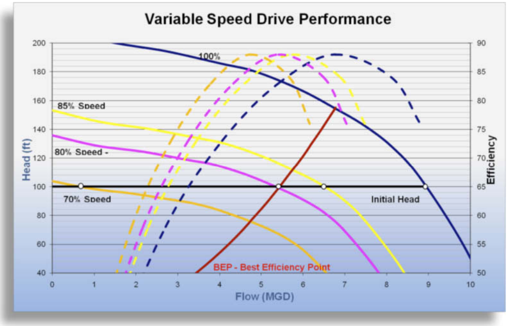

Figure 7. Variable speed pump best efficiency curve.

characteristic (Black-line) which is perpendicular to the best efficiency curve. This shows that a fixed head target pressure is not a good strategy to adopt to achieve most efficient operation. A better strategy, is to allow the pump to move up and down within a pressure band to the point where the efficiency is highest and which also meets the flow and head requirements, this point has to balance with the effects of other pumps and demand which will affect the system head in that part of the network.

4 CONCLUSIONS

Substantial improvements in pump efficiency can be achieved through real-time monitoring and optimisation. Average pump energy efficiency improvements have ranged from 6% to 8.4% for the existing Aquadapt clients with a few individual pump stations showing improvements of greater than 20%.

When it comes to variable-speed pumps, often installed to save energy, the efficiency of pumps supplying variable demand is a complex function which is not usually taken into account in the design or operation of the system. Cases have been found where the efficiency can be as low as 8%.

Significant increases in the efficiency of interconnected pumped systems can only be achieved by continuous monitoring of the pump and the system curve and then optimisation of the whole system. The rewards are impressive and lead to real reduction in the carbon footprint, requiring less MWh to deliver the same volume of water. This has enabled four US utilities to make practical steps towards meeting realistic carbon reduction targets.

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