**Institution: DE MONTFORT UNIVERSITY**

**Unit of Assessment: 15 – General Engineering**

**Title of case study: Saving Water Through Optimal Energy and Leakage Management in Water Distribution Systems**

## 1. Summary of the impact

Water distribution systems (WDS) are highly complex, spatially distributed networks comprising thousands of different components which deliver drinking water to customers. The impact described here has been achieved in areas of energy management, pressure control and burst detection in WDS. Some developed solutions, such as the model reduction method, model of pump stations and pressure control algorithms, have been widely accepted by the water research community and then filter down to industrial applications or implemented in a widely available shareware. Direct economical and environmental impacts have been achieved by projects for the UK companies with measurable benefits in pounds through reducing water losses and energy consumption as described in Section 4. These include South Staffordshire Water, Aquavent and Scottish Water in the pressure control area and Affinity Water (former Veolia) in the energy management and burst detection areas.

## 2. Underpinning research

Bogumil Ulanicki joined the institution as a Research Assistant in 1987 and has progressed through the ranks, being appointed Professor of Engineering Systems in 2007. He is Head of Centre for Engineering Science and Advanced Systems (CESAS) and the Water Software Systems (WSS) research group.

The model reduction algorithm was first developed at De Montfort University (DMU) between 1993 and 1995 by Ulanicki, in collaboration with Prof Martinez from University of Valencia (who was visiting DMU at the time). The method was based on the variable elimination concept and was very efficient and robust when compared to other available methods based on optimisation techniques. This phase of the research was funded by DMU and led on to the projects described below. (The method was first presented at the Hydroinformatics conference in Zurich in 1996 but due to the commercial sensitivity of this research, full journal publication of the method was delayed and appeared in 2012[1].)

The model reduction method facilitated solving many optimisation problems for WDS, including pump scheduling and pressure control. As part of the WaterCIME project (project no 8399, 1994–1997, funded by the EU's ESPRIT III programme) Ulanicki developed a general optimal scheduling algorithm [2]. This was distinct from other algorithms at that time, which were crafted for particular distribution systems. The general optimal scheduling algorithm was subsequently enhanced during EPSRC grant "Efficient Energy Management for Water Distribution Systems and Treatment Processes" (GR/N26005, 2000–04, PI Ulanicki). Traditional nonlinear programming was replaced by a dynamic optimisation algorithm [4]. The algorithm was implemented by Jens Kahler, a research fellow working on the grant. The dynamic optimisation algorithm performs a search in a reduced space, which significantly reduces the calculation time and makes the algorithm much more suitable for real time applications. Another result of the GR/N26005 project was a new pump station model which removed numerical singularities from the optimisation problems [5]. Two approaches for pump modelling were considered: in the first approach, the power characteristic was evaluated from hydraulic and efficiency curves; in the second approach, the mechanical power was approximated directly by a cubic polynomial and scaled by pump speed and number of pumps. In both cases, the obtained power curves are well suited for use in simulation and optimization software.

Reducing water losses (leakage) in WDS was another important focus of the WSS research. Leakage reduction can be achieved by a co-ordinated action of pressure control and burst detection. Ulanicki investigated pressure control in the "Optimised Pressure Control for Networks with Multiple Pressure Reducing Valves Inputs" project (EPSRC, GR/M67360, 1999–2002, PI Ulanicki). Solutions were provided for district metering areas (DMA) with many inlets in the form of time or flow modulation strategies [3]. Even with the pressure controls in place, bursts still happen and need to be located and repaired quickly. A burst detection method was developed in the "Reduction of Water Losses and Energy Consumption Using an Effective Process for Burst

Detection" project (EPSRC/STI, GR/S25715/01, 2003–2005, PI Ulanicki). As a result of collaboration between Ulanicki and John May (an independent consultant, later Aquavent), an active burst identification experiment, e-FAVOR, was developed.

These four methodologies (network model reduction, pump scheduling, pressure control and burst detection) were developed further as a part of the EPSRC "Neptune" project (EP/E003192/1, 2007–2010) – a strategic partnership of six leading UK universities [Cambridge, DMU, Exeter, Imperial College, Sheffield and Leicester and three industrial partners Yorkshire Water, United Utilities and ABB Ltd]. Ulanicki led one of the three Research Priority Areas – the Integration of Pressure and Energy Management with Leakage Reduction. An online version of the model reduction method was implemented including a new feature of network nodes re-ordering which accelerated the calculations by several orders of magnitude [1]. Hossam AbdelMeguid employed by DMU as a RA on this project, investigated an alternative approach to pump control based on feedback rules which depend on reservoir levels and electrical tariffs. The pressure control research initiated in GR/S14382 was extended during Neptune to include dynamic pressure transient aspects. A number of novel control algorithms and controllers were investigated, including one built by Aquavent (a company associated with the project) [6]. The burst detection method was enhanced by introducing a new indicator of bursts: a difference of head loss between the monitored nodes. This indicator removed errors caused by inaccurate elevation information and logger offsets.

**3. References to the research**

All peer reviewed:

*[1] Martinez Alzamora F., Ulanicki B & Salomons E. (2012). A fast and practical method for model reduction of large scale water distribution networks, Journal of Water Resources Planning and Management, DOI 10.1061/(ASCE)WR.1943-5452.0000333.
[2] Ulanicki B., Bounds PLM & Rance J.P. (1999). Using a GAMS Modelling Environment to Solve Network Scheduling Problems, Measurements and Control, Vol 32, No 4, pp 110–115.
[3] Ulanicki B., Bounds PLM, Rance J.P. & Reynolds L (2000). Open Loop and Closed Loop Pressure Control for Leakage Reduction, Urban Water Journal, Vol 2, No 2, pp 105–114.
*[4] Ulanicki, B., Kahler, J. and See, H. (2007). Dynamic Optimization Approach for Solving an Optimal Scheduling Problem in Water Distribution Systems. ASCE Journal of Water Resources Planning and Management, Vol 133, No 1, pp 23–32.
*[5] Ulanicki B, Kahler J & Coulbeck B (2008). Modelling the Efficiency and Power Characteristics of a Pump Group, J Water Resources Planning and Management, Vol 134, No 1, pp 88–93, DOI 10.1061/(ASCE)0733-9496(2008)134:1(88).
[6] AbdelMeguid H, Skworcow P & Ulanicki B (2011). Mathematical modelling of a hydraulic controller for PRV flow modulation, Journal of Hydroinformatics, Vol 13, No 3, pp 374–389, DOI 10.2166/hydro.2011.024.

**4. Details of the impact**

The model reduction algorithm (described in section 2) reduced the simulation time of water distribution network models by several orders of magnitude and has been used by various companies including OptiWater in Israel [i1], who routinely use the algorithm in their projects.

The new pump models described in section 2 generated significant interest from the water community and have been adopted for implementation in the new version of Epanet – Epanet 3 [i2]. Epanet software is free to download and is currently the most extensively used water distribution system modelling software across the world.

The findings of the EPSRC grant GR/M67360 were implemented by South Staffordshire Water Company, with support from the EPSRC RAIS grant (GR/S14382, 2002–2003). This led to the introduction of pressure control still in use today [i3]. The benefits of pressure control include: reduced unwanted consumption; reduced flow from leaks; fewer bursts; and fewer customer complaints. It is estimated that the introduction of pressure control by South Staffordshire Water corresponds to both a 20% reduction in water loss from leak flow (which equates to savings of *ca* £7,000 per annum per metering area where the system is implemented) and 100 fewer bursts in a year (leading to a total saving to the company of £0.5 million in the relevant DMAs). The estimates are based on the Allen Lambert report (2012) for IWA Water Loss Specialist Group.

The controller developed with Aquavent (a part of the MIDAS company) and modelled and tested in the Neptune project has subsequently been installed at six sites by Aquavent, with each installation reducing losses from background leaks by 20%. This approach simultaneously reduces the number of bursts and automatically adjusts the pressure to meet current water demands, thereby leading to greater cost savings for the water company. The controller has recently been installed (2012) at Addenbrookes Cambridge University Hospital, Royal United Hospital Bath NHS Trust and HMS Drake Fleet Maintenance Base, Davenport [i4], leading again to reduction of leaks by 20% and an anticipated cost saving of £50,000 per annum in each institution (assuming an average consumption of 300 $m^3$ per day and the water price of £2 per $m^3$).

In May 2013, Prof Ulanicki was commissioned by Scottish Water to provide consultancy and assess the major pressure control scheme in Edinburgh, to resolve instability issues occurring in some specific conditions [i5], the project was completed in July 2013. Prof. Ulanicki diagnosed precisely the cause of the instability and provided a general answer to the question which had puzzled water engineers for years – why PRVs tend to oscillate at low flows. Each instability incident causes multiple bursts, resulting in a loss of tens of thousands of pounds. The findings are now being implemented in practice.

The burst detection method, based on the e-FAVOR active identification experiment and the new burst indicator developed by the EPSRC Neptune project, has been adopted by Affinity Water ("the largest water-only supplier in the UK" https://stakeholder.affinitywater.co.uk/about-us.aspx, accessed 25/07/13) as standard practice for bursts detection since 2010 under the coded name, PlaN [i6]. The impacts derive from the shorter duration of the unreported bursts. The implemented systematic method allows the company to perform more inspections per year in each DMA and identifies bursts faster during the inspection. In financial terms it will reduce water losses by 400$m^3$ per burst. With 90 bursts per year it brings £72k/year savings (based on Lambert et al. report, Financial Times, 1998).

## 5. Sources to corroborate the impact

[i1] In a written testimonial, a consultant from OptiWater, Haifa, Israel stated: "*As a water resources consultant engineering, with over 15 years of experience, one of my main working tool is a hydraulic model. Most of the water distribution systems are large and complex making their models difficult to work with and, for some uses, these large models, requires comprehensive computational resources. Our work*[1]*, which extend previous work by Prof. Alzamora and Prof. Ulanicki provided a practical method to reduce and simplify large water network models. This method has been used on a number of real-world projects in number of fields: online network operations, water security, sensor placement and more.*"

[i2] In a written testimonial, a scientist from the Environmental Protection Agency, US, stated: *"I am writing to confirm that we intend to use the results published in your paper "Modeling the efficiency and power characteristics of a pump group" (Ulanicki, B. et al. (2008), JWRPM, 134 (1) pp. 88-93) in the next version of the EPANET program. As you know, EPANET is used throughout the world for modeling the hydraulics and water quality behavior of water distribution systems. The elegant approach you presented in the paper for computing the power consumption of both fixed and variable speed pumps will allow EPANET to more accurately handle this type of calculation."*

More information about Epanet 3 can be seen on the blog www.water-simulation.com/wsp/2010/09/21/epanet-3 (accessed 17/09/13), which includes the following comments (taken from a sample of 27 similar notices) to illustrate how widely the software is used:

- EPANET had been a great tool to design aqueducts in Guatemala and God had blessed us with the no cost of this program against the excessive price of similar programs in the market.
- EPANET has been used to design hundreds of rural and urban water supply schemes in Sri Lanka for the last 13 years. The free software helped many engineers and university students to learn network analysis
- Epanet is widely used in my country Venezuela

[i3] In a written testimonial, a Network Director form South Staffordshire Water has recently confirmed that: *"During Simon's secondment to South Staffs Water a significant amount of investigation, analysis and follow on work was undertaken to understand the way the Company's water supply pipe network responded to different forms and degrees of pressure control, with the overall aim of improving leakage management and customer service. …This work was a great success and set the foundations for further work undertaken by the Company, all of which has lead to a much greater understanding of the impacts and management of pressure on the water supply pipe network. The Company was very pleased by the work undertaken by Simon and the resulting improvements this achieved."*.

South Staffordshire Water lists "monitoring the pipe network" on the Leak Management section of their website (see http://www.south-staffs-water.co.uk/community_environment/leak_management.asp accessed 17/09/13).

This includes "**Key facts and figures**": It is now more than 30 years since we last imposed a hosepipe ban; we have achieved a water quality performance of 99.99%; we have continually met Ofwat's leakage target; we are one of the leading companies for operating cost efficiency.

[i4] The Director of Aquavent UK Ltd, Peterborough, has expressed the following opinion about the impact of this research in the recent letter to DMU: "*Just a note to thank you for your continued support in respect of our water savings product Aquai-Mod®. Without your expertise and commitment and that of your department, we would not be where we are now with our unique approach to water savings, and leakage reduction via hydraulic water pressure management. We started this development some 10 years ago and you have been a valuable partner during that time, not only helping with technical and development support but providing us with links to potential clients."*

[i5] In personal correspondence (which can be made available upon request), a Senior Project Manager from Scottish water recently stated that "*Applying a rigorous challenge to the operating control measures of the Pressure Reducing Valve was a necessary intervention to maintain the water supply to thousands of customers. The delivery of a project into the hands of our Operations needed high level academic appraisal in order to increase confidence going forwards. It was important to include a non-biased academic assessment as part of a competent and successful project*."

i6] Evidence for the roll-out of "PLaN" can be seen in private correspondence (2010) from an Asset Performance Specialist at the company, which included the following statement: *"We are now rolling out PLaN (Pressure Loss across Networks) to 100 DMAs! This as you can imagine will involve improvements to the way we do things so that we can keep up with demand. So far we've had 100% success with the method. The first trial found 2 leaks and a school with flushing urinals at night, oh, and also a valve that was letting by, the second trial found 2 leaks, the third found 6 leaks and the last one found 10! So far, every time we say go there they find a leak :-)"*. Copies of this correspondence can be made available upon request.