Institution: De Montfort University		
Unit of Assessment: 12		
Title of case study: Improving Operation and Control of Water Distribution Systems		
Period when the underpinning research was undertaken: 2000–2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Bogumil Ulanicki	**Role(s) (e.g. job title):** Professor of Engineering Systems	**Period(s) employed by submitting HEI:** November 1987–June 2018
Period when the claimed impact occurred: August 2013–December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Water distribution systems (WDS) are large-scale systems used to extract water from nature and supply it to domestic and industrial consumers. Water utilities face many challenges in constructing and operating such systems. Prof. Ulanicki and his team at DMU have developed mathematical models and computer methods for WDS. This research has led to

1. exploitation of our model reduction method by company OptiWater in seven countries;
2. embedding our pump station models in EPANET, the most used WDS modelling software in the world;
3. exploitation of our burst detection method by Affinity Water, which helped the company localise between 300 and 750 leaks in their water distribution network;
4. [text removed for publication]
5. informing La Société Wallonne des Eaux's selection of control strategies for pumps and valves in their WDS by developing a model that can predict the dynamic behaviour of the system;
6. exploitation of our PRV model by Bentley Systems in their HAMMER software with several hundred registered users worldwide.

2. Underpinning research

The overarching theme of the research is developing modelling methods to solve challenging problems for the water industry. The model reduction method [R1] is based on the variable elimination concept. The method reduces the simulation time of water distribution network models by several orders of magnitude and is more robust than other methods based on optimisation techniques [R1]. The model reduction method facilitated solving many optimisation problems for WDS, including pump scheduling. Network model reduction and pump scheduling were developed further in the EPSRC 'Neptune' project [G1]. An online version of the model reduction method was implemented, including a new feature of network nodes reordering that accelerated the calculations by several orders of magnitude [R1].

One of the results of the EPSRC project 'Efficient Energy Management for Water Distribution Systems and Treatment Processes' [G2] was a new pump station model that removed numerical singularities from the optimisation problems [R2]. For pump station modelling, the power characteristic was evaluated from hydraulic and efficiency curves, or the mechanical power was approximated directly by a cubic polynomial and scaled by pump speed and the number of pumps.

Reducing water losses (leakage) in WDS was another important focus of Ulanicki's research. Leakage reduction can be achieved by a coordinated action of pressure control and burst detection. Ulanicki investigated pressure control in the 'Optimised On-line Pressure Control for Networks having Multiple Pressure Reducing Valve Inputs' EPSRC project [G3]. Solutions were provided for district metering areas (DMA) with many inlets in the form of time or flow modulation strategies. Even when the pressure controls are 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' EPSRC/STI project [G4]. The pressure control research was initiated in the EPSRC RAIS project [G5]. Pressure control and burst detection were developed further in the EPSRC 'Neptune' project to include dynamic pressure transient aspects. The burst detection method was enhanced by using an active identification procedure that exploits the difference of head loss between the monitored nodes [R3]. This indicator removed errors caused by inaccurate elevation information and logger offsets.

WDS are equipped with sophisticated instrumentation for monitoring and control purposes, including local and global control loops, which, if not designed properly, can lead to spurious dynamic behaviour and instabilities in the water distribution system. Ulanicki developed methods [R4] to analyse the dynamic behaviour of WDS equipped with control components. In [R5, R6], he explained the root cause of instabilities that tend to arise in PRVs under low-flow conditions. He found that the loss of stability in PRVs is a direct result of an increase in the static valve-network gain as the valve position gets smaller, thus making pressure changes more sensitive to valve position adjustments. If the valve controller is tuned at medium valve openings characteristic of normal operating conditions, the increased gain at low valve openings can cause the control system to be too aggressive in its valve position adjustments, leading to oscillations. In [R6], he derived the gain equation for a simplified pipe-PRV-pipe model. The gain equation curve was then used to derive the formula for a gain compensator whose purpose is to keep the static gain constant across an entire range of permitted valve openings. A network transient model was then used to show the remedial effects of the gain compensator.

3. References to the research

[R1] Martinez Alzamora F., Ulanicki, B. and Salomons, E. (2014) 'Fast and practical method for model reduction of large-scale water-distribution networks', *Journal of Water Resources Planning and Management*, 140(4): 444–456; DOI: 10.1061/(ASCE)WR.1943-5452.0000333

[R2] Ulanicki, B., Kahler, J. and Coulbeck, B. (2008) 'Modeling the efficiency and power characteristics of a pump group', *Journal of Water Resources Planning and Management*, 134(1): 88–93; DOI: 10.1061/(ASCE)0733-9496(2008)134:1(88)

[R3] Skworcow, P. and Ulanicki, B. (2011) 'Burst detection in water distribution systems via active identification procedure', in *Proceedings of the Eleventh International Conference on Computing and Control for the Water Industry (CCWI2011)*, 5–7 September 2011, Exeter, UK, pp 545–550; ISBN: 0-9539140-8-9; https://www.dora.dmu.ac.uk/handle/2086/9285

[R4] Prescott, S.L. and Ulanicki, B. (2003). 'Dynamic modeling of pressure reducing valves', *Journal of Hydraulic Engineering*, 129(10), 804–812; https://doi.org/10.1061/(ASCE)0733-9429(2003)129:10(804)

[R5] Ulanicki, B. and Skworcow, P. (2014), 'Why PRVs tends to oscillate at low flows', *Procedia Engineering*, 89: 378–385; DOI: 10.1016/j.proeng.2014.11.202

[R6] Janus, T. and Ulanicki, B. (2018) 'Improving stability of electronically controlled pressure-reducing valves through gain compensation', *Journal of Hydraulic Engineering*, 144(8); DOI: 10.1061/(ASCE)HY.1943-7900.0001498

Grants:

[G1] EPSRC Neptune (2007-2010) (EP/E003192/1): Delivering Sustainable Water Systems by Optimising Existing Infrastructure via Improved Knowledge, Understanding and Technology (£2,326,981). Ulanicki was CoI (PI NJ Graham).

[G2] EPSRC (2001-2004) (GR/N26005): Efficient Energy Management for Water Distribution Systems and Treatment Processes (£177,084). Ulanicki was PI.

[G3] EPSRC (1999-2002) (GR/M67360): Optimised On-Line Pressure Control for Networks having Multiple Pressure Reducing Valve Inputs (£107,939). Ulanicki was PI.

[G4] EPSRC/STI (2003-2005) (GR/S25715/01): Reduction of Water Losses and Energy Consumption Using an Effective Process for Burst Detection (£85,820). Ulanicki was PI.

[G5] EPSRC RAIS (2002-2003) (GR/S14382): Optimised On-line Pressure Control for Networks Having Pressure Reducing Valve Inputs (£26,636). Ulanicki was PI.

4. Details of the impact

- The model reduction algorithm described in Section 2 [R1] has supported the work done by OptiWater (an Israeli consultancy company) since 2014 for water companies in Israel, the UK, the USA, Singapore, Australia, France and Germany [C1].
- EPANET is the most extensively used WDS modelling software in the world. It is free to use, and tens of thousands of copies have been downloaded to date (https://doi.org/10.1061/41203(425)4). The new pump models [R2] described in Section 2 generated significant interest from the EPANET community [C2a]. They were integrated by DMU into an EPANET branch called dev_pump_battery in May 2020 [C2b]. The merge was approved by the Open Water Analytics (OWA) Community in July 2020 [C2c].
- The burst detection method based on the active identification experiment and the new burst indicator [R3] has been adopted by Affinity Water [C3] ('the largest water-only supplier in the UK' https://stakeholder.affinitywater.co.uk/about-us.aspx, accessed 03 August 2020) as standard practice for burst detection since 2010 and beyond July 2013 under the coded name PlaN. From 2014 to January 2020, the method was applied successfully to 150 DMAs [C3]. Each test usually finds two to five leaks [C3] (300 to 750 leaks in total). It was used to find hidden leaks where the traditional techniques were not successful. Affinity Water have had 100% success with the method [C3]. The benefits derive from the shorter duration of the unreported bursts. The implemented systematic method allows the company to increase the number of inspections per year and DMA due to the reduction in the time required for each inspection. It also identifies bursts faster during each inspection. It has also enabled to find illegitimate water use and areas with unusual night usage [C3].
- [text removed for publication]
- Using his PRV model [R4], Ulanicki completed between February 2019 and April 2020 two tasks for La Société Wallonne des Eaux (SWDE), the most important water production and distribution company in the Wallonia region in Belgium, with a distribution network stretching over 40,000 km and 2,500,000 customers (70% of the Walloon population). The first task was a steady-state analysis of combined pressure control (in Chamber 20) and pump speed operation (in the Hollogne-aux-Pierres chamber), while the second one was a dynamic and stability analysis for the whole system, which developed and evaluated a number of control strategies for combined pressure reduction and pump speed. SWDE selected two of the proposed control strategies and started implementing them in the Eupen-Wellin system in the second half of 2020 [C5]. The benefits of the work are difficult to predict in monetary terms but they include prevention of (1) significant material loss (underground pipes), (2) disruption of water supply to customers and (3) disturbance of local transport and flooding of households [C5].
- The analysis of WDS is done at two levels: extended period simulations at typically 15-minute steps and analysis of transients (hammer phenomena) at single-second steps. Unchecked transients can have catastrophic consequences on pipes and control equipment. There is no public domain package available for transient analysis. The most popular commercial package is HAMMER from Bentley Systems. The PRV model developed by Ulanicki [R4] has been part of the HAMMER product since 2011 [C6a]. Currently, there are at least several hundreds of registered users of HAMMER around the world [C6b]. Indirect financial benefits resulting from a properly designed water

distribution system with protection against surges and instabilities can be estimated in millions of pounds [C6c].

5. Sources to corroborate the impact

[C1] Testimonial from OptiWater dated 17 January 2020.

[C2a] Email from creator of EPANET: I just posted an issue on the Open Water Analytics (OWA) EPANET GitHub site requesting that your formulas for modeling pump groups be added to EPANET dated 19 September 2019. You can view the request at https://github.com/OpenWaterAnalytics/EPANET/issues/532

[C2b] Evidence that DMU's code has been merged into EPANET's OpenWaterAnalytics:dev_pump_battery: https://github.com/OpenWaterAnalytics/EPANET/pull/599#event-3408630887

[C2c] Evidence that the merge has been approved by Open Water Analytics (OWA) Community: https://github.com/OpenWaterAnalytics/EPANET/tree/dev_pump_battery

[C3] Testimonial from Affinity Water dated 27 January 2020.

[C4] Testimonial from [text removed for publication] dated 1 December 2020.

[C5] Testimonial from SWDE dated 6 January 2021.

[C6a] Testimonial from Bentley Systems dated 26 July 2019.

[C6b] Email from Senior Product Manager, Bentley Systems on 28 September 2020 confirming the current number of users 'We first implemented the modulating PRVs in 2011. We don't give out detailed information about users. But you can safely say that we have several hundred HAMMER users around the world'.

[C6c] Brad Clarke, 'Transient and Surge Related Pipe Bursts, Water Loss and Damage Prevention', White Paper, Singer Valve Inc; https://www.wateronline.com/doc/transient-surge-related-pipe-bursts-water-loss-damage-prevention-0001