

Conceptual design of a generic, real-time, near-optimal control system for water-distribution networks

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ABSTRACT

This paper is intended to serve as an introduction to the POWADIMA research project, whose objective was to determine the feasibility and efficacy of introducing real-time, near-optimal control for water-distribution networks. With that in mind, its contents include the current state-of-the-art and some of the difficulties that would need to be addressed if the goal of near-optimal control was to be achieved. Subsequently, the approach adopted is outlined, together with the reasons for the choice. Since it would be somewhat impractical to use a conventional hydraulic simulation model for real-time, near-optimal control, the methodology includes replicating the model by an artificial neural network which, computationally, is far more efficient. Thereafter, the latter is embedded in a dynamic genetic algorithm, designed specifically for real-time use. In this way, the near-optimal control settings to meet the current demands and minimize the overall pumping costs up to the operating horizon can be derived. The programme of work undertaken in achieving this end is then described. By way of conclusion, the potential benefits arising from implementing the control system developed are briefly reviewed, as are the possibilities of using the same approach for other application areas.

Key words | optimal-control, POWADIMA, real-time, water distribution

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INTRODUCTION

Background

At the present time, the operation of water-distribution networks is managed by skilled staff who use their experience and judgement in adjusting the control apparatus such as pumps and valves to ensure customer demands are met. More often than not, the operators are provided with little or no assistance in deciding how to meet a highly-variable demand with the required delivery pressure whilst, at the same time, minimize the pumping costs by taking account of the energy tariff structure. Even where guidance is provided by means of, say, a pump-scheduling program, the actual operational decisions relating to the control apparatus are left to the discretion of the operators. Bearing in mind the uncertainties associated with demands, not to mention the limitations of the control techniques currently available, it is perhaps not surprising that the tendency is to

err on the side of caution by keeping water pressures in the network higher than would otherwise be necessary. This, in turn, leads to higher leakage from the distribution network since leakage is a function of pressure.

If the pressure in the distribution network were kept as low as possible whilst still complying with the standards of service required by customers (continuity of supply, minimum acceptable delivery pressure, etc.), this would not only minimize the use of pumping but also reduce leakage. Simple as this may seem, the problem with water-distribution networks is that they are both large and complex, in addition to being subjected to highly variable demands over which there is little control. However, with the predictive and optimization techniques now available, it is possible to envisage an on-line control system, which dynamically responds to short-term demand fluctuations

whilst, at the same time, minimizes the longer-term operating costs. For a complex network, it is almost certain that an objective control system could identify a better, overall solution than could be achieved by human judgement alone. Additional savings would arise from the reduction in leakage and the ability to defer capital expenditure necessitated by a genuine increase in demand.

Current state-of-the-art

Over the past thirty years or so, a significant investment has been made in developing hydraulic simulation software for water-distribution networks (Water Research Centre 1987; Coulbeck *et al.* 1995; Rossman 2000; *etc.*) All are based on solving the hydraulic equations relating to pipe flow and, as such, are computationally time-consuming. Whereas in the past, these modelling packages have been used for the design of water-distribution networks based on trial-and-error, more recently various forms of optimization have been introduced, including genetic algorithms (for example, Dandy *et al.* 1996). Although this type of optimization is very efficient, it can still require long run times but for design purposes, this is generally acceptable, as there are seldom any limits on the computing time available. However, for operational control purposes where there is a need to regularly update the control strategy to account for the fluctuations in demands, the combination of a hydraulic simulation model and optimization is likely to be computationally excessive for all but the simplest of networks.

Whilst some hydraulic simulation models have been adapted for operational purposes (Orr *et al.* 1999; Tiburce *et al.* 1999), none have been used for optimal control of water-distribution networks in any formal sense of the phrase. Other approaches that have been proposed include capturing operator experience by means of an artificial neural network (Bhattacharya *et al.* 2003) and the use of a fuzzy expert system for the same purpose (Angel *et al.* 1999). By definition, neither of these techniques can improve on a skilled operator's capability. Therefore, up until the present time, the only way of augmenting operator competence has been to introduce pump scheduling. This is usually based on one or another form of mathematical programming including linear programming, dynamic programming, non-linear

programming and decomposition-coordination methods (Ormsbee & Lansey 1994). Previous efforts include Fallside & Perry (1975) (hierarchical decomposition), Sterling & Coulbeck (1975) (dynamic programming), Zessler & Shamir (1989) (iterative dynamic programming), Jowitt & Germanopoulos (1992) (linear programming) and Chase & Ormsbee (1993) (non-linear programming). More recently, other approaches have been used to achieve the same end, such as Mackle *et al.* (1995) (genetic algorithms) and Sakarya *et al.* (1999) (simulated annealing). As a result, pump scheduling is gradually being adopted by the water industry as a means of reducing energy costs. Estimates of potential cost savings are of the order of 10% (Water Research Centre 1985).

CHARACTERISTICS OF A REAL-TIME CONTROL SYSTEM

Structuring the problem

It will, of course, be appreciated that pump scheduling does not equate to real-time control inasmuch that the former is limited to deriving a series of targets or set points to minimize pumping costs over a 24-h period, assuming a given demand profile: decisions relating to the control settings to achieve these set points are left to the judgement of the operating staff who also have to take account of pressures and flows in the distribution network. Various claims have been made about optimal operational-control models but invariably, these transpire to be pump-scheduling programs. Indeed, it would appear from the literature that there has been no serious attempt to develop (let alone achieve) a real-time control system for water distribution in which the performance of the network is optimized to meet the current demands whilst, at the same time, energy costs over the longer term are minimized.

For real-time control of water-distribution networks, the objective should be to optimize the whole process for both improved performance and operational-cost reduction, rather than one or the other. As demand is continuously fluctuating, it would be necessary to adjust the control apparatus frequently if optimal control is to be

achieved or at least approximated. This implies the use of SCADA (Supervisory Control and Data Acquisition) facilities to define the existing state of the network and transmit these data to a control centre at regular, short time intervals. Rather than simply reacting to the current situation, the aim should be to treat water-distribution management as a feed-forward control system in which the control decisions also anticipate future requirements which, in this case, are the demand forecasts. Since perfect foresight cannot be assumed and the predicted consequences of different control settings may contain small errors, there has to be some means of correcting for these discrepancies as time progresses. Perhaps the simplest way in which this can be achieved is to 'ground' the discrepancies at each update of the SCADA information: that is to say, the previously predicted values of the storage-tank water levels for the next time step are re-set to the corresponding SCADA measurements at each update. Any similar discrepancies in the demand forecasts can be automatically compensated for in the forecasting procedure.

In searching for the optimal combination of pump and valve settings, it is necessary to calculate not only what the current control setting should be but also those up to the operating horizon, in order to select the least-cost pumping strategy. The latter would be achieved by using the storage-tanks' capacities to transfer pumping to periods of lower energy costs wherever possible, taking account of forecast demands. Having an operating strategy also provides a degree of comfort that the control system is capable of recovering from the current state to any prescribed storage-tank water levels at a specified time that might be imposed for operational reasons. However, only the optimal control settings for the current time step would be implemented by means of the SCADA facilities. Thereafter, at the next SCADA update, the predicted storage-tank water levels would be grounded before the whole process is repeated and a new operating strategy generated. In this way, the control process moves forward in time, correcting any discrepancies as it progresses.

Anticipated difficulties

Developing a generic, real-time, optimal control system for water distribution is beset by difficulties. Firstly, there are

those caused by the network's size and complexity. Since most urban water-distribution networks comprise hundreds if not thousands of interconnected pipes, which have been added to over the years in a piecemeal fashion, it follows that few, if any, have been designed with optimal control in mind. Moreover, many networks have more than one source of supply, which may have different production costs. Additionally, within the one network, it is not uncommon to have a number of pressure zones, particularly in hilly areas. Whatever their configuration, these networks are used to supply various types of customers ranging from domestic to industrial, each with their own water-using characteristics, over which there is little control. As a result, the pattern of water demand varies in different parts of the network at different times of the day, depending on the mix of customers as well as other exogenous variables such as the prevailing weather, day of the week, etc.

Given the high variability of demand and the need to adjust the control apparatus frequently, the time available between successive SCADA updates is a limiting factor in calculating the optimal-control strategy. Even for comparatively small networks, the number of combinations of pump and valve settings is enormous. When scaled to a large network size, the computational time and memory requirements necessary to calculate the optimal control settings not only for the current time step but also those up to the operating horizon pose a potential problem. Furthermore, energy tariff structures are usually complicated, with different rates for various hours of the day, which can change from one month to the next. Therefore, the question arises as to how the optimal-control strategy can be derived in a short period of time.

APPROACH ADOPTED

Control process

Although the use of a hydraulic simulation model has its limitations for real-time control because of the computational burden optimization imposes, nevertheless a process-based model is required to estimate the physical consequences of different pump/valve settings, since it would be impractical to experiment with the real network.

One possibility for addressing this conundrum is to capture the knowledge-base of the hydraulic simulation model in a much more efficient form. To that end, the approach adopted has been to replicate a conventional hydraulic simulation model, using an artificial neural network (ANN) as a universal function approximator. This would be achieved by first running off-line a large number of steady-state hydraulic simulations of the network, using different combinations of initial starting conditions, control settings and demand requirements (the input values) to determine the changes in storage levels, hydrostatic pressures, flow rates, etc. (the output values) at critical locations throughout the network. The ANN would then be trained to use the input values to predict the output values at critical points so that it could be used in place of the conventional hydraulic simulation model for control purposes.

After training and testing, the ANN would be embedded in an optimization process whose function is to select the best combination of control settings to satisfy the current and future demands up to the operating horizon at minimal cost, subject to operational constraints. In this particular case, the optimization process selected was based on a genetic algorithm (GA) which is a probabilistic search technique, ideally suited to integer-programming problems with zero-one decisions. For example, each possible configuration (say, pump no. 2 off/on, valve no. 5 open/close) would be represented by a string of decision variables. Each string is evaluated relative to a set of objectives (e.g. minimize operating costs) and those which do not meet the constraints are penalized. A GA operates with a population of these strings, using processes such as reproduction, cross-over and mutation, to develop a new generation of improved strings. Experience has shown that the best solution identified after a large number of generations should be very close to the global optimum.

Perceived advantages

Whilst the combination of a GA with an ANN has previously been used for computationally demanding problems such as groundwater remediation (Rogers & Dowla 1994; Rao & Jamieson 1997; Aly & Peralta 1999) and regional wastewater-treatment planning (Wang & Jamieson 2002), to date all known applications have been

related to system design: optimal control of water-distribution networks would appear to be the first real-time application. Here, the need for computational efficiency is considerably more important than for design problems since the time between successive updates is short. By using an ANN in preference to a hydraulic simulation model, the overall computational time needed can be reduced significantly. Even so, notwithstanding that a GA is a very efficient optimization process, efforts have also been made to improve its computational efficiency as well as the effectiveness in converging on the global optimum. However, since no guarantee can be given that the global optimum will be found within the computational time available, the preference in this research project has been to adopt the term 'near-optimal control'.

Another advantage of the GA-ANN combination is the high degree of realism provided. Unlike some analytical techniques, the use of an ANN predictor builds on a detailed understanding of the physical network which is imparted by the hydraulic simulation model. Obviously, the methodology is conditional upon being able to represent the real network using a conventional hydraulic simulation model with a reasonable level of accuracy, but from there onwards, no further assumptions are required. The methodology is also rigorous inasmuch that whilst the global optimum cannot be guaranteed, it can be approximated to a degree that makes little or no practical difference. Moreover, the ability to separate the ANN predictor from the GA optimizer enables the control system to be easily updated, should the network be modified in any way. In this instance, all that would be required is to re-run the hydraulic simulation model with the amended configuration so that a new ANN can be trained. If additional control apparatus were to be installed, that might also require the GA to be altered slightly.

POWADIMA RESEARCH PROJECT

Aims and objective

POWADIMA (Potable Water Distribution Management) is the name given to a Vth Framework research project,

funded by the European Commission. The acronym reflects one of the main aims of the project, which is to reduce the energy costs involved in water distribution. The other is to improve the performance of the water-distribution network in terms of delivering the required quantities at a specified minimum pressure. Besides improving services to customers and reducing the cost of doing so, other secondary benefits arising from this research project include reducing leakage from the water-distribution network and lowering the overall use of energy, both of which would result from a general reduction of hydrostatic pressures in the network. These in their own right contribute to achieving a more sustainable future by decreasing the demands on water resources and promoting measures to increase energy efficiency.

With this in mind, the primary objective of the POWADIMA research programme was to determine the feasibility and efficacy of introducing real-time, near-optimal control for water-distribution networks. The way in which this objective would be achieved was through the development of the required analytical components such as the ANN predictor and the GA optimizer, using a slightly modified version of the hypothetical Any Town network (Walski *et al.* 1987) for experimental purposes. Having perfected the techniques on this very small network, they would then be applied to two real water-distribution networks, one in Israel, the other in Spain, each with its own distinct characteristics. Thereafter, the results from both case studies would be rigorously analyzed in terms of operational-cost savings, as well as the performance of the control system in complying with the operational constraints.

At this stage, the intention is simply to demonstrate the capability of the generic system developed. However, the experience gained in applying the control system to two very different networks would be highly beneficial if it were decided to implement the system at a later date. If that happens, then obviously these control systems would at least initially be advisory to experienced staff and restricted to identifying an efficient set of operational decisions that could be over-ridden if necessary. Nevertheless, this does not preclude the possibility of closed-loop control in the longer term.

Selection of case studies

Given that the two partners responsible for leading the application stage of the programme were based in Haifa and Valencia, there was obvious merit, not to mention convenience, in selecting these cities as case studies, naturally with the agreement of the respective water companies who acted as subcontractors. No pretence is made that either network is typical: indeed they might be regarded as being at opposite ends of the spectrum. Whereas Haifa's topography is decidedly hilly, that for Valencia comprises a gently sloping coastal plain. These differences are reflected in the characteristics of their distribution networks, with Haifa having many more separate storage tanks at different locations in comparison with Valencia. Conversely, Valencia has a larger number of operating valves relative to Haifa, in order to control the network flows over a large, relatively-flat area.

Rather than using the whole of the Haifa network, only a portion has been considered, originally to give some variation in the scale of operation. This amounts to about 20% of the total network and is referred to as Haifa-A (Figure 1). The Haifa-A network is supplied from two directions but both from the National Water Carrier, so there is no difference in the unit production-cost of supply. It comprises 126 pipes configured to create 112 nodes, with 17 pumps (including 4 on standby), grouped in 5 pumping stations. Additionally, there are 9 storage tanks and one operating valve. Minimum and maximum storage levels have been assigned to each tank, as well as some having a minimum prescribed storage level at a fixed time each morning. The objective function is to minimize the pumping costs, subject to meeting the demands in 6 discrete areas and complying with the operational constraints.

The Valencia network, which is used for the second case study, serves the whole city in addition to many surrounding towns (Figure 2). It too is supplied from two sources but each treatment plant has a significantly different unit production cost. Although the full network contains some 30,000 pipes, for the purposes of operational control, this number has been reduced to form a 725-node network. Of the 20 pumps installed, 17 are operational, the other 3 being standby. These are grouped in 2 pumping stations, one at each treatment plant. The only storage available is also located at the two

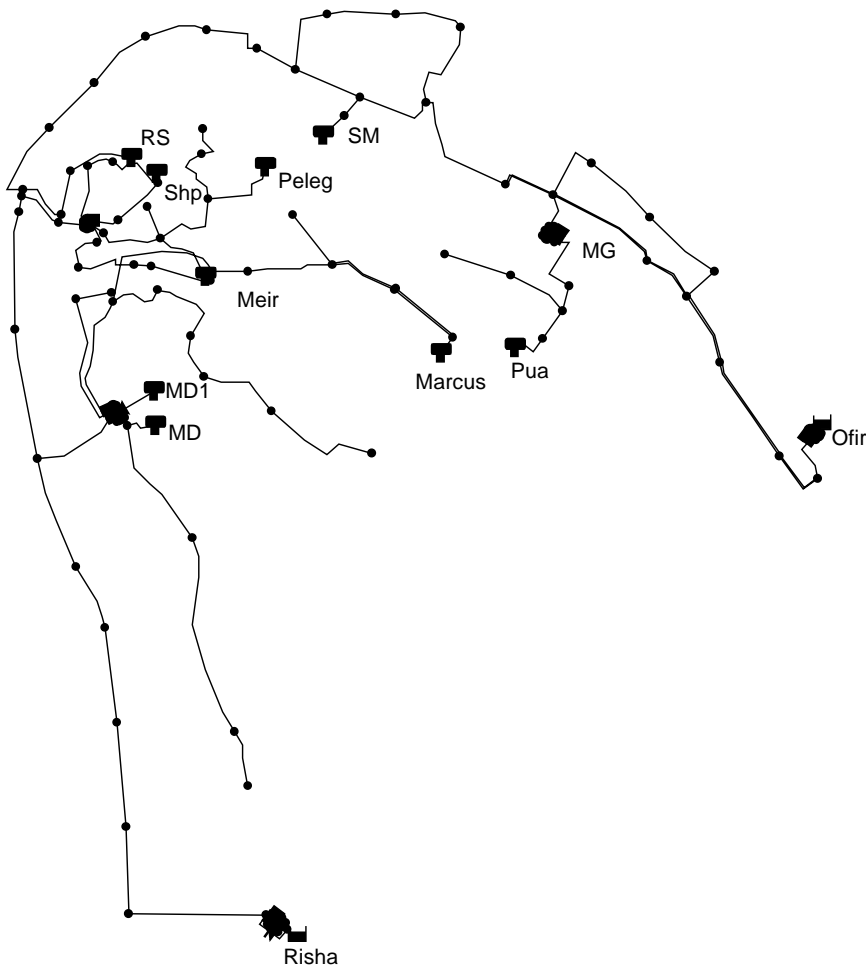


Figure 1 | The Haifa-A water-distribution network.

treatment plants, which for the purpose of this exercise, has been regarded to be a composite tank at each. Flows in the network are controlled by the hydrostatic pressure created by the pumps and storage-tank elevations, together with 49 operating valves, 10 of which are adjusted on a routine basis. The objective function is to minimize operating costs, including the cost differential between the two treatment plants, subject to meeting the demands in 6 discrete areas and complying with the operational constraints.

Table 1 summarises the main features of the three distribution networks used as part of this research project, in terms of physical characteristics, model representation and control aspects. Although it is evident that scale is not a problem for these three examples, complexity may be an issue for larger networks. In the case of Valencia, it would have been entirely feasible to have employed the detailed

30,000-pipe hydraulic simulation model rather than the simpler one actually used: the only significant difference would have been the large increase in the amount of time that would have been required to generate the ANN training and testing sets. Thereafter, the real-time computational load for each would have been similar as that is primarily dependent on the number of input/output neurons, which in this instance would have been the same. However, if the number of pumps/valves had been substantially more or had the pumps been variable-speed rather than fixed-rate, then the complexity would have increased considerably as a result of the larger number of decision variables. In such circumstances, perhaps it would have been necessary to look for natural cleavage lines within the network, either spatial or hierarchical (or indeed both), with a view to limiting the amount of interaction

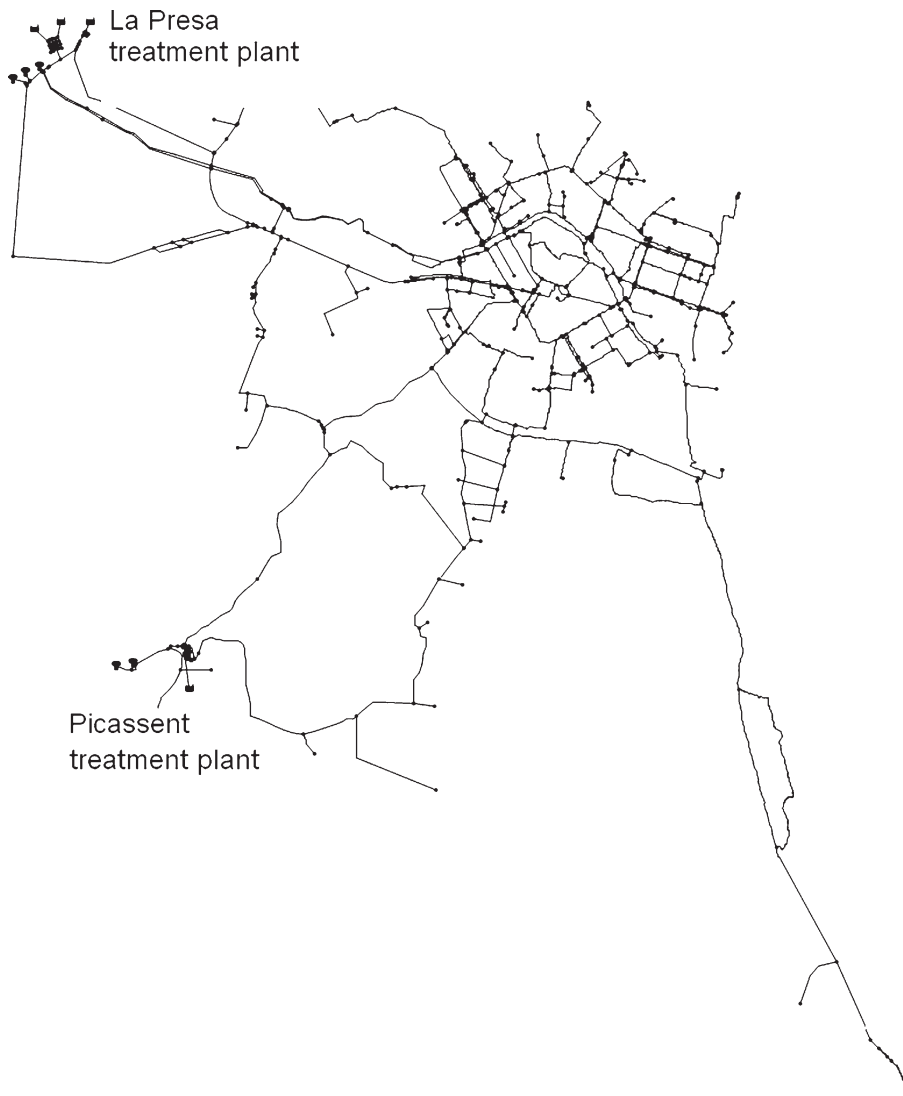


Figure 2 | The Valencia water-distribution network.

between the constituent parts. For example, in the case of, say, London (UK) which has a low-pressure tunnel ring main to move water in bulk around the city before pumping it to the surface and distributing locally under high pressure, there would be one control system for the ring main and one for each of the semi-autonomous, high-pressure networks serving the customers.

Programme of work

The overall programme of work relating to the POWADIMA research project was subdivided into some seven

work packages, the first of which was largely administrative and confined to agreeing work practices, programming standards, selection of case studies etc. In this way, all the key issues were identified and agreed in advance of initiating the research phase, thereby avoiding any misunderstandings at a later date. The initial phase of Work-package 2 was limited to experimentation in replicating a conventional hydraulic simulation model of the modified Any Town (AT(M)) network using an ANN. Having proved that this was possible with an acceptable degree of accuracy, the remainder of Work-package 2 was devoted to undertaking the same exercise for the two case

Table 1 | Comparison of the three networks used in the POWADIMA research project

Feature	Any Town	Haifa-A	Valencia
Physical characteristics			
Topography	Flat	Hilly	Gently sloping
Population served	N/A	60,000	1200,000
Average daily consumption (m ³)	131,000	13,000	322,000
Peak daily consumption (m ³)	N/A	21,000	430,000
Length of pipes (km)	82	42	1200
Range of pipe diameters (mm)	150–600	100–600	40–1600
Model representation			
Number of sources of supply	1	2	2
Number of pipes	41	126	772
Number of nodes	19	112	725
Number of storage tanks	3	9	2
Number of pumping stations	1	5	2
Number of operational pumps	3	13	17
Type of pumps	Fixed-rate	Fixed-rate	Fixed-rate
Number of operating valves	0	1	10
Type of valves	N/A	Variable	Variable
Number of pressure zones	1	6	4
Number of demand areas	1	6	6
Control aspects			
Number of pressure constraints	3	1	4
Number of flow constraints	0	0	3
ANN input values	5	29	24
ANN output values	7	15	15
GA string length	72	408	1368
Number of GA generations	1000	1000	2000
Computational time (min)	0.5	4	9

studies. A similar approach was adopted for Work-package 3 whose goal was to develop a GA optimizer specifically for real-time control. Initially, attention was focussed on experimenting with the AT(M) model to test the improvements resulting from changing the GA penalty functions, inclusion of the elitist principle and other such measures designed to improve both the computational efficiency and the consistency of convergence. In the second phase of Work-package 3, the first attempt to combine the ANN predictor for the AT(M) network with the GA optimizer was undertaken to gain experience before progressing to the two case studies.

Originally, Work-package 4 comprised combining the ANN predictor with the GA optimizer for each of the two case studies. Initially, this was restricted to a series of 24-h simulations, using historic demand profiles rather than forecast demands. Subsequently, the dynamic version of the GA optimizer was introduced in which the control process was continually updated and any errors between the predicted values and surrogate SCADA measurements were grounded. Since distribution networks are not 100% reliable, Work-package 5 examined the impact of pump failures, inoperable valves and pipe bursts on the control system, with a view to determining the appropriate course of action in the event of an emergency. Work-package 6 used data from a small but real network to experiment with different types of short-term demand-forecasting models. Subsequently, the selected forecasting methodology replaced the demand profiles in the dynamic version of the control system. Finally, the results from the two case studies were evaluated in Work-package 7, where initially long-term simulation runs were carried out for each case study to estimate the reduction in operating costs that would arise from adopting the control system developed. These were compared with the costs of the measurement instruments and SCADA facilities necessary to support the implementation of the control system, assuming none were in place at the present time. The opportunity was also taken to assess how well each control system performed in terms of meeting the imposed operational constraints such as maximum/minimum water levels in storage tanks, the prescribed storage levels at a specific time, etc. The way in which these work packages related one to another, as originally conceived, is shown in Figure 3.

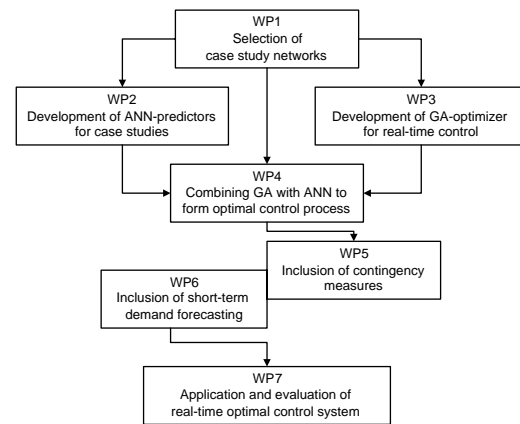


Figure 3 | Original work-plan for POWADIMA research project.

In the event, somewhat different arrangements were adopted, with Work-package 4 being expanded to cover the whole of the integration phase, rather than just that associated with the GA-ANN. This was necessitated by having to revisit the GA-ANN integration not only during the application phase when Work-packages 5 and 6 were included but also in the course of the fine-tuning, which was part of the evaluation process. Therefore, besides the expansion of Work-package 4, Work-package 7 became the focus for the application of the control system to the case studies, as well as their evaluation. The consequences of these changes are depicted in Figure 4.

Allocation of responsibilities for work programme

Although all partners were involved to a greater or lesser extent in most aspects of the research project, each work package was assigned a nominated lead organization which was responsible for co-ordinating the activities in that particular portion of the work programme. For example, Work-package 3 (development of a dynamic GA optimizer) and Work-package 4 (integration of the various components) were overseen by the University of Newcastle (UK), whilst Work-package 6 (short-term demand forecasting) was largely undertaken by the Università degli Studi di Ferrara (Italy). Similarly, the Technion–Israel Institute of Technology (Israel) was assigned Work-package 5 (using the GA under emergency conditions), and shared the responsibilities for Work-package 2 (replication of a hydraulic simulation model by means of an ANN) with the Universidad Polytechnica de Valencia (Spain). As part

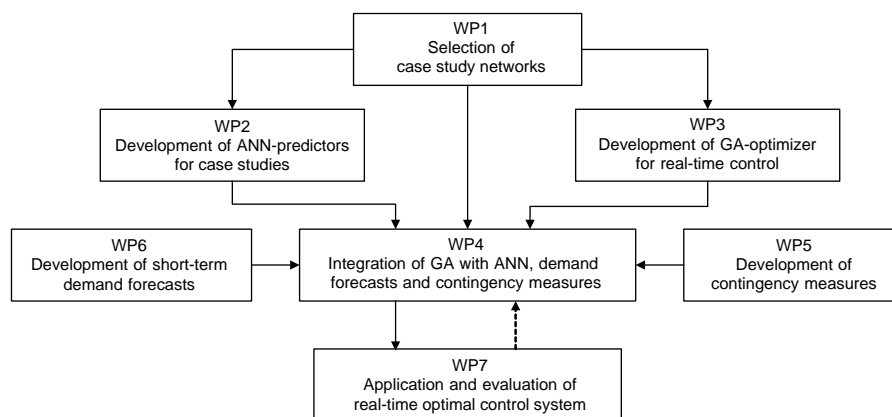


Figure 4 | Revised work-plan for the POWADIMA research project.

of their remit for co-ordinating the application of the control system developed to the two case studies, the Technion and the Universidad Polytechnica also assumed responsibility for the revised Work-package 7 (application to the case studies and subsequent evaluation).

Following on from this introductory paper, the next five contributions and their authorship generally reflect the above allocation of responsibility. The first describes the initial attempts to replicate a conventional hydraulic simulation model by means of an ANN, with reference to the AT(M) network. The next paper covers the development of a GA optimizer specifically for real-time control, together with the embedding of the ANN predictor for the AT(M) network. This paper also refers to the subsequent extension to create a dynamic version of the GA optimizer, as well as the provisions necessary to cover emergencies. The fourth paper in the series gives an account of the experimentation with the short-term demand data for the Castelfranco Emilia network in Italy and the formulation of a demand forecasting procedure for real-time use. The remaining two papers describe the application of the dynamic GA-ANN control system to the two case studies, including the evaluation of the results. Finally, the epilogue to this special edition summarizes what has been achieved so far and outlines some possible improvements for the future.

CONCLUSIONS

Potential benefits

The successful completion of this research project offers the prospect of improvements to the standard of services

provided for customers in terms of not only delivery pressures but also the quality of water supplied. Improved delivery pressure does not necessarily imply increasing the pressures but rather ensuring that the minimum acceptable pressures are met throughout the network. This can be achieved by locating the critical pressure points towards the periphery of the network or any other site where pressures tend to be at their lowest. Similarly, water quality can be improved by imposing minimum flow constraints at critical flow points within the network, with a view to avoiding the possibility of water stagnating. Any infringement of these operational constraints would result in an infeasible solution for the control system and therefore rejected. In this way, pressure and flows would only be increased where necessary and then in the most cost-effective manner possible.

The main beneficiary of reduced operating costs would be the water industry itself. Unlike capital expenditure where normally there would be a return on investment, operating costs are a direct charge on the balance sheet of the company and therefore should be curtailed wherever possible. The potential savings in operating the network more efficiently are significant and likely to be of the order of 20%. Extrapolating the operational costs for the Valencia network to the size of the European Union suggests that a saving of this magnitude would represent about 103 million euros per year. Further savings would be network-specific but may result from reducing leakage, which again is a complete loss on the balance sheet. Moreover, if leakage can be lowered, that would enable the deferral of any

upgrading of the network necessitated by increased demands, thereby reducing the overall economic cost.

Lowering leakage from water-distribution networks would also have a beneficial impact on the environment by reducing the amount required for public water supply. The resultant savings could then be used for other purposes including environmental enhancement, or alternatively, permit the deferment of further water-resources development which would otherwise be necessary to meet future demand growth. Either way, the environmental benefits arising from minimizing the use of a natural resource would contribute to its sustainability in the longer term. Similarly, there will be a saving on the amount of energy used, as a consequence of better pressure management. Again, the aim should be to minimize the overall use of a valuable resource. Moreover, by transferring as much of the pumping as possible to off-peak periods, the need for generating-capacity expansion would be reduced. The extent of these resource savings is difficult to estimate since they will be site-specific and dependent upon existing conditions. Nevertheless, it is confidently expected that the benefits to the environment will be both significant and worthwhile to realize.

Other potential application areas

It should be noted that the concept of using an ANN to capture the knowledge base of a complex simulation model and combining it with a dynamic GA to optimize the operational decision variables is not limited to water-distribution networks, or for that matter the water industry. Indeed, provided the consequences of the control settings can be predicted using a conventional simulation model, this approach is generic in the sense that it can be applied to any network or industrial process. For instance, if storm-water sewer networks were equipped with control apparatus (sluices, pumps, etc.), then there is no reason why hydraulic simulation models which hitherto have only been used for design purposes could not be used for operational control. Similarly, the domain knowledge of a wastewater-treatment simulation model could be captured in a much more efficient form which would enable the control settings for a treatment plant to be optimized in a real-time environment. Outside of the water sector, there could be

interest from, say, the gas industry to ensure compliance with statutory regulations without the need for excessive pressures in the distribution network. Elsewhere, the chemical industry may well be attracted by the possibility of improving the control of industrial processes. These and perhaps many other sectors could well benefit from the approach developed in this research project.

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