Online simplification of water distribution network models for optimal scheduling

Daniel Paluszczyszyn, Piotr Skworcow and Bogumil Ulanicki

ABSTRACT

This paper presents an implementation of an extended simplification algorithm of water distribution network models for the purpose of inclusion in the online optimisation strategy for energy and leakage management in water distribution systems. Whereas the previously proposed reduced model represented accurately the original hydraulic water network characteristics, the energy distribution in the simplified model was not preserved. This could cause a situation where the pump speed required to satisfy specified minimum pressure constraints is different for the reduced model and the original model. This problem has been identified, and an appropriate modification to the simplification algorithm has been introduced. The idea comprises introduction of the energy audit of the water network and the calculation of new minimum service pressure constraints for the simplified model. The approach allows the preservation of both hydraulic and energetic characteristics of the original water network and therefore meets the requirements of the online optimisation strategy. Suitability of the proposed approach is evaluated via a case study. The modern parallel programming implementation allowed water network models consisting of several thousand elements to be reduced within 2 min with an average relative accuracy of less than 2% in terms of tanks flows.

Key words | energy distribution, Gaussian elimination, online model simplification

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INTRODUCTION

Nowadays, it is common that water distribution system (WDS) models consist of thousands of elements to accurately replicate hydraulic behaviour and topographical layout of real WDSs. Such models are appropriate for simulation purposes; however, online optimisation tasks are much more computationally demanding, hence, simplified models are required. There are different techniques of model reduction; the outcome of most of these methods is a hydraulic model with a smaller number of components than the prototype. The main aim of a reduced model is to preserve the nonlinearity of the original network and approximate its operation accurately under different conditions. The accuracy of the simplification depends on the model complexity and the selected method such as skeletonisation (Walski *et al.* 2003; Saldarriaga *et al.* 2008), decomposition (Deuerlein 2008), usage of artificial neural network (ANN) metamodels (Rao & Alvarruiz 2007; **Q1** Broad *et al.* 2010) and variable elimination (Ulanicki *et al.* 1996).

Skeletonisation is the process of selecting for inclusion in the model only the parts of the hydraulic network that have a significant impact on the behaviour of WDSs (Walski *et al.* 2003), e.g. use of equivalent pipes in place of numbers of pipes connected in parallel and/or in series. However, skeletonisation is not a single process but several different low-level element removal processes that must be applied in series. This makes the utilisation of this technique difficult for online optimisation purposes. Saldarriaga *et al.* (2008) presented an automated skeletonisation methodology that can be used to achieve reduced models of WDSs that accurately reproduce both the hydraulics and non-permanent water quality parameters (chlorine residual) of the

doi: 10.2166/hydro.2012.029

original model. The proposed methodology was based on the resilience concept (Todini 2000); by using the resilience index as selection criterion to remove pipes from the prototype, reduced models that simulate the hydraulics of the real network were achieved. However, the method focused on pipe removal only, thereby it can be mainly applied to looped pipe networks. Moreover, the achievable degree of model reduction is not significant if the pressure in the simplified model is to be simulated accurately. Rao & Alvarruiz (2007) and Broad *et al.* (2010) have successfully employed ANNS to approximate the water network model. The use of ANNs, due to time-demanding training process, is not suitable for online water network optimisation where adaptation to abnormal structural changes is required. Deuerlein (2008) proposed a graph-theoretical decomposition concept of the network graph of WDSs. The approach involves a decomposition with several steps to obtain a block graph of the core of the network graph. During that process, the demands of the root nodes are increased by the total demand of the connected trees to ensure that the simplified network replicates the hydraulic behaviour of the total network. In addition, this approach, due to its complexity and the number of calculations involved, is not applicable for online optimisation requirements.

The approach of variable elimination, considered in this article, is based on a mathematical formalism originally presented in Ulanicki *et al.* (1996). The algorithm involves a number of steps: model linearisation, Gaussian elimination and reconstruction of a reduced nonlinear model. This method of water network model reduction was successfully applied to many water networks (Rance *et al.* 2001; Preis *et al.* 2011). Moreover, it is fully automatic, hence, it naturally meets online optimisation requirements. However, to increase the accuracy of the optimisation studies with the use of reduced water network models, apart from hydraulic characteristics, energy distribution should also be considered. The energy distribution aspect might be a significant factor when calculating optimal schedules for control elements, especially when demands at the removed nodes are being distributed in isolation from minimum service pressure constraints. In such a situation, the optimised pump speed required to satisfy specified minimum pressure constraints would be different for the reduced model and the original model.

This paper presents an extension and a new implementation of the simplification algorithm developed in Ulanicki *et al.* (1996). The main purpose of the implementation is the integration of the model reduction module with the online optimisation strategy developed for energy and leakage management in WDSs (Skworcow *et al.* 2010). Additionally, the paper discusses the issue of the energy distribution when reallocating demands in the simplified model and proposes a solution to preserve the original model energy distribution in the reduced water network model. The proposed solution is evaluated via a case study.

A NEED FOR A MODEL REDUCTION TECHNIQUE

Optimisation studies of medium- and large-scale water networks are typically carried out offline. This means that any changes to the water network may require significant changes in the optimisation model, which leads to high costs of system maintenance. Skworcow *et al.* (2010) proposed a methodology for online energy and leakage management in water networks, formulated within a model predictive control (MPC) framework. The objective was to calculate control actions, i.e. time schedules for pumps, valves and sources, that minimise the costs associated with energy used for water pumping and treatment and water losses due to leakage, whilst satisfying all operational constraints. The proposed control scheme is illustrated in Figure 1.

The model predictive controller computes the control actions based on the telemetry readings, provided by the supervisory control and data acquisition (SCADA) systems, operational constraints, boundary conditions specified by operator and future demands predicted by the demand forecaster. Inclusion of the model reduction module enables automatic adaptation to abnormal situations and structural changes in a network, e.g. isolation of part of a network due to pipe burst. In such a case, an operator can change the full hydraulic model and run model reduction module to automatically produce an updated simplified model.

The approach proposed in Skworcow *et al.* (2010) is model based, and water network models can consist of thousands of elements, each described by nonlinear equations; this, together with the MPC algorithm computational

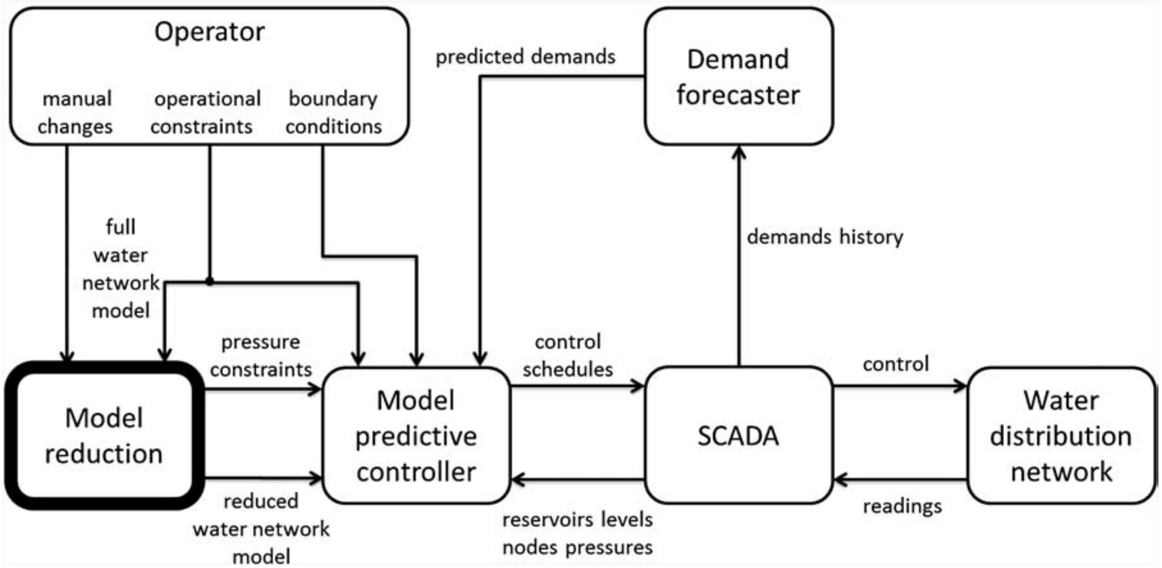

Figure 1 | The control scheme for online energy and leakage management.

complexity, created a requirement for simplified models. It was essential that the reduced model preserves the original water network nonlinearities and was suitable for the online calculation.

The simplification method that satisfied the above requirements was presented in Ulanicki *et al.* (1996). It is a mathematical method for the reduction of network models described by a large-scale system of nonlinear differential algebraic equations. The approach is illustrated in Figure 2 and proceeds by the following steps: full nonlinear model formulation, model linearisation at a specified time, linear model reduction using Gaussian elimination and nonlinear reduced model reconstruction. The method has been successfully implemented and tested on many water networks (Rance *et al.* 2001; Preis *et al.* 2011). More details about the water network model reduction algorithm can be found in Appendix I. In this paper, the reduction algorithm was modified to include energy aspects and meets the requirements of the online optimisation strategy.

IMPLEMENTATION

The simplification algorithm, shown in Figure 2, is fully automatic and therefore it naturally meets the online optimisation requirements.

The requirements summarised in Table 1 were identified for the model reduction application to be integrated into the control scheme introduced in the previous section.

Compatibility on software level

C# programming language and the Microsoft development environment Visual Studio 2010 were used to implement the reduction algorithm. Visual Studio 2010 comes with an integrated support for the .NET 4.0 Framework, which enhanced the parallel programming by providing a new runtime, new class library types and new diagnostic tools (Microsoft 2011). These features allowed for the implementation of the scalable parallel C# code without having to

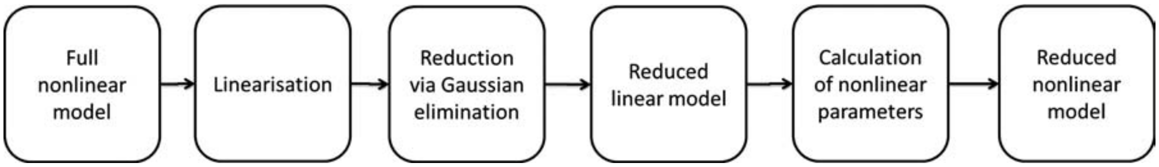

Figure 2 | The model reduction algorithm.

Table 1 | Implementation requirements

Requirement	**Reason**
Software level compatibility	The main module of control strategy illustrated in Figure 1 was implemented in C# and additionally included the following components: the open-source hydraulic simulator EPANET (Rossman 2000), general algebraic modelling system (GAMS) (Brooke *et al.* 1998) and nonlinear programming solver CONOPT (Drud 1985).
Short calculation time	The idea of an online optimisation required the simplification process to be completed within a specified time to allow the controller to compute the control schedules.
Demand distribution logger	During the simplification process, nodes are removed and associated demands are re-distributed based on pipe conductance. For control purposes, it was necessary to log the demand reallocation.
Energy distribution	The controller aims to calculate optimal control schedules for pumps, and therefore, it is crucial to preserve the original water network energy distribution.

work directly with threads or the thread pool and improved performance of the numerical calculations.

EPANET is an open-source software to perform extended period simulation of hydraulic and water quality parameters in pressured pipe networks (Rossman 2000). Initially designed to be a research tool, it quickly became a widely used standard for water network modelling, simulation and analysis. EPANET provided compatibility with 'inp.' (INP) format as it is a commonly recognized file format to store water network models. However, additional scripts were developed for the EPANET Toolkit to allow for dynamical hydraulic data export.

The developed model reduction application was coded in C# with employed EPANET libraries, which ensured compatibility with the overall control scheme depicted in Figure 1. Although the model reduction application was developed with an aim to be a module, it can also work as a standalone application.

Model reduction implementation

The implementation was carried out based on the process illustrated in Figure 3. First, a water network model stored in the INP file format is simulated with the aid of the EPANET Toolkit to obtain the hydraulic results.

Next, the water network model is inspected to locate any rules or controls associated with water network elements. Complex and large water networks modelled in EPANET often contain rules and controls that can decrease the accuracy of the simplification. It is highly recommended to eliminate controls and rules and instead use the time

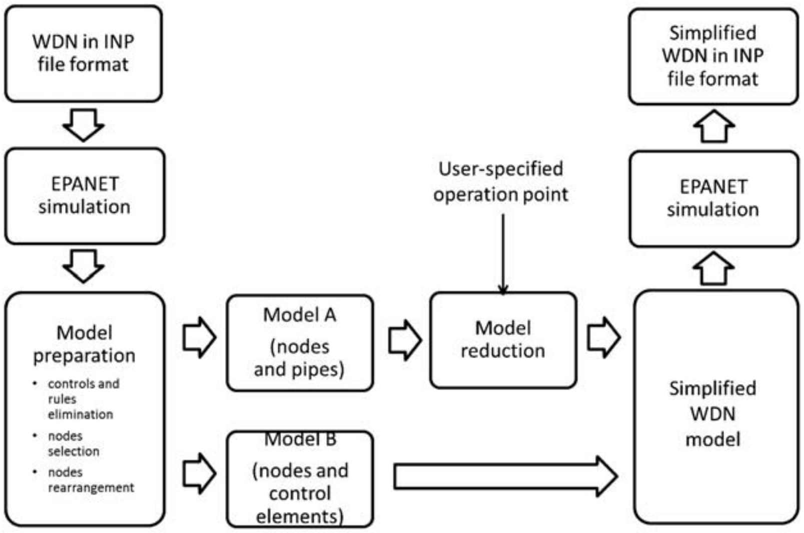

Figure 3 | The implemented simplification process of the water distribution network (WDN).

patterns resulting from the simulation of the original model (with control and rules) and associate the patterns with the water network elements. Such an approach serves as ahydraulic benchmark when original and simplified models are compared. Note that in EPANET, the user can associate rules or controls with pipes, transforming them into valves. Since no time patterns can be assigned to the pipe, such rules or controls cannot be automatically eliminated. All components with controls/rules that could not be replaced with a time pattern are automatically selected for retention.

The model preparation stage also involves a selection of important other water network hydraulic elements to be retained. A typical hydraulic simulation model contains thousands of pipes, but only a few tanks, pumps or control valves. Therefore, it is an adopted strategy here to reduce the number of pipes and nodes only and retain all other important elements. The identified non-pipe components of a WDS are listed in Table 2. The default is to retain all these elements, however, one can define a list of additional elements not to be removed.

Subsequently, the input model is split into the two sub-models depicted in Figure 3. One sub-model, containing pipes and nodes, is subjected to the reduction, and then reunited with the other part containing non-pipe elements to form the complete reduced model, which is saved in the INP file format.

Algorithm calculation time

The original application (Ulanicki *et al.* 1996) performed the simplification process with sufficient accuracy, however, because the model reduction algorithm involved a number of matrix operations with time complexity of order $O(n^3)$ for an $n \times n$ matrix, the calculation time for large-scale networks (more than 10,000 elements) could take up to several hours, and was too long for online applications. Therefore, it was decided to investigate parallel programming and exploit the potential of recent multi-core central processing units (CPUs).

Modern computers have two or more CPU cores that allow multiple threads to be executed simultaneously. Moreover, computers in the near future are expected to have significantly more cores. To take advantage of these hardware developments, it was decided to parallelise the simplification algorithm code by distributing calculations among multiple processors. The inclusion of the parallel programming techniques drastically reduced the algorithm calculation time. Additionally, a multi-dimensional matrix structure used in the initial implementation was replaced by a jagged array (array of arrays) structure (Microsoft 2012), which performed much faster. In the .NET framework, jagged arrays have faster access to their elements due to optimisations in the runtime for one-dimensional arrays, which jagged arrays are made out of. Table 3 contains calculation times performed on a workstation powered by an Intel® Core™ i7 980X processor for a large-scale network that consisted of 3535 nodes, 3279 pipes, 12 tanks, 5 reservoirs, 19 pumps and 418 valves.

Online adaptation to abnormal situations and structural changes

One of the main goals of the considered implementation was to allow online structural changes to the water network and automatic model simplification. Many abnormal situations could occur in a real water network, e.g. the pump station could be disconnected due to reallocation or

Table 2 | Important elements in the water distribution network

Water distribution network elements
Tanks (variable head)
Reservoirs (fixed head)
Pumps
Valves
Pipes with associated controls or rules
Nodes connected to any of the above

Table 3 | Time taken to complete the simplification process

CPU threads	Simplification process time
1	1 h 36 min 01 s
2	1 h 13 min 37 s
4	0 h 36 min 57 s
12	0 h 12 min 38 s
12 + jagged arrays	0 h 01 min 21 s

maintenance service, the tank could be under maintenance service or a pipe burst would require isolation of part of the network. The idea of the optimisation scheme, shown in Figure 1, is that the operator could modify the original model structure in response to the occurrence of the abnormal situation. Such a modified model is subsequently simplified within the time interval required to calculate new optimal schedules. Figure 4 illustrates the Net 3 EPANET benchmark model. Figures 4 and 5 demonstrate reduced models in response to abnormal structural changes. Figure 5(a) depicts the outcome of simplification of the original model. Figure 5(b) shows a reduced model structure when Pump 10 is out of service due to power supply failure. The reduced model in Figure 5(c) is a result of Tank 2 being removed from the original network due to, for example, service maintenance.

In the deployed application, offline operations include: water network pre-processing to identify any issues with the EPANET model (e.g. mixed US/SI units), selection of additional critical nodes (e.g. nodes associated with pressure sensors), definition of operational constraints and water network structural changes. The water network model reduction with preservation of the energy distribution, calculation of optimal schedules and demand prediction are carried out in the online mode.

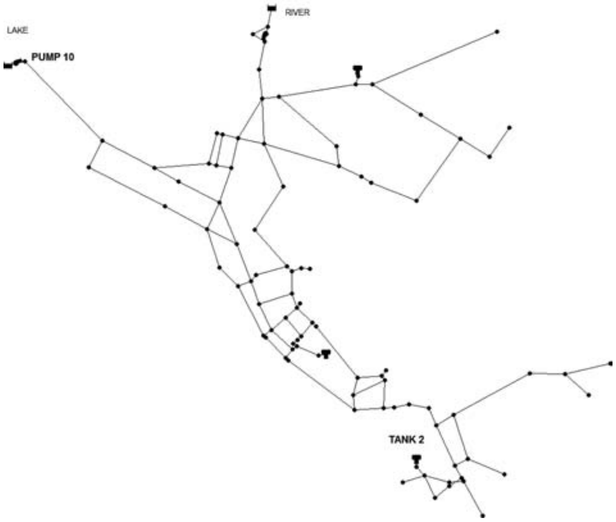

Figure 4 | EPANET benchmark Net 3 model.

RESULTS AND DISCUSSION

The implemented module was tested on water network models of different sizes and topologies. The details of the networks and results of the simplification are summarised in Table 4 and Figure 6. Figure 6 depicts several simulated tank trajectories from the water networks given in Table 4. The simplification algorithm performed as expected, i.e. all the reduced models adequately replicate the hydraulic behaviour of the original model. The tank flow balance was used to compare simulation results from the original and the reduced model. The tank flow for each tank was integrated over the time horizon of 24 hours and denoted by $T_{\mathrm{d}}^{\mathrm{O}}$ for the original model and $T_{\mathrm{d}}^{\mathrm{S}}$ for the reduced model. The Average Relative Error (see Equation (1)) was a measure of the quality of the reduced model:

$$\text{Average Relative Error} = \sum_{i=1}^{i=T} \left| \frac{T_{\mathrm{d}_i}^{\mathrm{O}} - T_{\mathrm{d}_i}^{\mathrm{S}}}{T_{\mathrm{v}_i}} \right| \Big/ T \times 100\% \tag{1}$$

where T_{v_i} is tank i capacity and T is the number of tanks.

Initially, only the hydraulic comparison was performed in order to validate the accuracy of the reduced models. However, it was observed that the energy distribution was different in the full and the simplified models. The reason was that the node elevation and the pressure constraints were not considered during the model reduction. Subsequently, the pump speed required to satisfy minimum pressure constraints might be different for the reduced model and the prototype. This especially affects the tree-shaped parts of the models, which after simplification are typically represented by a single node with the demands transferred from the removed nodes.

Aspect of energy distribution

To demonstrate the problem, consider the leak-free simple theoretical water network shown in Figure 7. The network consists of a reservoir and a pump that pumps directly to the demands on nodes 3, 4 and 5 whilst satisfying the minimum pressure constraint of $p_{\min} = 16\,\mathrm{m}$ at all nodes. The pump is described by the head-flow curve

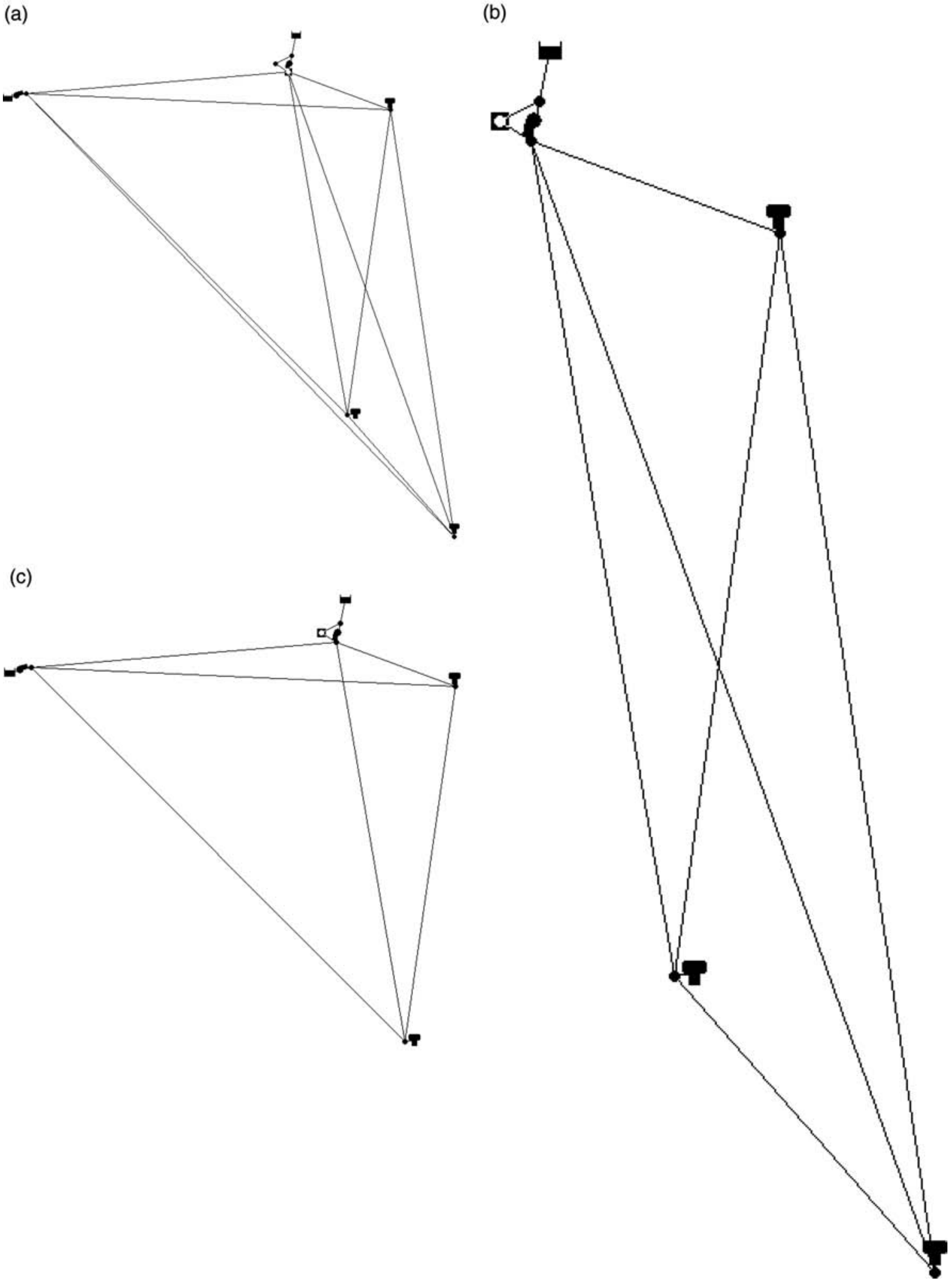

Figure 5 | Illustrating an adaptation to structural changes in water network. (a) EPANET Net 3 after standard model reduction. (b) EPANET Net 3 simplified model layout when Pump 10 was removed. (c) EPANET Net 3 simplified model layout when Tank 2 was removed.

Table 4 | Results of the simplification of water networks

Network elements	Network 1	Network 2	Network 3
Tanks	1	3	12
Reservoirs	1	1	5
Pumps	1	1	19
Valves	0	11	418
	Before	*simplification*	
Nodes	166	1009	3535
Pipes	200	1102	3279
	After	*simplification*	
Nodes	5	78	1023
Pipes	2	243	1340
Reduction (%)	97.3	84.2	61.2
Average Relative Error (%)	0	0.99	1.16

$h_p = 53.33 - 0.005334q^2$ and all the pipes are 1,000 m long, with 300 mm diameter and a roughness parameter of 100. The pressure values shown in Figure 7 were calculated using EPANET.

Figure 7(b) illustrates an outcome of the simplification when node 3 was selected for retention. The algorithm has removed nodes 4 and 5 and transferred the node demands to node 3. When the both networks were compared, the water volume and energy balance were similar, as well as the pressure and flow values in the retained components. However, the optimal solutions for the two models are different if the original pressure constraints of 16 m are used. The full model would still maintain the pressure of 16 m at node 5, whereas in case (b) where the pressure at node 3 was 37.41 m; an optimisation algorithm would detect an excess of the energy supplied by the pump to the system and lower the pump speed to meet the requirements for the minimum service pressure of 16 m at node 3 (see Figure 8). Figures 7(c) and 7(d) show cases when nodes 4 and 5, respectively, were kept. It can be observed that only the simplified model with node 5 retained (Figure 7(d)) would give a similar optimal solution to the full model.

To investigate this problem further, an energy audit was carried out for the original and the simplified models. The energy audit was based on the concepts proposed in Cabrera *et al.* (2010) and further extended in de Souza *et al.* (2011). Appendix II 10 contains a concise description of the methodology.

The energy indicators proposed in Cabrera *et al.* (2010), see Table 5, were adopted to compare both original and simplified models in terms of energy distribution. I_1 is the ratio between the real energy entering the system and the minimum useful energy. I_5 is the direct ratio between the energy delivered to users and the minimum useful energy. I_5 shows how average pressure levels meet the minimum pressure constraints. Note that $E_R(t_p)$ is an input energy supplied by reservoirs for simulation time t_p, $E_P(t_p)$ is an energy introduced by pumps, $E_{U_{\min}}(t_p)$ is a minimum useful energy, $E_U(t_p)$ is an energy supplied to users and $E_D(t_p)$ is an energy dissipated in links (see Appendix II for details).

In order to preserve the original energy distribution in the simplified models, the calculated energy indicators should be approximately the same for both the full and the corresponding simplified model. Energy audits and associated performance indicators for the four cases are summarised in Table 6. The conclusion from the energy audits was much the same as from the pump head curves illustrated in Figure 8, i.e while energy balance was kept almost the same, the energy $E_{U_{\min}}$ associated with the minimum service pressure was different for each case. In addition, the indicators I_1 and I_5 were different for all three cases of the simplified models.

Model reduction algorithm extension

In order to retain the input model energy distribution, a modification to the original simplification procedure, given in Ulanicki *et al.* (1996), was proposed. The following steps were introduced to the simplification algorithm.

- Perform an initial energy audit for the original water network as in Cabrera *et al.* (2010).
- Calculate a minimum useful energy $E_{i_{U_{\min}}}$ for each node $i \in U$:

$$E_{i_{U_{\min}}} = \gamma \left[\sum_{t_k=t_1}^{t_k=t_p} d_i(t_k) H_{\min i}(t_k) \right] \Delta t, \quad \forall i \in U \qquad (2)$$

  where U is the number of demand nodes.
- The resulting vector of minimum useful energies is subject to the Gaussian elimination in a similar way to the vector of nodal demands, i.e. the nodal minimum useful

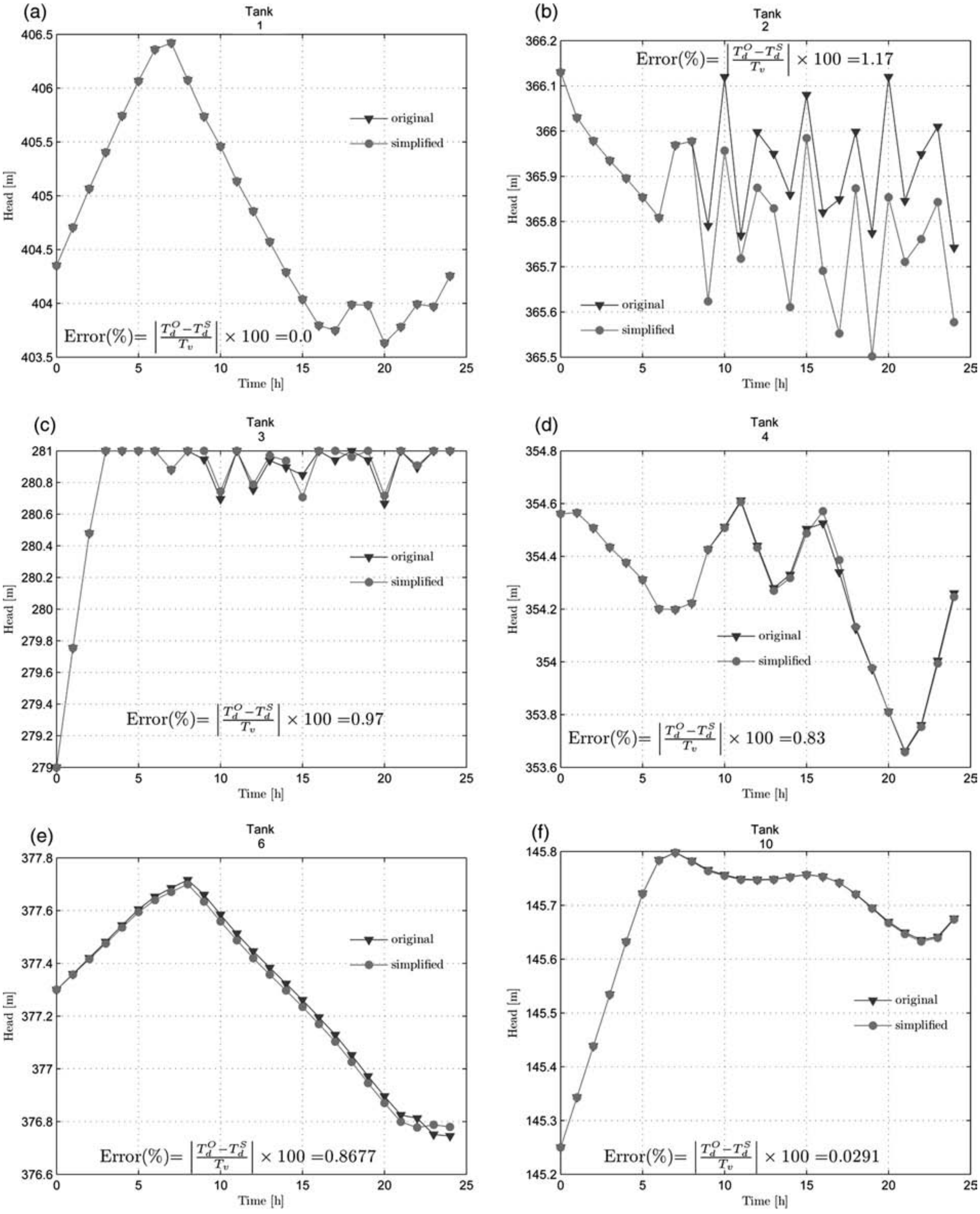

Figure 6 | Comparison of simulated tank trajectories for water networks from Table 4. (a) Simulated trajectories for Tank 1 from Network 1. (b) Simulated trajectories for Tank 2 from Network 2. (c) Simulated trajectories for Tank 3 from Network 2. (d) Simulated trajectories for Tank 4 from Network 2. (e) Simulated trajectories for Tank 6 from Network 3. (f) Simulated trajectories for Tank 10 from Network 3.

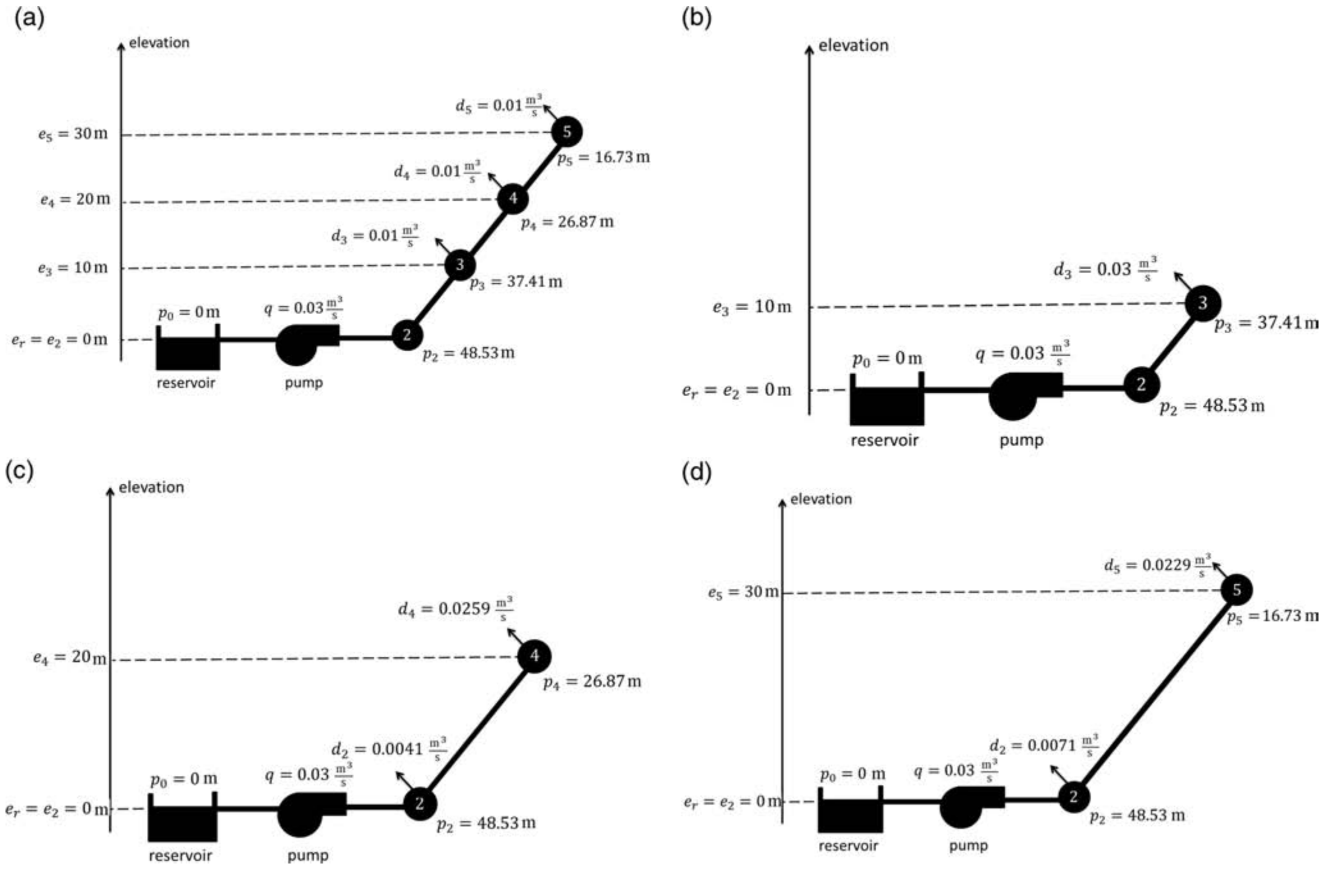

Figure 7 | Illustration of the energy distribution problem when reallocating demands to the nodes with a different elevation. The symbols in the figure are as follows: *e* is an elevation, *p* is a pressure, *d* is a demand and *q* is a flow. (a) The original water network to be simplified. (b) The water network after simplification with node 3 selected to be retained. (c) The water network after simplification with node 4 selected to be retained. (d) The water network after simplification with node 5 selected to be retained.

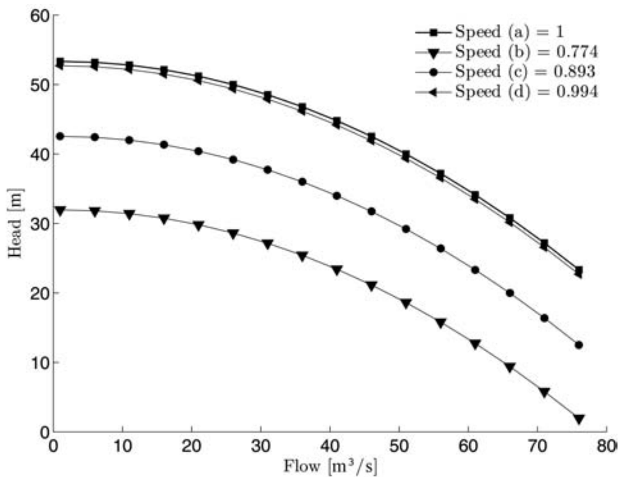

Figure 8 | The original and optimised pump head curves calculated to satisfy the pressure constraint of 16 m.

Table 5 | Energy efficiency indicators

Indicator	Definition
Excess of supplied energy	$I_1 = (E_R(t_\mathrm{p}) + E_\mathrm{P}(t_p))/E_{U_{\min}}(t_\mathrm{p})$
Excess of energy delivered to users	$I_5 = E_U(t_\mathrm{p})/E_{U_{\min}}(t_\mathrm{p})$

energy $E_{i_{U_{\min}}}$ is distributed to neighbouring nodes proportionally to the link conductance.

- Calculate a new minimum pressure constraint $p^S_{i_{\min}}$ for each node to which any demand was transferred to:

$$p^S_{i_{\min}} = \frac{E^S_{i_{U_{\min}}}}{\gamma D^S_i \Delta t} - e_i,\ \ \forall i \in U^S \qquad (3)$$

Table 6 | The energy audit carried out for all four cases illustrated in Figure 7

	Energy balance (in kWh) per day **(a)**	**(b)**	**(c)**	**(d)**
E_U	345.74	348.70	346.48	346.85
E_R	0	0	0	0
E_P	356.96	356.96	356.96	356.96
E_D	11.22	8.27	10.49	10.11
$E_{U_{\min}}$	264.78	191.23	244.46	286.06
$E_B = E_R + E_P - E_U - E_D$	-1.97×10^{-6}	-1.41×10^{-5}	-2.09×10^{-5}	9.78×10^{-6}
I_1	1.35	1.87	1.46	1.25
I_5	1.31	1.82	1.42	1.21

where U^S is the number of nodes in the simplified model, $E^S_{U_{\min}}$ is the new i nodal minimum required energy obtained via Gaussian elimination, D^S_i is the new total demand at node i and e_i is the node i elevation with reference to the lowest point in the water network.

- Carry out an energy audit for the simplified network and compare it with the initial audit.

The above methodology was applied to the example water network illustrated in Figure 7. The results are shown in Table 7. It can be seen that the $E_{U_{\min}}$ and indicators I_1 and I_5 for the simplified networks ((b), (c) and (d)) are almost the same as for the original network (a). It can also be observed that, before, it would be recommended to keep the highest located node in the network to maintain initial energy distribution, whereas for the modified reduction process with inclusion of the additional steps that modify the pressure constraints the need to select such a node is unnecessary. This makes the extended simplification algorithm a straightforward process where no manual network pre-processing is required to preserve the energy distribution.

Table 8 contains the new service pressure constraints calculated for each node. Such a set of pressure constraints are sent to the controller, illustrated in Figure 1, as modified operational constraints.

Case study – a small water network

The described methodology was applied to a model of a small district meter area (DMA) depicted in Figure 9. The structural characteristic is similar to that in Figure 7(a), i.e the pump is delivering water directly to the demand nodes. This leak-free network consists of 165 nodes with a typical diurnal domestic demand pattern, 201 pipes with different

Table 7 | The energy audit with $E_{U_{\min}}$ included in the reduction process

	Energy balance (in kWh) per day			
	(a)	**(b)**	**(c)**	**(d)**
E_U	345.74	348.70	346.48	346.85
E_R	0	0	0	0
E_P	356.96	356.96	356.96	356.96
E_D	11.22	8.27	10.49	10.11
$E_{U_{\min}}$	264.78	264.78	264.76	264.79
$E_B = E_R + E_P - E_U - E_D$	-1.97×10^{-6}	-1.41×10^{-5}	-2.09×10^{-5}	9.78×10^{-6}
I_1	1.35	1.35	1.35	1.35
I_5	1.31	1.32	1.31	1.31

Table 8 | The new pressure constraints

	Minimum service pressure constraints (in m)			
	(a)	**(b)**	**(c)**	**(d)**
$p_{2_{\min}}$	16	16	26.031	28.612
$p_{3_{\min}}$	16	25.999	–	–
$p_{4_{\min}}$	16	–	17.596	–
$p_{5_{\min}}$	16	–	–	8.295

length, diameter and roughness parameters, 1 pump and 1 reservoir. The minimum service pressure is assumed to be the same for all nodes.

The simplifications and energy audits were performed for the set of 10 representative nodes. The arbitrarily selected set of nodes from which a single node to be retained was selected vary in elevation with reference to the reservoir and in location in the water network model (see Figure 9(a)). The original network was simplified 10 times, resulting each time with the same topology illustrated in Figure 9(b). The energy audits calculated for each simplified model are summarised in Table 9. Columns numbered from 1 to 10 correspond to nodes from Figure 9(a) selected to be retained in the simplified model.

In Table 9, the performance indicators I_1, I_5 and minimum useful energy $E_{U_{\min}}$, calculated for a standard simplification procedure (i.e. not considering energy) in most cases significantly differs from the benchmarks values of $I_1 = 1.37$, $I_5 = 1.35$ and $E_{U_{\min}} = 215.91$ kWh/day.

It is worth highlighting that the case with node 10 retained, which represents a case when no node has been selected to retain, except nodes connected to the

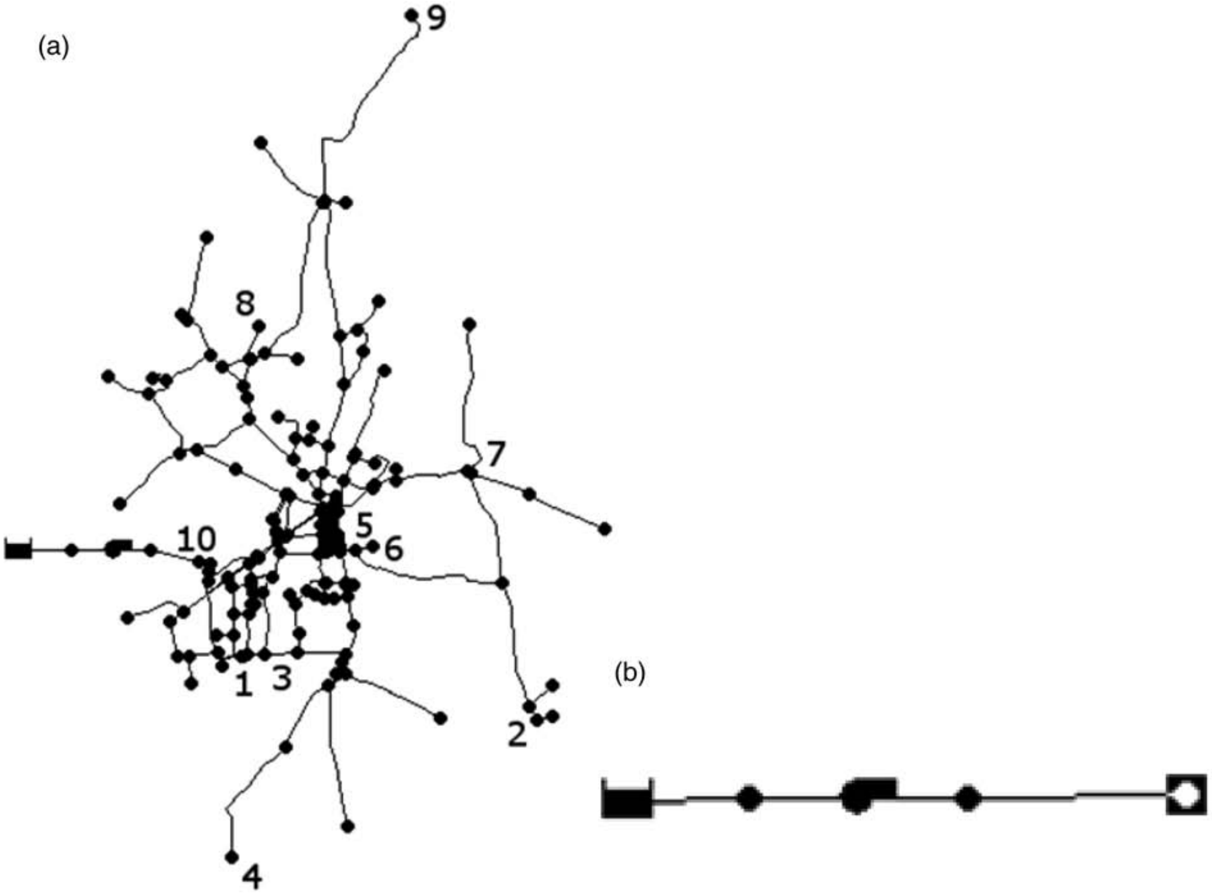

Figure 9 | The water network model before (a) and after (b) the simplification. Numbers indicate a single node to be retained, varied in elevation with reference to the reservoir and in location in the water network. Q3

control elements, $E_{U_{\min}} = 77.12$ kWh/day, $I_1 = I_5 = 3.84$ are almost three times higher when compared to the original water network. Such an excess of potentially recoverable energy $I_1 = 3.84$, dependent on the minimum pressure constraint $p_{\min}$, would mislead the optimiser and thereby the optimal solution applied to the original water network would not guarantee the minimum service pressure.

Intuition suggests to keep the highest node, 1, whose energy audits values are the closest to the original water network; indeed, it is standard practice to locate a pressure sensor at the highest nodes in a DMA in pressure control schemes. However, when a water network consists of many nodes with similar elevations, the selection of the best node would be difficult. Columns labelled 5, 6, 7 and 8 in Table 9 illustrate such a case. The four nodes share the same elevation, but their energy distribution and performance indicators are different. However, when the aspect of energy distribution is taken into account during the water network simplification, a selection of nodes is not needed, but then new pressure constraints must be imposed on those nodes. In all cases, the simplified minimum useful energy was $E^{S}_{U_{\min}} = 215.91$ kWh/day, ensuring that the ratio of water energy introduced to the network to energy required to deliver water under minimum service pressure was kept the same (see bottom rows in Table 9).

CONCLUSIONS

An online simplification algorithm has been presented and implemented using modern parallel programming techniques. The implemented module can be integrated with the online control strategy applied to the water network model, or it can be used as a standalone application. The advantage of the online model reduction can be used to manage abnormal situations and structural changes to a network, e.g. isolation of part of a network due to pipe burst. In such a case, an operator can change the full hydraulic model and run the model reduction module to automatically produce an updated simplified model. The developed module is able to simplify the water network model, consisting of several thousands elements, within a calculation time of 2 min and with an average relative accuracy of less than 2% in terms of tanks flows.

A methodology based on energy audit concepts was incorporated into the model reduction algorithm, allowing the preservation of the original model energy distribution. The idea is based on the distribution of minimum useful energy that is dependent on the network minimum service pressure. The standard model reduction algorithm was modified to reallocate not only the demand of the removed nodes, but also their minimum useful energy (pressure constraints). The simplified model kept the original model energy distribution due to new pressure constraints. Such

Table 9 | The energy audits for the original water network and simplified models (note that elevation is in metres and energies are in kWh per day)

Model	**Original network**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Elevation	–	49.5	47.5	45.5	42.5	32.5	32.5	32.5	32.5	24.5	0
E_U	292.21	295.16	295.46	294.90	295.65	293.19	293.60	293.24	295.51	294.85	295.95
E_R	0	0	0	0	0	0	0	0	0	0	0
E_P	295.95	295.95	295.95	295.95	295.95	295.95	295.95	295.95	295.95	295.95	295.95
E_D	3.74	0.79	0.50	1.06	0.30	2.76	2.35	2.71	1.44	1.10	0.0005
$E_{U_{\min}}$	215.91	221.47	95.98	202.83	89.73	172.13	157.20	146.12	110.68	94.80	77.12
E_B	5.1×10^{-5}	5.1×10^{-5}	5.4×10^{-5}	4.9×10^{-5}	5.2×10^{-5}	5.1×10^{-5}	5.1×10^{-5}	4.8×10^{-5}	4.8×10^{-5}	4.9×10^{-5}	4.9×10^{-5}
I_1	1.37	1.34	3.08	1.46	3.30	1.72	1.88	2.02	2.67	3.12	3.84
I_5	1.35	1.33	3.08	1.45	3.29	1.70	1.87	2.01	2.66	3.11	3.84
I_1^S	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37
I_5^S	1.35	1.37	1.37	1.37	1.36	1.36	1.36	1.36	1.36	1.37	1.37

an approach allowed to preserve both the hydraulic and energetic characteristics of the original water network and therefore met the requirements of the control strategy designed for a water network optimal scheduling.

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First received 8 February 2012; accepted in revised form 9 August 2012. Available online 3 January 2013

Author Queries

Journal: Journal of Hydroinformatics

Manuscript: HYDRO-D-12-00029

Q1 Please confirm the correct year of Rao & Alvarruiz (2007) as per the reference list.

Q2 Please provide location for Walski et al. (2003).

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