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Incorporation of variable-speed pumping in multiobjective genetic algorithm optimization of the design of water transmission systems

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Abstract

Global warming caused by human activities presents serious global risks. Individuals, governments and industries need to be more energy efficient and contribute to the mitigation of global warming by reducing their greenhouse gas (GHG) emissions. In previous research, GHG emission reduction has been identified as one important criterion in improving the sustainability of urban infrastructure and urban water systems. Within the water industry, opportunities exist for reducing GHG emissions by improving pumping efficiency via the use of variable-speed pumps (VSPs). Previously, VSPs have been used in the optimization of the *operation* of existing water distribution systems (WDSs). However, in WDS design optimization problems, fixed-speed pumps (FSPs) are commonly used. In this study, a pump power estimation method, developed using a false position method based optimization approach, is proposed to incorporate VSPs in the conceptual design or planning of water transmission systems (WTSs), using optimization. This pump power estimation method is implemented within the solution evaluation process via a multiobjective genetic algorithm approach. A case study is used to demonstrate the application of the pump power estimation method in estimating pump power and associated energy consumption of VSPs and FSPs in WTS optimization. In addition, comparisons are made between variable-speed pumping and fixed-speed pumping in multiobjective WTS optimization accounting for total cost and GHG emissions. The results show that the use of variable-speed pumping leads to significant savings in both total cost and GHG emissions from WTSs for the case study considered.

Keywords: Variable speed pump; Water transmission system; Multiobjective optimization; Greenhouse gases

Introduction

Global warming caused by increased concentration of greenhouse gases (GHGs) in the atmosphere is a significant threat facing our generation. Extreme weather conditions, such as severe droughts, floods and hurricanes, which are exacerbated by global warming, are already affecting a large number of people around the world. However, more GHGs are still being added into the atmosphere by human activities, such as burning fossil fuel for energy. Consequently, individuals, governments and industries need to be more energy efficient and contribute to the mitigation of global warming by reducing their GHG emissions.

In a number of studies, the minimization of GHG emissions has been identified as one important criterion for improving the sustainability of urban infrastructure and urban water systems (Sahely et al., 2005; Filion, 2008). Within the water industry, GHG emissions are mainly generated from system operation related to pumping. In a study by Tarantini and Ferri (2001), the authors found that pumping had the highest environmental impact on the water and wastewater system of Bologna in Italy. In a similar finding, a survey conducted by the South Australian Water Corporation showed that major pumping accounts for 46% of GHG emissions from their activities across South Australia (Kelly, 2007). Consequently, opportunities exist within the water industry for GHG emission reduction by improving pumping efficiency.

In order to reduce GHG emissions in the water industry, tradeoffs between GHG emission minimization and the traditional objective of economic cost minimization have been investigated via a multiobjective approach in previous studies (Wu et al., 2008; Wu et al., 2010a; Wu et al., 2010b). The authors found that a moderate increase in capital investment can result in substantial reductions in GHG emissions from water distribution systems (WDSs). In these studies, a number of commercially available fixed-speed pumps (FSPs) were used as decision variables. FSPs have smaller capital costs compared with variable-speed pumps (VSPs). However, VSPs have many advantages over FSPs in terms of performance. As Wood and Reddy (1995) pointed out, VSPs provide easier control over the system, which enables a better response to abnormal situations, such as fire and breakage. More importantly, pressures or flowrates can be maintained very close to minimum allowable levels by using VSPs, thus, there is great potential for saving energy and hence for reducing GHG emissions in new pumping systems (Lingireddy and Wood, 1998). Therefore, it is important to consider the incorporation of VSPs in WDS optimization when investigating total cost and GHG emissions from WDSs.

VSPs have been incorporated in the optimization of the *operation* of existing WDSs in previous studies (Wegley et al., 2000; Rao and Salomons, 2007; da Costa Bortoni et al., 2008; Wu et al., 2009). However, for the optimal design of WDSs involving pumping, FSPs have often been used, despite the advantages of VSPs discussed above. One reason for this is that FSPs are commonly used in existing WDSs. In addition, FSPs can be easily simulated in an optimization process by using a fixed pumping head or a pump curve (Duan et al., 1990; Wu et al., 2010a; Wu et al., 2010b), whereas the dynamic features of VSPs make their simulation within optimization iterations a more difficult task.

In previous studies, commercially available FSPs have been used as decision variables in WDS optimization (Wu et al., 2010a; Wu et al., 2010b). However, there is a significant drawback to this approach. This is because it is not practical to include all available pumps as decision variable options in the optimization process due to limited availability of pump information and the high computational effort required to include a large number of pump options in a multiobjective optimization process. When limited numbers of real pumps are used in the WDS optimization process, the optimization may favor network configurations that match the characteristics of the selected pumps. Therefore, a generic approach to pump sizing and pump power estimation, which allows easy adjustment of pump power based on specific network configurations, is more appropriate for WDS optimization (Hodgson and Walters, 2002). This allows different network configurations generated as part of the WDS optimization process to be compared fairly without introducing distortions resulting from use of a specific pump.

In order to be able to incorporate VSPs into the conceptual design or planning of WDSs using optimization and ensure different network configurations generated during the optimization process are compared fairly, a generic pump power estimation method is required. In this paper, such an approach is proposed for water transmission systems (WTSs), which is the portion of a WDS that delivers water from water sources into storage facilities, such as reservoirs and/or tanks. The proposed method does not directly deal with the simulation of a particular VSP or an existing WTS with VSPs. Instead, it automatically calculates the pump power, and thus the pump energy, required for a particular network configuration, subject to multiple flow constraints. This method is suited to fast and repeated estimation of operating energy consumption of a large number of network configurations, rather than to modeling of the full range of behavior of a particular VSP within an existing WTS. The method can also be used to incorporate FSPs into the conceptual design or planning of WTSs using optimization with appropriate assumptions, provided FSPs are treated as a special case of VSPs.

Methodology for incorporating VSPs in conceptual design or planning of WTSs

Problem formulation

The WTS optimization problem considered in this study is illustrated in Figure 1. The two objectives considered include: 1) the minimization of the total economic cost of the system; and 2) the minimization of the total GHG emissions of the system. In order to calculate the total economic cost and total GHG emissions of a WTS, a life cycle analysis and the proposed pump power estimation method are required.

The constraints include equality constraints and inequality constraints, as shown in Figure 1. Equality constraints often refer to the physical laws (e.g. the continuity of flow and the conservation of energy) that apply to the network. In practice, these constraints do not need to be considered explicitly in an optimization process, as they are often satisfied automatically by using a hydraulic solver, such as EPANET (Rossman, 2000). The inequality constraints are often design constraints that a WTS needs to satisfy, for example, the minimum flowrates within the system. Some of the inequality constraints can be handled by using the proposed pump power estimation method, which is introduced later in this section.

Estimation of total economic cost

The total economic cost (TEC) of a particular network is defined as

$$TEC = CC(\vec{x}) + OC(\vec{x}, OR) + MC(\vec{x}, MS) + EC(\vec{x}, DM) \tag{1}$$

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where, CC, OC, MC, and EC are capital cost, operating cost, maintenance cost and end-of-life cost, respectively; $\vec{x}$ represents the decision variables (e.g. pipe sizes, pipe material, etc.); OR and MS are the operational rules and maintenance strategies that will be used; DM represents the disposal/recycling methods used at the end of the service life of the system. The capital cost results from the purchase and installation of network components (e.g. pipes, pumps, valves, tanks etc.), and construction of pump stations, storage facilities, etc. The maintenance and end-of-life costs are functions of the decision variables. Pumps also contribute to these two costs. In addition, the maintenance strategy selected and disposal/recycling methods used at the end of the service life of the system have a significant impact on the values of the maintenance and end-of-life costs. In this study, the pump refurbishment costs are not considered, as they contribute only a relatively small amount to the total cost once they are converted into their present values (Wu et al., 2010b). It should also be noted that the end-of-life costs of WTSs are often not considered. This is mainly because these costs occur at the very end of the design period of the system, which is often 50 to 100 years for a WTS. Once the end-of-life costs are converted into their present values as part of present value analysis (PVA), the impact of these values on the total cost is usually negligible. In addition, the uncertainty associated with end-of-life costs is often the reason why they are omitted from the analysis.

The operating cost is mainly due to the electricity consumption of system operation related to pumping, which can be calculated based on the annual energy consumption (AEC) as defined below:

$$AEC = \sum_{t=1}^{T} \frac{P(t)}{\eta(t)_{motor}} \times \Delta t = \sum_{t=1}^{T} \frac{1}{1000} \frac{\gamma \times Q(t) \times H(t)}{\eta(t)_{pump} \times \eta(t)_{motor}} \times \Delta t \tag{2}$$

where, t is the time step (e.g. the time step in an extended period simulation (EPS)); $P(t)$ is the pump power (kW); γ is the specific weight of water (N/m^3); $Q(t)$ is the pump flow (m^3/s); $H(t)$ is the pump head (m); $\eta(t)_{pump}$ and $\eta(t)_{motor}$ are the pump efficiency and motor efficiency, respectively; T is the number of time steps; and Δt is the duration of each time step (hours). The annual operating cost can be taken as the AEC (kWh) multiplied by the projected average electricity tariff (ET) of the corresponding year (based on an electricity tariff forecasting model). As operating costs occur progressively during the whole design period, PVA needs to be used to convert the operating costs in each year to their present values, in order to allow costs occurring at different times to be compared.

As part of the conceptual design or planning of WTSs, the simplest way to estimate the AEC for each potential solution network in the optimization process is to use the average flowrate during a year. However, the estimation of energy consumption can be improved by using a seasonal EPS, which takes into account the seasonal variation of demand. In both cases, an estimate of pump power $P(t)$ is required and can be obtained using the proposed pump power estimation method. In addition, in order to account for changes in pipe roughness over the design period, a pipe aging model can be used. Ideally, such a model should take into account any maintenance strategies.

Estimation of total GHG emissions

The total GHG emissions (TGHG) of a particular network are defined as

$$TGHG = CGHG(\vec{x}) + OGHG(\vec{x}, OR) + MGHG(\vec{x}, MS) + EGHG(\vec{x}, DM) \qquad (3)$$

where $CGHG$, $OGHG$, $MGHG$, and $EGHG$ are capital emissions, operating emissions, maintenance emissions and end-of-life emissions, respectively. These emissions are also functions of decision variables $\vec{x}$ (e.g. pipe size, pipe material, etc.). The capital emissions are mainly due to energy consumption that occurred during the fabrication stage (including material extraction, material production, product manufacturing, and product transportation and installation) of network components during the life cycle of the system (Filion et al., 2004), which can be estimated using embodied energy analysis (EEA) (Treloar, 1994). Emission factor analysis (EFA) can then be used to estimate the capital GHG emissions in the form of CO_2-e (carbon dioxide equivalent) in kilograms (kg) based on the embodied energy values (The Department of Climate Change, 2008). In practice, embodied energy values and emission factors are likely to vary across regions and with time, depending on the material excavation and extraction methods used and the way electricity is generated (e.g. thermal, nuclear, wind, hydroelectricity, etc.). Ideally, a preliminary study should be carried out to determine the embodied energy of the specific types of network components considered and the emission factor values for the study region.

Similar to the operating cost, operating emissions are predominantly caused by system operation related to pumping and therefore, can be calculated using AEC. Once the AEC for a particular future year is estimated using Eq. (2), the operating emissions of the year are obtained by multiplying the AEC and the projected average emission factor of the corresponding year, which can be obtained by using an emission factor forecast model for the study region. The operating emissions due to pumping also occur progressively over the design period; therefore, PVA may be required to convert the operating emissions in each year to their present values.

GHG emissions will also be generated during system maintenance and at the end of system service life, when network components are disposed of or recycled. These emissions are a function of the network components selected at the beginning of the project (that depends on the value of decision variables), the maintenance strategies adopted throughout the life of the project and the disposal methods and recycling options selected at the end-of-life, but are often not considered.

<u>*Impact of use of FSPs or VSPs on objective evaluation*</u>

Whether FSPs or VSPs are used has an impact on the evaluation of the two objectives. Firstly, VSPs are generally more expensive than FSPs. However, the capital cost of VSPs can be offset by eliminating some network components, such as control valves, bypass lines and conventional starters, which are required by FSPs (Europump and Hydraulic Institute, 2004). Similarly to pipes, the capital emissions of pumps mainly depend on the material of the pump and where it is manufactured (Filion et al., 2004), which have a significant impact on the embodied energy of pumps, rather than whether FSPs or VSPs are used. Therefore, any differences between the capital GHG emissions of FSPs and VSPs are usually small.

As VSPs have a variable frequency drive (VFD), which FSPs do not have, they can incur additional maintenance costs. However, these costs can generally be offset by the maintenance costs for the additional components required by FSPs, as mentioned previously. In addition, VSPs generally operate at lower speeds and have lower loads on the shaft, bearings and gaskets compared to FSPs, which result in lower failure frequency and can reduce maintenance costs significantly (Hovstadius, 2001). In addition, Wu et al. (2010b) showed that the lifecycle maintenance costs for FSPs are a small percentage of the total cost. Therefore, the difference between the lifecycle maintenance costs of FSPs and VSPs is negligible in the evaluation of the total cost.

The most significant impact of the selection of either FSPs or VSPs is on operating cost and emission estimation. As the speeds of VSPs can be adjusted to maintain flowrates at their minimum allowable levels, the average pump flowrates for VSPs are generally lower (Hovstadius, 2001). As a result, in order to deliver the required demand, VSPs are likely to operate for most of the time during a day. In contrast, FSPs can only operate at a single speed and their average pump flowrates are generally higher than those for VSPs. However, the time during which FSPs are operating is less than that of VSPs, provided they deliver the same quantity of water. The difference between the pump flowrates of FSPs and VSPs has a significant impact on their respective energy consumption (The U.S. Departement of Energy's Industrial Technologies Program and Hydraulic Institute, 2006). At higher pump flows, FSPs need to overcome higher friction losses, which are sometimes significant, especially for systems with small pipes. In addition, newer VSPs can also operate at high efficiency (Burt et al., 2006). As a result, the AEC and associated operating costs and GHG emissions of FSPs can be higher compared to those of VSPs. It should be noted that in regions where electricity tariffs are lower during off-peak periods, the operating cost of FSPs can be reduced by scheduling most of the pumping to occur during these periods; however, the GHG emissions associated with pumping cannot be reduced.

Proposed pump power estimation method

FCV based pump power estimation method

For the purpose of calculating the required pumping power for the estimation of maximum pump capacity and AEC, a pump (either VSP or FSP) can be artificially represented by a control valve combined with an upstream reservoir with a high head within a hydraulic solver, as shown in Figure 2. For WTSs, where system flow is of primary concern, it is proposed that a flow control valve (FCV) be used as the control valve, as this provides a simple control of system flow.

When estimating pump power for a WTS, an appropriate setting of the FCV needs to be determined, such that the flows into the downstream storage tanks are maintained as close to the required flows as possible. Thus, the task of determining the most appropriate FCV setting for calculating pump power for a WTS is a constrained single-objective minimization problem, which is defined as:

$$\text{minimize} \qquad g(y) = \min\left\{ \mathbf{Q_a} - \mathbf{Q_r} \right\} \tag{4}$$

subject to

$$y \in \left[Q_L, Q_U \right] \tag{5}$$

$$\mathbf{Q_a} = \left\{ q_j \right\} \qquad \forall j = 1, 2, ..., nt \tag{6}$$

$$\mathbf{Q}_r = \left\{ q_j^r \right\} \qquad \forall j = 1, 2, ..., nt \tag{7}$$

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$$\mathbf{Q_a} - \mathbf{Q_r} \geq 0 \tag{8}$$

where, g is the objective function of the single-objective minimization problem; y is the desired optimum FCV setting; $\mathbf{Q_a}$ and $\mathbf{Q_r}$ are the vectors of actual and required flows into the storage tanks, respectively; Q_L is the lower bound of y, which is often taken as the minimum required flowrate of the system; Q_U is the upper bound of y, which is defined by the user; q_j and q_j^r are the actual and required flows into the storage tank j, respectively; and nt is the number of storage tanks.

By searching for a suitable FCV setting y between Q_L and Q_U, the differences between the actual flows the system delivers into the storage tanks and the corresponding required flows are minimized. The pump head associated with a particular flow distribution can then be obtained from the head of the downstream node of the FCV within a hydraulic solver. Thus, the pump power for the WTS can be calculated.

Pumping energy estimation using the proposed pump power estimation method

The process for estimating pumping energy using the false position method based pump power estimation method for a WTS is illustrated in Figure 3. First, the upper and lower bounds of the valve setting need to be defined (Step 1). Then, the false position method, combined with a hydraulic solver, is used to find the FCV setting y such that the objective defined in Eq. (4) is minimized and the design constraints are satisfied during time t (Step 2). The pump head can be obtained as the head of the downstream node of the FCV within the hydraulic solver (Step 3). The actual pumping time can be calculated based on the demand during time t (Step 4). Thus, the pumping energy consumption during time t can be computed (Step 5).

Both VSPs and FSPs are sized to meet the same design criteria of the system. As the speed of a VSP can be adjusted to match the required flowrates for a WTS, it is assumed that the valve setting is determined in a way that maintains the flows at just above their minimum allowable levels. However, when FSPs are used, flowrates will exceed their minimum requirements. As a result, FSPs will operate for fewer hours compared to VSPs when the same volume of water is delivered in a WTS.

The false position method (Burden and Faires, 2005) has been selected for the purpose of solving the constrained single-objective valve setting search problem because it is a bracketing method, which is guaranteed to converge. This is essential in an optimization process, as an estimate of pump power has to be made for each potential network solution at each iteration to ensure a fair comparison between different networks is made.

Solution evaluation process within a genetic algorithm framework

The proposed solution evaluation process, incorporating the pump power estimation method for WTSs, within a genetic algorithm framework is illustrated in Figure 4. There are five steps in evaluating a network solution, which are marked from 1 to 5 in the figure. The proposed pump power estimation method is employed in Steps 2 and 4 for estimating the maximum required pump capacity and annual energy consumption, respectively. In the first step, a threshold test is performed to determine whether or not

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the current solution network needs to be evaluated. A threshold value for the valve setting is first defined, often as the upper bound of the valve setting for estimating the maximum capacity of the pump. If the current solution can satisfy the design requirements when the valve setting is set at the threshold value, the solution is evaluated. Otherwise, the network is considered to be infeasible and removed from further consideration in order to reduce the size of the search space during the optimization process, thereby increasing computational efficiency and the chances of finding a globally optimal solution.

Once a solution has passed the threshold test, the maximum pump power required is calculated based on the design criteria defined for the case study under consideration using the proposed pump power estimation method (Step 2). For example, a WTS is often designed to meet the average flow on a peak-day (referred to as peak-day flow in this paper) during the highest demand year of the design period. The pump related costs and emissions can be estimated based on the maximum pump power of the pump. Thus, the capital cost and emissions of the solution network can be calculated (Step 3).

The fourth step is to calculate the annual energy consumption (AEC) and associated operating cost and emissions, and in turn, the total operating cost and operating GHG emissions of the system during its design life. In this step, the proposed pump power estimation method is used to estimate the pump power and pumping energy for each time step t. The AEC can be calculated by summing the actual pumping energy of each time step t. Once the AEC has been obtained, the operating cost and GHG emissions of the corresponding year can be calculated based on the electricity tariff and emission factor of that year and thus, the total cost and GHG emissions can be calculated (Step 5).

Case study

In this paper, a case study is used to demonstrate the application of the proposed pump power estimation method in multiobjective WTS optimization accounting for total economic cost and GHG emissions and investigate the impact of variable-speed pumping on the optimization results. The case study network and assumptions made in the objective and solution evaluation processes are presented in this section.

Example network

The network configuration of the case study used to illustrate the approach introduced in this paper is shown in Figure 5. For this case study, water needs to be delivered from a water source (reservoir 6) to three storage reservoirs (reservoirs 7, 8 and 9). The demands of the three storage reservoirs are assumed to be the same (i.e. one third of the total annual demand). This case study is a network conceptual design problem, in which pipe diameters are decision variables, and pumps are sized and pump power is calculated using the proposed pump power estimation method for each network configuration determined by the pipes. Sixteen ductile iron cement mortar lined (DICL) pipes with different diameters are used as choices. The details of the pipes can be found in Wu et al. (2010a).

Case study objective function evaluation and assumptions

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For calculating the total economic cost for the case study, only capital and operating costs of the network are considered. The capital cost results from the purchase and installation of network components (pipes and pumps) and the construction of pump stations. The pipe costs can be computed from the pipe data provided in Wu et al. (2010a). The cost of pumps and pump stations can be estimated using the maximum power capacity of the pump (Wu et al., 2010a; Wu et al., 2010b), which is determined using the pump power estimation method based on the peak-day flow of the maximum demand during the design period. The peak-day flow is assumed to be 1.5 times the average-day flow based on the recommendation of the Water Services Association of Australia (2002) for populations over 10,000. In this study, the capital costs of VSPs include the costs of variable frequency drives (VFDs), which are taken as 10% of the pump cost (based on consultation with a number of experienced design engineers), and therefore are higher than the capital costs of FSPs.

The calculation of operating cost requires a demand forecasting model, the estimation of the annual energy consumption (AEC) (defined in Eq. (2)) and an electricity tariff forecasting model over the design period. Demand is dependent on both the average water consumption per capita and population size. In general, demand will increase as population grows. However, this might not be the case if policies aimed at reducing per capita demand are successful (Australian Bureau of Statistics, 2006). In order to avoid the introduction of unnecessary uncertainties into the optimization process and emphasize the comparison between FSPs and VSPs, a constant annual water demand of 2,522,880 m^3/year, corresponding to a peak-day flow of 120 L/s and an average-day flow of 80 L/s, is used for the case study. Therefore, the case study network is relatively small, supplying around 20,000 people. In addition, a design period of 100 years is used in this paper, which is consistent with the recommendation for the design of water mains by the Water Services Association of Australia (2002).

In estimating the AEC for FSPs, a flowrate determined using the proposed pump power estimation method based on the peak-day flow, is used. The exact value of this flowrate depends on the specific network configuration and will be just above the peak-day flow for which the FSPs are sized. This flowrate is considered to be able to provide a good estimate of the energy consumption associated with fixed-speed pumping for this case study. When VSPs are used, an EPS with four simulation periods is used to account for seasonal variations in demand during a year. During each of the four seasonal simulation periods, an average flowrate is used to estimate the energy consumption during that quarter of the year (values of 110L/s, 90L/s, 70L/s and 50L/s have been used to estimate the AEC for VSPs in this case study). As the same quantity of water is delivered, the actual annual pumping time for FSPs is less than that for VSPs. In addition, an average pipe roughness value of 0.25 mm over the entire design period (i.e. a pipe-aging model was not used) is used, as it has been found in a number of test runs that considering pipe aging by changing pipe roughness values over the design period does not have a significant impact on the results of WTS optimization accounting for cost and GHG emissions.

The average electricity tariffs (prices) in the retail market in Australia are determined by both wholesale prices and contract market prices, which are difficult to predict into the future (Electricity Industry Supply Planning Council, 2005). Saddler et al. (2004) suggested that in 30 years time, fossil fuels will still be the main source of electricity in Australia and that the prices of electricity generated by all fossil fuels will be higher. As a result, electricity tariffs are assumed to average \$0.14 per kWh (estimated by averaging on-peak and off-peak values in South Australia) at the beginning of the design period and to increase at 3% per annum from the second and subsequent years of the design period.

Motor efficiency and pump efficiency are also required to calculate the AEC, as shown in Eq. (2). In this study, an average motor efficiency of 95% and an average pump efficiency of 85% are assumed. VSPs also have variable frequency drives (VFDs). Burt et al. (2006) found that although the efficiency of VFDs depends on the type of VFD, VFD rotational speed and VFD load, for all of the VFDs tested, efficiency was higher than 97% at full loads, and for some types of VFDs, the efficiency was higher than 99%. The study indicated that even at lower loads, efficiencies did not fall below 95%. This finding is in agreement with the information cited by Rooks and Wallace (2003): for large pumps (greater than 100 horse power or 74.6 kW), the efficiency of VFDs is generally greater than 95% when the speed is higher than 75%. As a result, a VFD efficiency of 95% is used in this case study. Finally, in the PVA that converts the operating costs in each year to their present values, a discount rate of 8% is used, which is a value commonly used by many water utilities in Australia.

In calculating total GHG emissions, only capital and operating GHG emissions of the network are considered, as mentioned previously. In this study, capital emissions are predominantly from pipe manufacture, as this represents the largest proportion of the impact (Filion et al., 2004). In calculating the embodied energy of the DICL pipes used in this study, a specific value of the embodied energy of 40.2 MJ/kg is used. This value was estimated by Ambrose et al. (2002) based on a combination of published and actual factory manufacturing data. In calculating capital emissions, an average emission factor of 0.98 kg CO_2-e/kWh is used, which is the full-fuel-cycle emission factor value of South Australia in 2007 (The Department of Climate Change, 2008).

The annual operating emissions are taken as the AEC multiplied by the projected average emission factor of the corresponding year. In this study, an average emission factor of 0.98 kg CO_2-e/kWh is used for the first year of the design period. Thereafter, the emission factor is assumed to decrease linearly to 70% of the 2007 level at the end of the design period of 100 years due to Government policies of encouraging clean energy. This assumption is based on the Australian Government's commitment to reduce GHG emissions by at least 5% below 2000 levels by 2020 (The Department of Climate Change, 2010). It should be noted that there are many uncertainties involved in projecting emission factors, particularly for a long time period, such as 100 years. The operating emissions due to pumping also occur over time during the design period, however, no discounting (that is a discount rate of zero percent) has been applied to the calculation of pumping GHG emissions based on the recommendation of the Intergovernmental Panel on Climate Change (IPCC) (Fearnside, 2002).

Case study solution evaluation

The FCV based pump power estimation method is used to estimate the maximum pump capacity and energy consumption for this case study. For Step 1 in Figure 4, a flow of 1.5 times the peak-day flow is used as the threshold flow. This value is also used as the upper bound Q_u (Eq. (5)) for maximum pump power estimation and energy consumption estimation. The lower bound Q_l (Eq. (5)) is set to a target flow, which depends on specific case study assumptions and what the pump power is estimated for. For this case study, the target flow is the peak-day flow for estimating the maximum pump capacity of both VSPs and FSPs; while the target flow is the average-day flow of each of the four seasonal simulation periods and the peak-day flow for estimating the AEC using VSPs and FSPs, respectively. Consequently, the vector $\mathbf{Q_a}$ (Eq. (6)) contains the actual flows in pipes 3, 5, 7 (Figure 5) that a particular system (a pipe network with a particular FCV setting) delivers; while the vector $\mathbf{Q_r}$ (Eq. (7)) contains the required flows in the pipes, which is defined as one third of the target flow.

A tolerance of 0.5 L/s is used in the false position method based FCV setting search algorithm for this case study. Therefore, the FCV setting search optimization is considered to have converged if the objective function value g (Eq. (4)) is less than 0.5 L/s. For the particular optimization problem presented in this paper, it takes around two to five iterations for the false position method to converge. In addition, a stochastic optimization algorithm, such as a genetic algorithm, cannot guarantee that the final solutions are Pareto-optimal. Therefore, for the genetic algorithm runs conducted in this study, a total of 100 random seeds (i.e., random starting positions) have been used to ensure near-globally optimum solutions are found. As a result, the optimal fronts presented in this paper are formed using the best values obtained from the 100 runs.

Optimization results and discussion

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The Pareto-optimal fronts obtained from the optimization runs using VSPs and FSPs are plotted in Figure 6. Eight typical solutions from the Pareto-optimal fronts are selected in this section to compare the optimization results obtained using VSPs and FSPs. These eight solutions are sorted according to the costs of the pipe networks and numbered consecutively from 1 to 8. Network 1 is the least-cost network and Network 8 is the highest-cost network. The pipe information for these eight networks is summarized in Table 1. The costs, GHG emissions and actual annual pumping hours of these networks with either variable- or fixed-speed pumping are presented in Table 2. The breakdown of the total cost and GHG emissions of these solutions is plotted in Figure 7.

It can be seen from both Figure 6 and Table 2 that six out of the eight networks (Networks 2 to 7) are on both the Pareto-optimal fronts obtained using variable- and fixed-speed pumping. However, the total cost and GHG emissions of the networks obtained using variable-speed pumping are much lower than those obtained using fixed-speed pumping. For example, the total cost of Network 4 with variable-speed pumping is 20.65 million dollars in contrast to 21.07 million dollars when fixed-speed pumping is used. In addition, the use of variable-speed pumping leads to a 16.7 kilotonne (kt), or 12.5%, saving in GHG emissions compared to the case when fixed-speed pumping is used.

Figure 6 also shows that both Pareto-optimal fronts obtained using FSPs and VSPs converge to a single GHG emission level of approximately 100 kt at the low emission end of the horizontal axis. This is because the solutions on the right hand side of the

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optimal front are solutions with large pipes and high capital costs. For these solutions, the friction losses in the pipes are so low that the operating energy consumption is mainly dependent on the static head (determined by the elevation difference between the water source and storage tanks). In other words, the effectiveness of replacing FSPs with VSPs in reducing operating costs and emissions by reducing friction losses within the system is more significant for smaller pipe diameter systems with higher dynamic heads (friction losses) relative to static heads.

It is also observed that use of VSPs leads to smaller optimal networks that are both cheaper in terms of economic cost and GHG emissions. For example, the lowest-cost network on the far left end of the Pareto-optimal front obtained using variable-speed pumping (Network 1) has a pipe cost of 13.20 million dollars (see Table 1), while the lowest-cost network obtained using fixed-speed pumping (Network 2) has a pipe cost of 13.58 million dollars. In previous research, it has been found that when FSPs are used, smaller networks often have higher GHG emissions compared to larger networks due to the higher friction losses in pipes with smaller diameters (Wu et al., 2010b). However, this is not the case when different types of pumps are used. For example, Network 1 with variable-speed pumping generates 32.0 kt less GHG emissions due to pumping compared with Network 2 with fixed-speed pumping, resulting from reduced annual energy consumption (Table 2 and Figure 7). In addition, the capital emissions of Network 1 are lower than those of Network 2 (Table 1 and Figure 7). As a result, Network 1 with variable-speed pumping generates 32.6 kt less GHG emissions compared to Network 2 with fixed-speed pumping. The reason for this is that the effect of increased friction loss on operating energy consumption due to

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reduced pipe diameters in smaller networks is less significant than the effect of increased friction losses due to increased flowrate (resulting from the use of FSPs).

For the same reason, the least-GHG emission solution obtained using variable-speed pumping (Network 7) emits 0.9 kt less GHG emissions than the least-emission solution obtained using fixed-speed pumping (Network 8), even though Network 8 uses pipes with larger diameters compared with Network 7. Similar results can be obtained from analyzing the breakdown of total costs, but the difference between the costs of the two least-cost solutions or the two least-emission solutions obtained using different types of pumps is not significant due to the effect of the 8% discount rate used in the PVA.

In addition, the fact that the same solutions exist in the middle regions of both optimal fronts shows that the choice of using a FSP or VSP mainly alters the solutions at the two extreme ends of the optimal front. This demonstrates the advantage of the proposed generic pump power estimation method over the approach used in previous studies, where a number of commercially available FSPs have been used as decision variables (Wu et al., 2010a; Wu et al., 2010b). Because the operating range of a specific pump may not suit every single potential network solution in the optimization process, some network configurations are favored by the use of certain pumps, which results in an unfair comparison in the optimization process. For example, a FSP which suits a sharp system curve (with small flow and high head) may not perform well when connected to a system with large pipes whose system curve is flatter (with lower total head due to lower friction losses). Thus, the selection process within the

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optimization may be biased towards smaller networks with high friction loss and large networks with less friction losses may be disadvantaged.

Conclusions

In this study, a generic pump power estimation method has been developed in order to incorporate variable-speed pumping into the conceptual design or planning of water transmission systems (WTSs) using optimization with multiple flow constraints, so that the costs and GHG emissions for a new WTS associated with pumping can be minimized. This pump power estimation method makes use of a flow control valve (FCV) and can be implemented using a hydraulic solver, such as EPANET, through a false position method based single-objective optimization approach.

In this study, a case study is used to demonstrate the application of the proposed pump power estimation method and investigate the impact of variable–speed pumping on the optimization of WTSs accounting for both total cost and GHG emissions. It has been found that the use of VSPs can reduce both the total cost and GHG emissions of the optimal solutions for a WTS. The effectiveness of replacing FSPs with VSPs in reducing operating costs and emissions is more significant for a smaller pipe diameter system with higher dynamic heads (friction losses) relative to static heads. As a result, compared with FSPs, use of VSPs leads to smaller network solutions which are both cheaper in terms of cost and GHG emissions. Therefore, switching from fixed-speed pumping to variable-speed pumping can be an effective method for reducing total cost and GHG emissions of WTSs when used in conjunction with multiobjective optimization.

The proposed pump power estimation method employs a generic pump concept, which enables pump power to be adjusted easily according to the characteristics of each specific network configuration generated in the optimization process. This feature avoids possible distortions resulting from a specific pump curve being introduced into the optimization process, enabling a fair comparison between different network configurations to be achieved.

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Figure 1 Proposed multiobjective WTS design problem

Figure 2 Proposed pump power estimation method within a hydraulic solver

Figure 3 Pump power and associated pumping energy estimation processes

Figure 4 Proposed solution evaluation process within a genetic algorithm

Figure 5 Case study network configuration (adapted from Wu et al. (2010a))

Figure 6 Comparison of Pareto-optimal fronts obtained using variable-speed pumping (VSP) and fixed-speed pumping (FSP) (Networks 2 to 7 are identical in pipe configuration for FSP and VSP systems)

Figure 7 Breakdown of life-cycle cost and GHG emissions of selected solutions with variable-speed pumping [plot (a)] and fixed-speed pumping [plot (b)]

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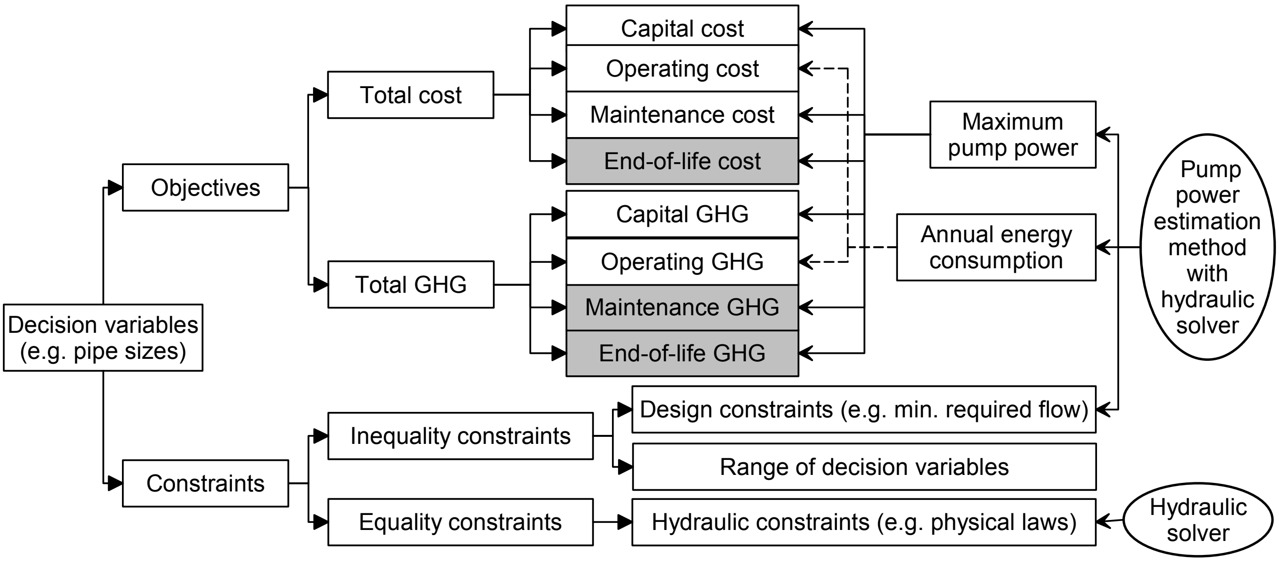

Figure 1 Proposed multiobjective WTS design problem

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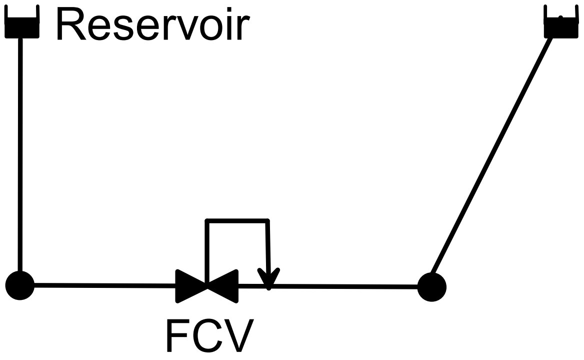

Figure 2 Proposed pump power estimation method within a hydraulic solver

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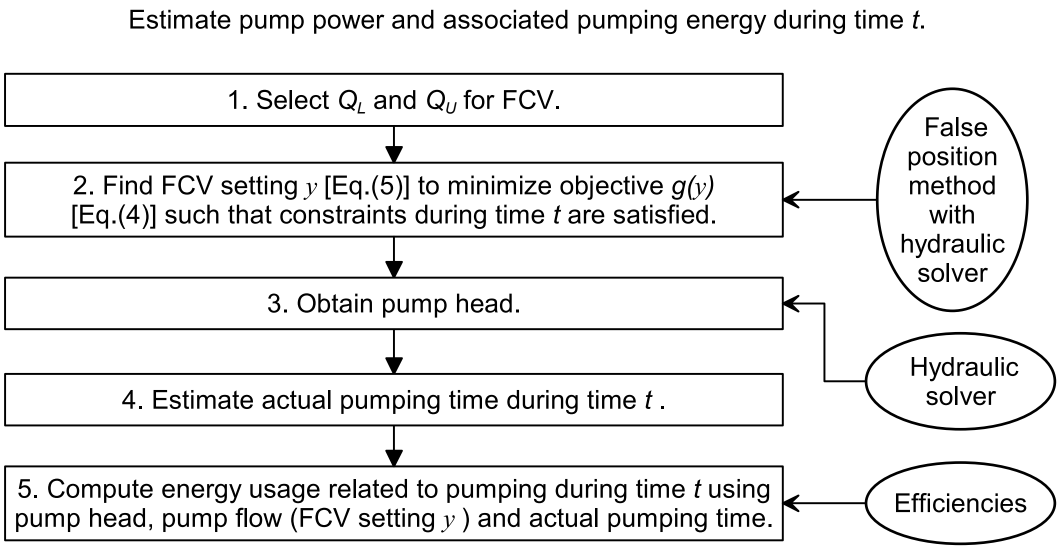

Figure 3 Pump power and associated pumping energy estimation processes

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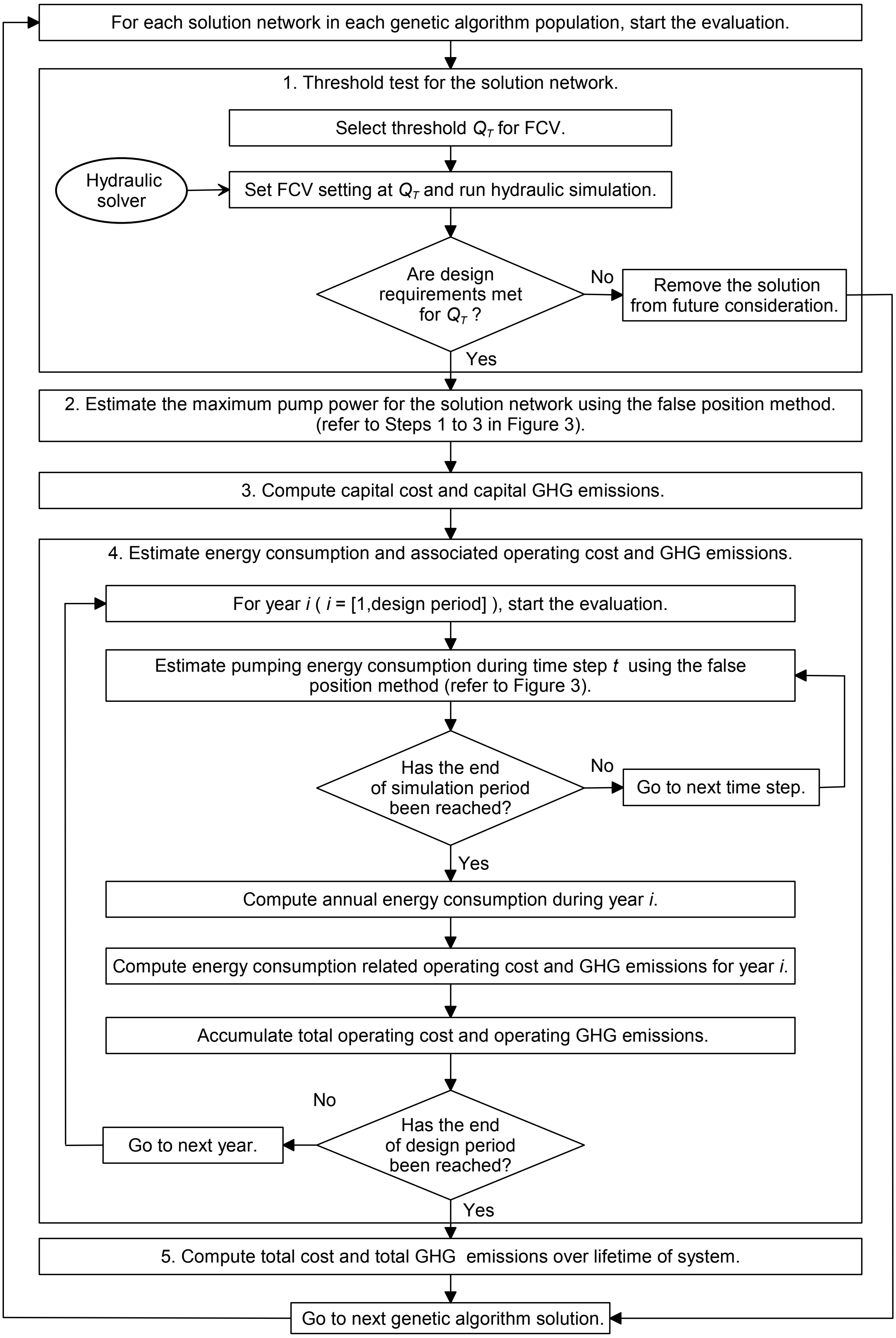

Figure 4 Proposed solution evaluation process within a genetic algorithm

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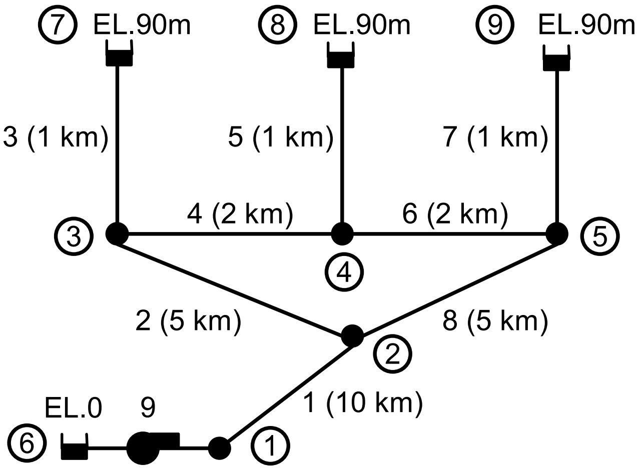


Figure 5 Case study network configuration (adapted from Wu et al. (2010a))

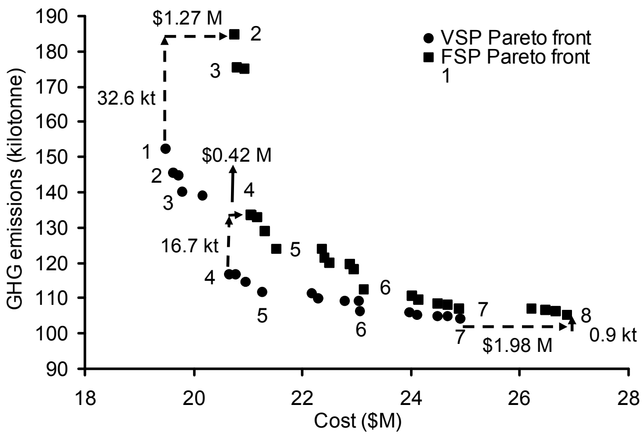
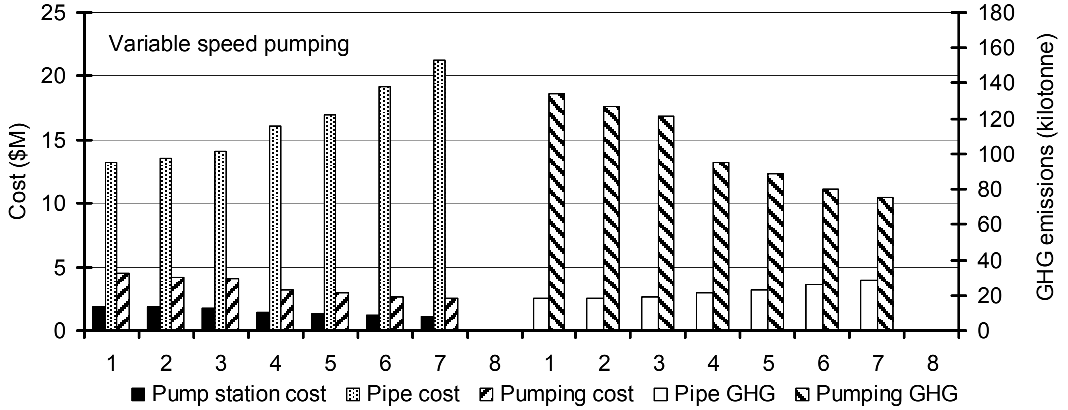


Figure 6 Comparison of Pareto-optimal fronts obtained using variable-speed pumping (VSP) and fixed-speed pumping (FSP) (Networks 2 to 7 are identical in pipe configuration for FSP and VSP systems)

(a) Breakdown of total cost and GHG emissions of selected solutions when variable speed pumps are used



(b) Breakdown of total cost and GHG emissions of selected solutions when fixed speed pumps are used

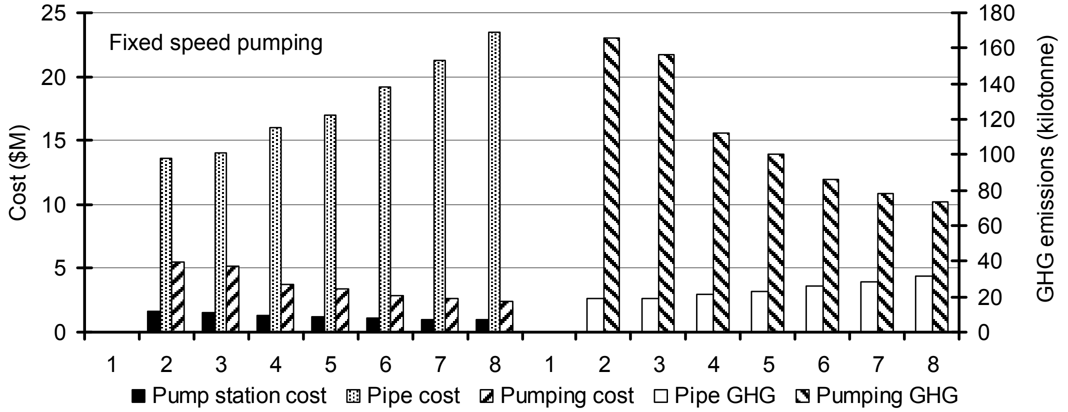


Figure 7 Breakdown of life-cycle cost and GHG emissions of selected solutions with variable-speed pumping [plot (a)] and fixed-speed pumping [plot (b)]

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Table 1 Pipe information of selected Pareto-optimal solutions

Network No.	Pipe 1 Dia. (mm)	Pipe 2 Dia. (mm)	Pipe 3 Dia. (mm)	Pipe 4 Dia. (mm)	Pipe 5 Dia. (mm)	Pipe 6 Dia. (mm)	Pipe 7 Dia. (mm)	Pipe 8 Dia. (mm)	Pipe Cost ($M)	Pipe GHG (kt)
1	300	225	150	100[a]	150	300	150	300	13.20	17.9
2	300	300	225	300	225	100	225	225	13.58	18.6
3	300	225	225	100	225	375	225	300	14.07	19.2
4	375	225	225	100	225	300	225	300	16.03	21.4
5	375	300	225	225	300	225	225	300	16.98	23.1
6	450	300	225	225	300	225	225	300	19.18	26.0
7	450	300	300	100	375	375	300	375	21.27	28.5
8	525	300	300	100	375	375	300	375	23.46	31.5

[a] The designs with the 100 mm pipe are not necessarily suitable solutions when considering network reliability.

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Table 2 Costs and GHG emissions of selected solutions using variable- and fixed-speed pumps

No.	Variable-Speed Pumping						Fixed-Speed Pumping					
	Total Cost ($M)	Total GHG (kt)	Annual Pumping Energy (10^3 kWh)	Pumping Cost ($M)	Pumping GHG (kt)	Actual Annual Pumping Hours	Total Cost ($M)	Total GHG (kt)	Annual Pumping Energy (10^3 kWh)	Pumping Cost ($M)	Pumping GHG (kt)	Actual Annual Pumping Hours
1	19.49	152.1	1,610	4.47	134.1	8,675						
2	19.63	145.6	1,524	4.23	126.9	8,084	20.76	184.7	1,994	5.54	166.1	5,400
3	19.80	140.1	1,452	4.03	120.9	8,521	20.81	175.1	1,872	5.20	155.9	5,686
4	20.65	116.7	1,145	3.18	95.4	8,084	21.07	133.4	1,344	3.73	112.0	5,400
5	21.27	111.7	1,064	2.95	88.6	8,336	21.54	123.7	1,208	3.35	100.6	5,546
6	23.06	106.2	963	2.67	80.2	8,336	23.15	112.2	1,035	2.87	86.2	5,546
7	24.91	104.2	909	2.52	75.7	8,486	24.90	106.9	942	2.61	78.4	5,640
8							26.89	105.1	883	2.45	73.5	5,640

[a]Note: Networks 2 to 7 are identical in pipe configuration for VSP and FSP systems.