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The Battle of the Water Networks II (BWN-II)

By

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Abstract

The Battle of the Water Networks II (BWN-II) is the latest of a series of competitions related to the design and operation of water distribution systems (WDSs) undertaken within the Water Distribution Systems Analysis (WDSA) Symposium series. The BWN-II problem specification involved a broadly defined design and operation problem for an existing network that has to be upgraded for increased future demands, and the addition of a new development area. The design decisions involved addition of new and parallel pipes, storage, operational controls for pumps and valves, and sizing of backup power supply. Design criteria involved hydraulic, water quality, reliability, and environmental performance measures. Fourteen teams participated in the Battle and presented their results at the 14th Water Distribution Systems Analysis (WDSA 2012) conference in Adelaide, Australia, September 2012. This paper summarizes the approaches used by the participants and the results they obtained. Given the complexity of the BWN-II problem and the innovative methods required to deal with the multi-objective, high dimensional and computationally demanding nature of the problem, this paper represents a snap-shot of state of the art methods for the design and operation of water distribution systems. A general finding of this paper is that there is benefit in using a combination of heuristic engineering experience and sophisticated optimization algorithms when tackling complex real-world water distribution system design problems.

INTRODUCTION

The Battle of the Networks II (BWN-II) is the third of a series of competitions undertaken within the Water Distribution System Analysis (WDSA) Symposium series, the previous competitions being the Battle of the Water Calibration Networks (BWCN) (Ostfeld et al. 2011), and the Battle of the Water Sensor Networks (BWSN)

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(Ostfeld et al., 2008). All of these are predated by the original Battle of the Network Models (BNM) (Walski et al., 1987), which was organized as a part of the American Society of Civil Engineers (ASCE) conference "Computers in Water Resources" at Buffalo, New York, in June 1985. To celebrate the 25th year since the publication of the first BNM, the BWN-II focuses on the optimal design and operation of a water distribution system (WDS), where not only capital and operational costs are considered, but additional objectives, including water quality, reliability, and environmental considerations are considered.

Even in its most idealized form, the design of WDSs is a non-deterministic polynomial-time hard (NP-hard) problem (the definition of NP-hard problems can be found in Yates et al., 1984), which can be attributed to the non-linearity of the hydraulic equations, and the presence of discrete diameter size variables. The WDS design problem could be treated as a non-linear problem (NLP) (Duan et al. 1990) if pipe sizes were assumed to be continuous, or as a linear problem (LP) (Alperovits and Shamir, 1977) if the decision variables were the pipe lengths. However, in both cases, the resulting continuous solution has to be 'rounded' to discrete sizes, resulting in approximations (Savic and Walters, 1997). The split-pipe solutions obtained using LP are often not allowed in WDS pipe design problems, where each pipe has to have one single diameter. Moreover, the LP formulation requires the objective function to be a linear relationship of the pipe lengths: not all problems in WDSs can be expressed in this way. In its original definition, the WDS problem is a mixed integer non linear problem (Bragalli et al. 2012) and belongs to the NP-hard category (Burer and Letchford, 2012). The practical implication of this is that no algorithm can guarantee an optimal design in polynomial time. Typical of these problems is that full enumeration is impossible due to the size of the decision variable search space, motivating many researchers and research groups to develop algorithms and strategies aimed at finding good near-optimal solutions. Building on this history, the aim of the BWN-II was to test the performance of a range of strategies on a large and complex multi-objective problem to gain insight into the state of the art of optimization algorithms applied to WDS problems. The aim of this paper is to report on approaches, difficulties and results as outlined by the competition participants in solving the problem. Note that our aim is not that of identifying the best approach to solve WDS problems, because i) no algorithm will necessarily perform best for each class of WDS problems (Wolpert and Macready, 1997); and ii) the participants used different amounts of resources, hence a comparison on purely algorithmic grounds is not possible.

As in previous competitions, the BWN-II was advertised to teams/individuals from academia, consulting firms and utilities to submit their strategies and proposed design solutions. The submissions from the participants were presented at a special session of the 14th Water Distribution Systems Analysis (WDSA 2012) conference in Adelaide, Australia, September 2012.

The objective of this paper is to summarize the major characteristics of the BWN-II design solutions and approaches and to highlight future research directions based on insights gained. The BWII-II rules and data are presented in the next section, followed by a synopsis of each team's design approach, a comparison of the optimization results, and conclusions and future research directions.

PROBLEM DESCRIPTION

The aim of the competition was to identify the best long-term design improvements and associated operational strategy for D-Town (see Figure 1), given projected future

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water demand and development of a new area. The aim was to identify a single strategy leading to minimized capital and operational costs whilst minimizing greenhouse gas (GHG) emissions and improving water age. A summary description of D-Town is outlined below, followed by the design decision options, and the design constraints and performance criteria. The full problem details can be found in the supplemental material of the paper.

D-Town Network Description

As depicted in Figure 1, the D-Town network consists of five existing district metered areas (DMAs) requiring upgrades and an additional new zone to be designed. In total, the D-Town network consists of 399 junctions, 7 storage tanks, 443 pipes, 11 pumps, 5 valves, and a single reservoir. The pipe network properties, and other pump, valve and nodal data, used for the existing regions in D-Town were taken from the C-Town network used in the BWCN (Ostfeld et al. 2011). The only changes for the existing D-Town regions were an increase in nodal water demands to reflect population growth in the regions and a few modifications to node elevations and pipe roughness. All data for the existing network components were incorporated into the EPANET input file *D-Town.inp* (for version 2.00.12) available as supplemental material.

Design Decisions

As outlined previously, the BWN-II involved the design of the new zone, and the upgrade of the existing zones. For the new zone, pipes were required to be sized from one of 12 diameter options (varying from 102 mm to 762 mm) for each link. The new zone was able to be connected via pipelines to either, or both, DMA 2 and DMA 3. For the pipe connection to DMA3, the design of a pressure-reducing valve (PRV) was permitted.

The improvement options available to adapt the existing DMAs involved: addition of parallel pipes for all existing pipes (12 diameter options); increasing of storage volumes by one of six tank sizes (500 to 10,000 m^3); addition of new pumps at the existing pumping stations (10 pump options were provided with varying head-discharge relationships); and sizing of backup power diesel generators for the pump stations (8 diesel generator options were available). For the existing DMAs, the valve settings for the existing valves were also allowed to be modified.

In addition to the design options, operational pump scheduling decisions were also required to be made. As the network was specified to have a single week balancing period, the pump schedule for a single week needed to be determined. Operational controls were allowed to be either time-based, or based on threshold tank elevations.

Design Constraints and Loading Scenarios

Two operational scenario types for D-Town were specified, a normal operation scenario, for which the network was subject to normal demand loadings, and an emergency scenario, representing the event of a power failure. The design constraints for the normal operating scenario were specified as nodal constraints for the balancing period of a single design week. At each time point within this design week, the demand nodes were required to satisfy minimum head constraints, and the tanks were required to not empty. The evaluation of these criteria clearly required an extended period simulation (a hydraulic time-step of 15 minutes, and a water quality time-step of 5 minutes were specified for the EPANET simulations).

The emergency scenarios were characterized by a power outage that can begin at any hour within the design week, and last for a duration of two hours (therefore resulting in a total of 167 independent emergency scenarios). Within the emergency scenario, all pumps not powered by diesel generators were required to be shut down. The constraints of minimum head for demand nodes, and non-emptying of tanks were also required to be met.

Performance Criteria

The evaluation of whether the BWN-II design solutions satisfied the design constraints outlined above was based on three performance criteria: total annualized cost; the environmental criterion of estimated green house gas (GHG) emissions; and water age as a surrogate indicator of water quality.

The total annualized cost was based on annualized capital costs and operational costs. The capital costs consisted of component costs of pipes, pumps, valves, tanks and generators. The operational costs were calculated from the total system power usage under normal operating conditions based on a single design week. The electricity costs within the design week were specified according to normal peak and off-peak tariffs.

The total GHG emissions included the emissions associated with the energy required for manufacturing, transportation and installation of the new pipes and the power usage from the operation of pumps (GHGs caused by the increase in tank volume or replacement and addition of pumps were not considered). The capital GHG emissions were annualized considering a 0% discount rate, as suggested by the International Panel on Climate Change (IPCC) (Fearnside, 2002).

The defined metric for water age WA_{net} (evaluated only within the design balancing week) was specified as the weighted average network water age (hours), given by

$$WA_{net} = \frac{\sum_{i=1}^{N_{junc}} \sum_{j=1}^{N_{time}} k_{ij} Q_{dem,ij} WA_{ij}}{\sum_{i=1}^{N_{junc}} \sum_{j=1}^{N_{time}} Q_{dem,ij}} \qquad (1)$$

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where is WA_{ij} is the water age at demand node i at time t_j, k_{ij} is a binary variable defined as 1 if WA_{ij} is greater than the threshold WA_{th} and zero otherwise, $Q_{dem,ij}$ is the demand at junction i and time t_j, where t_j is the simulation time, which is given by $t_j=j\Delta t$, where Δt is the time step, N_{junc} is the number of system junctions and N_{time} is the number of simulation time steps (equal to 168, as the extended period simulation time is one week). The water age threshold was set to 48 hours, and the time step to 1 hour, resulting in all water age and demand variables to be computed only on the hour. Note that, if all nodes always have a water age below the 48h threshold, the value of $\mathrm{WA}_{\mathrm{net}}$ is zero. Decreasing the water age results in higher operational costs and GHG emissions. Therefore, there is a trade-off between the three objectives analyzed: costs, GHGs and water quality.

Assessment of Participant Design Solutions

Participants were required to submit an EPANET input file with the implemented design and operational options, and a spreadsheet file summarizing the modifications made to the original system (i.e. replaced, duplicated and new pipes; replaced and added pumps; additional tank volumes; valves and diesel generators inserted). The spreadsheet contained the details necessary to compute the capital costs and capital GHGs of the solution (ID, size, cost and, if applicable, GHGs of the component). The spreadsheet also contained a summary of the operational costs, GHG emissions and the water age metric. Pump controls and valve settings had to be implemented in the EPANET file directly. All design submissions were independently evaluated using EPANET2 for the normal loading scenario and the power outage scenarios. Only solutions satisfying the design constraints for these loading scenarios were considered eligible to be evaluated based on the performance criteria.

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COMPETITOR CONTRIBUTIONS

Fourteen competitors submitted solutions for BWN-II. The methodologies used to find these solutions differed significantly; however, a common consideration was that heuristic engineering judgment strategies had to be incorporated to deal with the size and complexity of the problem. If formulated purely as an optimization problem, the search space could easily reach over 7,500 decision variables, depending on the options considered (Iglesias-Rey et al. 2012). As mentioned in the Introduction, all WDS optimization problems are NP-hard and are therefore difficult to solve, even for a relatively small number of decision variables. However, solving an NP-hard problem with such a large search space, and likely high correlation among the variables (e.g. the tank sizes are related to the pump sizes and controls), was not the only challenge experienced by competitors. Checking the design solution for adherence to the power outage scenario required multiple simulations, as the power outage could occur at any time during the simulation week. This emergency scenario evaluation represented a significant computational burden.

To overcome the difficulties of high dimensionality and computational complexity, different approaches were adopted, from the use of solely engineering experience (Walski, 2012) to the use of parallel computing (Wu et al. 2012, Matos et al. 2012, Guidolin et al. 2012, Wang et al. 2012, Kandiah et al. 2012 and Morley et al. 2012). In addition, modifications to the EPANET code were made by Matos et al. (2012), Guidolin et al. (2012) and Kandiah et al. (2012) to speed up computation or to define ad-hoc functions suitable for the specific problem (Kandiah et al. 2012, Guidolin et al. 2012).

Many authors further reduced the computational effort required by reducing the number of decision variables (Wu et al. 2012, Iglesias-Rey et al. 2012, Kandiah et al.

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2012, Wang et al. 2012, Stokes et al. 2012, Tolson et al. 2012) or the range of the possible values for each decision variable (Wu et al. 2012, Iglesias-Rey et al. 2012, Kandiah et al. 2012, Tolson et al. 2012). When the decision variables were pipes, engineering judgment was often used, such as the adoption of larger diameter options for pipes with large headlosses. A slightly different approach was used by Wu et al. (2012), where the number of possible parallel pipes was limited, considering that, in practice, only a small number of pipes would need to be replaced in a network. In this case, the optimization algorithm was used to define which pipes were critical and which diameter was to be assigned to the parallel pipe. Yoo et al. (2012) and Iglesias-Rey et al. (2012) skeletonized the network to decrease the number of decision variables related to pipes, thereby reducing the number of nodes and pipes by 40% and 30%, respectively (Iglesias-Rey et al. 2012). Other common considerations were related to the capacity of the initial pumping stations *S1* compared to the system demand: as the existing pumps could barely provide the required flow, additional pumps were inserted (Alvisi et al. 2012; Kandiah et al. 2012; Iglesias-Rey et al. 2012; Morley et al. 2012; Stokes et al. 2012; Walski, 2012; Wang et al. 2012).

To reduce the number of decision variables and the computational time required to evaluate a single solution, the power outage was usually left as a final evaluation, in which the installation of diesel generators could be optimized separately from the rest of the system, or, as in Matos et al. (2012) and in Morley et al. (2012), simulated once a feasible solution for normal operating conditions was found. An exception to this is Stokes et al. (2012). In this case diesel generators were used to back up all pumps. These authors assumed that this would meet the power outage requirements in a more cost effective way than increasing the tank volume, as diesel generators were found to be less expensive using an a priori analysis. This assumption worked well for their solutions, but is not always valid, as shown by discussion on this issue in the frequently asked questions (FAQs) in the supplemental material. The pressure deficit during power outages when all pumps are equipped with diesel generators is caused by three factors: i) several pumps in the system act as boosters; ii) pumps have different capacities and tanks can be filled or emptied despite downstream pumps or upstream pumps being switched on, respectively; iii) pumps with diesel generators do not follow normal operation controls (i.e. they are forced to be constantly switched on). If the tank level on the suction side reaches lower levels than under normal operating conditions, the headlosses could cause pressure deficits under abnormal operating conditions. In addition, if the static head between two reservoirs decreases, the larger flow delivered by the pump results in larger headlosses and in possible pressure deficits on the pump suction side. Under normal operating conditions, these pressure deficits can be avoided by turning off the pump; however, changing the pump status is not allowed during the power outage scenario.

The majority of competitors chose to formulate and solve an optimization problem at some stage of their methodology. Different optimization algorithms were used for this (see Table 1). Both single and multi-objective algorithms were used and different combinations of the objectives were considered. For example, Matos et al. (2012), Iglesias-Rey et al. (2012) and Kandiah et al. (2012) used a single objective algorithm, where the objective function contained a weighted sum of all three objectives. Wu et al. (2012), Saldarriaga et al. (2012), Bent et al. (2012) and Yoo et al. (2012) also used a single objective algorithm, but cost was used as the only objective. Multi-objective algorithms were used by Morley et al. (2012), Tolson et al. (2012), Wang et al. (2012), Stokes et al. (2012), Guidolin et al. (2012) and Alvisi et al. (2012). An interesting feature of Alvisi et al.'s approach was that, after optimizing the three

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objectives separately, the water age metric was included as a constraint and set equal to zero, while only cost and GHGs were optimized. In addition to several three-objective problem formulations, Guidolin et al. (2012) defined a formulation with a fourth objective, i.e., a sum of all three objectives (Equation (2)), to guide the search towards the potentially preferred space in the competition.

$$S_{TOT} = S_c + S_{GHG} + S_{WA_{net}} \tag{2}$$

where S_{C}, S_{GHG}, S_{WAnet} are the values of the specific objective normalized according to the minimum and maximum values among all feasible submitted solutions, for example:

$$S_c = \frac{C - C_{min}}{C_{max} - C_{min}} \tag{3}$$

where c is the total cost of the solution, c_{min} and c_{max} are the minimum and maximum costs among the entire set of feasible solutions received.

Although the majority of authors used meta-heuristic algorithms, approaches based on global search techniques or heuristic analysis of WDS properties were also used, as shown by Bent et al. (2012) and Saldarriaga et al. (2012), respectively.

A common feature of the approaches taken by all participants was that the optimization problem under normal operating conditions was tackled in stages in order to guide the algorithm towards specific regions of the search space. To reduce the number of EPANET model evaluations necessary to find good solutions, many authors seeded the search algorithm with what they envisaged as good initial solutions derived from heuristic engineering judgment. For example, Alvisi et al. (2012), Kandiah et al. (2012), Morley et al. (2012), Tolson et al. (2012) and Bent et al. (2012) initialized the algorithms with feasible solutions found using engineering judgment.

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Stokes et al. (2012) divided the optimization problem into a number of components by first considering the optimization of pipes and tanks, followed by the optimization of system operation. Wu et al. (2012) adopted a similar approach, although for the pipe design, only four single-step scenarios based on demands and pump operations were chosen instead of a full extended period simulation. In Guidolin et al. (2012), this first stage was left to the algorithm, where a limited number of decision variables were considered initially and, once these had been optimized, problem complexity was increased, followed by another optimization step and so on. Wang et al. (2012) used engineering judgment to identify the decision variables that should be considered in the initial stages of the process, as well as at the end of the optimization stage in order to ensure solution feasibility. Finally, Saldarriaga et al. (2012) and Yoo et al. (2012) optimized the design of each district separately, and pump controls were optimized manually at the end of the design process. In this regard, their approach was similar to that which a design engineer would adopt. A different approach was used by Matos et al. (2012), where the impact of human judgment was reduced as much as possible and, in the initial stage all decision variables were considered simultaneously.

Tables 2 and 3 summarize the main heuristics used by the participants to tackle the BWN-II problem. These lists are not exhaustive and are not always guaranteed to obtain the best results. (In addition, the classification of the heuristics in the in 'manual design' and 'algorithmic optimization' is not definitive, as many elements could be listed in both categories).

Manual design often starts by identifying pipes with large unit friction losses, which are more likely to need a larger diameter. Note that different values of unit friction losses have been adopted to identify these pipes. Often, pressure constraint violations and their causes are also analyzed: if low pressure is due to a high node elevation, pipe sizes do not affect the pressure significantly, and low pressure can be increased by increasing the lower tank trigger level of a given pump-tank coupling. A cost analysis is useful to reduce the set of available options. For example, power outage constraints can be satisfied using larger tanks or diesel generators: as the latter is more cost-effective, the former option is usually excluded.

In order to improve algorithm performance, algorithms are usually seeded with a feasible solution, to serve as a good "initial guess", and the optimization problem is divided into stages. These stages can start from the global problem and then refine the solution or, on the contrary, start from a sub-problem and progressively increase its complexity. Most heuristics aim to reduce the number of decision variables (e.g. by excluding the variables that do not significantly impact the objective function values or the feasibility of the solution) and to reduce the number of options: for example, Tolson et al. decided to not use pipe sizes smaller than those of the existing pipes for pipe replacement. Other heuristics are related to the use of engineering knowledge to bias algorithm search: for example, in Matos et al. GA mutation was incentivized to select smaller tank sizes for solutions with a large water age and to increase tank size if the tank level was not balanced at the end of the simulation. Finally, it is important to note that reducing the number of objectives can also improve algorithm performance, because of the shorter time required for sorting the solutions and because often a reduced number of objectives also results in faster algorithm convergence.

RESULTS

Although posed as a multi-criteria problem, each competitor was allowed to submit only one solution for evaluation. As part of the evaluation process, the three criteria were combined, resulting in a unique value, S_{TOT} described in (2), used for ranking the solutions. Other, more sophisticated, methods exist to perform multi-criteria ranking, but the committee (Salomons, Ostfeld, Kapelan, Zecchin, Marchi, Simpson and Maier) decided to keep the assessment process clear and transparent by using the above approach. As the minimum and maximum values of the objectives were unknown by individual competitors, the participants had to decide which solution represented the best trade-off among the objectives.

The costs, GHGs and water age metrics of the submitted solutions, as provided by the competitors, are shown in Table 4. However, in order to ensure consistency in results and assure a fair ranking, the objective function values of all submitted solutions were evaluated by the committee; discrepancies between the objective function values submitted by some of the competitors and those obtained as part of the validation process were identified in this process. For example, some authors considered the cost of replacing pipes to be equal to the cost of new pipes, instead of the greater cost of parallel pipes. There were also discrepancies in some of the energy calculations, which were due to the use of incorrect pump efficiency values (i.e. new pumps have an efficiency equal to 75%, existing pumps have an efficiency equal to 65%), or the method used to calculate energy values (e.g. each computational time step used by EPANET was considered in computing the operational cost and GHG emissions, which can be shorter than the simulation time step set in the hydraulic file (15 minutes)).

Compliance with constraints was also verified independently and, for ranking purposes, all solutions that did not strictly comply with the constraints were excluded from further evaluation. Pressures equal to 24.995 m or above were considered to satisfy the minimum pressure constraint of 25.00 m. Even though such precision is unlikely to be used in engineering practice where a larger tolerance is acceptable, given the approximations and uncertainties in the input data. The above threshold minimum pressure value was adopted purely for the purpose of consistency between the problem specification, and the analysis of the results for this competition. Note that, from a practical point of view, the infeasible solutions are likely to be acceptable, and are therefore included in the analysis and discussion in the subsequent sections.

The top three solutions in rank order are: 1) Guidolin et al. (2012); 2) Tolson et al. (2012); and 3) Kandiah et al. (2012). These top three solutions are presented in Figures 2, 3, and 4, where the changes made to the original network are shown in black and the size of the symbol for the diesel generators is proportional to power generating capacity.

ANALYSIS OF THE SUBMITTED SOLUTIONS

The solutions presented by the remaining authors, i.e. top-three solutions excluded, are summarized in Figure 5. In this figure, thicker and darker lines for pipes in existing zones indicate that a larger number of authors included modifications of this pipe in their submitted solutions and thicker lines for pipes inside the new zone show that a larger number of authors included sizes of these pipes that are larger than the minimum in their submitted solution. For pipes 1 and 2, the thickness of the lines is proportional to the number of times the pipe has been selected to feed the network. A larger tank corresponds to a larger increased volume and the size of the diesel generator is proportional to the sum of the power generated. It should be noted that these relative sizes are not at the same scale as those in Figures 2 – 4.

Additional pumps were included at the first pumping station (*S1*) in solutions 1 (Guidolin et al. 2012) and 3 (Kandiah et al. 2012), while there was no increase in

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pumping capacity of the system in solution 2 (Tolson et al. 2012), only an increase in pump efficiency. The pumps that are added and replaced in each solution are shown in Table 5. It can be seen that, in general, the approaches that used a larger degree of engineering judgment resulted in a limited number of pump modifications. Also, although use of the engineering approach often required the addition of pumps at the first pumping station, some solutions did not include any modification to the pumps, as in Saldarriaga et al. (2012) and Tolson et al. (2012).

Different types of pump controls were implemented in the solutions: pump scheduling was used to reduce energy consumption (Stokes et al. 2012) and tank trigger levels were used to reduce the number of variables and to have a set of controls that can better adapt to the variability in demand (Walski, 2012; Bent et al. 2012; Iglesias-Rey et al. 2012; Wang et al. 2012). However, most authors used a combination of these two types of controls, so that pumps are operated according to schedules and tank levels (Wu et al. 2012; Alvisi et al. 2012; Saldarriaga et al. 2012; Matos et al. 2012; Yoo et al. 2012; Guidolin et al. 2012; Kandiah et al. 2012; Morley et al. 2012; Tolson et al. 2012).

In general, as can be seen in Table 6, many of the optimal solutions included only a limited increase in tank capacity, because, as reported by several participants, tanks were found to be more expensive than diesel generators, and larger tank volumes were found to increase water age. For example, the third best solution did not include any increases in tank capacity (Kandiah et al. 2012), similarly to many other solutions, while the best solution (Guidolin et al. 2012) and the second best solution (Tolson et al. 2012) increased the capacity of tank T4 by 1,000 m^3 and the capacity of tank T2 by 500 m^3, respectively.

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The solutions differ in the way they provide water to the new zone. For example, Kandiah et al. (2012) achieved this by connecting the new zone to DMAs 2 and 3 and using a PRV; Guidolin et al. (2012) connected it to both DMAs, but did not use the PRV; and Tolson et al. (2012) only linked the new zone to DMA 3. As shown in Table 7, some of the submitted solutions only include a link between the new zone and DMA2.

In the top three solutions, all of the pipes in the new area were set to the minimum diameters; however, different pipe sizes, which were generally small, were used by the other authors. Nine pipes, with a total length L_{Tot} equal to 2,150 m and an average diameter D_{ave} equal to 208.8 mm, were replaced or duplicated in Tolson et al. (2012), 28 pipes (L_{Tot} = 2,689 m, D_{ave} = 215.8 mm) were modified in Kandiah et al. (2012), and 38 pipes (L_{Tot} = 4,901 m, D_{ave} = 270.0 mm) were modified in Guidolin et al. (2012). The number of pipes modified and their total length are very small compared with the overall number of pipes in the network and with the potential for duplication or replacement. As can be seen in Table 7, many optimal solutions included a limited number of replaced or parallel pipes. In particular, many solutions where engineering judgment was used to find an initial good solution have fewer than 40 pipes replaced. In contrast, when all pipes had the possibility to be duplicated or replaced by the algorithm, the number of pipes changed usually exceeded one hundred.

The number of pumps backed up by diesel generators varied from 6 for a total pump power of 217.15 kW (Wu et al. 2012 and Tolson et al. 2012) to 17 for a total pump power of 513.47 kW (Morley et al. 2012). The cost for the diesel generators ranged from $38,910 to $56,130: the first cost corresponds to a total diesel generator capacity of 250 kW (Wu et al. 2012 and Tolson et al. 2012); the latter cost corresponds to the

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solution of Stokes et al. (2012), where the diesel generator power installed is 650 kW to back up a total pump power of 497.64 kW (Table 8).

Operational costs in the form of energy costs associated with pumping was a significant component of total costs for most solutions (e.g. exceeding 60% of the total cost in Tolson et al. and Kandiah et al.'s solutions). In contrast, in Guidolin et al.'s solution, where larger capital costs were introduced to reduce operational costs and GHGs, the energy costs were only 40% of the total costs. This is also reflected in the GHG emissions of the solutions; however, in this case, the operational GHG emissions are always greater than or equal to 90% of the total GHG emissions.

Finally, it has to be noted that, despite the differences in the design options adopted and in the methodology used to solve the BWNII problem, the solutions had similar values of the performance criteria.

GENERAL OBSERVATIONS

The BWN-II is a challenging problem in the optimization of WDSs, because of the large number of decision variables and related optional choices, their correlation and the large computational effort required to properly evaluate each solution. In addition, the BWN-II raised issues that go beyond the application of optimization algorithms, including i) the different potential interpretations of the problem, and ii) the different ways of ranking the solutions in the competition.

Misunderstanding the decision variables and constraints results in a different problem to be optimized and in unexpected ranking values. Obviously, it is important to clearly define the problem, but this task is difficult to achieve. From this perspective, the BWN-II is similar to real-life problems, for which objective functions, constraints and design options are usually not clearly defined. Problems were also encountered when

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the hydraulic simulation software was used in a LINUX operating system (simulation files were not deleted, Stokes et al.) and when a double-precision version of the EPANET library was used (Morley et al.). In the latter case, the small numerical difference resulted in a different pump operation, affecting nodal pressures: the different solver precision adopted caused the failure of the pressure requirements in the solution reported by Morley et al. (2012).

Defining when constraints are satisfied was also a topic of discussion. From a practical perspective, pressures that are slightly lower than the target values do not compromise the design, but in an optimization competition, it is not possible to allow for constraint violations, as it is necessary to compare the solutions on an equal basis. A small difference in the constraint values could make a large difference in the searching procedure of the algorithm, and can change the optimal solution to the problem.

The ranking of the submitted solutions raised some criticism among participants. First, as the problem could have been formulated as a multi-objective optimization, participants were left with the hard task of selecting the solution with the best trade-off among the objectives. The submission of a single solution was justified by the need to simplify the submission procedure and solution checking, although it would be possible to improve these aspects. Secondly, the method chosen to rank the solutions considered all feasible solutions, regardless of whether they were non-dominated or not. The solutions on the optimal front computed using all received solutions could have been used for the ranking, but it was preferred to use a ranking method that was not restricted to the use of multi-objective optimization methods, as the problem was meant to be open to all approaches.

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Although the ranking method did not use a multi-objective approach, three non-dominated solutions were selected as winners for the BWN-II. Figures 6, 7 and 8 present the partial scores of the solutions (obtained using the recomputed values of the objectives) in multi-objective space. From the plot of cost vs. GHG emissions (Figure 6), it can be seen that the three winning solutions dominate the others. Two of the three winning solutions are also non-dominated in the S_c - S_{WAnet} space (Figure 7). Here, the solution from Alvisi et al. (2012) has a lower cost than Guidolin et al.'s solution. This is different from the original data reported by the authors because of the lower recomputed energy cost. The other non-dominated solution when only costs and water age are considered is the solution from Wang et al. (2012) that, similarly to the solution of Alvisi et al., had larger GHGs emissions.

The plot of the scores for water age vs. GHG emissions suggests that the final ranking among the three best solutions was probably most strongly influenced by the S_{GHG} and S_{WAnet} scores, as the order of the solution ranking matches the order of the non-dominated ranking (Figure 8).

FUTURE RESEARCH DIRECTIONS

The Battle of the Water Networks (BWN-II) provided a great opportunity for both researchers and practitioners in this field to solve a challenging real-world WDS optimization problem and, in particular, to test a wide range of methodologies involving traditional engineering experience and modern computing techniques. Although, the scale of the network is still small compared with that of the WDS of a major city, the BWN-II network is larger than those of past benchmark problems, such as the New York Tunnels (Schaake and Lai, 1969), Anytown (Walski et al.,

1987) and Hanoi (Fujiwara and Khang, 1990) problems and captures many real world features covering both design and operation.

However, the problem still contains a number of simplifications, compared to real problems, which limit the applicability of the proposed methodologies. These simplifications will be highlighted in the following. We hope that the realism of future test problems will be increased so that the results obtained, and the optimization methods used, are more widely applicable in practice. The ultimate objective is to obtain better solutions (in terms of all real world design objectives) more quickly. Note that the emphasis on the development of algorithms capable of dealing with more realistic problems does not mean that engineering judgment can be eliminated or its quality decreased.

One of the most important simplifications is the use of a constant pump efficiency, instead of an efficiency curve. The assumption of a constant pump efficiency eliminated the necessity of operating the pumps near their best efficiency point (as energy cost was a major component of this problem) and represents a large simplification compared with reality.

Other simplifications (also frequently assumed in other case studies) are related to the fact that demands are assumed to be known with certainty and no reliability issues, other than the power outage, are considered, e.g. the effect of demand variations, pipe breaks and equipment failure in general is not evaluated. In addition, all pipes and other facilities are installed contemporaneously at time zero, without considering the time scheduling of interventions over some pre-defined long-term planning horizon. The problem does not consider construction times or the possibility of future expansions. In addition, the BWN-II problem uses a fairly low target value for maximum water age (48 hours). This resulted in making the installation of additional storage in the system undesirable in terms of providing reliability. Note that for this case study, the water age of most nodes reached a dynamic equilibrium after the first 24-48 hours. However, the assumption that a single week simulation is sufficient for equilibrium of the water quality results (as was assumed in this competition for practical reasons of not making the water quality evaluation to onerous for the contestants) has to be tested in future competitions. Moreover, water leakages and their costs are not taken into account, as well as the presence of allowances for asset deterioration over time. Another simplification is with regard to energy costs, which were represented by a simple cost per kilowatt hour as a function of time. However, real energy tariffs often contain a peak demand charge that is based on the peak kilowatts used during some period of time (e.g. peak 15 minutes between noon and 6 pm during summer months).

Most countries account for fire flow during the design of WDSs because, although they are rare events, they have a significant influence on pipe, pump and storage sizing. Despite this, provision for fire flow was not included in this problem.

Other simplifications compared to the real world are: i) the pump wear and tear (typically approximated by counting the number of pump switches) is not considered; ii) pump replacement is limited to fixed speed pumps without the possibility of evaluating variable speed pumps, iii) pump cavitation is not taken into account and the only requirement is to have a pressure larger than zero if the node has demand equal to zero; iv) the cost of the diesel generators does not take into account maintenance costs; v) only GHG emissions from pipe construction or pump operations are considered; vi) pumping costs and water quality should be estimated taking into account the variability of the demand throughout the year.

Finally, the absence of a scale map that shows road layouts and other physical features and of previous information related to the operational costs of the network provided limitations in terms of solving the problem using engineering judgment. Therefore, it would be desirable to provide this information in future competitions.

For the next battle, we also suggest the inclusion of some measure of the personnel and computational time required to reach the solution. This information could lead to interesting results by analyzing the trade-off between engineering experience and computational time. Unfortunately, we did not have such data for the BWN-II. In addition, in order to solve the issues related to constraint precision and to improve the applicability of solutions, practicing engineering could be involved in the problem definition and solution evaluation steps.

CONCLUSIONS

Following the successful series of “Battle Competitions” in past years, the Battle of the Water Networks II (BWN-II) provided an opportunity for both researchers and practitioners in this field to solve a challenging real-world WDS optimization problem. A wide range of methodologies involving traditional engineering experience and modern computing techniques was employed by the participants to tackle the problem. However, in general, the problem was divided into multiple phases, at least two, to account for the power outage scenario. Thus, the involvement of practical experience and/or expert opinion played an important role in determining the most suitable solution. The results of the Battle show that, given a precise definition of a problem in terms of decision variables, objective functions and constraints, i) the use of optimization can enhance the solutions found using engineering expertise; ii) the use of large computational resources can overcome relatively small amounts of engineering judgment, as shown by the Guidolin et al. (2012) solution; iii) the use of limited computational resources can be successful if a larger amount of engineering judgment is used, as shown by the Tolson et al. (2012) solution. This does not mean that engineering judgment can be completely avoided – we believe that this will never be the case – but it means that there is a trade-off between the engineering experience and computational resources needed for solving a problem. The results also show that there is no one algorithm that is universally better than the others, as very different methods yielded fairly similar results, where their differences could be due to non-algorithmic factors, such as the way in which the problem was formulated and the different computational resources used. Hence, as demonstrated within this paper, different combinations of engineering experience, computational power and problem formulation can give similar results.

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Figure 7. Solution scores plotted in the multi-objective space S_c-S_{WAnet}. Non-dominated solutions are presented using a different symbol.

Figure 8. Solution scores plotted in the multi-objective space S_{WAnet}-S_{GHG}. Non-dominated solutions are presented using a different symbol.

Figure 1

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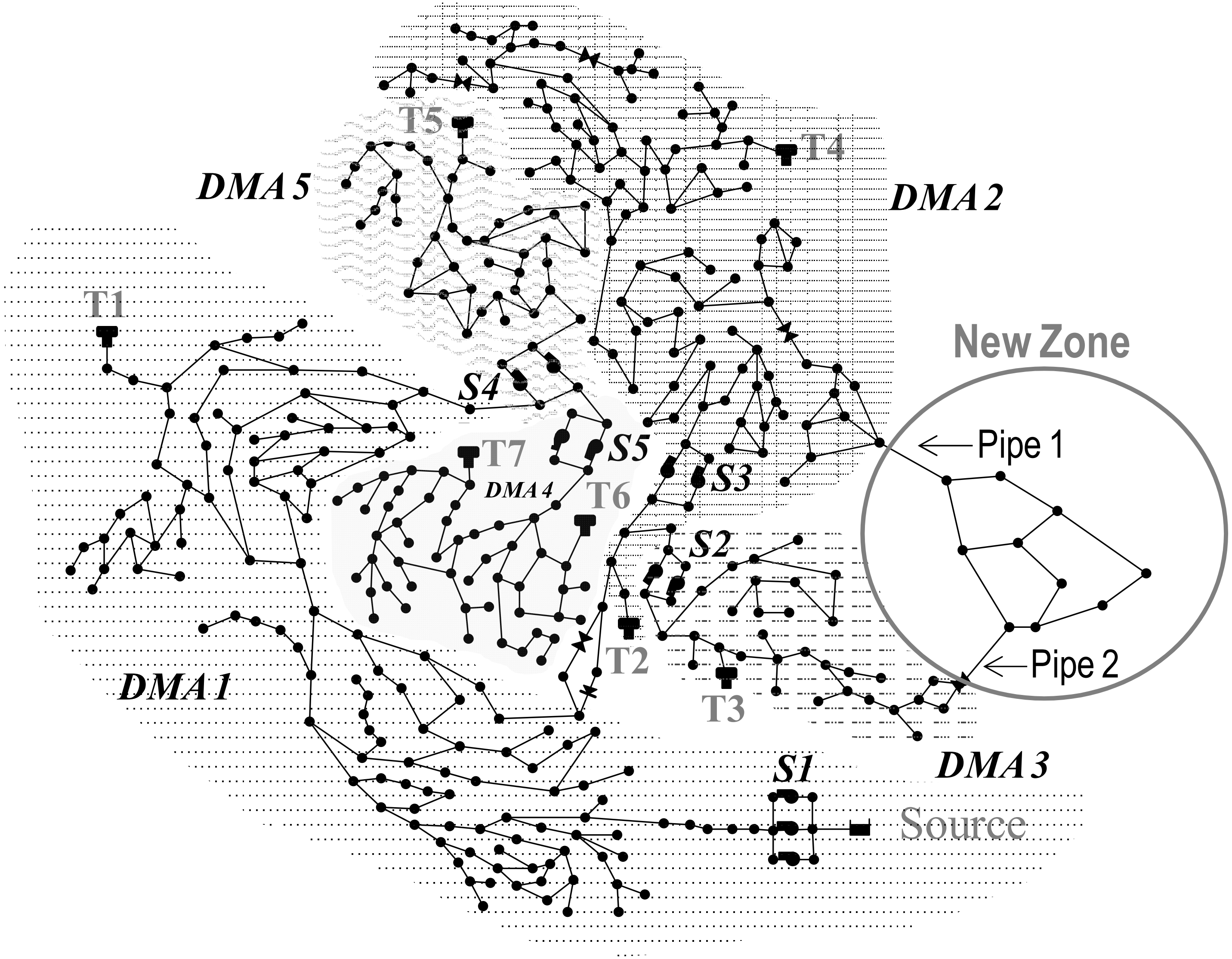

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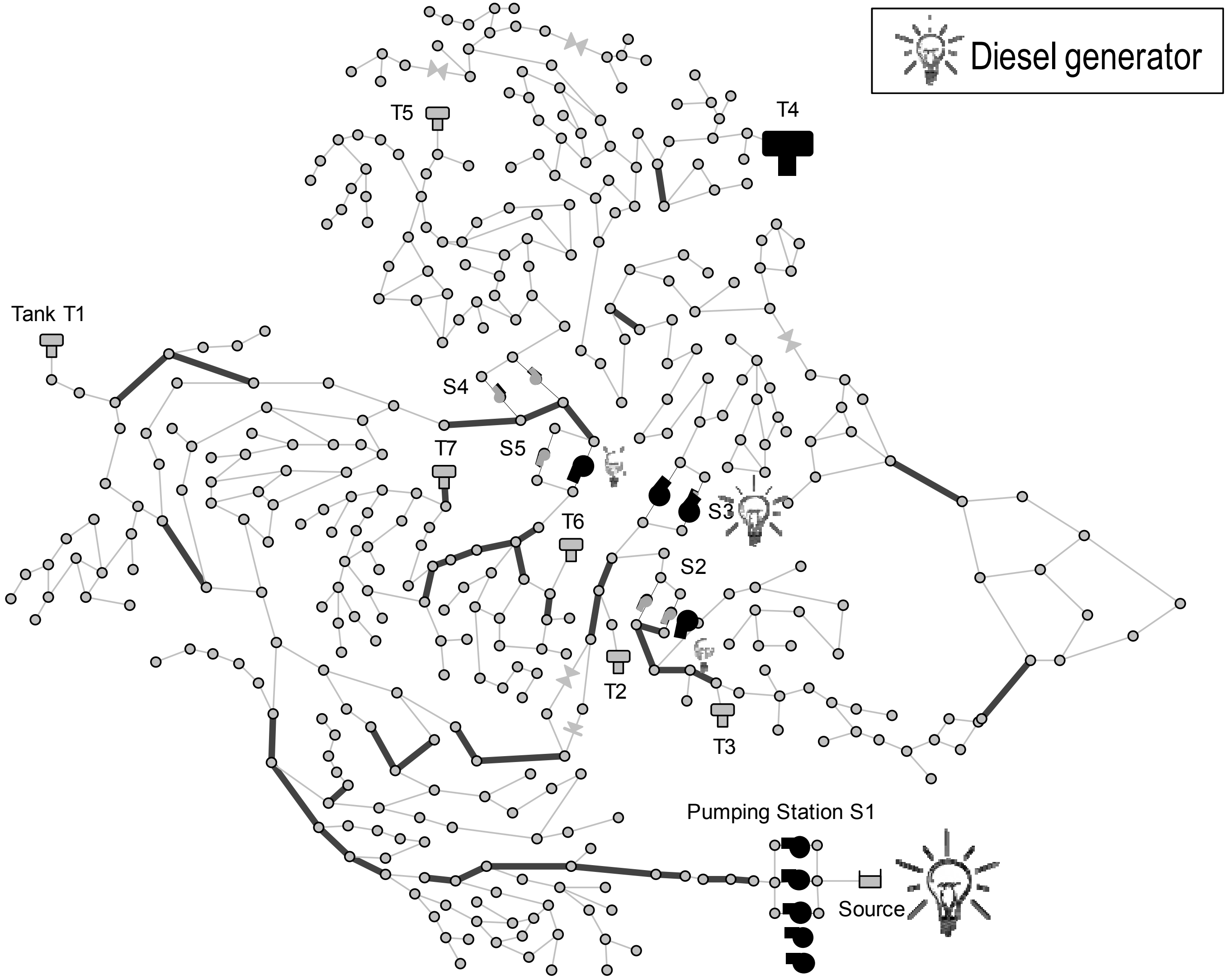

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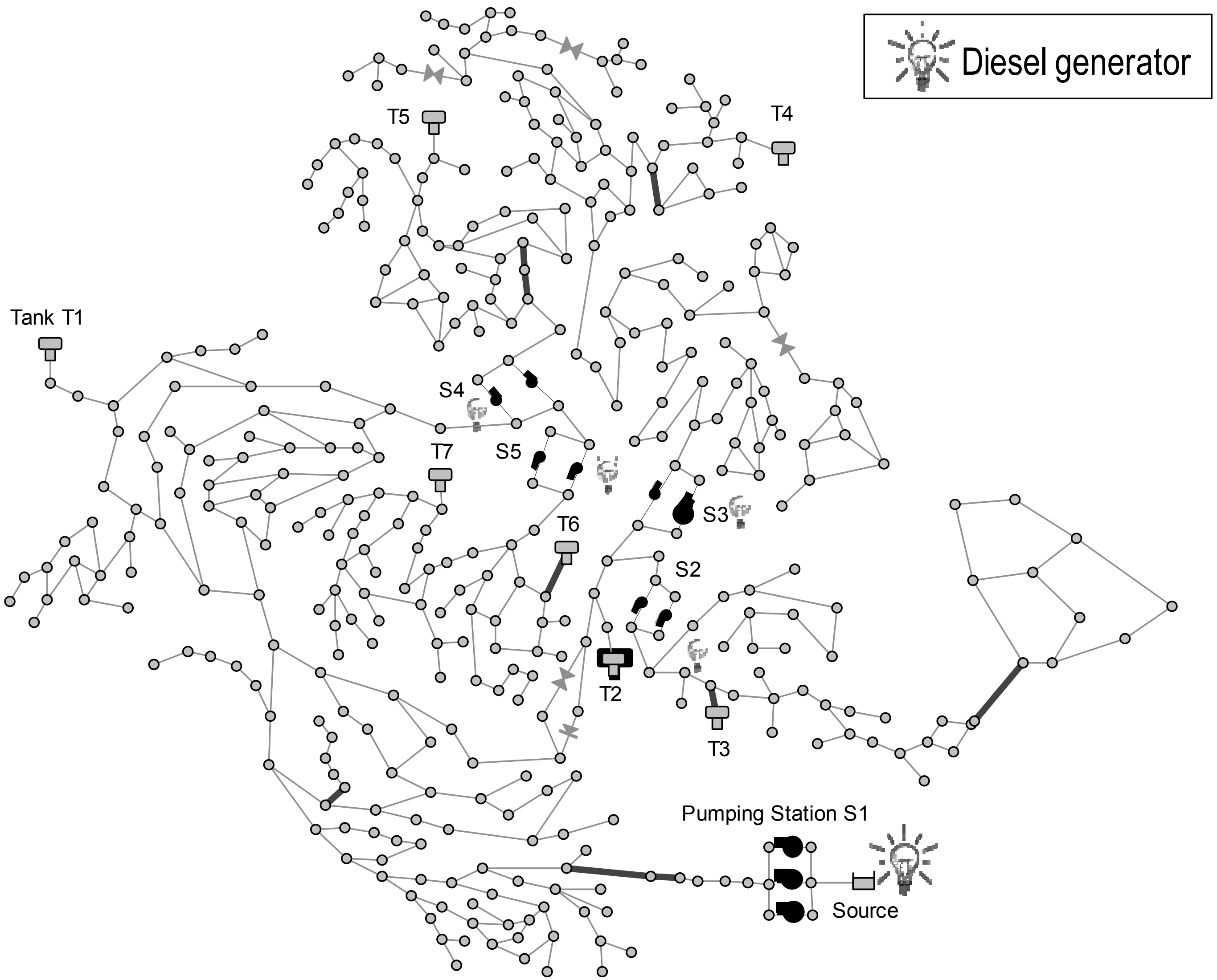

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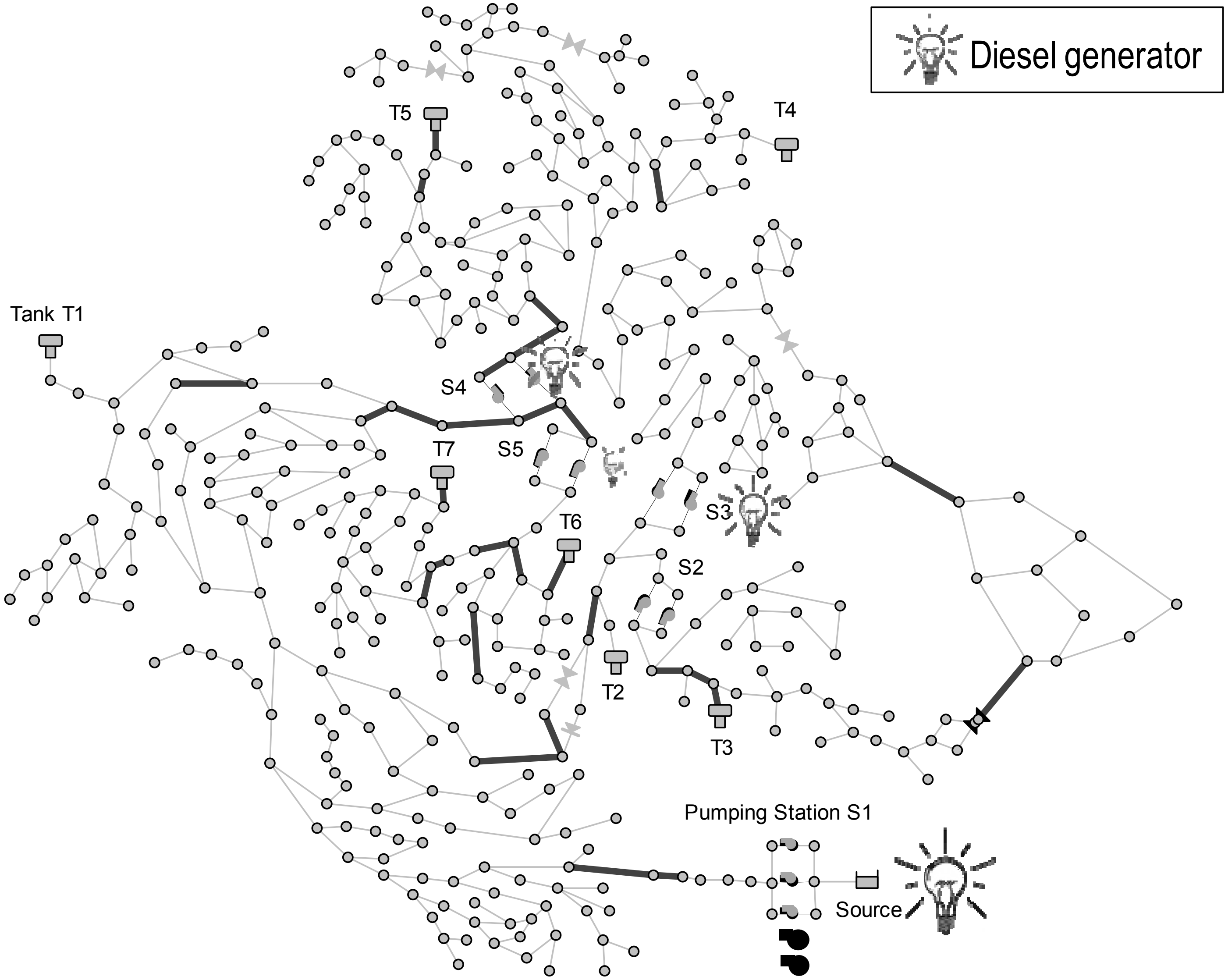

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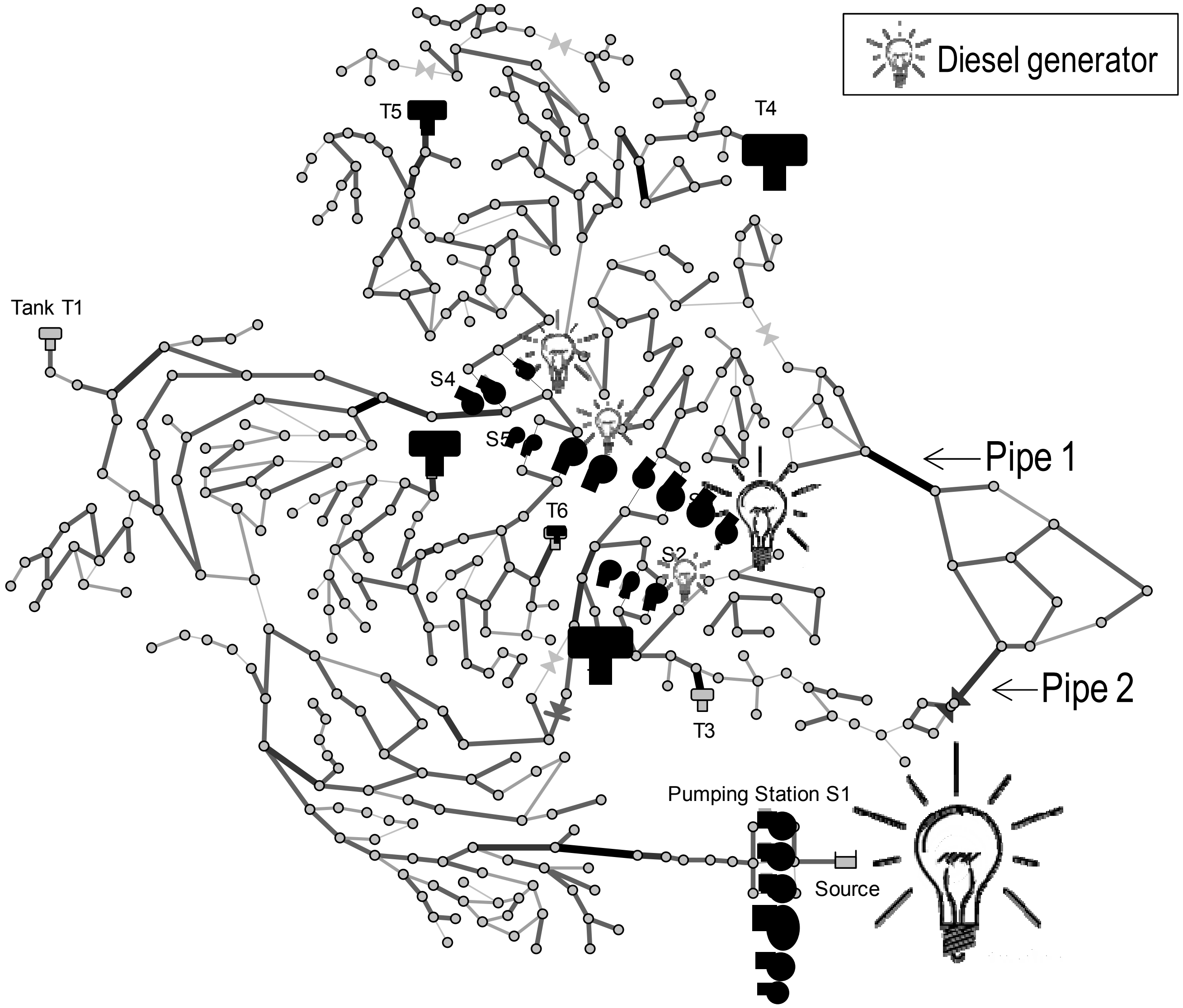

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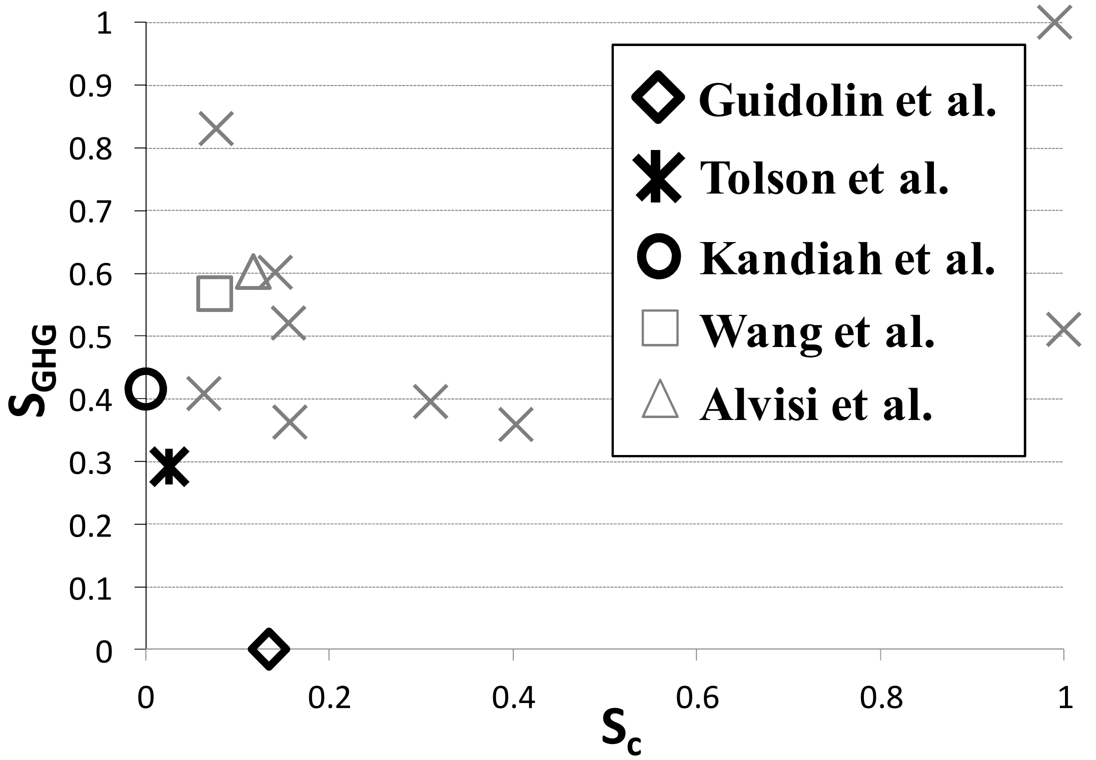

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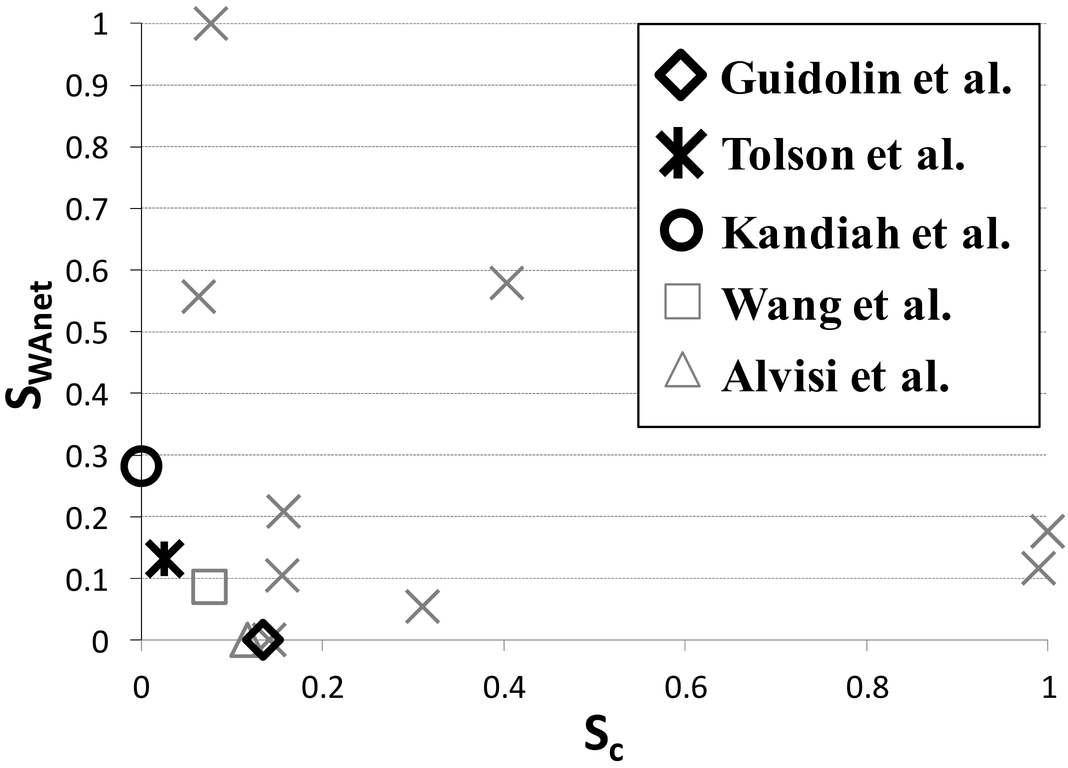

Figure 8

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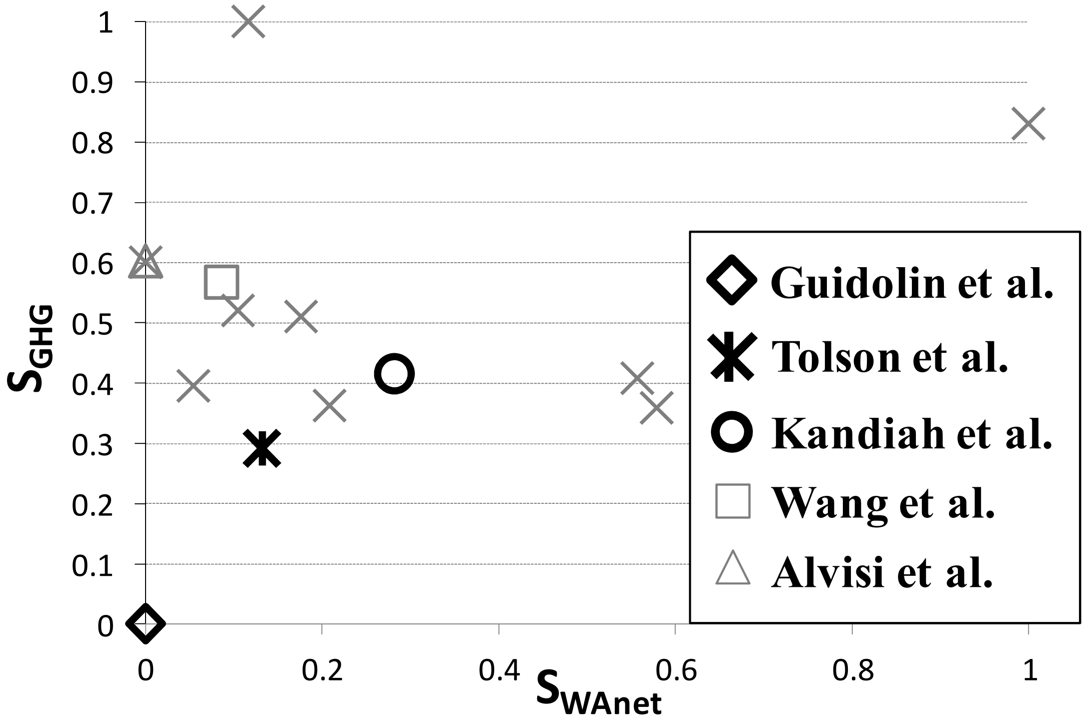

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Author	Algorithm	Number of Objectives	Objectives	Manual Pre-Processing	Power Outage	Parallel
Wu et al.	GA	1	C	2	Post, Algorithm	✓
Walski	-			4	Manual	
Stokes et al.	NSGA-II	3	C, GHG, WA_{net}	1	-	
Alvisi et al.	NSGA-II	2 (3)	C, GHG, (WA_{net})	3	Post, Manual	
Saldarriaga et al.	OPUS	1	C	3	Manual	
Bent et al.	LNS	1	C	3	Post, Full enumeration	
Matos et al.	GA	1	C, GHG, WA_{net}	0	Post, Algorithm	✓
Yoo et al.	HS	1	C	3	Post, Manual	
Iglesias-Rey et al.	PGA	1	C, GHG, WA_{net}	2	Post, PGA	
Guidolin et al.	ε-NSGA-II	4	C, GHG, WA_{net}, S_{TOT}	1	In ε-NSGA-II	✓
Wang et al.	NSGA-II	3	C, GHG, WA_{net}	2	Post, Algorithm	✓
Kandiah et al.	GA	1	C, GHG, WA_{net}	3	Post, Algorithm	✓
Morley et al.	Omni Optimizer	3	C, GHG, WA_{net}	1	In Algorithm	✓
Tolson et al.	PA-DDS	3	C, GHG, WA_{net}	3	Post, Full enumeration	

Legend: GA (Dandy et al. 1996), NSGA-II (Deb et al. 2002), OPUS (Saldarriaga et al. 2010), LNS (Shaw, 1998), HS (Geem et al. 2001), PGA (Iglesias et al. 2007), ε-NSGA-II (Tang et al. 2007), Omni-Optimizer (Deb & Tiwari, 2008) , PA-DDS (Asadzadeh and Tolson, 2012).

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Table 2: Summary of the main heuristics used to tackle the BWN-II: heuristics for manual design.

Engineering experience/heuristics	Objective/Action	Authors
Check proportion of volume supplied/demand (if the volume of water supplied by pumps is smaller than the volume of water required, the pump capacity requires upgrading)	Define if and how many new pumps are necessary	Walski; Stokes et al.; Alvisi et al.
Use of storage during peak tariff periods (if pumping in peak tariff period is required, increase capacity of strategically located tanks to supply required volume, and defer pumping to off peak tariff period)	Reduce the number of decision variables	Walski
Divide the network into DMAs	Reduce the complexity of the problem	Walski; Alvisi et al.; Saldarriaga et al.; Yoo et al.
Analyze friction head losses and pressure constraint violations of existing network	Identify pipes that need to be replaced and reduce the search space	Walski; Alvisi et al.; Iglesias-Rey et al.; Wang et al.; Kandiah et al.
Skeletonize the network	Reduce the number of pipe variables	Yoo et al.; Iglesias-Rey et al.
Analyse cause of pressure constraint violation: if low pressure is caused by high elevation, change the lower tank trigger level of a pump	Reduce the number of options	Walski; Stokes et al.
Formulation of the decision variables for operating the pumps	Reduce the number of decision variables using tank trigger levels vs reducing pumping costs using pump scheduling	All participants
Cost/benefit analysis of the options	Reduce the number of options	Walski et al.; Bent et al.; Iglesias-Rey et al.

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Table 3: Summary of the main heuristics used to tackle the BWN-II: heuristics for algorithm optimization.

Engineering experience/heuristics	**Objective**	**Authors**
Seeding the algorithm with an initial "good" solution	Reduce the computational time to reach a near-optimal or acceptable solution	Alvisi et al.; Bent et al.; Wang et al.; Kandiah et al.; Morley et al.; Tolson et al.
WDS optimized for abnormal conditions only at the end of the optimization during normal operation	Reduce the time to simulate a solution	Wu et al.; Walski; Alvisi et al.; Saldarriaga et.; Bent et al.; Matos et al.; Yoo et al.; Iglesias-Rey et al.; Wang et al.al.; Kandiah et al.; Tolson et al.
Abnormal conditions evaluated only if solution complies with constraints during normal operation	Reduce the time to simulate a solution (time savings relatively small compared to row above)	Matos et al.; Morley et al.
Divide the problem into stages (e.g. optimize pipes separately from the other components; optimize system capacity separately from network operation)	Reduce the complexity of the problem	Wu et al.; Stokes et al.; Saldarriaga et al.; Yoo et al.; Tolson et al.
Parallel computing	Reduce time	Wu et al; Matos et al.; Guidolin et al.; Wang et al.; Kandiah et al.; Morley et al.
Optimize the solution globally and then fine tune it / Optimize a sub problem and progressively increase its difficulty	Reduce the complexity of the problem	Matos et al. / Guidolin et al.
Choose objective function weights so that infeasibility is penalised and objectives have similar importance	Shape the objective space so as to guide the algorithm	Matos et al.; Iglesias-Rey et al.
Restrict the set of decision options based on current system properties (e.g. do not use a smaller diameter to replace a pipe)	Reduce the size of the search space	Stokes et al.; Tolson et al.
Tailoring algorithm operations based on the solution characteristic	Guide the algorithm towards better solutions	Matos et al.
Reduce the number of objectives (e.g. insert the water quality criteria as a constraint)	Reduce computational time and increase rate of convergence	Alvisi et al.
Variables with limited impact on the objective functions or constraints are not included in the problem (e.g. short pipes that have small unit	Reduce the size of the search space	Wang et al.; Kandiah et al.

headlosses in areas with relatively high pressures do not need to be changed)		
Consider network behaviour in peak hour only	Reduce solution simulation time	Wu et al.
Optimize operation of pump one day at a time	Reduce solution simulation time	Wu et al.

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Table 4: Objective function values of the submitted solutions, as reported by the authors and as recomputed for the competition in brackets.

Authors	Total Cost ($/year)	Total GHG ($kg_{CO2\text{-}e}$/year)	WA_{Net}	S_{TOT}
Wu et al. [a]	1,553,295 (432,900)	2,183,932 (2,183,932)	0.110 (0.114)	- (0.780)
Walski [b]	314,477 (424,446)	2,061,875 (2,276,659)	0.000 (0.000)	- (0.742)
Stokes et al.	990,069 (922,421)	3,622,803 (2,733,235)	0.122 (0.127)	- (2.106)
Alvisi et al.	464,797 (410,414)	2,913,365 (2,278,017)	0.000 (0.000)	- (0.720)
Saldarriaga et al.	361,801 (433,790)	2,506,219 (2,003,077)	5.300 (0.229)	- (0.728)
Bent et al.	386,725 (396,723)	2,538,970 (2,539,008)	25537 (1.099)	- (1.907)
Matos et al.	512,875 (523,682)	1,890,816 (2,040,622)	0.070 (0.059)	- (0.759)
Yoo et al.	928,951 (928,227)	2,600,656 (2,172,386)	0.193 (0.193)	- (1.686)
Iglesias-Rey et al.	378,860 (378,860)	2,055,239 (2,055,239)	0.612 (0.612)	- (1.028)
Guidolin et al.	420,537 (420,410)	1,588,413 (1,588,458)	0.000 (0,000)	- (0.134)
Wang et al.	385,777 (385,777)	2,237,599 (2,237,599)	0.095 (0.095)	- (0.728)
Kandiah et al.	338,840 (341,717)	2,060,809 (2,063,490)	0.310 (0.310)	- (0.697)
Morley et al. [b, c]	448,110 (578,218)	978,019 (1,998,674)	0.145 (0.636)	- (1.341)
Tolson et al.	356,368 (356,639)	1,922,532 (1,922,533)	0.148 (0.145)	- (0.449)

[a] Pressure violation in power outage; [b] Pressure violation in normal operation (0.4 m and 0.2 m for Walski and Morley et al., respectively). [c] due to issues with the hydraulic solver precision.

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Table 5: Pumps added and replaced in each solution. The pump curve is reported in brackets.

Authors	Pump replaced	Pump added	Cost ($/year)
Wu et al.	-	PU1-1 (8) PU6-1 (10)	8,472
Walski	-	PU1-1 (8a)	3,225
Stokes et al.	All: PU1-PU3 (8) PU4-PU5 (9) PU6-PU7 (10) PU8-PU9 (9) PU10-PU11 (11)	PU1-1 (8) PU2-1 (8)	50,045
Alvisi et al.	-	PU1-1 (8b)	4,554
Saldarriaga et al.	-	-	0
Bent et al.	-	PU1-1 (8b)	4,554
Matos et al.	-	PU1-1 (10a) PU5-1 (8) PU6-1 (10b) PU7-1 (10) PU8-1 (11a) PU10-1 (9b) PU11-1 (11a)	26,122
Yoo et al.	PU1 (8b) PU2 (8a) PU4 (9b) PU6 (10) PU7 (10a) PU8 (9b) PU10 (11)	PU1-1 (8a) PU2-1 (8b) PU3-1 (8a) PU10-1 (11)	40,519
Iglesias-Rey et al.	-	PU1-1 (8b) PU2-1 (11a)	7,404
Guidolin et al.	PU1 (10a) PU2 (8b) PU3 (10a) PU6 (10a) PU7 (8b) PU10 (10a)	PU1-1 (8b) PU2-1 (8a) PU4-1 (10a)	33,422
Wang et al.	PU2 (8) PU3 (8) PU7 (10)	PU1-1 (8b)	17,159
Kandiah et al.	-	PU1-1 (8) PU2-1 (8)	8,266
Morley et al.	PU3 (10) PU10 (8a)	PU3-1 (11) PU5-1 (11a) PU6-1 (8a) PU7-1 (11a) PU8-1 (8a) PU10-1 (11a)	25,789
Tolson et al.	PU1 (8) PU2 (8) PU3 (8) PU7 (10)	-	16,738

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Table 6. Tank volume added in the solutions.

Authors	Tank # (vol. added, m^3)	Total vol. (m^3)	Total Cost ($)
Wu et al.	T4 (1,000), T5 (500), T7 (500)	2,000	58,680
Walski	T4 (1,000)	1,000	30,640
Stokes et al.	T2 (2,000)	2,000	61,210
Alvisi et al.	T4 (500), T5 (500), T6 (500), T7 (1,000)	2,500	72,700
Saldarriaga et al.	T7 (500)	500	14,020
Bent et al.	-	0	0
Matos et al.	T2 (500)	500	14,020
Yoo et al.	-	0	0
Iglesias-Rey et al.	-	0	0
Guidolin et al.	T4 (1,000)	1,000	30,640
Wang et al.	-	0	0
Kandiah et al.	-	0	0
Morley et al.	-	0	0
Tolson et al.	T2 (500)	500	14,020

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Table 7: Pipe design in the submitted solutions.

Authors	DMA connected to new zone	No. of parallel or replaced pipes	GHG (kg_{CO2-e}/year)	Cost ($/year)
Wu et al.	2	16	146,768	127,318
Walski	2,3 + PRV	12	72,430	70,058
Stokes et al.	2	159	659,141	508,030
Alvisi et al.	2,3	15	80,077	81,952
Saldarriaga et al.	2,3	10	138,371	111,266
Bent et al.	2	6	28,073	35,896
Matos et al.	2,3 + PRV	131	258,200	233,432
Yoo et al.	3 + PRV	306	785,491	680,400
Iglesias-Rey et al.	2,3 + PRV	15	81,590	79,160
Guidolin et al.	2,3	38	165,354	138,869
Wang et al.	3 + PRV	14	35,471	49,116
Kandiah et al.	2,3 + PRV	28	71,817	76,522
Morley et al.	2,3	457	292,948	287,540
Tolson et al.	3	9	60,229	65,282

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Table 8: Diesel generators inserted in the submitted solutions.

Authors	Power (kW)	Pump backed up	Cost ($/year)
Wu et al.	100	PU1, PU2	38,910
	50	PU6	
	50	PU8	
	50	PU10, PU11	
Walski*	100	PU1, PU2	49,470
	50	PU4	
	100	PU6, PU7	
	50	PU8	
	50	PU10,11	
Stokes et al.	300	PU1, PU2,PU3, PU1-1, PU2-1	56,130
	100	PU4, PU5	
	100	PU6, PU7	
	100	PU8, PU9	
	50	PU10,PU11	
Alvisi et al.	200	PU1, PU2, PU3, PU1-1	50,540
	50	PU4	
	100	PU6, PU7	
	50	PU8	
	50	PU10, PU11	
Saldarriaga et al.	200	PU1, PU2, PU3	42,200
	100	PU6, PU7	
	100	PU8, PU9	
	50	PU10, PU11	
Bent et al.	200	PU1, PU2, PU3, PU1-1	41,090
	100	PU6, PU7	
	50	PU9	
	50	PU10, PU11	
Matos et al.	200	PU1, PU2, PU3, PU1-1	52,720
	100	PU4, PU4-1	
	200	PU6, PU6-1, PU7-1	
	50	PU8, PU8-1	
	50	PU10-1, PU11-1	
Yoo et al.	300	PU1, PU2, PU3, PU1-1, PU2-1, PU3-1	46,680
	100	PU6, PU7	
	100	PU8, PU9	
	100	PU10, PU11, PU10-1	
Iglesias-Rey et al.	200	PU1, PU2, PU3, PU1-1	52,760
	100	PU4, PU5	
	100	PU6, PU7	
	100	PU8, PU9	
	50	PU10, PU11	
Guidolin et al.	200	PU1, PU2, PU3, PU1-1	50,540
	50	PU2-1	
	100	PU6, PU7	
	50	PU4-1	
	50	PU10, PU11	
Wang et al.	200	PU1, PU2, PU3, PU1-1	52,760
	100	PU4, PU5	
	100	PU6, PU7	
	100	PU8, PU9	
	50	PU10, PU11	
Kandiah et al.	200	PU2, PU3, PU1-1, PU2-1	42,200
	100	PU6, PU7	
	100	PU8, PU9	
	50	PU10, PU11	
Morley et al.	200	PU1, PU2, PU3, PU3-1	54,940
	100	PU4, PU5, PU5-1	
	200	PU6, PU7, PU6-1, PU7-1	
	100	PU8, PU9, PU8-1	
	100	PU10, PU11, PU10-1	
Tolson et al.	100	PU1, PU2	38,910
	50	PU7	
	50	PU8	
	50	PU10, PU11	

* Only the pumping stations are specified in the original paper: pumps are assumed depending on the size of the diesel generator.