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A HYBRID OPTIMIZATION METHOD FOR REAL-TIME PUMP SCHEDULING

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Linear, non-linear and dynamic programming, heuristics and evolutionary computation are amongst the techniques which have been applied to obtain solutions to optimal pump-scheduling problems. Most of these either greatly simplify the complex water distribution system or require significant time to solve the problem. The scheduling of pumps is frequently undertaken in near-real time, in order to minimize cost and maximize energy savings. However, this requires a computationally efficient algorithm that can rapidly identify an acceptable solution. In this paper, a hybrid optimization model is presented, coupling Linear Programming and Genetic Algorithms. The resulting hybrid optimization model has demonstrated more rapid convergence with respect to the traditional metaheuristic algorithms, whilst maintaining a good level of reliability.

INTRODUCTION

The complexity of the current water distribution systems leads managers to accomplish a more reliable control of the operations, including monitoring and optimization. Energy cost represents the major if not the largest component of the operational cost for a water utility. Considering a historical lack of investment in infrastructure rehabilitation owing to the insufficient financial resources, pump scheduling optimization can be considered one of the most effective ways to reduce expenses, without direct changes in the infrastructure of the layout.

The pump scheduling optimization aims to minimize the operational cost, while maintaining the physical and hydraulic constraints. The operational cost can include energy cost, maintenance cost and environmental costs.

Several techniques have been proposed in the literature to solve this optimization problem: linear [1], non-linear [2, 3] and dynamic programming [4, 5], heuristic [6] and meta-heuristic algorithms [7], [8] and [9]. According to the number of variables and objectives considered, optimizing this problem may become highly complex, particularly for large networks.

Genetic Algorithm (GA) optimization has been shown to be able to contend with such complexity. However, GA optimizations are time consuming due to the high number of function evaluations required to achieve convergence. As shown by Savić *et al.* [10], in order to improve the convergence speed and the solution quality the randomized initial solutions have to be replaced with particular, high-quality initial solutions. To improve GA performance, in this study, two local search methods based on two different definitions of the neighbourhood of a binary string representing a pump schedule were applied.

Thereafter, Van Zyl *et al.* [8] coupled a GA to two hill-climbing search algorithms, the Hooke and Jeeves and Fibonacci methods, for improving the local GA search, once close to an optimal solution. This method proved to be superior to the pure GA in finding a good solution quickly, both when applied to a test problem and to a large, existing water distribution system.

Wang *et al.* [11] used a greedy algorithm for choosing a good initial solution for GA application, according to the water demand and the constraints. Moreover, a local search, named binary local search, was developed according to the properties of the problem in order to enhance the solution quality in each generation.

The hybrid optimization approach has been also proposed with different techniques. Recently, Giacomello *et al.* [12] have developed a methodology in which Linear Programming (LP) is coupled with a greedy algorithm. The former solves a "reduced complexity" hydraulic model, then the latter the "full complexity" hydraulic model: the greedy algorithm performing a search starting from the pumping schedule identified by the LP method.

LP is one of the most widely used techniques in water resources system management [13]. It deals with the problem of minimizing or maximizing a linear function in the presence of linear equality and/or inequality constraints. The advantage of the LP model is that it can be solved quickly and then a near-optimal solution can be achieved with a real-time scheduling application [1]. Some LP applications are also explored in recent literature [14], [15].

According to previous studies the hybrid methods seem to be reliable and efficient in solving the pump scheduling optimization problem. The resulting methodologies overcome the compromises inherent in the selection of a single optimization technique. For this reason, in this paper the capabilities of a new hybrid method have been investigated. The hybridization is performed by coupling two techniques, LP and GA. The hybrid model was applied to a synthetic case study derived from the benchmark Anytown [16] network.

METHODOLOGY

The optimization problem is formulated as a single objective optimization aimed to minimize the energy cost related to pumping station operational power. The proposed hybrid method is based on two stages: firstly a simplified optimization problem is solved by the LP technique, then the solution is used to generate the initial seeding solutions for the application of the GA approach, which represents the final stage. Specifically, the capability of LP to rapidly find acceptable solutions was exploited to identify regions of optimality in the search space.

The LP single-objective model is based on an implicit formulation for the decision variables in order to reduce the total number of variables. In particular, the model determines the optimal operation flow rate for each pumping station for each hour of the simulation period. The pump scheduling optimization problem can be formulated as follows:

$$\min \sum_{t=0}^{T} c_t \cdot Q_t \tag{1}$$

Subject to:

$$S_{\min} \le S_t \le S_{\max} \tag{2}$$

$$Q_{\min} \le Q_t \le Q_{\max} \qquad (3)$$

$$\sum_{t=0}^{T} Q_t = \sum_{t=0}^{T} q_t \qquad (4)$$

$$Q_t \cdot \Delta t + \left(S_t - S_{t-1}\right) \cdot A = q_t \cdot \Delta t \qquad (5)$$

where Q_t are the unknown pump station discharges, c_t the objective function coefficients, q_t the known demand, A is the tank surface area, S_t, S_{t-1} are the tank water level at time t and $t - 1$ respectively; Δt is the optimization control interval (often fixed to 1 hour), S_{min}, S_{max} are the lower and upper bound of the tank water levels while Q_{min}, Q_{max} are those related to the pump station discharges.

Prior to solving the system of linear equations, the objective function coefficients c_t have to be evaluated. In addition to the electricity tariff, these coefficients take into account the network hydraulics, or more precisely, the effect of the water distribution system hydraulic conditions on pump hydraulic power. The pump energy consumption is dependent upon the pump total head which is connected to the pipe resistance curve upstream and downstream of the pump. If the head lift across the pump does not vary by more than few meters, the pump operates practically at the same point on its pump curve, in spite of variations in the network pressure regime. Conversely, changes in pressure may have major effect on the pump energy consumption.

In order to identify these effects, the energy consumption is combined with pump discharge for each specific tank initial level and system demand. A generic WDN is simulated for each demand factor, for each pump combination, for a range of water levels. These points are fitted with a single regression line for each tank water level and constant demand factor combination. Amongst the slopes for all pump combinations, the average slope value can be derived.

Since LP provides a continuous solution, in order to generate members of the GA initial population, several schedules are obtained by applying different criteria to convert the solution into a discrete schedule. Several discrete pump combinations, able to provide a similar rate on a 24-hour basis, are then selected. Given that GA work with discrete values, for pump scheduling, the use of the classical binary coding is the obvious choice, since each binary value can represent a single pump that is either on or off during a particular time interval [17]. The remainder of the population initializing the GA is produced by randomly combining the generated solutions by following a uniform normal distribution.

The performance of the hybrid method is compared with that of standard GA randomized initialization with regard to the benchmark Anytown network.

TEST NETWORK: ANYTOWN

The Anytown test network was firstly presented in Walski *et al.* [16] as a benchmark for identifying designs able to meet future water demand. Nowadays, this network is still employed to verify reliability and optimization methods for water distribution networks. Herein, one of the feasible networks derived from the Anytown optimization, whose layout is shown in Figure 1, has been selected for the purpose of the present study. It is composed of 19 junctions, 1 tank, 37 pipes and 1 reservoir, representing the only external source, from which four different pumps in parallel supply water to the remainder of the system. The demand varies according to a demand pattern with peak factors ranging from 0.4 – 1.2 (Figure 2). The daytime tariff cost is set to be twice that charged during the night, namely the peak electricity tariff period ranges from 7:00 to 24:00 and an off-peak tariff from 0:00 to 7:00. The optimization problem is on 24-hours basis.

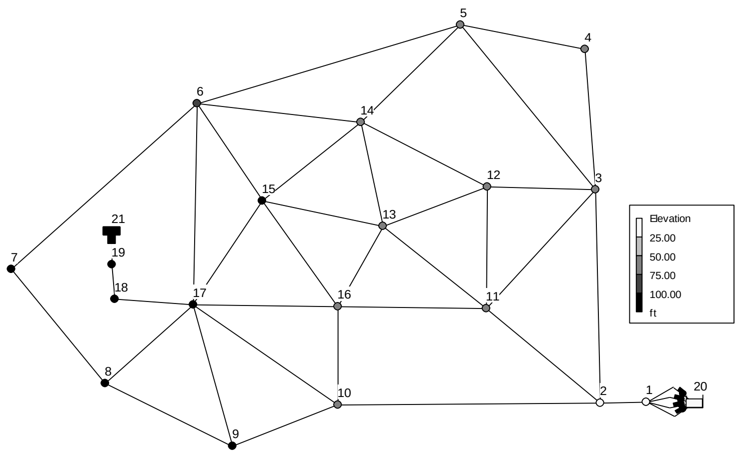

Figure 1 Anytown benchmark network

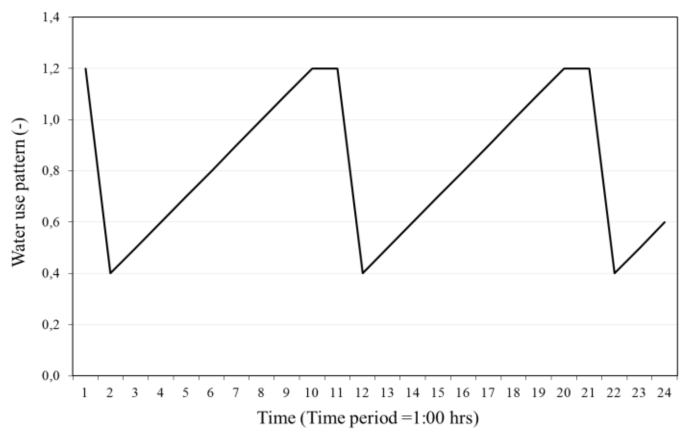

Figure 2 Anytown water use pattern

RESULTS AND DISCUSSION

The LP solution was quickly identified once all of the information about constraints and objective function coefficients were calculated. At this stage the continuous solution has to be converted into a discrete schedule. To this end, a *connection matrix*, which relates pump discharges, user water demand and pump combinations, resulting from a number of pre-cursor steady-state simulations used for the objective function coefficient evaluation, was defined. For each control interval the most suitable schedule was identified by selecting the combination able to provide the required discharge with the lowest energy consumption. The discharges do not match exactly the solution generated by LP, hence the discrete solution can be chosen from either the closest e.g. above or below the required flow rate, or the nearest value above that required. Subsequently, the schedules derived from the LP continuous solution are randomly recombined, by following a uniform normal distribution, in order to complete the required number of solutions in the GA population.

As mentioned above, the LP-derived schedule was tested as initial seed solution in GA in order to investigate the hybridization capabilities to find a reliable and effective solution. For the Anytown test network the size of the GA population was set to 150, for a fixed duration of optimization of 1000 generations. The mutation and the crossover coefficients are fixed to 1.5 and 2, respectively. A large value of crossover coefficient gives a higher probability for creating solutions near to the parent and a small value allows distant points to be selected as child solutions.

The solutions obtained from six different optimization runs using the LP-derived solutions as initial seeds are reported in Table 1. For all of the optimization runs, the hybridized GA results in lower costs with respect to those generated with a purely random initialization (Figure 3) of which the obtained average value is about £402. The best improvement is in run 5: equal to 10.6%.

Table 1 Solutions generated by GA with LP-derived schedules as initial solution.

	Best solution (£/day)	
Run number	GA with randomized initial solution	GA with LP initial solution
1	399.34	367.88
2	393.73	367.88
3	406.08	368.60
4	394.44	368.60
5	416.43	372.30
6	400.27	367.88
Average	401.715	368.86

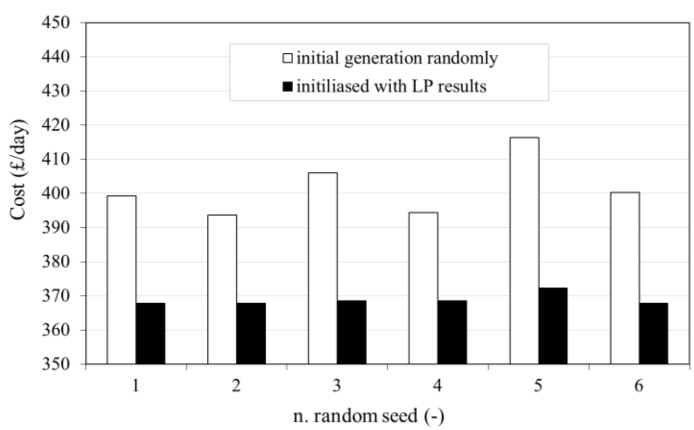

Figure 3 Comparison between solutions generated by GA with LP-derived and randomized solutions as initial seeds.

Further conclusions can be drawn by examining the progress of the objective function (pump operating cost) evaluation during the GA optimization with respect to the different types of seeding.

Figure 4 shows the pumping cost evaluations with regard to the random seed 2, for both randomized and LP-derived initialization. Less than 16 iterations are sufficient to the hybrid model for identifying a better solution respect to the randomly initialized GA. In this case, the best solution is reached after more than 800 objective function evaluations. In other words, the application of the LP initialization leads to obtain the same solution generated by traditional GA by 25 seconds rather than 1,200 seconds.

Moreover, with regard to random seed 5, in which the hybrid model provides the best improvement respect to the traditional GA, less than 10 iterations are needed to identify lower pumping cost (Figure 5). In this case the traditional GA needs about 240 seconds rather than 15 seconds of the hybrid model.

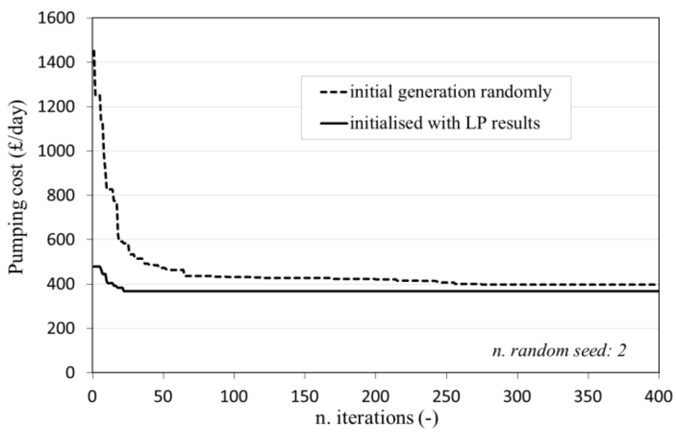

Figure 4 Pumping cost evaluations during GA optimization for run 2 with random and LP-derived solutions as initial seed.

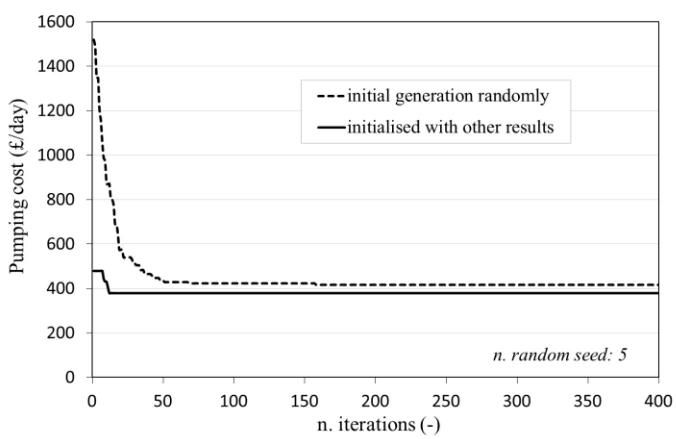

Figure 5 Pumping cost evaluations during GA optimization for run 5 with random and LP-derived solutions as initial seed.

CONCLUSIONS

In this work a hybrid optimization technique was proposed. The hybridization was performed by coupling Linear Programming with a Genetic Algorithm technique. The LP ability to rapidly determine an approximate, though acceptable, solution was exploited to provide a good initial seeding to the GA with very low computational effort. The application of the hybrid method to the benchmark Anytown network has demonstrated promising results. The resulting cost was lower than that obtained using randomized initialization of the GA for several different optimization runs. The improvement in convergence was also mirrored by an improvement in terms of simulation time. For the best near-optimal solution, the hybrid algorithm has shown to reduce the computational efforts by 16 times. The results show that the hybrid method demonstrates the potential to be adopted to provide a quick solution with a good level of reliability.

Further studies are needed in order to verify the reliability of the proposed methodology to complex system applications, in particular its scalability, and the inclusion into a real-time control architecture.

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