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A Lagrangian decomposition approach for the pump scheduling problem in water networks

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ABSTRACT

Dynamic pricing has become a common form of electricity tariff, where the price of electricity varies in real time based on the realized electricity supply and demand. Hence, optimizing industrial operations to benefit from periods with low electricity prices is vital to maximizing the benefits of dynamic pricing. In the case of water networks, energy consumed by pumping is a substantial cost for water utilities, and optimizing pump schedules to accommodate for the changing price of energy while ensuring a continuous supply of water is essential. In this paper, a Mixed-Integer Non-linear Programming (MINLP) formulation of the optimal pump scheduling problem is presented. Due to the non-linearities, the typical size of water networks, and the discretization of the planning horizon, the problem is not solvable within reasonable time using standard optimization software. We present a Lagrangian decomposition approach that exploits the structure of the problem leading to smaller problems that are solved independently. The Lagrangian decomposition is coupled with a simulation-based, improved limited discrepancy search algorithm that is capable of finding high quality feasible solutions. The proposed approach finds solutions with guaranteed upper and lower bounds. These solutions are compared to those found by a mixed-integer linear programming approach, which uses a piecewise-linearization of the non-linear constraints to find a global optimal solution of the relaxation. Numerical testing is conducted on two real water networks and the results illustrate the significant costs savings due to optimizing pump schedules.

1. Introduction

With the demand for water expected to double by the year 2035 (National Geographic, 2013), water utilities are facing unprecedented challenges to maintain a reliable infrastructure with sustainable costs.

The expected population growth and the shrinking supply of fresh water are among the main reasons for the urgent need to optimize the cost effectiveness of water resources. Energy costs are a major operating expense for water utilities; approximately 4 percent of all electricity used in the United States is attributed to the operation of potable water and waste water networks (Denig-Chakroff, 2008). Besides the economic benefits, optimizing the operation of water networks could avoid unnecessary use of resources and minimize the ecological impact caused by pollution and greenhouse gas emissions.

Over the last few decades, practitioners and researchers have addressed several problems in water networks, mainly in reliability (Sherali, Smith, & Kim, 1996), network expansion (Bragalli, D'Ambrosio, Lee, Lodi, & Toth, 2012; Sherali, Subramanian, & Loganathan, 2001), pipe sizing (Eiger, Shamir, & Ben-Tal, 1994), and network operations (Nitivattananon, Sadowski, & Quimpo, 1996). The problem of optimal pump scheduling has recently gained attention due to the increasingly complex electricity tariff schemes: energy utilities are providing incentives by offering cheaper electricity at low demand periods. For instance, the typical day-night pricing approach offers a night-time electricity price that is 50 percent cheaper than the day price. As renewable energy sources (i.e., wind and solar power) are being integrated into energy supply networks, electricity providers are beginning to offer dynamic electricity pricing, which varies in real time based on the realized supply and demand. Hence, forecasting electricity prices and optimizing pump schedules accordingly is becoming essential to capitalize on dynamic pricing and reduce operational costs.

Several approaches have been proposed for the optimal pump scheduling problem. Zessler and Shamir (1989) proposed an iterative dynamic program that finds an optimal pump schedule for a 24-hour period given forecasted demands, the initial and final levels in the tanks, and the forecasted energy cost over the day. Brion and Mays (1991) described a methodology that combines a non-linear

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optimization model with a hydraulic simulation model to implicitly enforce the conservation of energy and flow equations. Jowitt and Germanopoulos (1992) presented a linear programming model where the constraints are linear approximations of the non-linear network equations; the parameters of the linear approximations are determined using simulation. Yu, Powell, and Sterling (1994) presented an optimization algorithm that uses the generalized reduced gradient method coupled with sensitivity analysis to find optimal schedules; this algorithm needs a feasible starting point and iterates so that all the interim points are feasible. Lansey and Awumah (1994) introduced simplified hydraulic and cost functions for the pumps and implemented a dynamic programming optimization algorithm. Sherali and Smith (1997) use the reformulation-linearization technique to construct a tight linear programming relaxation of the pump scheduling problem and then uses a branch-and-bound algorithm to obtain global optimal solutions. Sakarya and Mays (2000) include water quality constraints and use a simulation optimization approach that combines a non-linear optimization solver with a water network simulator. McCormick and Powell (2003) present a stochastic dynamic program that includes maximum demand charges by enforcing constraints and penalty costs on power use, which provides solutions for the case where a single maximum demand charge is considered. A pump scheduling problem similar to the one considered in this paper is presented by McCormick and Powell (2004), who proposed a two-stage simulated annealing heuristic that produces high quality solutions in relatively short computational time. A two-stage heuristic approach was also proposed by Ulanicki, Kahler, and See (2007), where the first stage optimizes the tank trajectories and the second stage attempts to find a schedule that tracks the optimal trajectories. Another metaheuristic based on ant colony optimization was presented in López-Ibáñez, Prasad, and Paechter (2008). Giacomello, Kapelan, and Nicolini (2012) also proposed a heuristic that is based on linear programming coupled with a greedy search algorithm and demonstrated the effectiveness of the method on water networks from the literature. Gleixner, Held, Huang, and Vigerske (2012) proposed problem-specific presolving techniques for the pump scheduling problem that are of interest in this paper, and demonstrated the effectiveness of the proposed approaches on water networks from industry. Most recently, de la Perrière, Jouglet, Nace, and Nace (2014) approximated the complicating hydraulic equations using a linear function leading to a mixed integer linear model for the pump scheduling problem and showed that good feasible solutions are reached in low computational time.

The main challenge for the pump scheduling problem is the non-linearities in the hydraulic and energy conservation equations that define the way water flows through a network (D'Ambrosio, Lodi, Wiese, & Bragalli, 2014). These translate to non-linearities in the constraints and the objective of the optimization problem, which makes the problem difficult to solve, and there is no guarantee that any solution will be globally optimal. The problem is further complicated by multiple time periods (typically of 30 minutes each), which lead to a very large integer optimization problem that is often challenging to solve within reasonable computational time. This paper proposes a Lagrangian decomposition (Fisher, 2004; Geoffrion, 2010) approach to exploit the structure of the problem and alleviate the computational burden. The Lagrangian decomposition relaxes the constraint that links the time periods, decoupling the problem into smaller subproblems. The smaller problems are completely independent and thus can be solved individually and in parallel, because no interaction among them is present. This Lagrangian decomposition is implemented using a cutting plane approach. Similar approaches have been successfully applied to solve several challenging problems, such as Aykin (1994), Detienne (2014), Diabat, Abdallah, and Henschel (2013), Elhedhli, Li, Gzara, and Naoum-Sawaya (2011), Geoffrion (2010), Fisher (2004), Gzara and Erkut (2009), Wang and Huang (2013), Wang, Huang, and Yang (2012), Zheng, Sun, Li, and Cui (2012). Because the Lagrangian decomposition is a relaxation, the Lagrangian subproblem solutions may not be feasible for the original problem, and thus a neighborhood search based on Improved Limited Discrepancy Search (ILDS) (Korf, 1996) is proposed to explore the search space for high quality feasible solutions. Our proposed search algorithm couples ILDS with the EPANET (EPANET (v. 2), 2008) water network simulator, which is used to verify the feasibility of solutions. ILDS provides an upper bound on the optimal objective function value, while the Lagrangian relaxation provides a lower bound. Thus, the proposed approach provides solutions of guaranteed quality. The proposed Lagrangian decomposition approach is further evaluated by comparing its performance against a Mixed-Integer Linear Programming (MILP) formulation; this MILP is a relaxation of the MINLP formulation that uses a piecewise-linearization of the non-linear constraints, and is solved using CPLEX (IBM ILOG CPLEX Optimization Studio, 2013). Our results show that the proposed approach finds solutions that are close to optimal in only a fraction of the computational time of CPLEX. Furthermore, we show that dynamic pricing electricity tariff leads to a significant reduction in energy costs when compared to the day/night pricing. Finally, the numerical results show that the optimized pump schedules lead to a reduction in average tank levels thus reducing both pumping energy and pumping cost.

The contributions of the paper are threefold: (1) to the best of our knowledge, the proposed approach is the first to exploit the structure of the pump scheduling problem using Lagrangian decomposition in order to alleviate the computational burden, (2) the application of the simulation-based ILDS is novel and is shown to find solutions that are close to optimal in relatively short computational time, (3) we evaluate the effect of various dynamic pricing schemes that are currently being used in practice.

The rest of the paper is organized as follows. The problem formulation and the application of Lagrangian decomposition approach are detailed in Section 2. Computational results are presented in Section 3. Finally, Section 4 concludes and illustrates future research directions.

2. Problem formulation

2.1. Notation

A water network consists of a set of nodes connected by pipes (or links). The nodes consist of three subsets: reservoirs (or water sources), tanks used to store water, and junctions that connect nodes and may have a demand. Pumps are a subset of the pipes, which are used to increase the pressure within the network by generating sufficient water flow to satisfy the demand. Without loss of generality, we assume that a pipe may not contain more than one pump and the pumps have a constant speed. We also assume that the planning horizon is divided into equally-sized time periods, and the water demand must be satisfied at each time period. Below is the terminology that we will use throughout the paper.

Parameters:	*Sets:*
C_t: Electricity cost in time period t	N: The set of pipes
γ: Specific weight of water	P: The set of pipes that contain pumps
η_{ij}: Efficiency of pump installed on pipe (i, j)	R: The set of reservoirs
Q^U_{ij}: Maximum rate of flow through pipe (i, j)	K: The set of tanks
$D_{j,t}$: Demand at junction j in period t	J: The set of junctions
E_i: Elevation of node i	T: The set of time periods
P^L_j: Minimum water level in tank j	
P^U_j: Maximum water level in tank j	
A_j: Surface area of tank j	
Δ_T: Length of each time period	