Multiobjective energy management optimization

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1 Purpose of the STSM

Short Term Scientific Mission was held in Faculty of Engineering and Sciences, International University of Sarajevo in cooperation with prof. Haris Gavranovic. It was aimed at the development of heuristic approach combining constraint satisfaction and a constructive optimization algorithm for an energy management and pump scheduling problem.

The specific objectives of STSM were to:

1. To examine the existing literature in the field of multi-objective water distribution problems, focused on the a methodology for determining the optimal operation of water distribution system pumps with water quality considerations. The result of the state of the art review will be a formulation of a optimization model for efficient multiobjective energy management in water network.
2. Integrate hydraulic simulation model of the system with optimization model considering, in one framework together with constraints on threshold storage-reliability. The resulted solution will be aimed at support decisions on trading-off pumps operation versus surplus storage requirements.
3. To demonstrate the methodology on real water network based in Silesia Province in Poland.

2 Description of the work carried out during the STSM

2.1 Literarture review

Optimization of water supply system, so as to satisfy water delivery constraints, has been a research subject for a long time ie. investigated in Arulraj and Rao (1995); Engelhardt et al. (2000); Daniela et al. (2008); Alegre et al. (2012); Stachura et al. (2012); Fajdek et al. (2014). Most of the water distribution networks (WDN) were developed to operate in near to optimal conditions. Improvement in a system performance can be achived through optimal operation of water network. One of the main problem in water distribution system operation is effective control of pumps in stations. Pump scheduling is one of the most important tasks of the operation of a water distribution system. The problem of efficient operation of pumps in water networks has been subject to research over the last several years. As has been summarized in López-Ibáñez et al. (2008) several techniques have been proposed: linear Jowitt and Germanopoulos (1992), non- linear, Chase and Ormsbee (1993), dynamic programming, Lansey and Awumah (1994), Nitivattananon et al. (1996), heuristic Ormsbee and Reddy (1995), León et al. (2000), meta-heuristics algorithms Van Zyl et al. (2004). Because of the large scale of the problem only algorithms based on meta-heuristics (evolutionary algorithms) have shown promise results and it seems that could be used in real-world water distribution networks. Despite the promising results of the research there is limited acceptance of optimal control models in engineering practice.

The pump scheduling problem can be solved in different ways using evolutionary Fajdek et al. (2015) or nonlinear least squares algorithms Pytlak et al. (2013). A multi-objective methodology utilizing the Strength Pareto Evolutionary Algorithm (SPEA2) linked to EPANET for trading-off pumping costs, water quality, and tanks sizing of water distribution systems was demonstrated in Kurek and Ostfeld (2013). The applied model integrated variable speed pumps for modeling the pumps operation, two water quality objectives (one based on chlorine disinfectant concentrations and one on water age), and tanks sizing cost which are assumed to vary with location and diameter. The water distribution system is subject to extended period simulations, variable energy tariffs, Kirchhoff's laws 1 and 2 for continuity of flow and pressure, tanks water level closure constraints, and storage-reliability requirements. In Lopez-Ibanez et al. (2005) fixed speed pumps and fixed time intervals were considered, with use of a natural binary representation and simple and straightforward initialisation and recombination operators. In both papers authors, handled feasibility constraints a methodology based on the dominance relation rather than using penalty functions or reparation mechanisms. On other hand Puleo et al. (2014) presented Linear Programming approach for determining the optimal pump schedule on a 24-hour basis,considering as decision variables the continuous pump flow rates which are subsequently transformed into a discrete schedule. The authors shown that the cost associated with the result derived from the LP initial solution was shown to be lower than that obtained with repeated Hybrid Discrete Dynamically Dimensioned Search runs with differing random seeds.

In Price and Ostfeld (2012) a review on optimal WDN control models was provided. The authors indicated that he number of variables and objectives considered, optimizing the pump-scheduling problem may become very complex, particularly for large networks.

2.2 Integration of a hydraulic simulation model of the system with optimization model

The main task of a water supply system is to provide a sufficient amount of water at the appropriate pressure to all users of the system. Each water network consists of three main components: pumps, storage tanks and distribution network.

2.2.1 Decision variables

The decision variables in this study are the relative speed values of each pump u_i expressed as discrete patterns with durations corresponding to the control evaluation horizon H_p.

$$\mathbf{u} = [\underbrace{u_1, \ldots, u_{Hp}}_{p_1}, \ldots, \underbrace{u_1, \ldots, u_{Hp}}_{p_{N_P}}]. \tag{1}$$

where: p_i is an ith pump installed in a system, N_p is a number of pumps, H_p is the control horizon. Each pump relative speed can vary from o to 1, $u_i \in \langle 0, 1 \rangle$

2.2.2 Objective functions

Operational cost The first objective $I_c(\mathbf{u})$ is the overall energy consumed by the pumps during the control evaluation horizon H_p. Different energy tariffs for each pump can be considered:

$$I_c = \sum_{k=1}^{H_p} \sum_{i \in P} \eta_i(k) E_i(k) \tag{2}$$

where $\eta_i(k)$ is the energy cost of pump i over time period k, and $E_i(k)$ is the energy consumed by pump i over time period k and P is a number of pumps. The operational cost objective will drive the system to minimize the amount of pumping during peak energy tariffs and utilize the systems storage for reducing energy cost.

Surplus power The surplus head at node j is the excess pressure available above the required service level p^{req}. This surplus head indicates the available energy for dissipation during failure conditions and is given by:

$$I_S = \sum_{i=1}^{N} \sum_{k=0}^{H_p} p_i(k) - p^{req} \tag{3}$$

2.2.3 Constraints

Tanks levels The next indicator is the amount of water stored in the tanks within the control horizon:

$$I_t = \sum_{t=1}^{T} \{0, |h_t(H_p) - h_t(1)| - \alpha h_t(1)\} = 0, \tag{4}$$

where $h_t(k)$ is the head at tank t at time instant k, a is the coefficient that relaxes the terminal constraint introducing tolerance to the constraint, and T is the set of all tanks in the network. In this study α was set to 0.1.

Failure index Failure index can be used both to identify infeasibilities during the optimization process and to evaluate and compare the effect of pipe failures. The idea is to maximize the minimal resilience index for the whole control horizon H_p. This will result in minimizing the network vulnerability:

$$I_f = \max \left\{ \frac{\sum_{i=1}^{N} I_{f,i}(k)}{\sum_{i=1}^{N} q_{d,i}(k) h_{req,i}} \right\}, \quad \forall k \in \{1, 2, \ldots, H_p\} \tag{5}$$

$$I_{f,i}(k) = \left\{ \begin{array}{cc} 0 & \forall i : h_i(k) \geq h_{req_i} \\ q_{d,i}(k) \left(h_i(k) - h_{req,i}\right) & \forall i : h_i(k) < h_{req_i} \end{array} \right. \tag{6}$$

2.3 Optimization problem

Assembling the above objectives and constraints yields the following multi-objective optimal control problem:

$$\min_{\mathbf{u}} \{I_c, -I_S, \} \tag{7}$$

subject to:

$$\left. \begin{array}{rcl} H_i(k) - H_j(k) & = & rQ_{ij}^n(k) + mQ_{ij}^2(k) \\ h_{ij}(k) & = & -\omega^2(k) \left(h_0 - r \left(\frac{Q_{ij}(k)}{\omega(k)}^n\right)\right) \\ Q_{ij}(k) - D_i(k) & = & 0 \end{array} \right\} \forall k \in \{1, 2, \ldots, H_p\}, \tag{8}$$

and:

$$I_f \leq 0, \tag{9}$$

$$I_t \leq 0, \tag{10}$$

$$u_i \geq 0 \quad \forall u \in \mathbf{u} \tag{11}$$

$$u_i \leq 1 \quad \forall u \in \mathbf{u}, \tag{12}$$

where:

$$\mathbf{u} = [\underbrace{u_1, \ldots, u_{Hp}}_{p_1}, \ldots, \underbrace{u_1, \ldots, u_{Hp}}_{p_{N_P}}]. \tag{13}$$

and H is nodal head at network node i, h is the headloss, r is the resistance coefficient, Q is the flow rate, n is the flow exponent, and m is the minor loss coefficient, h_{ij} is the the headloss (negative of the head gain), h_0 is the shutoff head for the pump, ω is a relative speed setting and r and n are the pump curve coefficients, D_i is a flow demand at node i, and by convention, flow into node has a positive value. For a set of known heads at the fixed grade nodes.

3 Description of the main results obtained

The tests of the presented methodology were performed on the example of water distribution system in Glubczyce. It is a town in the Opole province, Poland, in the district of Glubczyce situated on the river Psina. The town is inhabited with 23 778 people. Water production in 2011 was estimated at 2.782 m^3/day. The WDN in Głubczyce was selected mainly due to a relatively low complexity of a network, which helped to conduct the simulations and to analyze the results. The necessary simulations were performed in EPANET2 toolkit. Next a specialized software was implemented so as to calculate the above presented quality indices and to couple the simulation software with an optimization algorithm. During the work the optimization task was splitted into two separate, tasks that were easier to solve. In the first stage the necessary flow and head delivered by all the pumps was optimized as a multiobjective task with use of AMGA2 genetic algorithm Tiwari et al. (2011). In the context of WDN multiobjective optimization various evolutionary algorithms are applied in literature, the most popular being `NSGA-II` by Deb et al. Deb et al. (2002), `SPEA2` by Zitzler and Thiele Zitzler et al. (2001) , and `FFGA` by Fonseca and Fleming Fonseca and Fleming (1993). However, in Tiwari et al. (2011) it was shown that the `AMGA2` procedure has better performance on the ZDT, DTLZ, and practical engineering problems. Next, the load was distributed into individual pumps, maximizing its efficiency using general pupropse optimization solver implemented in `Mathematica` software.

4 Future collaboration with the host institution

Both the grantee and the host truly believe that the STSM is a start of the scientific cooperation. Currently, the work performed within STSM is beeing extended so as to improve the achieved results.

5 Foreseen publications/articles resulting from the STSM

The article in a scientific journal is foreseen. Currently the grantee, Marcin Satchura and the host, prof Haris Gavranovic are preparing the paper to be submitted.

6 Confirmation by the host institution of the successful execution of the STSM

The confirmation is presented in the file attached to this report.

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