Final Report

# Optimal design, identification and energy-efficient operation of large-scale hydraulic systems

Detailed research plan

OTKA K106141

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## 1 Introduction

This report summarizes the work performed within the OTKA project K106141. As described in details in the project proposal, the research aimed at the following results:

- Development of a fast, reliable hydraulic solver, see section 3.1. ✓
- Pump schedule optimization techniques for stochastic water demand, see section 3.2. ✓
- Improved demand forecast models using hybrid fuzzy logic, see section 3.3. ○
- Sensitivity analysis of hydraulic networks, see section 3.4. ✓
- Optimal measurement layout, see section 3.5. ✓

In the above list ✓ stands for a task that was completely fulfilled while partially completed aims are denoted by ○. In the next section we give detailed description of the achievements and the causes behind partial fulfilments. Beyond the above, originally planned outcomes, the following additional results were obtained.

- A freely available, web-based software tool was developed for hydraulic system simulation, see section 3.6. ✓
- Successful application of network theory for the qualitative analysis of water distribution systems (WDS), see section 3.7. ✓

## 2 Project history overview - personell

Due to a series of unforeseen events, the participants contributing to the project significantly changed in the first third of the project:

**Z. Pandula (PhD)** passed away in the spring of 2014 after a long illness.

**J. Bene (PhD)** left the academic field for an industrial carrier in the January of 2014.

**G. Bárdossy (PhD)** also left the academic field for an industrial carrier in the middle of 2013.

All these changes were posted to the OTKA Office in time. Recruiting new participants was immediately started and as a result, **K. Klapcsik** (PhD student), **R. Varga** (PhD student), **Gábor Vér** (MSc student) and **G. Keszthelyi** (BSc student) joined the project. However, acquiring the sufficient knowledge and experience consumed some time and hence a 1-year augmentation of the project was requested by the PI and also approved by the OTKA Office.

## 3 Scientific achievements

### 3.1 Fast hydraulic simulation software

We developed a C++-based computer code to cope with real-size hydraulic networks, which is capable of computing the steady-state hydraulics of networks with several tens of thousands of edges (pipes). The underlying numerics uses sparse matrix technology and specialized numerical schemes. To give an impression of the scale of the problem: the hydraulic model of the Sopron Waterworks consists of more than 25k nodes and about 30k edges. When computing a 24-hour load scenario, we typically perform 48 of such computations (30min time step). Thus, the hydraulic model consisting of more than 50k nonlinear algebraic equations has to solved 48 times, for which the CPU time is well below 1 second (excluding file I/O operations) on a standard desktop PC.

This computational speed opened the possibility of performing optimization tasks on detailed, high-fidelity mathematical models (see later). All the publications given in the later subsections (apart from the demand forecast model) are based on this solver. Finally, see section 3.6 for further details on the software tool.

### 3.2 Pump schedule optimization techniques for stochastic water demand

We conducted a large number of numerical experiments to study the effect of demand uncertainty on the optimal pump schedule. It was revealed how the deviation in the (optimized) cost and reservoir water levels (at the end of the optimization horizon) changes with the increase in the demand uncertainty. We hoped to give a general approach (based on variance-covariance analysis of the network) to estimate these quantities without the need of performing a large number of optimizations. We managed to come up with such techniques for simple systems, however, we found it cumbersome to make them more general and applicable to real-life ones. Apart from two MSc student projects (by G. Vér), no publication was written on this topic.

However, in cooperation with the researchers of the University of Oulu (Finland) a robust, tube-based optimization framework was developed that allowed the computation of optimal pump schedules in the presence of demand uncertainty, see [8, 2]. Exploiting the characteristics of "well–designed" water networks an operation decision policy was derived which is calculated *on–line* utilizing the receding horizon principle. The obtained policy is robust both in terms of optimality and feasibility, that is, it remains nearly optimal and feasible for all admissible realizations of the water demand trajectory.

### 3.3 Improved demand forecast models using hybrid fuzzy logic

The forecasted water consumption values are the most critical input data in the case of pump schedule optimization of water distribution systems. The aim of this phase was to develop a simple technique which is able to estimate the mean consumption and its distribution for a given demand zone. Simplicity is advantageous since the forecast model needs to be ran for every optimisation computation. Although we planned to use Fuzzy logic it was found that based on the database of hourly water consumption a reasonable estimate can be given. First, the database content is automatically grouped based on the similarity of the elements (more precisely, their normality). This step is time-consuming but is performed only once for a given database independently of the optimization. The second step – which is quick but has to be performed before the actual optimization – makes use of this grouping for forecasting mean value and standard deviation. We presented test results that prove the applicability of the technique for real-life problems. Moreover, it was demonstrated that the confidence interval provided by the technique includes the actual measured data. Further details can be found in [1].

### 3.4 Sensitivity analysis of hydraulic networks

The response of hydraulic systems to a change in the pipe loss coefficient (e.g. after replacing and old pipe by a new one) or demand (e.g. due to new buildings) was studied by means of experimental and numerical techniques. We analysed both simple, 'toy' hydraulic systems and real-life networks. The aim of this phase was to explore the most sensitive segments of a water distribution system (WDS) and to find a suitable ranking of the pipes to use the financial resources dedicated to reconstruction the most efficient way. We published several papers on this topic, i.e. [4, 9, 6].

Sensitivity information was found to be extremely helpful in both finding optimal measurement layouts or splitting the network into subgraphs for, say, exploring its community structure (i.e. are there any "islands" or weakly connected parts). For further details, see section 3.7.

### 3.5 Optimal measurement layout

We addressed the the problem of locating the optimal pressure measurement points in a water distribution system (WDS) to help the calibration of model parameters, notably pipe roughness values or nodal demands. Two novel weighting schemes of the modularity index were introduced to detect hydraulic communities in complex WDSs: the first one is based on the pressure differences along edges while the second uses sensitivity information to segment the system into communities of equal overall weight. Once the segmentation is performed, the actual pressure measurement locations can be identified by higher-level decision, e.g. by means of classic FOSM models or simply the most sensitive node can be used for pressure logging. Genetic algorithm was used to find the optimal segmentation (i.e. to maximize modularity) along with a dedicated mutation algorithm to accelerate convergence. Starting from a simple example, we systematically increased the complexity of the WDS up to systems of real-life size. Further details can be found in [5, 3, 7].

### 3.6 Web-based freely available GUI tool

A web-based graphical user interface was also developed as a front-end for efficient and intuitive use of the software tool, see

`www.hds.bme.hu/staci_web`

for details. This tool is freely available for research and educational purposes and is actively used in the teaching of several BSc and MSc courses of the Dept. (>80 students per year).

The tool is server-based, i.e. the users do not have to install any software on their PC/laptop (apart from Java Runtime Environment) and all the computations are performed by the Staci server (which was acquired with the help of the current project). This simplifies the code development and maintenance.

### 3.7 Using network theory for qualitative analysis of WDSs

Water distribution systems (WDS) can also be viewed as looped graphs: the nodes are the junctions while the edges are mostly pipes, but can also be pumps or isolation/restriction valves. While the project developed on course and the water distribution systems analysed grew it became clear that modern network theory is a promising tool to analyse such infrastructural networks. Concepts such as modularity, flows in networks, community structure can be generalized to WDSs and provide valuable insight and understanding on their behaviour. This headway is already covered in [3] but we see a large potential in this direction.

## 4 Additional achievements

Besides the scientific results, let us add some more highlights of the project.

- J. Bene finished his PhD in 2013. The current project was a catalyst during his research.
- Another PhD student (R. Wéber) starting his work in February 2017 chose to further develop some aspects of the current grant, notably on using graph theory.
- Several BSc and MSc student projects (both mid-term projects and Diploma projects) were motivated by various sub-projects of the OTKA grant.
- We developed a fruitful cooperation with several Hungarian water suppliers (notably Sopron and Budapest) who provided real-life networks, consumption databases and everyday operational experience.
- We hope that the software tool `Staci`, developed with the help of the current project will contribute to teaching and research of both domestic and international colleagues.

## 5 Closing

This OTKA Grant allowed the PI to focus on this extremely interesting and motivating project for four years. On behalf of all the participants, the PI gratefully acknowledges the funding received from OTKA and is thankful to its colleagues for providing the necessary guidance concerning the implementation and administration of the project.

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