CALIBRATION OF WATER DISTRIBUTION MODELS BY GENETIC ALGORITHMS

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ABSTRACT

The paper discuses the calibration of water distribution models by means of genetic algorithms as the optimization method. Calibration of hydraulic models is a procedure of determining individual unknown parameters of a hydraulic model, which minimizes the differences between the measurements performed on a real water distribution system and the results of the hydraulic model. The applied calibration approach is consisting of the "macro" and "micro" calibration level. The "macro" calibration allows the hydraulic model to become a "rough" approximation of the real system, by ensuring that the system variables are in reasonable agreement with collected measurements. At this stage all major possibilities of model discrepancies should be uncovered and resolved. Afterwards the "micro" calibration procedure is applied to identify the unknown model parameter values by using the optimization method of genetic algorithms. The optimization problem is structured so as to search for values of optimization variables or unknowns, which minimize the objective function while in the same time fulfilling all constraints. The objective of the calibration optimization problem is expressed in a form, which allows minimization of the differences between measurements and model predictions. The aforementioned modeling and calibration approaches were applied to a real water distribution system of a part of the Slovenian capital Ljubljana. It can be concluded that the calibration approach was successfully applied and that genetic algorithms have proven its robustness in identifying near optimal solutions of the calibration problem.

KEY WORDS

hydraulics, water distribution systems, modeling, calibration, optimization, genetic algorithms.

INTRODUCTION

Mathematical modeling of water distribution systems (WDS) is scientifically very well developed discipline successfully finding place among other decision support tools. The GIS support in connection with other information technology allows building of hydraulic models in an efficient way, which allows specific analysis, and planning, and finally also carrying

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out of the necessary measures. Figure 1 presents a procedure of water distribution system management with an emphasis on hydraulic modeling.

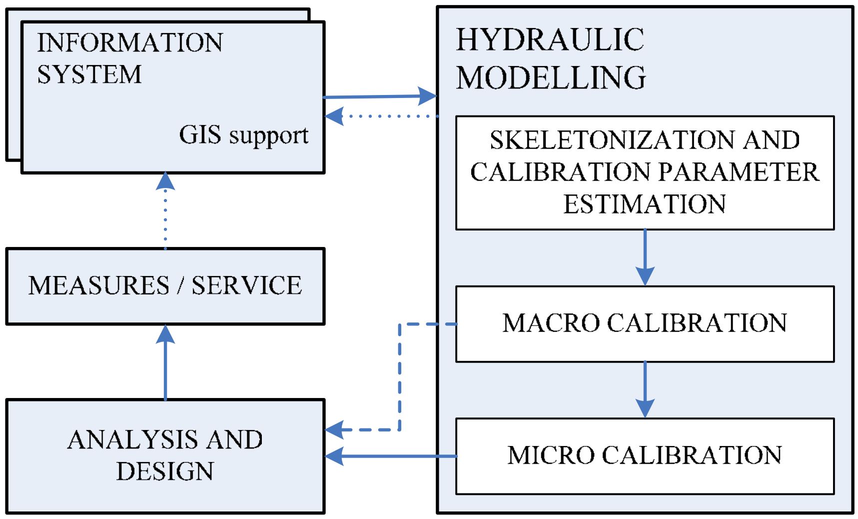

Figure 1: Water distribution system management with emphasis on modeling

The information system serves as a source of the data available on physical characteristics of a water distribution system deriving from actually known data or measurements as well as from the evaluations of individual hydraulic parameters if the exact quantities are not known. These data allow building of a hydraulic model, the size of which has to be adapted to a manageable situation. Hydraulic models of the same water distribution system can differ with regard to the purpose of the analysis to be performed with this model. The purpose of the model is essential since it determines the accuracy level of the model and its simplification. The adaptation involves a procedure of skeletonization or simplification of the hydraulic model, the aim of which is to exclude from the model all those elements which are not essential to its hydraulic identity with the actual developments in a water distribution system. When such model has been built, the procedure of “macro calibration” is first carried out (Figure 2). This involves a control of the hydraulic model as a whole and adjustment of hydraulic parameters until the results of the model show correspondence with the existing measurements, e.g. with the differences not exceeding 30 percent (Ormsbee et al., 1997). This process tries to identify a possible cause of such differences, such as incorrect data on model parameters, pressure zone settings, parameters of system equipment and facilities and measuring equipment, and measurement reading.

In the majority of cases, the macro calibration allows the hydraulic model to become a "rough" approximation of the real system, which can already be used, to a certain level of accuracy, to perform analysis and planning. However, since the engineering practice aims at a higher level of accuracy, the hydraulic model has to be calibrated more precisely. This is described under the term of “micro” calibration, where higher accuracy of individual model parameters are sought to ensure also higher model accuracy (Figure 2).

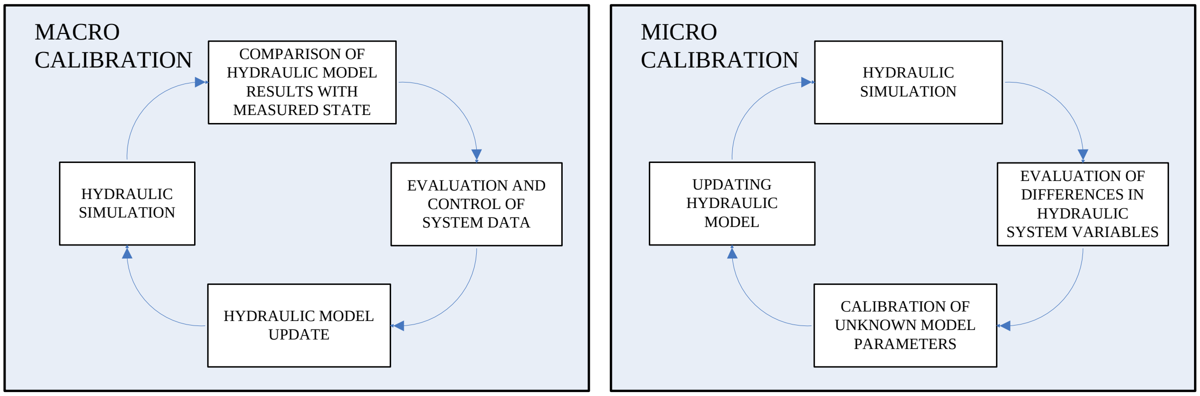

Figure 2: “Macro” and “Micro” calibration levels

The aim of the presented work is to determine the individual model parameters of water distribution models under the aforementioned approach. A specific explanation of both calibration procedures and their application on a real water distribution system model are presented in the next sections.

CALIBRATION OF WATER DISTRIBUTION SYSTEM MODELS

“MACRO” CALIBRATION OF WATER DISTRIBUTION MODELS

After building a hydraulic model of a water distribution system and its application for specific analysis it is necessary to first evaluate its accuracy due to collected field measurements. Before applying an optimization procedure on calibration of individual model parameters the hydraulic model needs to be adjusted to show certain correspondence of model predictions with the real system behaviour. This is done at the “macro” calibration level. Besides the reliability of the predictions, calibration offers a deep insight into the water distribution system operation. Calibration is therefore very useful also in the planning phase of the measures since thorough understanding of the hydraulic model comprises the aspect of model sensitivity to changes in individual physical and/or non-physical data.

Some model parameters can be determined under reasonable accuracy due to available measurements and data. With high accuracy model parameters of physical characteristics of water distribution devices or industrial user demands can be determined. But some model parameters, which could be directly measured, are due to their complexity and amount very costly and not feasible. Those parameters are domestic user demands and pipe diameters. Besides the fact that those parameters could be measured they are usually determined through a calibration procedure. Model parameters like pipe roughness can not be measured and are therefore indirectly determined by measurement of system variables, e.g. pressures or heads, tank water levels, flows or even water quality measurements.

Calibration of water distribution models is also a time consuming procedure and needs to be terminated, when certain criteria are fulfilled. There are some existing calibration guidelines, which provide also criteria of desired model accuracy to be achieved. One of those guidelines is from Water Research Center (WRc, 1989), which provides system variable accuracy as follows:

- Flows: a) ±5% of difference, when flow measurements are more then 10% of all system flows or b) ±10% of difference, when flow measurements are less then 10% of all system flows.
- Pressures: a) ±0.5m or ±5% of difference at 85% of all measurements, b) ±0.75m or ±7.5% of difference at 95% of all measurements or c) ±2.0m or ±15% of difference at 100% of all measurements.
- Reservoir turnover: ±5% of the volumetric difference of reservoirs between to consecutive time steps (for EPS simulations).

Those calibration performance criteria are desired for the termination of the complete calibration procedure, i.e. "micro" calibration, which is presented in the next section.

OPTIMIZATION MODEL FOR "MICRO" CALIBRATION OF WATER DISTRIBUTION MODELS

The "micro" calibration procedure (hereinafter referred to as "calibration") is conducted to provide confidence in the predictions of the hydraulic model, which will prove the actual operation of the water distribution system and will provide the designer with a reliable decision-making support. Calibration of hydraulic models is thus a procedure of determining individual unknown parameters of a hydraulic model, which minimizes the differences between the measurements performed on a real water distribution system and the results of the hydraulic model. The predefined calibration problem can be solved with the objective function expressed in a form:

$$\min E = \sqrt{\frac{\sum_{k=1}^{N_{Load}} \sum_{i=1}^{N_{MH}} (y_{ik}^{*} - y_{ik})^2}{N_{Load} * N_{MH}}} + \sqrt{\frac{\sum_{k=1}^{N_{Load}} \sum_{j=1}^{N_{MQ}} (y_{jk}^{*} - y_{jk})^2}{N_{Load} * N_{MQ}}} - Pe \quad , \qquad \text{(eq. 1)}$$

where E – the value of the objective function of the calibration problem; y^{*}_{ik} – measurements of system variables; y_{ik} – model predictions (i=1,…N_{MH} or N_{MQ}; k=1,…N_{Load}); N_{Load} – number of loading conditions, where measurement were carried out; N_{MH} and N_{MQ} – number of pressure and flow measurement locations; Pe – penalty function.

In the area of water distribution system calibration, several approaches and methods were developed, which, in general, comprise the trial-and-error method and the explicit and implicit methods. The first trial-and-error methods are today the basis for numerous guidelines on calibration of water distribution system hydraulic models and represent much needed instructions for all water distribution system managers and planners. Developed explicit methods of hydraulic model calibration imply direct solving of a set of hydraulic equations for the parameters sought and of an additional set of hydraulic equations obtained from the measurements on a system. On the other hand the implicit methods of calibration are methods, which are formulated and solved as optimization problems. Their objective function is usually expressed in a form, which allows minimization of the differences between measurements and predictions or the results of the model (see equation 1). Due to some good characteristics of implicit methods, several authors engaged in the development of optimization models for calibration in the last decade, which to a great extent contributed to the increased accuracy of hydraulic models. The criteria of accuracy of hydraulic quantity predictions are laid down in various guidelines, which define the levels of differences between the measurements and results of the model related to the purpose of the hydraulic model analyses (WRc, 1989).

For successful calibration, a set of measurements has to be gathered first by means of systematic capturing of data on hydraulic quantities during operation at the "representative locations" on a water distribution system. The quality of information collected with measuring has a great impact on the calibration accuracy of hydraulic model, while a higher number of information provides a higher level of confidence in the model. A hydraulic model not calibrated on the basis of quality measurements will consequently demonstrate poor assessments of the parameters sought and thus also a low level of confidence in the obtained hydraulic parameters of the model or its results.

USING GENETIC ALGORITHMS FOR OPTIMIZATION OF THE CALIBRATION PROBLEM

Optimization tools are used for solving demanding and comprehensive optimization problems. Genetic algorithms (hereinafter referred to as GA) are one of the optimization tools based on the simulation of evolution processes and their basic mechanism, i.e. natural selection. The first author to believe that the process of evolution and natural selection represents an efficient optimization tool was John Holland who in the 1970s developed the first concept of GA. He was followed by numerous authors who improved his approach; numerous researches followed as well as application in numerous areas (Goldberg, 1989).

The optimization problem involves the following parts: (a) the objective function (function which is minimized or maximized), (b) optimization variables or unknowns (variables which have a direct influence on the objective function values), and (c) constraints (they determine the variables' limits, within which their values are allowed, and exclude the solutions or values not falling within the defined ranges). The optimization problem thus searches for values of optimization variables or unknowns, which minimize or maximize the objective function while fulfilling constraints.

GA are often described as (integral) stochastic method, which is especially useful in solving large and complex problems with many local minimums and maximums and which almost always provides a solution close to the optimum one (Walters et al., 1989). This feature arises from the fact that GA explore the solution space with a population of chromosomes, i.e. possible solutions equally distributed across the entire solution space. Another advantage of is that they require only the evaluation of the objective function for the optimization procedure without demanding numerical operations, as well as the possibility of using both discrete and continuous variables in the optimization procedure. However, even the best tools are not faultless; therefore one needs to know the strengths and weaknesses of every method. A flow chart of the optimization method based on GA is given at figure 3 (Wall, 1996).

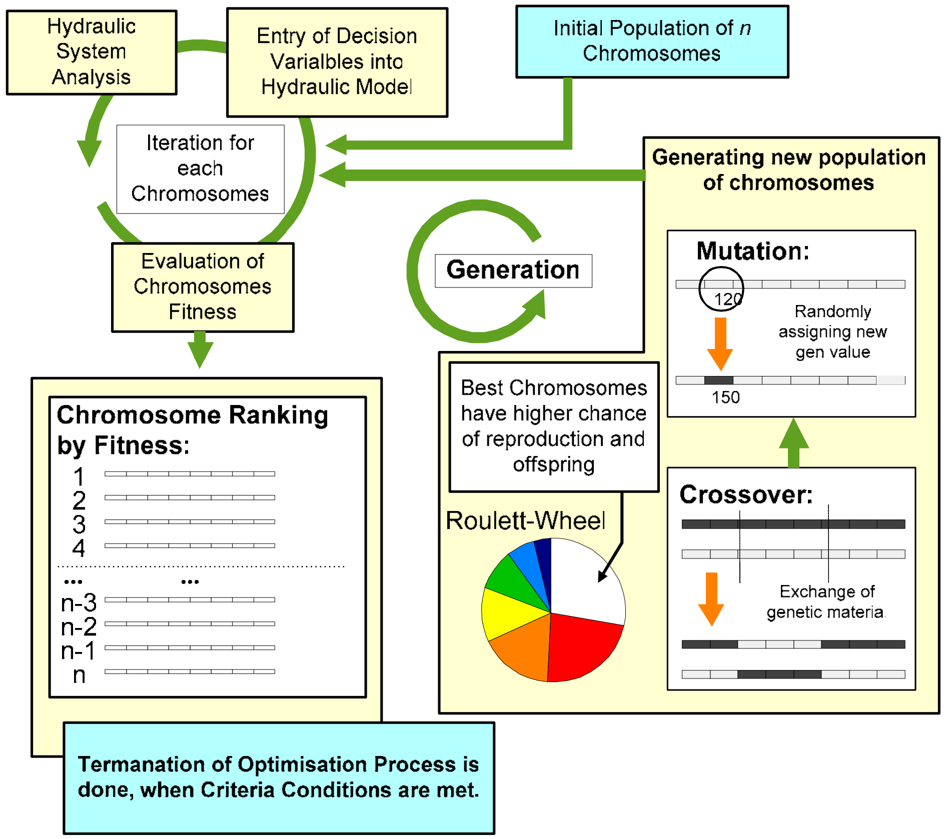

Figure 3: Flow chart of GA optimization

The presented calibration procedure and optimization tool have been applied and verified on on a hydraulic model »Anytown«, which was first defined by Thomas M. Walski (Walski, 1987). The above-mentioned model of WDS was selected due to its general application in the area of testing various tools for WDS analysis and its realistic concept including also certain characteristics of real WDS (Kozelj et al., 2005). The optimization model provided very good calibration results and has proven themselves as efficient in identifying individual model parameters of water distribution system models.

CALIBRATION OF WATER DISTRIBUTION SYSTEM OF LJUBLJANA-ŠENTVID

The verified optimization tool for solving the calibration model has been applied to the water distribution system of Ljubljana-Šentvid. The aim of the analysis was to calibrate the assemble model to predict hydraulic system variables as accurately as possible. The selected model parameters were nodal demands and pipe roughness values. After the "macro" calibration procedure has been applied and the model predictions have proven to be in correspondence with measurements, the "micro" calibration approach performed. The calibration optimization tool has been developed to identify: a) nodal demand at extended period simulation (normal loading conditions) and b) pipe roughness values at steady-state simulations (fire flow loading conditions). In both cases GA have been applied as the optimization method.

The water distribution system Šentvid is a hydraulic independent part of the Ljubljana water distribution system and a general representation is given on figure 4. The water distribution system serves a population of approximately 34.000 inhabitants and its estimated average demand is 51.53 l/s, while the average system input from the clear well on the 25th May 2005 was measured at 95 l/s. The main distribution system was assembled by means of GIS and CAD data and consists of 4 reservoirs, 2 tanks, 4 pumps, 1 PRV valve, 1601 junctions and 1858 pipes. For the calibration procedure the model has been skeletonized and a resulting model of 1416 junctions and 1684 pipe was achieved. The resulting model has been "macro" calibrated by determining model properties to become a "rough" approximation of the real operation conditions. Comparison between measurements and model predictions of pressures, flows and tank water levels have been performed. The pipe roughness values have been estimated by engineering judgment and relevant pipe roughness tables.

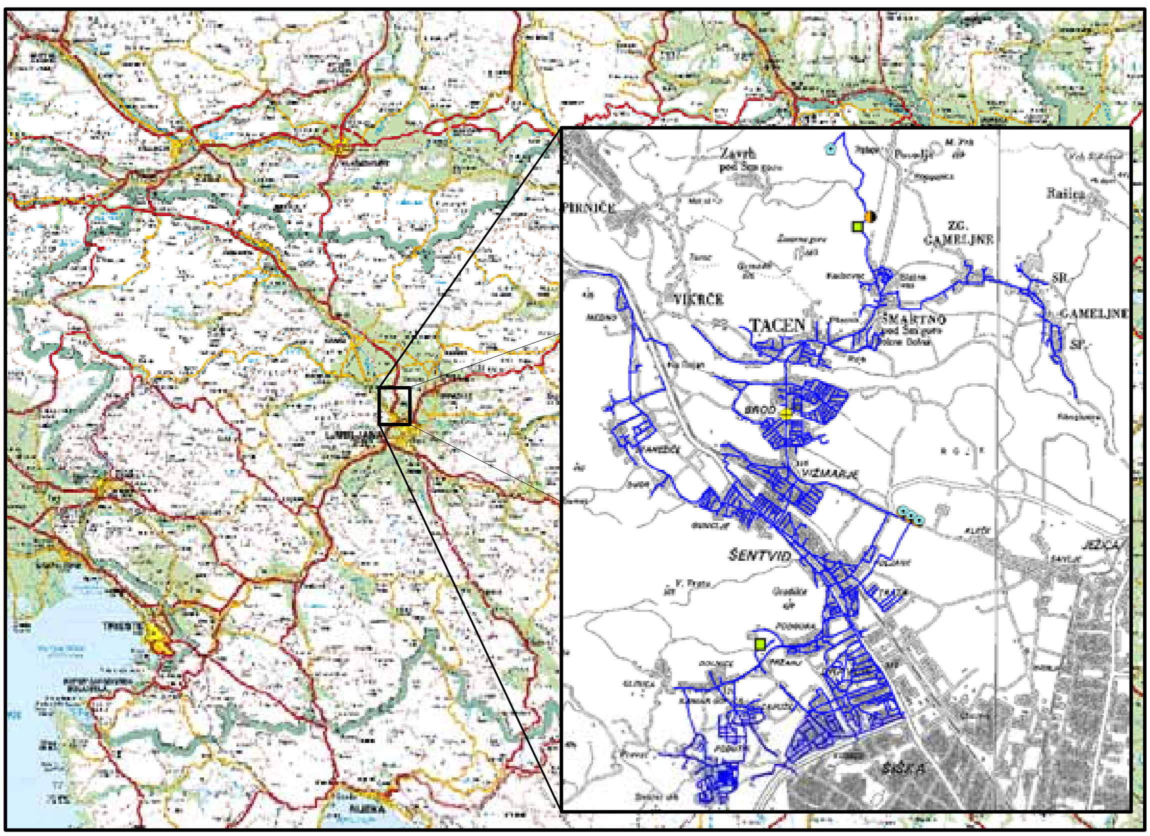

Figure 4: Water Distribution System of Ljubljana-Šentvid

The calibration of model parameters has been performed on the basis of a data collection procedure, where 16 pressure and 4 flow measurement locations provided data for the calibration process. Besides the aforementioned measurements also boundary conditions, i.e.

reservoirs and tanks pumps, have been monitored and additional 6 fire flow tests have been performed. The calibration of nodal demands was carried out by the optimization algorithm under extended period simulations. After a preliminary analysis of the decision variables (1416 junctions) have been grouped together and the final number of variables resulted in 1014 nodal demand groups. The decision to perform the aforementioned grouping arises from posting a well-posed calibration problem, i.e. not underdetermined (Mallick et al., 2002).

The hydraulic calculations of the extended period simulation have duration of 24 hours with a 15 minute time step. The collected measurements were processed to 15 minutes time steps and results in 1536 measurements out of 16 pressure measurement locations (16*24*4). Similarly at 4 locations 672 flow measurements have been prepared. As already mentioned boundary conditions of the water distribution system have been monitored and used in the optimization model. The optimization problem (see eq. 1) of the calibration process is solved by using GA. "Steady-State" GA were used together with real number coding of a population of 100 chromosomes. Two-point crossover at a probability of 0.85 and a gene mutation probability of 0.07 has shown best results in the optimization process. Several optimization processes have been performed and each of them has been terminated after 20.000 generations to ensure that the best solutions could be identified.

Some of the results of the calibration process are presented in figure 5 and 6. On figure 5 the left-hand side a correlation plot of heads of observed (measured) and computed values of all monitoring locations. On figure 6 a comparison of observed and computed head values at tank VH_Przanj are presented for an extended period simulation.

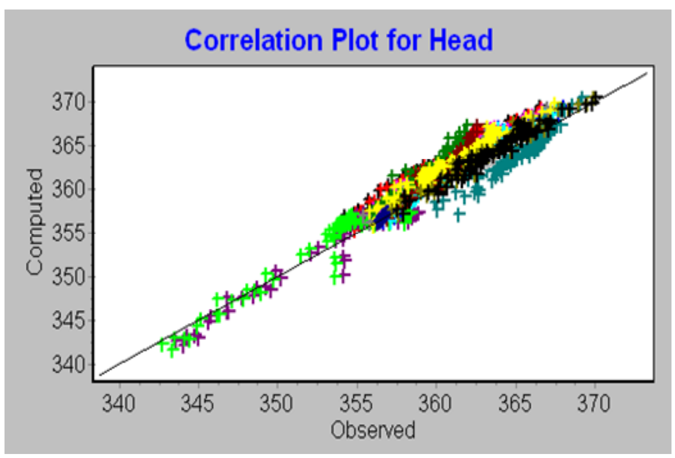

Figure 5: Plot of observed and computed heads of the calibration process

From both diagrams it can be concluded that there is a high agreement between measured and computed system variable values and gives a good estimation of the success of the calibration process. The results of the calibration process are according to the calibration guidelines presented previously. The root mean squared error of heads measurements is 1.564 m and the root mean squared error of flows is 1.345 l/s. The correlation coefficient between means of monitoring locations is 0.945 for heads and 0.999 for flows.

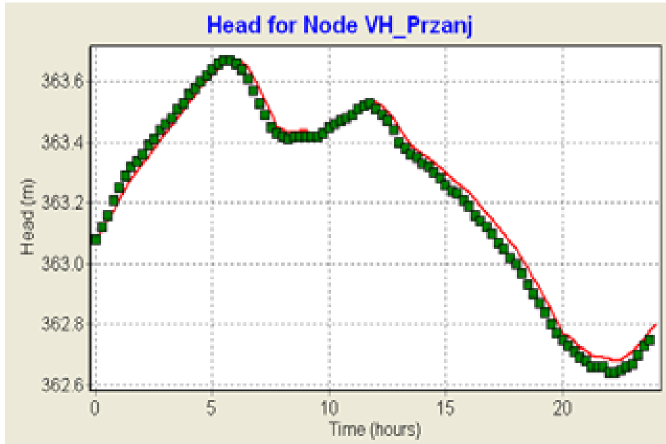

Figure 6: Plot of observed and computed heads of the calibration process

Afterwards the calibration process was extended to evaluate the pipe roughness values at steady-state simulation under fire flow loading conditions. Fire flow loading conditions add additional "information" value to the calibration process of pipe roughness values, because the extreme pressure drop in the system makes it easier to identify correct values. Besides the pressure and flow measurements at the fire flow tests also the aforementioned monitoring locations collected additional measurements. At 11 loading conditions a resulting number of 192 pressure measurements were collected.

The pipe roughness values were grouped together by specific criteria according to available pipe data and resulted in 19 pipe roughness groups. Only pipe roughness values of pipe placed before the fire flow tests were calibrated, because no pressure drop measurements are collected afterwards and it is not possible to estimate their values. The optimization problem of the calibration process (see eq. 1) has been reduced by the flow (second) component, so that only pressure measurements were used. In the optimization process the same GA parameters have been used only this time the termination condition was set to 10.000 generations. The results of the calibration process are within the calibration guidelines, where a root mean squared error of heads is 1.004 m and a correlation coefficient between means of monitoring locations is 0.997.

CONCLUSIONS

The paper discusses the development, application and verification of the calibration optimization tool by using GA. The calibration procedure is consisting of macro and micro calibration level, where the micro calibration level is solved by applying GA. The calibration procedure was successfully applied to a real water distribution system of Ljubljana-Šentvid and the achieved agreement between observed and computed system variables show high satisfactory. The use of GA has proven its robustness and efficiency in the highly complex problem of the calibration process.

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