

Use of genetic algorithms for calibration of hydraulic models of water supply systems

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Abstract. According to the legislation of the Russian Federation, it is required to establish an electronic model within the framework of a water supply plan development. It should be mentioned that in order to obtain the reliable results of modeling, it is necessary to verify the model; this verification is achieved based on the statistical data on the operation of a water supply system. For model calibration, foreign software complexes apply the programs based on genetic algorithms. At the same time, the analysis of Russian software products reveals the absence of such functions. The aim of this article is to describe the algorithm operation of the electronic model of a water supply system using a genetic algorithm by the example of a network taken from technical literature. The developed automatic calibration algorithm is applicable to Russian software “ZuLu”.

1. Introduction

On the basis of the requirements set by the Russian legislation, the development of water sector and engineering infrastructure in cities and other inhabited localities must be carried out in accordance with the projects of water supply and wastewater disposal plans. If the population of a city exceeds 150 thousand people, these plans must obligatory include the electronic models of water supply and wastewater disposal systems [1].

The electronic model of water supply and wastewater disposal systems is a geo-informational system (GIS), which electronically reflects the current information concerning the structure and technical and economic condition of the system and also provides the possibility of hydraulic calculations making.

Based on the electronic models of water supply and wastewater disposal systems, the existing condition of the system is evaluated and the future measures on its development and reconstruction are worked out.

The obtaining of reliable simulation results requires model verification, which, in its turn requires some statistical data on the operation of the system, as well as the measurements of pressure in the network.

The disagreements between the hydraulic characteristics of an electronic model and the operating characteristics of an actual system (determined by the results of full-scale measurements) may depend on the following reasons: incorrect network topology; mistakes in the data concerning the facilities of the system (for example: ground elevations, pipe lengths and diameters, operating characteristics of



regulating equipment, etc.); some changes in the hydraulic characteristics of the system elements occurring as time goes by (pipe friction growth, some changes in the Q-H operating characteristics of pumps); incorrect distribution of water flow rate in the system with regard to the actual water consumption; hidden leakages in the network.

The verification of a model is performed through the calibration stage implementation during the electronic model construction of a water supply network; it makes it possible to estimate the level of disagreement between the model and the actual characteristics (the flow rate and the pressure head) measured at certain points of the system.

Nowadays, foreign software systems (Mike Urban [2], Bentley [3]) apply optimization algorithms based on genetic algorithm. The analysis of Russian software products reveals the absence of such functions [4, 5, 6].

Taking into account that Russian software products are most popular on the territory of Russia (mostly as a result of their low cost) it is necessary to develop the algorithms aimed at the automatic calibration of electronic models with regard to Russian software.

2. The application of genetic algorithms for the problem solution

A genetic algorithm was used as an algorithmized calibration basis of an electronic model. Genetic algorithms are the adaptive search methods currently used for coping with the tasks of optimization [7].

Genetic algorithms are extensively used in many areas of activity, including the incomes management of air companies, biology, computational chemistry, optimization of mobile communication infrastructure, wireless technologies, financial mathematics, modeling of global temperature changes, and many others [8].

The following stages of the genetic algorithm operation are defined [9, 10, 11, 12]:

1. To specify an objective function for the specimens of the population
2. To set up the initial population
3. The beginning of iterative process:
 - a. Calculating the objective function for every specimen
 - b. Selection
 - c. Mating
 - d. Mutating
 - e. Formation of a new generation
 - f. Calculating the objective function for every specimen
 - g. If the conditions for the stoppage of an algorithm operation are met, the iterative process is ended, otherwise the iterative process is begun.

With the regard to the hydraulic models calibration, an objective function means the function which value makes it possible to estimate the disagreement between the actual operating characteristics of a water supply system and the characteristics of the system obtained as a result of simulation. Within the framework of a hydraulic model calibration, the term “specimen” implies a numerical series, summing up a certain characteristic of the model monotypic elements. Within the framework of this article, the pipelines of a water supply system are regarded as monotypic elements, while roughness is regarded. The population is a set of such N numerical series.

Within the framework of a hydraulic model calibration, the setting up of the initial population means the setting up of the N numerical series of a certain characteristic of the model monotypic elements. It should be mentioned that during the initial population establishing, characteristic values of the model elements are set at random. Selection means the selecting process the numerical series of a certain characteristic of the model monotypic elements, for the further participation in the operation of the algorithm, on the basis of the function value that reveals the level of disagreement between the model and the network actual operation. Mating is the process of “mixing” the characteristics values of two numerical series elements. The Mutating means changing the characteristic value of a random element in a numerical series for a random value. A new generation means newly composed N

numerical series resulting from the operation of the algorithm. The conditions of operation stoppage usually imply the selection of a certain function value whereby the difference between the model and the actual operation of the network is permissible.

The software system “ZuLu” was taken as a basis for the algorithmized calibration development of hydraulic models. At the moment it is most popular in Russia. It should be also mentioned that the popularity of this software results also from the fact that the development team of “ZuLu” software system gives their users a possibility to develop “ZuLu” software applications on a “do-it-yourself” basis, through the usage of ActiveX libraries of ZuLuXTools and ZuLuNetTools components.

A genetic algorithm-based program was made using the libraries of ZuluXTools and ZuluNetTools components. The program language is Visual Basic for Application (VBA).

3. The description of developed algorithm

As it was mentioned earlier, the disagreements between the model and the actual operation of the network may result from various reasons, including the changes in the hydraulic characteristics of pipe operation, such as: equivalent roughness and fouling.

Equivalent uneven-grained roughness is understood as the height of roughness projection that provides the resistance equal to the actual resistance of the pipeline being tested [13]. Pipe fouling implies the reduction of a pipe inner dimension resulting from physical, chemical and biological processes occurring inside the pipe. Figure 1 demonstrates the difference between the two represented hydraulic characteristics [14].

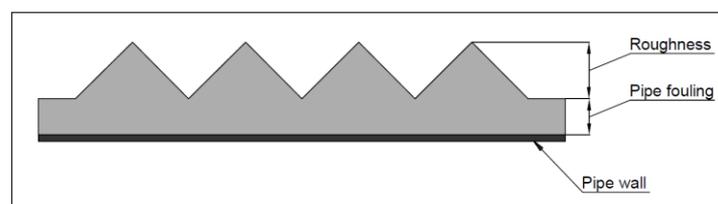


Figure 1. Pipe roughness and fouling.

This article reviews the calibration of the water supply system model by means of changing the pipe roughness.

3.1. Specifying the computational model of a network

An example of [15] was taken as a basis for the visual representation of algorithm operation. The computational model in Figure 2 comprises 1 water supply source, 18 conventional consumers and 10 circles of water supply system.

Let us assume all network pipelines are made of steel. We should divide this network into two parts conventionally. We also assume the pipes in different parts of the network, they are of different ages. The first part of the municipal network will have a considerable pipe age, the roughness value being 7 mm, while the second part of the network will contain the pipes of insignificant age, the roughness value being 1 mm.

It should be mentioned that if you specify a large number of unknowns, the operation time of genetic algorithm-based auto-calibrating functions is high enough. That is why [11] and [12] propose to preliminary group the pipelines on the basis of the material they are made of or on the basis of their other characteristics. In our case, in connection with the small size of the network and for the purpose of checking the developed algorithm possibilities, let us assume the maximum number of unknowns is the roughness value of 25 pipelines.

Taking into account the given roughness value, let us make a hydraulic calculation and record the hydraulic calculation pressure head values for all calculation nodes of the network under specified

conditions, as the actual values of the network operation (P act.). Afterwards we change the roughness of all network pipes to the value of 1 mm.

The under-mentioned algorithm was put in operation in order to select the pipe roughness values, while minimizing the objective function. In this case, as it was mentioned above, the answer was known in advance.

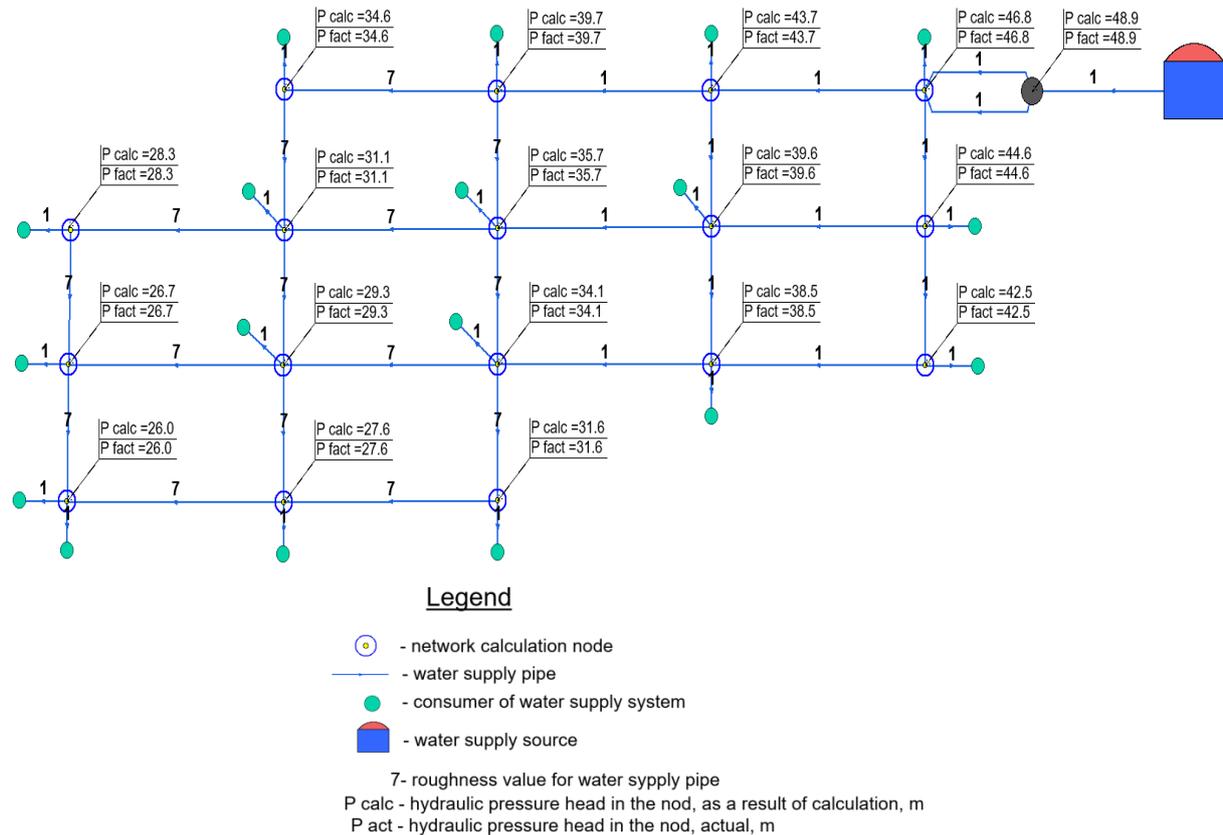


Figure 2. The computational model of a water supply network.

3.2. Objective function definition

From the mathematical point of view, the process of a water supply hydraulic model calibration consists of the E objective function minimization [16]:

$$E = \sum_{i=1}^P w_h (h_i^m - h_i)^2 + \sum_{i=1}^Q w_q (q_i^m - q_i)^2 + \sum_{k=1}^N w_p (p_i^m - p_i)^2 \quad (1)$$

where P and Q are the measurable values of pressure and flow rate; h_i^m is the measurable pressure in the i node; h_i - calculated pressure in the i node; q_i^m - measurable flow rate in the i pipe; q_i - calculated flow rate in the i pipe, p_i^m is an a-priori estimate, p_i is an a-priori estimate and N is the number of a-priori estimates, while w is the factor weight for pressure/flow rate and a-priori estimate.

In this case a simplification was used for algorithm development. A part of the E objective function was taken as a basis:

$$E = \sum_{i=1}^P w_h (h_i^m - h_i)^2 \quad (2)$$

Also within the simplification framework, the w factor weight was taken as 1 for every calculation node of the network within the framework of the given example.

3.3. Developing the initial population - the initial numerical series of roughness

The process of roughness initial numerical series development comprises the development of roughness series number, their roughness values are presented at random. In this case the roughness values in the series are within the range of the minimal – the maximal values specified by the user.

In the given example, the specified minimal and maximal roughness values amount to 1 mm and 7 mm correspondingly.

The initial population was developed in terms of genetic algorithm, i.e. a number of roughness series were developed and it was assumed this number amounted to 10 pieces. The initially specified number of series subsequently determines the algorithm operation time, as well as the algorithm convergence rate, expressed by the number of iterations.

3.4. The beginning of iteration process

3.4.1. *Computing the objective function for every pipe roughness series.* Using the established sets of roughness, a hydraulic calculation is made, as its result values of objective function are determined (equation 2) for every series (given in Table 1).

Table 1. Calculating the objective function values for a specified number of roughness series.

Sys	Ke	Ke1	Ke2	Ke3	Ke4	Ke5	Ke6	Ke7	Ke8	Ke9
3	1	6	3	6	1	4	7	7	6	6
5	1	6	5	6	2	5	3	6	7	2
7	1	7	6	3	4	5	3	3	3	1
9	1	1	7	6	2	2	5	3	3	2
11	1	7	6	6	2	3	4	4	6	5
13	1	6	2	5	2	2	6	4	5	4
14	1	7	7	4	2	6	2	1	2	2
66	1	3	3	2	6	4	4	3	7	4
68	1	7	3	2	2	2	2	6	2	7
15	1	3	5	6	4	6	4	1	2	1
17	1	5	5	4	1	2	6	2	1	4
18	1	6	7	4	4	3	3	1	7	5
20	1	3	4	2	3	4	6	7	5	3
21	1	6	1	7	1	2	5	7	4	7
23	1	5	5	7	7	1	5	3	3	6
24	1	2	2	3	1	1	7	5	4	1
26	1	3	4	4	3	1	4	6	5	7
27	1	6	5	6	7	2	7	3	6	1
29	1	5	4	6	1	5	7	5	2	4
30	1	7	1	3	6	3	5	6	3	5
32	1	1	2	4	7	1	1	1	7	4
34	1	3	5	3	3	7	6	7	1	2
35	1	1	3	4	6	7	6	7	3	7
36	1	7	4	7	1	3	4	1	5	2
37	1	3	7	6	4	6	4	1	4	5
Objective function values										
103.07	254.69	182.52	379.99	132.70	128.67	286.64	193.47	329.76	209.04	

3.4.2. *Selecting the roughness series for the subsequent algorithm operation.* Selection of roughness series for the subsequent operation of algorithm is performed on the basis of the objective function value. Within the framework of a developed algorithm, the method for roughness series selection of the roulette-wheel type was taken as a basis one.

A roulette-wheel selection method selects the roughness series by means of the n “starts-up” of the roulette. The roulette wheel contains one sector for every series.

In this case the i -th sector size is proportional to the relevant value of $P(i)$ % (relation between the objective function value of the i series and the objective function values sum of the roughness series), calculated according to the following formula:

$$P(i) = \frac{1}{f_i} \left(\sum_{i=1}^n \frac{1}{f_i} \right)^{-1} \quad (3)$$

where f_i is the objective function values of the i -th specimen. Value of $1/f_i$ was taken as a basis for the determination of the $P(i)$ value, because the lower the value of an objective function, the higher the convergence of the calculation model to the actual network operation is.

The “roulette wheel”, which sum amounts to 100 percent, is formed based on the $P(i)$ value calculated for every series. Every sector of the roulette is designated for a certain roughness series depending on the $P(i)$ value.

Every time “the roulette is started up”, depending on a random number value occurrence (the number within the range of [0; 1]), a single series of roughness is selected, in the interval which the random number occurred of. In this case the possibility for the roughness series to pass to the next algorithm step is equal to the $P(i)$ size.

The number of the roulette starts up was specified equal to: 2 x the number of series. The pool of roughness series (which basis of the algorithm operation will be subsequently carried out) is formed correspondingly. The results of roughness series selection are given in Table 2.

3.4.3. *“Mixing” the values of pipe roughness of different series.* The “mixing” of pipe roughness values is carried out on the basis of the roughness series that have passed to the next stage of algorithm operation after the selection stage. In this case the developed algorithm applies both the one-point and the double-point “mixing” of pipe roughness values depending on the random number occurrence.

If the random number value ≥ 0.5 (the number is within the range of [0; 1]), a double-point “mixing” of the two roughness series selected one by one, within the formed pool of series is carried out. The position in the first roughness series is selected at random and some part of this series is copied to the newly formed series. It should be mentioned that the copied fragment size depends on the $P(i)$ value. Correspondingly, the unoccupied positions in a newly formed series are filled from the second roughness series.

If the random number value is < 0.5 , a one-point “mixing” of two roughness series, selected one by one within the formed pool of series, is carried out. The copied fragment size of the first roughness series is determined depending on the $P(i)$ value. In this case the fragment from the end of the numerical series is copied to the end of a newly formed roughness series. Correspondingly, the unoccupied positions in a newly formed roughness series are filled from the second roughness set.

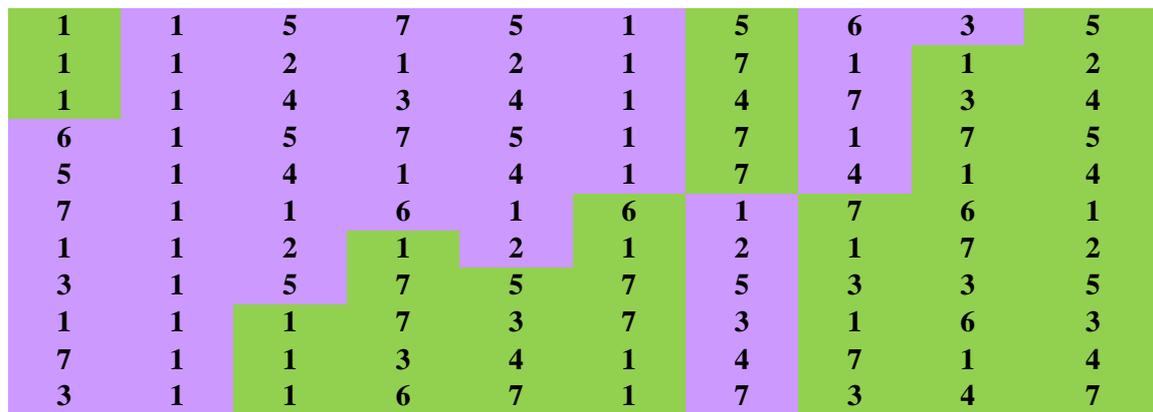
Table 3 contains the results of “mixing” the roughness values for the pipelines of different series, in accordance with the given example.

Table 2. Selecting the roughness series for the subsequent algorithm operation.

Series denomination	Ke	Ke1	Ke2	Ke3	Ke4	Ke5	Ke6	Ke7	Ke8	Ke9	
Objective function value $f(i)$	103.07	254.69	182.52	379.99	132.70	128.67	286.64	193.47	329.76	209.04	The pool of roughness series
$P(i)$ value	18.13%	7.34%	10.24%	4.92%	14.08%	14.52%	6.52%	9.66%	5.67%	8.94%	
Roulette wheel	18.13%	25.46%	35.70%	40.62%	54.70%	69.22%	75.74%	85.40%	91.06%	100.00%	
N of roulette starts up											
1		Ke1									Ke1
2						Ke5					Ke5
3	Ke										Ke
4					Ke4						Ke4
5			Ke2								Ke2
6	Ke										Ke
7					Ke4						Ke4
8						Ke5					Ke5
9			Ke2								Ke2
10			Ke2								Ke2
11	Ke										Ke
12								Ke7			Ke7
13			Ke2								Ke2
14							Ke6				Ke6
15										Ke9	Ke9
16		Ke1									Ke1
17									Ke8		Ke8
18					Ke4						Ke4
19		Ke1									Ke1
20			Ke2								Ke2

Table 3. The results of “mixing” the roughness values for the pipelines of different series.

Newly formed series									
N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
4	1	1	4	3	7	3	6	1	3
5	2	1	5	5	6	5	6	2	5
5	4	1	5	6	3	6	7	4	6
2	2	1	2	7	1	7	1	2	1
3	2	1	3	6	1	6	7	2	7
2	2	1	2	2	1	2	6	2	6
6	2	1	6	7	1	7	2	2	7
4	6	1	4	3	1	3	4	6	3
2	2	1	2	3	1	3	7	2	7
6	4	1	4	5	1	4	1	2	3
2	1	1	1	5	1	6	4	1	5
3	1	1	4	7	1	3	5	7	6
4	1	1	3	4	1	6	3	5	3
2	1	1	1	1	1	5	7	4	1



- Roughness values from the value of the 1-st numerical series

- Roughness values from the value of the 2-nd numerical series

3.4.4. *Changing the roughness values in a series for a random value.* The process of changing the roughness values is carried out on the series formed basis at the stage of roughness values “mixing”. This stage is carried out in order to provide step-by-step changes in the roughness series during the process of iterations.

The process of changing the values is carried out for every roughness value, if the value of random number is less than 0.04.

Correspondingly, the possibility of changing the value for every number in a preset roughness series amounts to 0.04. It should be mentioned the possibility of changing the values has a considerable impact on the operation of the algorithm. The “great” values of a change probability may result in a considerably prolonged operation time of the algorithm. Table 4 contains the results of the process of changing the roughness values in a series.

Table 4. Changes in roughness values.

Newly formed series									
N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
4	1	1	4	3	7	3	6	1	3
5	2	1	5	5	6	5	6	2	5
5	4	1	5	6	3	6	7	4	6
2	5	1	2	7	4	7	1	2	1
3	2	1	3	6	1	6	7	2	7
2	2	1	2	2	1	2	6	2	6
6	2	1	6	7	1	7	2	2	7
4	6	1	4	3	1	3	4	6	3
2	2	1	2	3	1	3	7	2	7
6	4	1	4	5	1	4	1	2	3
2	1	1	1	5	1	6	4	1	5
3	1	1	4	7	1	3	5	7	6
4	1	1	3	4	1	6	3	5	3
2	1	1	1	1	1	5	7	4	1
1	1	5	7	5	1	5	1	3	5
1	1	2	1	2	1	7	1	1	2
1	1	4	3	4	1	4	7	3	4
6	1	5	7	5	1	7	1	7	5
5	1	4	1	4	1	7	4	1	4
7	1	1	6	1	6	1	7	7	1

1	1	2	1	4	1	2	1	7	2
3	1	5	7	5	7	5	3	3	5
1	1	1	7	3	7	3	1	6	3
7	1	1	3	4	4	4	7	1	4
3	1	1	6	7	1	7	3	4	7

 - Changes in roughness values in a specified series

3.4.5. *Calculating the objective function for every newly formed series.* Subsequently the new roughness series are brought into the calculation layer database and a hydraulic calculation is made; the values of the objective function for every new series are determined according to this hydraulic calculation. Table 5 contains the results of objective function calculation for every new series.

Table 5. Results of objective function calculation for every new specimen.

Sys	Ke	Ke1	Ke2	Ke3	Ke4	Ke5	Ke6	Ke7	Ke8	Ke9
3	4	1	1	4	3	7	3	6	1	3
5	5	2	1	5	5	6	5	6	2	5
7	5	4	1	5	6	3	6	7	4	6
9	2	5	1	2	7	4	7	1	2	1
11	3	2	1	3	6	1	6	7	2	7
13	2	2	1	2	2	1	2	6	2	6
14	6	2	1	6	7	1	7	2	2	7
66	4	6	1	4	3	1	3	4	6	3
68	2	2	1	2	3	1	3	7	2	7
15	6	4	1	4	5	1	4	1	2	3
17	2	1	1	1	5	1	6	4	1	5
18	3	1	1	4	7	1	3	5	7	6
20	4	1	1	3	4	1	6	3	5	3
21	2	1	1	1	1	1	5	7	4	1
23	1	1	5	7	5	1	5	1	3	5
24	1	1	2	1	2	1	7	1	1	2
26	1	1	4	3	4	1	4	7	3	4
27	6	1	5	7	5	1	7	1	7	5
29	5	1	4	1	4	1	7	4	1	4
30	7	1	1	6	1	6	1	7	7	1
32	1	1	2	1	4	1	2	1	7	2
34	3	1	5	7	5	7	5	3	3	5
35	1	1	1	7	3	7	3	1	6	3
36	7	1	1	3	4	4	4	7	1	4
37	3	1	1	6	7	1	7	3	4	7
Objective function values										
	124.51	62.67	32.88	247.33	220.01	83.23	234.14	139.06	160.73	176.19

Table 5 reveals that the objective function values of roughness series was reduced at the first stage of the algorithm operation. The minimum value for the 3-rd series is 32.88. Nevertheless, this value is not sufficient for the completion of the iteration process.

3.4.6. *The end of iterative process.*

Within the framework of the given example, the number of iterations was limited to 1 000 pieces. It should be mentioned that algorithm automatically terminates the iterations, when the minimal value of

the objective function less than 0.8 was found. This is equivalent to the average difference between the model and the actual network operation in the context of the free head - 0.22 m.

4. The results of algorithm operation

As a result of algorithm operation, during 256 iterations, a series of roughness that met the specified requirement was found. The value of objective function was $E = 0.65$.

Figure 3 shows the changes in the minimal value of the objective function of specimens for iterations, beginning with the obtained value of the first iteration. Figure 4 shows the algorithmized calibration results.

It should be mentioned that the pipe roughness values obtained as a result of calibration (Figure 4) are equal to the assumed initial roughness values or approaching them (Figure 1). Full compliance of assumed initial roughness values with the values obtained as a result of calibration, may be achieved through the reduction in the required minimal value E of an objective function, as a condition for the algorithm operation termination. Nevertheless, as a result, the algorithm requires a greater number of iterations and correspondingly, the program operation time is increased.

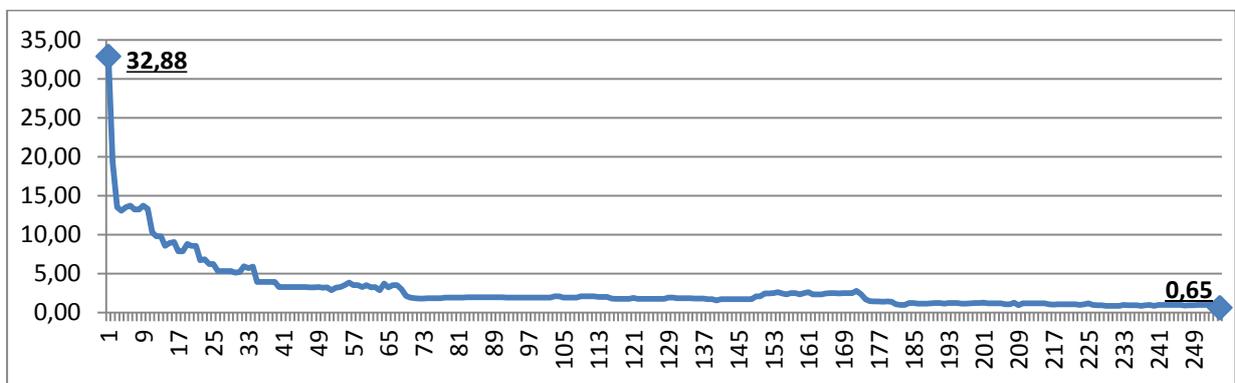


Figure 3. The changes in the minimal value of objective function of specimens vs. iterations.

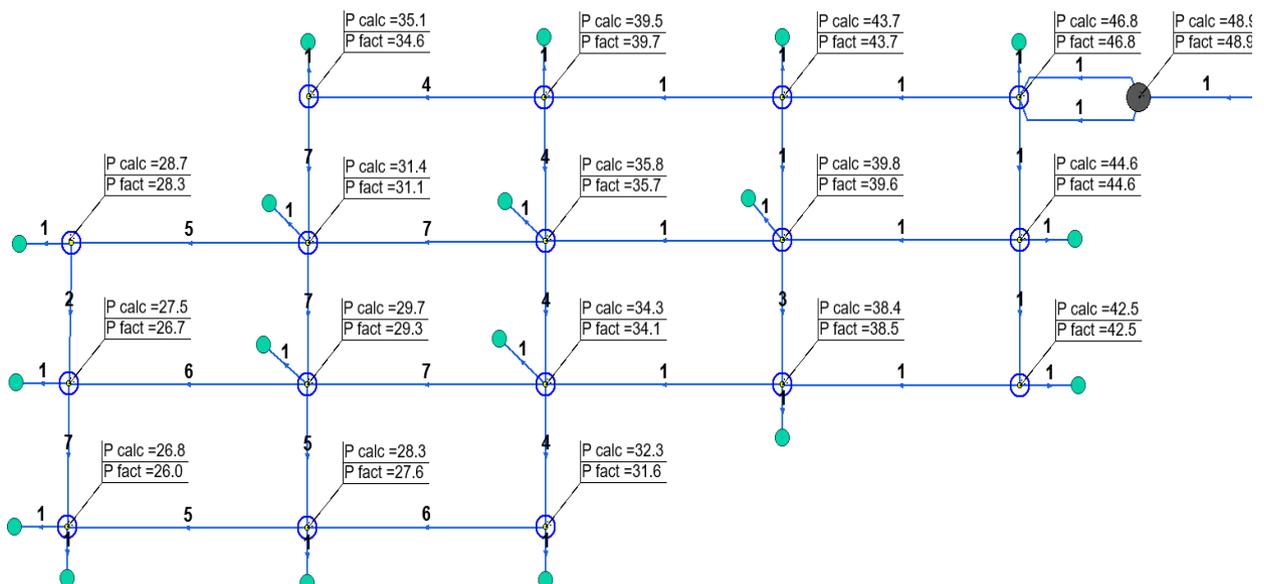


Figure 4. The results of electronic model calibration.

5. Conclusions

On the basis of genetic algorithm, an algorithm for the automatic calibration of electronic models for roughness selection carrying out was developed; the specified actual head values of water supply networks were specified.

The algorithm is developed based on Visual Basic for Application language, applying Excel tables, ActiveX library and “ZuLuNetTools” components; it is applicable for “ZuLu” software.

The operation of the algorithm resulted in the selection of such a pipe set roughness values that provided the minimal difference between the model and the actual values of the hydraulic pressure head in a specified network.

The algorithm operation was tested based on an example from technical literature. The assumed water supply network comprises 1 water source, 18 conventional water consumers and 10 circles of the water supply system. The average hydraulic pressure head difference between the model and the specified network was 0.20 m.

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