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A methodology for designing industrial water networks

Gennady Statyukha, Arcady Shakhnovsky, Jacek Jeżowski, Alina Jeżowska, Aleksander Kvitka
National Technical University of Ukraine “Kyiv Politechnical Institute”, 37 Peremohy ave., Kiev, Ukraine. kxtp@xtf.ntu-kpi.kiev.ua
Rzeszów University of Technology, Rzeszów, Poland. E-mail:ichjj@prz.edu.pl

The paper deals with some practical aspects of designing and implementing industrial water networks in process plants. The main issues addressed are: application of statistical analysis to the study of initial data collected at the plant for designing optimal water networks, simulation-based estimation of expediency of optimized water networks implementation. Methods developed are applicable for water usage networks with treatment processes, i.e. water networks with reuse and regeneration as well as wastewater treatment facilities.

1. Introduction

Despite achievements in water network (WN) design methods there are still problems with their industrial applications. This is caused by the fact that existing approaches are aimed at designing the network for fixed (nominal point) data. However, the data they require are highly uncertain in industrial practice. Hence, the network, which is considered optimal for nominal point and current cost parameters, may be expensive or difficult to control and operation under varying conditions in industry. In order to circumvent the problems we suggest the following three-stage procedure:

1. data preparation by statistical analysis.
2. design of WN using existing approaches, and finally;
3. networks evaluation.

In this contribution we will concentrate on steps 1 and 3. The basic methods in design of experiments for preliminary treatment of data for “input-output” regression models identification are addressed e.g. in Montgomery (1991). Mathematical methods for data reconciliation, detection, identification and abatement of systematic bias and gross errors effect in process data observation were examined by Bagajewicz (1996), Sanchez at al. (1999), Bagajewicz and Jiang (2000), Soderstrom at al. (2001) to list a few. In this paper we will make use of these achievements by adapting them to data preparation and validation for WN design under uncertain data. Additionally, to account for uncertainties of economic parameters and changes of environmental regulations a simulation of various scenarios was applied to test and analyse the feasibility and operability of designed WN.

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The issue of uncertain data in WN problem has been addressed in relatively few papers. Such works dealt mainly with designing approaches to reach robust or flexible solutions. The seminal work was likely that by Suh and Lee (2002) on designing robust water using systems. Then, Tan and Cruz (2004) proposed a simultaneous approach by one stage superstructure optimisation. Uncertainties were handled by symmetric fuzzy LP model, which is based on LP model for certain data. Al-Redhwan et al. (2005) applied sequential method with NLP optimization to deal with uncertainties. All these methods require complex optimization-based methods and did not address the question of determining the necessary data. This problem was addressed in papers by Foo et al. (2006) and Tan et al. (2007). The former work dealt with non-mass transfer processes. The latter developed the approach based on simulation of networks with fixed structure under stochastically disturbed parameters.

This work contributes to the problem of data preparation and, also, proposed overall design procedure. Similarly to paper by Tan et al. (2007) this approach is aimed at mass transfer operations. Multiple contaminants are accounted for. First we present data preparation techniques and, then, will proceed to network evaluation problem.

2. Statistical Treatment of WN Design Input Data

Design of optimal water networks requires the following basic information for each water using process within a network: maximum permissible concentration of contaminants at process inlet and outlet and, also, mass load of contaminants that should be transferred to water streams.

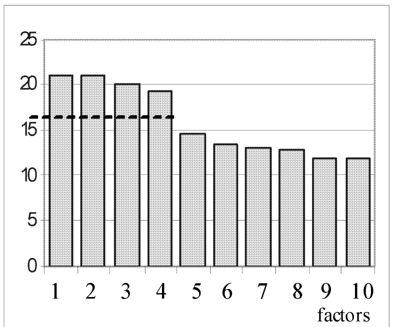
There are doubts among practitioners whether the data on mass loads can be estimated with sufficient accuracy – see e.g. Bagajewicz (2000). Hence, statistical analysis is necessary to assess their reliability. Furthermore, species transferred to water in water using processes have to be known ahead to final design. Their number influences greatly the design and, also, operation problems. Hence, reduction of the number of contaminants that have to be taken into account will be considered. This issue will be addressed first.

2.1. Ranking of contaminants

While collecting initial data about the plant on the stage of a preliminary analysis, decisions are taken about the conventional grouping of water usage processes, as well as about grouping of the contaminants. The decisions also concern ranging of the contaminants and screening the minor ones. Therefore, the additional problem of statistical evaluation of consistency in expert judgments appears. The concordance of experts' opinions is checked with the coefficient of concordance by the Pearson test for concordance.

The importance of each contaminant can be judged by the rank – a place which is given by an expert (proficient) to this contaminant while ranging all contaminants taking into account their supposed (quantitatively unknown) influence. The information for the ranging can be obtained by polling practitioners, analysing articles, case studies etc. In the process of polling specialists the special questionnaires (or polling lists) containing factors (here contaminants) are filled in. Filling a questionnaire, the expert determines

the location of contaminant in the ranged row. On processing the polling lists the compact table is finally drawn up.
A hypothesis about the experts' opinions concurrence can be accepted, if the theoretical (tabular) value of $\chi^2{}_T$ (taken from the table of chi-squared distribution with certain confidence level and the specified number of degrees of freedom) is less than calculated value of the criterion (χ^2). After estimating experts' opinions concurrence, the diagram of grades should be constructed (contaminants in the order of decreasing sums of ranges) – see Fig.1. In many cases the diagram of grades allows eliminating of some contaminants. For instance, in Fig. 1a, contaminants from 4 up to 10 can be excluded from further consideration, by relating their influence to the noise field. Note that the diagram in Fig. 1a is taken from a case study for concrete making facility. The most significant contaminants in this case are: pH, Salts, Sulfates, COD.



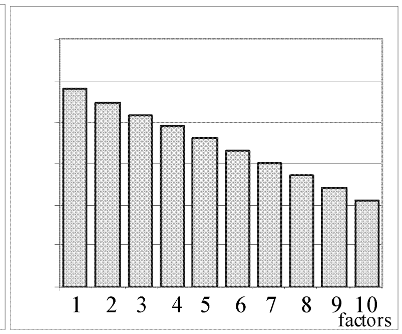


Fig. 1. Examples of screening the minor contaminants with diagram of grades: a – nonlinear distribution of ranks; b – equi-probability distribution of ranks.

If the distribution of factors in the diagram of grades is uniform (e.g. Fig. 1b), it is recommended to include all contaminants.

2.2. Estimating of Water Usage Units' Parameters

Here, we will concentrate on estimation of mass load of contaminants. For steady-state conditions, we can apply averaged, within predetermined time intervals, experimental data (Bagajewicz and Jiang (2000)). The mass load of contaminants can be, then, calculated from mass balance equation (1) of contaminant "c":

$$m_c = f(Cin_c - Cout_c) \tag{1}$$

where m_c is mass load; f is the water flow rate (measured parameter); Cin_c and $Cout_c$ are inlet and outlet concentrations, respectively (measured parameters).

To illustrate the procedure for estimating the averaged mass loads we present here the industrial example of pharmaceutical plant taken from Jeżowski et al. (2008). The contaminant was suspended solid phase. The measurements of inlet concentration (*Cin*), outlet concentration (*Cout*) were performed for bottle washing machine. 78 samples were taken. At the same time we measured total flow rate (*f*) for each sample. The measurements of parameter *f* are shown in Fig. 2.

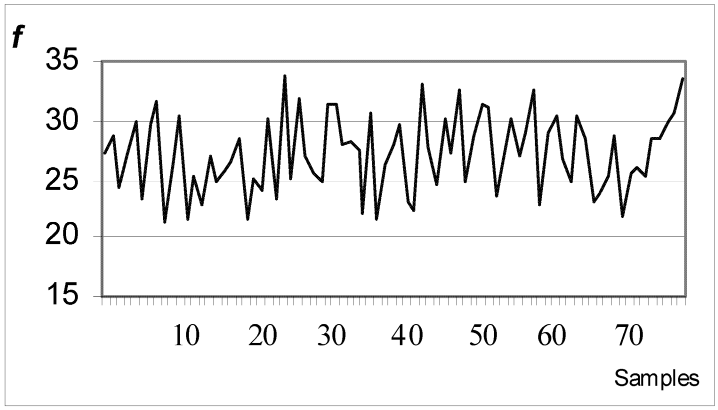


Fig. 2. Values of flowrates for bottle washing machine – 78 samples

First, for these directly measured parameters their compliance with the normal distribution was performed. The test for the compliance allows determining whether the average of a large number of independent measurements of a random quantity tends toward the theoretical average of that quantity according to the statistical Law of large numbers and Central Limit Theorem. In absence of systematic bias and gross errors of measurements the mean of Gaussian random variable agrees with the observation data. The verification of Gaussian hypothesis for measured values can be done with the Pearson test for concordance. For the case of the bottle washing machine the calculated value of Pearson criterion is χ_P^2 = 3,1286 (with significance level 5% and 4 degrees of freedom). Theoretical value of Pearson criterion amounts to χ_T^2 = 9,5. So, the distribution of the experimental data can be considered normal. The conclusion is that the calculated sample average $\overline{m}$ of the measurements can be accepted as reliable data for WN design.

3. Simulation-based evaluation of WN design feasibility and operability

To prove the feasibility of WN retrofit design the following simulation-based scenario approaches were proposed:

1. Economic profitability studies by changing, within some ranges, the parameters, which significantly influence cost (*economical test*).
2. Simulation of WN operation for selected most severe conditions (*feasibility test*).

Due to space limitations only the second issue will be addressed in this contribution. Feasibility test focuses on the simulation of different modes of WN operation before and after the optimization (for retrofit) including the cases of violations of the standard operation mode (for retrofit and synthesis). In this work the assurance (safety) factor δ =10% was included in the WN optimization procedure. Thus, the aim is to investigate the adequacy of such level of assurance. For modeling of the flows composition in WN the simulator programs (Hysys/UniSim Design, Aspen Plus) were used. The computer simulation included the following stages:

1) Presentation of network (water users, flowrates mixers and splitters, water tanks, pumps) in the simulator format.
2) Simulation of startup and operation of the WN in the regular mode.
3) The study of the network operation under imposed disturbances.

The approach provides also the solution of the inverse problem: determination of maximum possible concentration changes in every water user which do not affect the WN technological mode at the prescribed value of assurance factor.

The WN in oil refinery from Bagajewicz at al. (2000) is presented as a brief example. There are four groups of contamination in water: hydrogen sulphide, ammonia, inorganic salts, organics (COD). Eight basic water users exist. The WN was optimized using the procedure from Shakhnovsky at al. (2004). The optimization provides 24.3% of fresh water saving (with assurance factor 10%).

Fig. 3 presents the comparison of inlet concentrations of water usage processes (*Cin*) in the optimized WN under the normal operation conditions and in case of disturbance. The step disturbance by increasing the mass load of key contaminant (COD, mgO_2/l) by 69.2 mg/l in water usage process #1 was made. Notice that in Fig. 3 not all water users are shown for clarity sake (parameters of processes 7 and 8 subject minor changes).

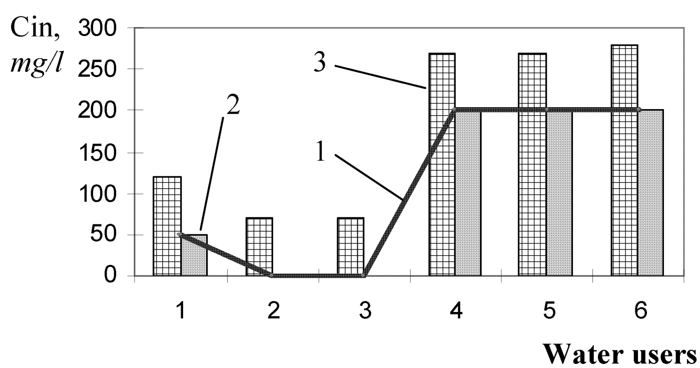


Fig. 3. Inlet concentrations of COD in the optimized WN: 1 – limiting values from input data; 2 – concentrations under the normal operation conditions; 3 – concentration after step disturbance.

As one can see from Fig. 3, violation of the operation mode of one water user can result in violation of the concentrations in almost all units of WN. Additionally, this increase is larger in some processes than that in process #1. The propagation of disturbances caused that the concentrations exceed the tolerances for the safety factor.

4. Summary

The application of the simple statistical approaches of data preparation for designing industrial water networks was presented for two issues:

- The data ranking procedures were applied to expert based ranging of the contaminants and screening the minor ones.
- Normality tests of experimental sample data were used to account of uncertain parameters of water usage units' models.

Systematic approaches for estimation optimized industrial water usage networks efficiency were presented and considered in more details. Industrial case studies with processing of experimental data for WN design proved the efficiency of the techniques used.

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