Development of Computer Science Tools for Solving the Environmental Engineering Problems

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Abstract
In the paper we present three software tools developed at the Systems Research Institute for solving some environmental engineering problem. These programs are: software package for the identification of dynamic linear objects, computer model of a communal wastewater treatment plan, and hydraulic model of a communal water network. All of them have been successfully applied with the aim to improve the management of waterworks in Poland.

1. Introduction
Environmental engineering is an area where very well known tools of applied mathematics, control theory, systems analysis and information technology can be combined and successfully used. The tool characteristic for these areas of science, such as mathematical modelling, optimization methods, systems identification, computer simulation, statistical data analysis, data mining, knowledge management, computer-aided decisions making systems etc., can be used in solving the tasks which arise in the investigation of environmental problems. We can use all these tools in two ways: either we can use and possibly adapt the already established methods, algorithms and computer programs taken from other disciplines in order to solve some new environmental tasks or we can develop new specific tools for solving these problems. The both approaches have got their advantages and disadvantages. The first approach is easier and seems to guarantee the faster solution of the problems investigated, but on the other hand it restricts the possibility of application of these algorithms and programs. Usually these programs, due to their close form, are not flexible enough to solve all of the new problems. The second approach is much more difficult and time consuming but it allows introduction of our own modifications of the algorithms and, as a result, these algorithms fit better to the new problems.

At the Systems Research Institute of the Polish Academy of Sciences the problems of environmental engineering and protection are theoretically and practically investigated for about twelve years (Hryniewicz and Studzinski, 2003). The development of new original mathematical and software tools for solving environmental problems has been accepted as the fundamental principle. The experience collected from many real applications has confirmed the rightness of this decision.

The mathematical models and software tools for solving environmental problems have been developed in the Systems Research Institute during many years. They can be used as stand-alone systems, but more often they are used together in different configurations. In the paper we would like to present three software packages developed at the Institute that have been used as principal components of the computer aided decisions making systems developed for the control and management of the wastewater treatment plants and communal water networks. First of these packages is a general-purpose software package used for the identification of linear dynamic systems. In the next section we present its application for the description of the sewage purification process. Software for the identification of dynamic systems described by differential equations is used for the identification of linear dynamic systems. In the next section we present its application for the description of the sewage purification process. Software for the identification of dynamic systems described by differential equations is used for the identification of linear dynamic systems.
the construction of a general computer model of the wastewater treatment processing. Software package developed for this particular purpose is very briefly described in the fourth section of the paper. The water treatment process is only one part of a communal water system. Another important part of this system is the water network. A short description of the computer model of this network which has been developed at the Systems Research Institute is presented in the fifth section of the paper. Some conclusions are presented in the last section of the paper.

All software packages mentioned in this paper should be regarded as a part of a large computer-aided decision support system which is now under development (Studzinski and Bogdan, 2000; Studzinski, 2002; Hryniewicz and Studzinski, 2005).

2. Identification of dynamic linear objects

The first software tool described in this paper is the package of the program for the Identification of Dynamic Linear Objects (IDLO). It consists of several modules for smoothing the noisy measurements data, for mathematical modelling of discrete and continuous objects using the least squares methods such as Kalman’s, Clarke’s, maximum likelihood, linear and nonlinear regression algorithms, and for statistical analysis of the calculation results to evaluate the quality of the models received. Thanks to these programs it is possible to calculate the continuous dynamic models of very high orders using the noisy impulse response data of the object investigated and its discrete description on the first stage of the identification approach. This approach makes possible to develop complex continuous models with the help of their discrete descriptions and it was also developed at the Institute. Because of its two-stage procedure it is called Indirect Identification Method.

The mathematical form of discrete linear models taken on in the package programs is following:

\[ y_n = -A(x^{-1})y_n + \sum_{j=1}^{M} B_j(x^{-1})u_m + v_n \]  

where: \( M \) is the number of model inputs, \( A(x^{-1}) \) and \( B_j(x^{-1}) \) are the difference operators of the model output and inputs, where \( A(x^{-1}) = a_0 x^{-1} + \ldots + a_M x^{-M} \) and \( B_j(x^{-1}) = b_{j0} + b_{j1} x^{-1} + \ldots + b_{jk} x^{-k} \). The orders of operators \( A(x^{-1}) \) and \( B_j(x^{-1}) \) are denoted as \( R \) and \( P (j=1, \ldots, M) \), respectively, and \( v_n \) denotes the component of the correlated noise.

Now, let us present the application of the model (2.1) in the analysis of sewage treatment systems. The package programs that are used for the identification of (2.1) have been applied to develop the hydraulic models of the primary and secondary settling tanks and of the activated sludge chambers of a mechanical-biological wastewater treatment plant and to find out the active tanks volumes which appeared to be very different from the geometrical ones.

The modeled dynamics of the sewage flow in a tank of the investigated wastewater treatment plant can be described with the following balance equation:

\[ \frac{dC}{dt} = \frac{Q(t)}{F}(C_{in} - \varepsilon(t)) - \varepsilon(t) \]  

where: \( F \) is the active volume of the tank, \( \varepsilon \) is concentration of any pollution component to be found in the sewage, \( \varepsilon \) is the current time, \( Q(t) \) is the sewage inflow to and outflow from the tank, \( C_{in} \) is concentration of the pollution investigated to be found in the sewage inflow, \( \rho \) is the shift between the
measurement time of the pollution concentration in the sewage inflow to and the measurement time of the pollution concentration in the sewage outflow from the tank.

Equation (2.2) is a linear differential equation with constant parameter $V$ and variable parameter $Q(t)$. There are several reliable methods for identification of linear dynamic objects with constant parameters and there is a lack of methods for objects with variable parameters. Therefore we transform (2.2) to the form with constant parameters replacing the time coordinate $t$ by a new variable $\tau$ depending on the flow $Q(t)$. As a result we get from (2.2) the following linear equation with only one constant parameter $V$:

$$\int \frac{d}{d\tau} \left( c(\zeta) - t \right) \cdot c(\zeta) \, d\tau$$

(2.3)

The analytical solution of (2.3) is the function:

$$c(\zeta) = e^{\frac{\zeta}{\tau_0}} + \frac{1}{\tau_0} \cdot \int_0^{\tau} e^{-\frac{\zeta}{\tau_0}} \cdot c_n(t - \tau_0) \, d\tau$$

(2.4)

where $C$ means the initial conditions of the equation. The effective methods of dynamic objects identification are known mostly for difference models and because of that we transform the continuous function (2.4) to its discrete form:

$$\int \left( e^{\frac{\zeta}{\tau_0}} + \frac{1}{\tau_0} \cdot \int_0^{\tau} e^{-\frac{\zeta}{\tau_0}} \cdot c_n(t - \tau_0) \, d\tau \right)$$

(2.5)

where $k = (\tau_0 / \Delta_n + 1) \cdot \Delta_n = \Delta_n (\zeta = \zeta_{n-1})$, $n = 1, 2, ..., N$ and $N$ is the measurements number. For $\Delta_n(\zeta) = \Delta_n = \text{const}$ one can write (3.5) in the form of the following difference equation:

$$c_n = a c_{n-1} + b n_{n-1}$$

(2.6)

where $c_n = c(\zeta_n)$, $c_{n-1} = c(\zeta_{n-1})$, $n_{n-1} = c_n(\zeta_{n-1})$ and $a = e^{\frac{\Delta_n}{\tau_0}}$ and $b = 1 - e^{\frac{\Delta_n}{\tau_0}} = 1 - a$.

Equation (2.6) is a discrete form of deterministic equation (2.3) that can be transformed to the statistic form needed by using the identification methods from IDLO package. To do it we accept that the marker measurements in the tanks are made with an error component $e_n$:

$$y_n = c_n + e_n$$

(2.7)

and then we get from (2.6) and (2.7) the following linear discrete equation:

$$y_n = a y_{n-1} + b n_{n-1} + e_n - a e_{n-1}$$

(2.8)
that can be used for calculating the active volumes of the tanks investigated with the programs from IDLO package.

Some exemplary results of the identification of the active volumes of the main tanks of a real wastewater treatment plant according to the equation (2.6) are shown in figure 2.1. As the coordinate notations there $t$ denotes time [in hours] and $c$ denotes concentration of a marker introduced into the sewage inflow. The measurement of concentration of a marker instead of the sewage pollution components makes the identification process easier and more reliable. The concentration values shown in figure 2 have been scaled according to the requirements of the identification methods applied.

![Fig. 2.1 Modeling results for the primary settling tanks.](image)

One can see on this figure a very good fitting of the model to the measurements data what is the evidence of the excellent quality of the identification approach and the programs developed. Similar results have been obtained for the models of primary settling tanks and activated sludge chambers.

### 3. Mathematical modeling of wastewater treatment processes

The second program presented here is the physical model of a communal wastewater treatment plant describing the mechanical and biological processes of the sewage treatment which are realized in the separated tanks of the plant. The model called STS for Sewage Treatment Simulation consists of ca. 300 ordinary differential equations and its structure and general contents are based on the ASM1 (Activated Sludge Model No. 1) model from IWA (International Water Association) (Henze et al., 1987) and on the ARASIM model developed at the University in Passau (Schmidt, 1994). However, it also contains original components developed at the Systems Research Institute (Studzinski, 2005).

The physical model consists of several sub-models describing the main systems of the wastewater plant such as primary and secondary settling tanks, activated sludge chambers and external recirculation system. It describes the main processes occurring in the object such as sewage mixing and wastes sedimentation in the primary and secondary settling tanks, and the reduction of organic and nitric wastes in the sludge chambers. To develop the model the waste fractions in the sewage and the biological processes occurred there have to be defined. We have defined 15 waste fractions and 10 processes. The sub-models of the physical model were formulated in the form of compartment models (Eisenfeld, 1979) The sub-model for the primary settling tank consists of 4 compartments, the sub-model for the secondary settling tanks
consists of 12 layers and the sub-model for the activated sludge chamber consists of 4 compartments. In each compartment the chosen fractions participating in different processes were described by separated nonlinear differential equations and this resulted in the equations number mentioned above for the whole model. The general structure of the physical model developed is shown on figure 3.1.

This model has been used to simulate the operation of the real treatment plant and to verify with the help of simulation runs some control signals generated by other models being the modules of an information system supporting the human operator of the sewage treatment process. To make the physical model useful the model calibration was done using some data published in the literature and the measurement data obtained from an experiment performed in the wastewater plant. In this way all parameters of the model equations have been estimated. The conclusion from using the physical model for operating the wastewater plant is that such model, because of its high complexity, is not suitable for optimization tasks and can be only used for separated simulation runs. To solve more sophisticated problems like forecasting, optimization and control more simple and less time consuming models must be worked out, for example the models described with the time series or neuronal nets. Such models have been either set up for the wastewater plant investigated and their consideration in the information system constructed is shown on figure 3.2.
4. Mathematical modeling of communal water networks

The third and last product developed at the Institute that we present in this is the hydraulic model of a communal water network called WNS for Water Net Simulation. The model consists of a set of linear and nonlinear algebraic equations describing the flows and pressures of the water in the pipes and nodes of the considered water net. These equations are calculated using an iterative method developed by Cross especially for solving very big equations systems formulated for water nets. Into the program also an algorithm for optimization of water nets and another one for generation of the work scenarios for filling and emptying the water net retention tanks are included.

There are on the market some water net models like the EPANET model (http://www.epa.gov/nrmrl/wswrd/epanet.html) but the benefit of development of the own program consists of the possibility of working out and testing different modelling algorithms like the Cross algorithm (Tamura, 2000) as well as of coupling with the modelling some optimization and control algorithms what is not possible with the standard models. The WNS model has been calibrated and tested on the basis of some real data from a communal waterworks. It was further introduced as a component into an information system supporting the management of a communal water network.

To make the model calibration possible a monitoring system for getting the data and a GIS system for visualization of the water-net and generation of the water-net graphs used by the model have been introduced in the investigated waterworks. In this way all components of the information system supporting decision process of the water-net operator were prepared and such system could have been designed and developed.
5. Conclusions

All the programs developed at the Systems Research Institute were made on demand of the enterprises dealing with the environmental engineering problems, and they have been successfully tested in the practice by their users. Positive results of putting our own programs into practice proved that the decision
taken at the Institute to develop new, own software products, in spite of the existence of other similar software available on the market, was correct. This approach let us be more flexible in solving particular problems of our customers.

Bibliography


http://www.epa.gov/nrmrl/wswrd/epanet.html.

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