Advanced control system for municipal wastewater treatment plant

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Abstract
In this paper a proposal of a predictive control of a wastewater treatment plant was presented. Proposed multilayer control structure is composed of direct access PID controllers and supervisory DMC (Dynamic Matrix Controller) predictive controller. Basic idea of applied multilayer control structure was to use DMC controller to predict and compensate present and future measurable disturbances (flow and load of a crude sewage). Validation of presented approach was performed with use of computer simulations with different disturbance scenarios. The research was based on data obtained from a wastewater treatment plant in Resovia.

1. Introduction
Currently, advanced control systems are becoming to play ever greater role in wastewater treatment plants. They can improve the technological (increasing the capacity of sewage treatment plants, wastewater treatment efficiency) and economic indices (lower energy consumption, the ability to avoid high penalties for the discharge of untreated sewage). In this case, it appears appropriate to take action to improve the functioning of existing facilities through their analysis and introducing appropriate improvements in both the modified treatment technology and the use of modern control algorithms.

In the Polish treatment plants, the classical solution often automatic control is a system that maintains a steady level of oxygen concentration in the cells with activated sludge (i.e. in the bioreactor) and the rate of recirculated sludge. In the treatment systems with a two-stage nitrification technology, sufficient degree of internal recirculation is also controlled.

A typical municipal sewage treatment plant works in the circadian rhythm. It means that in one day character of wastewater flowing into a treatment plant varies significantly. The main parameters of raw sewage can in general be taken: flow rate and the composition and concentration of impurities contained in them. Under normal circumstances, these parameters are changing rapidly and to a large extent, periodically during the day. To obtain the optimal technological process the setting of controllers should be changed periodically. This task is usually to the operator of the technological process. Therefore, experience and knowledge of the object determines the effectiveness of his actions. In case of bad decisions the person handling the process often comes to disruption of the technological process and consequently to deterioration of the treatment.

The paper presents a concept of a layered control system that provides the proper level of oxygen concentration in the activated sludge chambers. The direct control is continuously performed by PID controllers. Set points for these controllers is periodically generated by a parent predictive control. Predictive Control is a control algorithm, that usually based on determining the control signals - control trajectory, providing the desired output signal changes in a specified time interval called the control horizon. This requires a prediction of the input signals and hence the name - predictive control.

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Synthesis of the proposed control algorithm in real conditions (i.e., based on the process) would be extremely lengthy, costly, and, what seems to be most important, threaten to distort the technological process in the case of any mistakes. Therefore, to develop a control system a mathematical model of the process and the proposed algorithms were used. Calculations presented in this paper were performed with use of data obtained from the municipal sewage treatment plant in Resovia. Municipal waste water treatment plant in this city can be treated as a research object representing a large group of mechanical-biological treatment plants.

2. **Activated sludge technology applied in Resovia WWTP**

An activated sludge process, that was applied in considered WWTP, constitutes of several phases of sewage treatment processes. It contains an introductory mechanic purification section, followed by biological treatment and final sedimentation tank with recycling stream of activated sludge.

Technological process of the municipal WWTP can be divided into several sub-processes: at the beginning crude sludge is mechanically filtered by grit separator and next transferred to preliminary settling tank, to reduce mineral fixed components. The second stage is a biologically treatment of sewage, to reduce nitrogen components by activated sludge. At the last is the second sedimentation process, where some effects of biochemical processing (dead bacteria and heavy suspension) are divided from sewage flow by sedimentation and most flow of activated sludge is recovered to biochemical phase of WWTP process.

A concentration of oxygen in the vessels and the quantity and age of the activated sludge can influence the treatment processes and consequently the reduction of organic compounds and nitrification. Diagram of sewage treatment plant in Resovia is shown in Figure 1:

![Schema of Resovia waste water treatment plant.](image-url)

Figure 1

Schema of Resovia waste water treatment plant.
3. **Control task**

The sewage treatment control task seems to be the most obvious problem posed economical - lowest cost of system operation. Lowest power consumption, might be equivalent to the following task - the lowest expenditure of aeration fans and the lowest flow rates in the recirculation pumps that would ensure the necessary level of concentration of heterotrophic and autotrophic bacteria. This is a apparently simple approach. This job requires a minimum of flow rate which can result in the lack of regulation reserves in times of large disruption, such as during heavy rainfall which may lead to washout of activated sludge.

Prior to the development of control algorithms for the sewage treatment plant, the main objectives of the control should be presented. The first one will be to reduce concentrations of pollutants in treated wastewater. It is related to increased operating costs resulting from the blowers supplying oxygen into the chamber with activated sludge, or pumps responsible for the recirculation of sludge. Thus, in the sewage treatment process control algorithms should provide a reduction of the process variables to a level acceptable by the Ministry of Environmental Protection (Polish Ministry of Environment, 2002), with minimum energy consumption.

Processes of a wastewater treatment in biological - mechanical wastewater treatment plants are not yet fully described. Therefore there is a number of difficulties in controlling treatment plants. Wastewater as a control object has the following characteristics:

- due to the varying intensity of water inflow and pollution loads varying mechanical and biological processes occurring in the plant are in transient state,
- due to changes in water inflow rate, hydraulic loads are of purifying tanks are changing, therefore its time constants are also varying,
- processes in sewage treatment have the same time scale, some of them runs with time measured in minutes (i.e. aeration process: oxygen in the form of gas, in the air introduced into the wastewater goes into dissolved oxygen), some in days (5 days in the process of ammonification, and nitrification takes about 7 days), or even weeks (vitality of bacteria is a few weeks),
- number of processes in wastewater treatment is a non-linear.

To sum up the above issues it can be said, that the implementation of the basic economic task of the wastewater treatment plant control is associated with the following objectives (Brdyś et al., 2002):

- reduce to an acceptable level the possibility of process disturbances,
- providing adequate treated sewage parameters,
- minimizing the energy consumption.

In this order layered control structure elements are implemented. **Direct control layer** is responsible for the safety of the dynamic processes of wastewater treatment. Only this layer has direct access to treatment plant and the ability to directly influence the control variables (aeration, recirculation). Direct control layer algorithms are PID controllers performing the following algorithm:

\[
 u(t) = k_p \left[ e(t) + T_d \frac{de(t)}{dt} + \frac{1}{T_i} \int_0^t e(t) dt \right]
\]

where: \( k_p \) - proportional gain, \( T_i \) - integral gain, \( u \) – controller gain, \( e \) – error, \( e(t) = SP(t)−PV (t) \), \( SP \) – set point, \( PV \) – process variable, \( t \) - time.

The purpose of **master control layer** is to control the slowly changing process values (Cutler, Rmaker, 1980). Good stabilization of concentrations of pollutants in treated wastewater can lead the process at the working point lying closer to the maximum permissible concentrations of these pollutants. The proposed algorithm, DMC (Dynamic Matrix Control (Martin, 1981)) carries out the tasks of the parent layer.
3.1 Predictive control

Dynamic Matrix Control or in short DMC is a control algorithm designed explicitly to predict the future response of a plant. Now-a-days its applications are found in a wide variety of areas including chemicals, food processing, automotive, and aerospace applications. It is a form of control algorithm in which the current control action is obtained by solving a finite horizon of open loop optimal control problem using the current state of the plant as the initial state. This process is repeatedly done for each sampling point. The optimization yields an optimal control sequence and the first control in this sequence is applied to the plant. It is an algorithm based on the step response model.

Suppose the system is at rest. Here it is supposed, that the system settles exactly after \( N \) steps (Fig. 2). Step response models are obtained by making a unit step input change to a process operating at steady state. The model coefficients \( \{s_1, s_2, s_3, \ldots, s_N\} \) are same as the output values at each time step. Here “\( s_i \)” denotes the step response coefficients for the \( i \)th sample time after a unit step input change is made.

![Figure 2](image)

Step response model (\( K_o \) denotes static gain).

If there is a non-unit step change, the output is scaled accordingly. This is also known as the convolution model. The step response constitutes a complete model of the system, which allows to compute the system output \( y \) for any input sequence:

\[
y(k) = y(0) + s_0 \Delta u(k) + s_1 \Delta u(k - 1) + \ldots + s_{N-1} \Delta u(k - N + 1) + s_N \Delta u(k - N + 1) + \ldots
\]

\[
= s_0 \Delta u(k) + s_1 \Delta u(k - 1) + \ldots + s_{N-1} \Delta u(k - N + 1) + s_N \Delta u(k - N)
\]

(2)

where:

\[
\Delta u(k) = u(k) - u(k - 1)
\]

(3)

For real objects usually \( s_0 = 0 \) Then relation (3) can be written as:

\[
y(k) = y(0) + s^T u_k
\]

(4)

where:

\[
s = \begin{bmatrix} s_0 \\ \vdots \\ s_N \end{bmatrix}, \quad u_k = \begin{bmatrix} \Delta u(k) \\ \vdots \\ \Delta u(k - N + 1) \\ \Delta u(k - N) \end{bmatrix}
\]

Using the formula (2) the response of an object, for the excitation of a control signal \( u \) at a discrete moment \( k + p \), can be determined:
\[ y(k + p) = y(0) + \sum_{i=1}^{k+p} s_i \Delta u(k + p - i) \]  

(5)

To compute the control signal values, the following on-line optimization is performed at every sampling time:

\[ J = \sum_{i=1}^{N} \left\{ y^d(k + i) - y(k + i) \right\}^2 + \rho \left[ \Delta u(k) \right]^2 \]  

(6)

where \( y^d \) is a desired output value.

**3.2 Control of a wastewater treatment plant**

As described above, the task of controlling wastewater treatment can be reduced to stabilize concentrations of biodegradable pollutants and nitrogen in the chambers of the bioreactor. In this case preset values are the following concentrations of pollutants in waste water effluent from the bioreactor:

- Biological Oxygen Demand (BOD).
- Total Nitrogen (NT).

The control value was set point oxygen concentration in the bioreactor at the \( O_2 \) which is one element vector. Measurable disturbances, compensated open-loop control, were the following values in raw wastewater:

- Flow of a raw wastewater \( Q_{in} \),
- Biological Oxygen Demand \( BOD_{in} \),
- Total Nitrogen \( N_{Tin} \).

Other input signals is considered as unmeasurable disturbances, compensated for closed loop control.

**3.2.1. Operation of the control system for deterministic disturbances**

The first examined effects of the proposed control system were checked for deterministic disturbances, which were the same as their model. This approach had two objectives: first, a preliminary check of the algorithm, and secondly, analysis control values. In particular, the second of these goals was easier to achieve, the disturbances acting on the object had periodical nature.

The results presented at Fig 3. show the predictive control algorithm achieved good control quality. Taking into account the interfering signals and their impact on the object it can be concluded that the results are satisfactory (ie, the oscillations are relatively small).
In the next figure (Fig.4) the advantages of the predictive control can be presented. Shown transients of the selected disturbance signal (raw sewage flow, as a signal with the greatest impact on the process) and the control value (given $O_2$ concentration in the bioreactor) during the two days shows the way in which the controller precedes the impact of disturbance on the process. The positive increments of control signal begin when the disturbance decreases It is the result of predicting the future values of disturbance signal. In addition, the regulator precedes disturbance impact on the process (by taking into account the dynamics of these changes). Application of a predictive controller results in preparation of the process for future environmental conditions, thus minimizing energy costs (i.e., increments of the value of control signal that is proportional to the current power of aeration fans).

The presented, simplified example shows that the DMC algorithm can be a suitable way to control sewage treatment plant. Subsequently, the results of simulations seem to confirm this thesis.

### 3.2.2. Operation of the control system for real disturbances

In the next step measured values of the disturbance signals were used. The results were compared with measurements obtained from the treatment plant (with classical control algorithm). As it can be seen (Fig 5., 6) the application of predictive controller gave very good results. The process is stabilized, i.e. a deviation does not exceed acceptable limits (Fig 5., 6). The level of pollution is considered a safe level of a compromise (between minimizing the energy consumption needed for the process, and concentrations of pollutants) and has a natural reserve changes that are necessary for the safe conduct of the process. This is obviously a prerequisite for plant operation under real conditions. This control strategy was accepted by the technology supervisor of the plant.
3.2.3. **Operation of the control system for increased and decreased disturbances**

Another important issue was to check the sensitivity of the control structure for the disturbance signal amplitude changes. The simulation studies were carried out so as to check operation of the proposed control system for the disturbance amplitude increased by 50% and then decreased by 50%.

In the conducted simulations both the controller settings and disturbance model were not changed. As shown in Figures 7 and 8 results in all cases are satisfactory. For the increased oscillation of disturbance signal, control error increased, but remained within acceptable limits. Comparing the results with direct control, it might be seen that in every disturbance scenario it was better that direct control strategy.
4. Summary

The conducted simulation studies presented in this article were comprehensive approach to control sewage treatment plant. The paper formulates the primary objective of that task of automatic control system: to maintain concentrations of pollutants in treated wastewater within acceptable limits while minimizing the energy input necessary for this purpose. The proposed automatic control system has a hierarchical structure: direct impact on the object are acting controllers with a short-period of interventions, for which settings are worked out by the master controller with a longer period of intervention. Performed simulation experiments have shown that classical control of a treatment plant is not satisfactory. Effects of disturbances (flow and load of raw sewage) makes the sewage treatment control difficult task.

Proper control of the sewage treatment plant needs a prediction of the impact of the raw sewage flow and load and their future values on the treatment quality. With this information treatment plant can be prepared to treat different pollution loads. In order to realize the proposed predictive control DMC algorithm was proposed and shortly described. Verification of the presented approach was also presented on the example of simulations.

The simulation results were compared with actual measurements made on the plant in Resovia. Based on the presented study and analysis it might therefore be said, that the master predictive control, using the DMC algorithm, can be an appropriate way to control the wastewater treatment plants.

Bibliography


