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Review

Novel hierarchical nonlinear control algorithm to improve dissolved oxygen control in biological WWTP

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ABSTRACT

Wastewater treatment is a problem known to humankind for centuries. The quality of treated sewage determines the condition of reservoirs around the world. Control of such a complex and nonlinear system as a wastewater treatment plant requires thorough knowledge of the process. The paper presents a hierarchical control system of a Sequencing Batch Reactor (SBR) in Wastewater Treatment Plant (WWTP) taking into account a model based on actual measurements taken from a WWTP in Swarzewo, Poland. The authors designed and implemented a nonlinear model predictive controller (MPC) that allows for the optimal implementation of the desired DO level while minimising the operation of actuators (aeration system). The design description of the predictive controller was associated with the need to specify the performance function and define the optimisation problem. In a two-layer structure, a supervisory controller was implemented based on an actual time-based controller in Swarzewo WWTP. The overview showed the improved performance of the treatment plant and the versatility of the created solution. Results of simulation tests for the wastewater treatment plant case study are presented.

Contents

1. Introduction

The undeniable development of civilisation leading to the ever-greater development of urban areas and the rapid growth of the world's population presents humanity with problems that never before appeared on such a scale. One of these problems is

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the treatment of wastewater produced by human activity around the world.

At the same time, the European trend of caring about the environment means that wastewater treatment plants in Poland were subject to significant rigours in terms of the method of treatment or the quality of treated wastewater, mainly due to their subsequent discharge into natural reservoirs such as rivers, lakes or seas. The methods and accuracy of carrying out controls have also changed. It is enough to mention two European Union directives (91/271/EEC, 2000/60/EC) which formed the basis of national regulations.

Due to the condition of the wastewater infrastructure, the existing treatment plants were modernised to meet the deadlines set out in the European directives. Many local governments in Poland received financial support for this from the European Union, the European Regional Development Fund and the Cohesion Fund.

The performed modernisations undoubtedly improved the situation of many sewage treatment plants, but another challenge is the reduction of operating costs by optimising the system operation. This requires interdisciplinary cooperation between such fields of science as environmental protection, IT and control.

In industrial practice, two different types of biological WWTPs are used: WWTPs with the continuous flow throughout the plant, and Sequencing Batch Reactors (SBRs). In the first type of plant, several tanks are connected by recirculation flows (internal and external), while in the SBR, all biochemical processes occur in one tank, in a predefined sequence. This paper considers the second type of biological WWTP.

SBR is a fill-and-draw activated sludge treatment system. This technology is widely used under small wastewater inflow conditions and may be designed using a single tank or a system of multiple tanks working in parallel. A typical work cycle involves five operational phases: filling, biological reactions (aerobic, anaerobic), sedimentation, decantation, and idling [1]. The length of the full cycle and the individual phases determines the final effect of the wastewater treatment. Appropriate control of these processes allows the treatment plant to be adapted to the current needs and strategies.

The requirement to achieve an appropriate multiplication of microorganisms contained in the activated sludge is to provide them with an appropriate amount of dissolved oxygen (DO). To carry out biological reactions, it is, therefore, necessary to aerate the wastewater. The oxygen delivered into SBR by the aeration system is a fundamental component for the complex biological processes at WWTP. The denitrification, nitrification and phosphorus removal processes are dependent on the concentration of DO in SBR.

The aeration mechanism creates an oxygen environment in the reactor, which is designed to maintain the state of suspension in the tank. The newly formed cells mix with the old microorganisms and then carry out the process of removing contamination.

The aeration process is crucial for the proper biological reactions to proceed. A dissolved oxygen concentration that is too low will result in insufficient growth of microorganisms, which will then not be able to decompose nitrogen and phosphorus compounds. Excessive aeration will lead to overmixing in the reactor, which in turn may result in the breakdown of the activated sludge flocs. In addition, it will entail a significant economic burden, due to the fact that the costs of electricity consumed by blowers account for 50% and even up to even 75% of the total operating costs of the WWTP [2].

Research activities related to effective control of DO have a long history. Previous studies reported various structures and technologies of DO control, e.g., the multivariable PID controller [3], adaptive PID controller [4], fuzzy controller [5,6], adaptive controller [7], and predictive controller [8–10].

The second group of DO control strategies are algorithms in which, besides DO measurement, the concentrations of ammonium nitrogen (NH_4) [11,12] and nitrate (NO_3) [13,14] are also measured and applied for the designed control system.

The next group of DO control are algorithms with a supervisory controller, designed to determine the time-varying reference trajectory of DO–DO_{ref} [15–17].

The last, fourth group of research work is based on the optimisation of biological processes taking place in the SBR reactor. For this purpose, in addition to measuring DO, additional measurements are performed: pH, Oxidation Reduction Potential — ORP, Oxygen Uptake Rate — OUR, aeration time, phase sequence (anaerobic/aerobic), phase duration, and a number of phases and other parameters, e.g. [18–24].

Minimising the costs of work or operation of treatment plant equipment is an important issue comparable to meeting the standards of treated wastewater. Bearing in mind the need of taking into account the costs of the control process in a biological wastewater treatment plant, the authors decided to design a nonlinear predictive controller which will allow the desired level of dissolved oxygen to be achieved with minimal energy expenditure. To the best of the authors' knowledge, nonlinear MPC has not been applied in an SBR treatment plant to minimise energy in the hierarchical control structure.

The operation of the predictive controller is based on the use of information about the future behaviour of the controlled variable value in order to determine the optimal values of the control variables. Prediction is possible thanks to the knowledge of the mathematical model of the system, the measurements of the output variables and previous control signals.

The remainder of this paper is organised as follows. The case study control plant is described in Section 2. A novel hierarchical nonlinear control system is presented in Section 3. The control results of the analysis are illustrated in Section 4. Section 5 concludes the paper.

2. Control plant

The WWTP in Swarzewo is a biological–chemical–mechanical system, which means that the wastewater is treated in several processes. In the first stage of mechanical pretreatment, solid contaminants are retained on grids, screens, grit chambers and sand separators. Biological treatment follows with the activated sludge method, which is later separated from the treated wastewater in the sedimentation process. The mentioned processes can be supported by chemical reactions obtained with reagents.

The biological part of the WWTP consists of six independent reactors with a capacity of 5000 m^3 (three reactors) and 6500 m^3 (three reactors). The technological scheme of the plant is shown in Fig. 1.

As mentioned in the Introduction, a single SBR cycle includes the following phases: filling, biological reactions (aerobic, anaerobic), sedimentation, decantation, and idling (see Fig. 2). The final product of the treatment plant's operation, i.e., a mixture of treated wastewater, is discharged into the Baltic Sea. Moreover, the excess sludge is removed and further used as garden soil. In order to protect the environment, treated sewage must meet the relevant standards specified in the water permit. Compressed air aeration systems supply air to the reactor through appropriate nozzles mounted on the bottom of the tank. It is important to choose the right diffusers because of their significant influence on oxygen absorption. Depending on the size of the nozzles, air bubbles of different sizes can be obtained. The most common method is fine bubble aeration with a bubble diameter not exceeding 3 mm. The source of compressed air in such systems is a flow or rotary blower. Its selection depends primarily on the required capacity and the amount of compression.

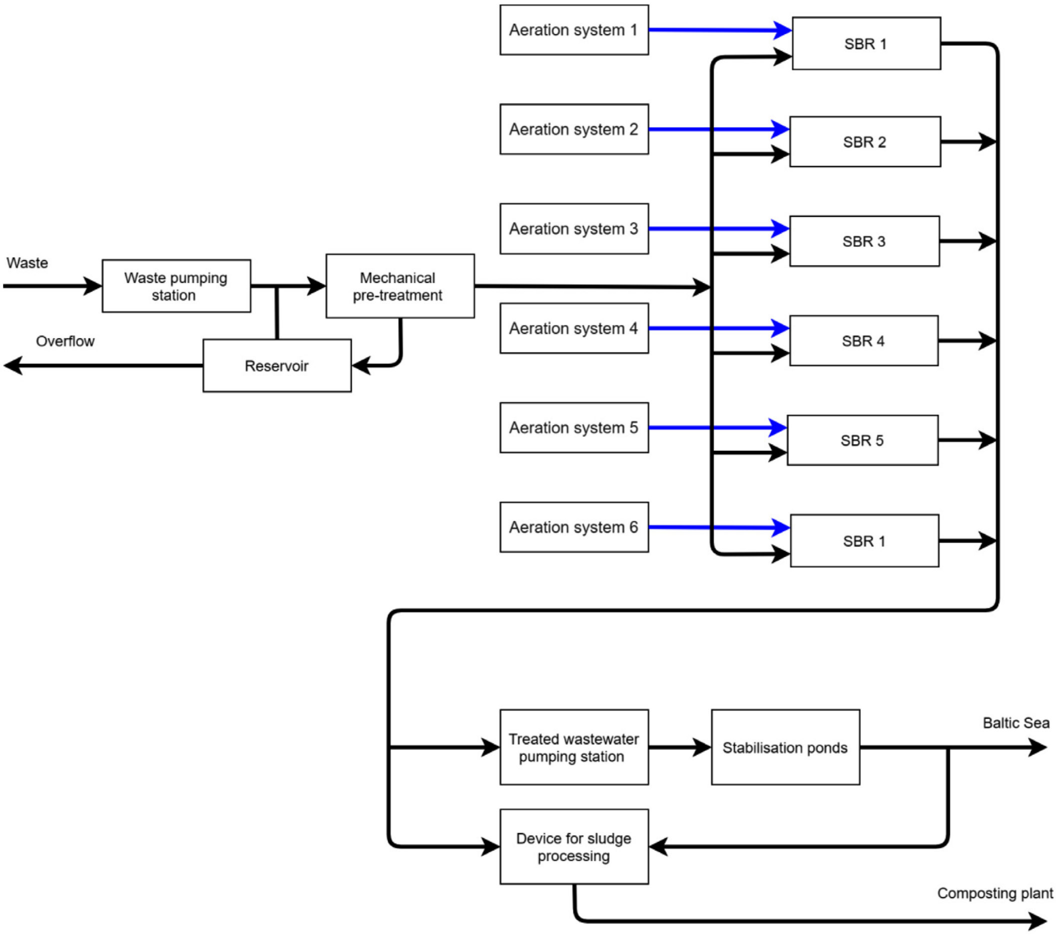

Fig. 1. Scheme of the Swarzewo WWTP.

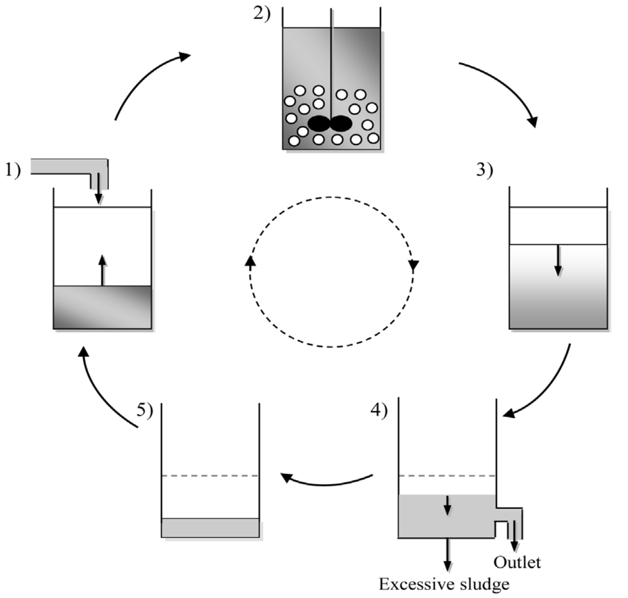

Fig. 2. Phases of the SBR operating cycle: (1) filling, (2) biological reactions (aerobic, anaerobic), (3) sedimentation, (4) decantation, (5) idling.

In the Swarzewo WWTP, the air supplies for all SBRs are provided by six aeration systems, which include a turbo blower, pipes and a diffuser system. The blowers are connected to each other by a manifold, the outlet of which then connects to the main pipeline leading to each of the reactors. Before the reactor itself, the pipeline splits into two parts, supplying air to the diffuser system, which is shown in Fig. 3.

The most popular mathematical description of the biological processes in a WWTP is a series of Activated Sludge Models (ASM) proposed by the International Water Association. In this paper, the biological processes are modelled using the ASM2d model [25], which consists of 21 state variables, and 20 kinetic and stoichiometric parameters. The values of those parameters are equal to their default values at 20 °C [25]. The ASM2d model was calibrated on real data recorded in the Swarzewo WWTP. The data from the plant was applied for model verification. The verification of the modelling results was satisfactory, and therefore they were used for control purposes.

The aeration system was also modelled. The authors proposed treating individual components of the aeration system as electrical elements. Therefore, the air flow is shown as the amperage in an electrical circuit and the pressure drop is shown as the voltage in the electrical circuit. The remaining elements are presented as resistors, capacitors, current and voltage sources. Based on the electrical diagrams, the model is presented in the form of mathematical equations. The aeration system was assumed to be a static element compared to the SBR. When the fast aeration system dynamics (seconds) is compared to the SBR dynamics (minutes and hours), it is noticed that during the operation of the aeration system, it is possible to assume that the air intensity coming from the blower is fed directly to the reactor, which significantly simplified the process of control system design.

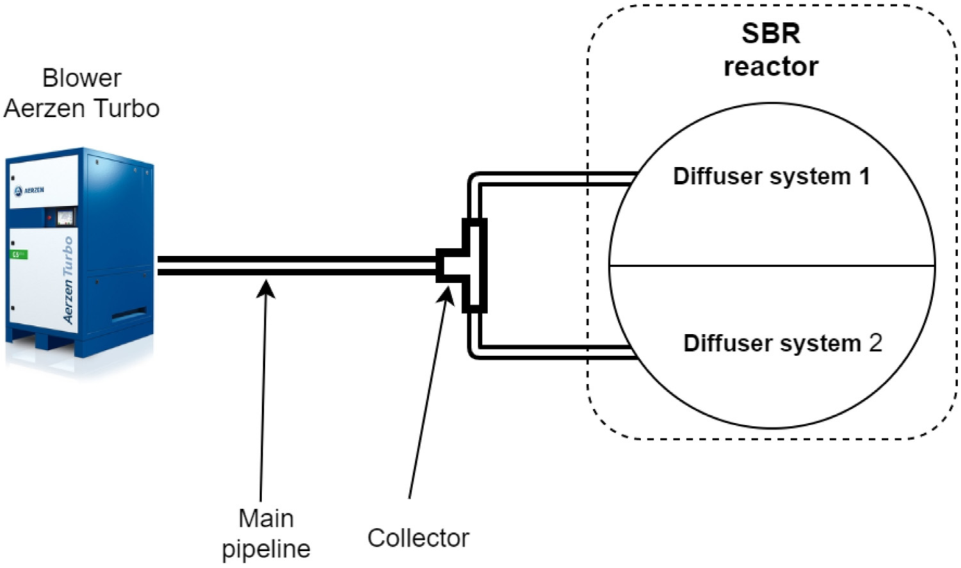

Fig. 3. Scheme of the Swarzewo aeration system.

Currently, control of the biological part of the WWTP in Swarzewo is based on a hierarchical structure. The main algorithm controls the operation of the reactor cycle and is responsible for switching between cycle phases. The downstream subsystem controls the aeration system.

The management of the SBR phase is sequential. After the waiting phase, 80% of the fresh wastewater portion is added. Anaerobic conditions allow the removal of phosphorus compounds. Then the aeration phase begins, during which the concentration of nitrate increases. Afterwards, another 15% of the amount of sewage is added, and a denitrification reaction occurs in the reactor, after which the wastewater is aerated. Eventually, the last 5% of the portion is poured into the reactor, followed by the next oxygen phase, the sedimentation process, decantation, and drainage of the sludge.

The aeration system is controlled by setting the appropriate blower power depending on the DO. Maximum power is determined on the basis of the wastewater temperature and the concentration of activated sludge in such a way that the concentration of nitrates decreases at a constant rate and the amount of DO is as low as possible. After reaching the set DO, the blower reduces its revolutions per minute (RPM), while in the case of a further increase in oxygen concentration at this minimum RPM, the blower switches off. After the oxygen drops to the minimum level, the blower restarts until the end of the aeration phase. The duration of the blower operation depends on the completion of the N-NH_4 oxidation process.

The analysis of the measurement data from the Swarzewo WWTP has shown that situations occur, especially in the summer period, when the support of biological processes by adding chemicals is not sufficient for proper treatment of the given sewage. As a result, the total nitrogen (N_{tot}) and total phosphorus (P_{tot}) values at the treatment plant's outlet do not match the given quality requirements, which can result in financial penalties for the WWTP. The solution may be introducing modifications to the existing DO control system.

3. Control system

3.1. Control structure

Taking into account other control systems based on the mathematical model of the WWTP in Swarzewo, the authors proposed a hierarchical control structure for SBR control (see Fig. 4). This approach allows for the distribution of a complex control task into individual subsystems that perform partial tasks.

where: DO, DO^{ref}, Q_{air}^{ref}, COD, N_{tot}, P_{tot}, R, V and h are the dissolved oxygen [g O_2/m^3], set point of the dissolved oxygen [g O_2/m^3], set point of the air flow [m^3/h], chemical oxygen demand [g O_2/m^3], total nitrogen [g N/m^3], total phosphorus [g P/m^3], oxygen respiration rate [gO_2/m^3h], sewage volume in the reactor [m^3] and sewage level in the reactor, respectively.

In the proposed structure, the Supervisory Sequential Controller (SSC) is responsible for managing the reactor's operating cycle. It determines the duration and number of oxygen phases, which results in determining the value of DO^{ref} for the nonlinear MPC controller. The DO controller adopts the trajectory determined by the SSC as the reference value, while its task is reduced to determining the $Qair^{ref}$ control, which will allow the desired DO level to be maintained. R is defined as the oxygen uptake rate by the effluent. It is an important parameter for biological processes. R describes the oxygen consumption by the microorganism.

3.2. Nonlinear MPC

The model predictive control (MPC) technology is an attractive method for dynamic optimising control. The performance of the predictive controller is based on the use of information about the future behaviour of the controlled variable to determine the optimal values of the control variables. The MPC optimiser enables for direct incorporation of the constraints in the control problem into the optimisation task at each time step, which is a great advantage of this technology. In recent years, many industrial applications of control systems have utilised the MPC technology [26].

For MPC technology (see Fig. 4) a nonlinear model of DO is applied. The DO dynamics is described as:

$$\frac{dS_o(t)}{dt} = k_La(Q_{air}(t)) \cdot \left(S_{o,sat} - S_o(t)\right) - \frac{S_o(t)}{K_o + S_o(t)} \cdot R(t) \quad (1a)$$

where S_o – dissolved oxygen concentration, k_La – oxygen transfer function, Q_{air} – airflow, R – oxygen respiration rate, $S_{o,sat} = 8.637$ g O_2/m^3 – dissolved oxygen saturation concentration, $K_o = 0.2$ g/m^3 – Monod's constant.

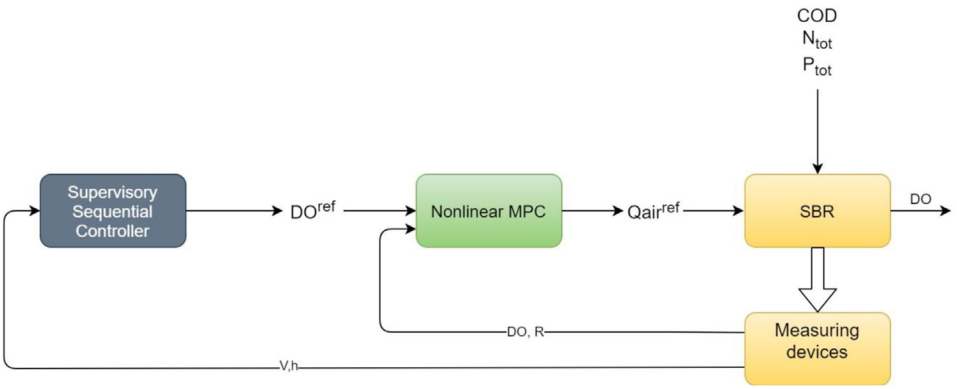

Fig. 4. Scheme of a hierarchical nonlinear control system.

The function, $k_{La}(Q_{air})$, describes the oxygen transfer and depends on the aeration actuating system and sludge conditions. Different approaches to modelling this function are presented in the literature. Here, the linear model is applied:

$$k_L a\left(Q_{air}\left(t\right)\right) = \alpha \cdot Q_{air}\left(t\right) \tag{1b}$$

where α = 0.208 1/m^3.

This parameter was determined by simulation tests.

The decision variable in the optimisation task is the intensity of air flow to the SBR – Q_{air}.

The control values for the current and next moments are determined based on the mathematical model by minimising the performance function, which determines the quality of the controller on the prediction horizon. The nonlinear MPC performance function is given by:

$$\min J(k) = \min \left\{ w_1 \sum_{p=1}^{H_p} \left(DO^{ref}\left(k+p|k\right) - DO\left(k+p|k\right)\right)^2 + w_2 \sum_{p=1}^{H_p} \left(Q_{air}(k+p|k)\right)^2 \right\} \tag{1}$$

where: $J(k)$ – value of the performance function for the discrete moment k, k – discrete moment for which the optimisation task is solved, $DO\left(k+p|k\right)$ – prediction of the output value at the moment k $+p$, determined at the moment k, $DO^{ref}\left(k+p|k\right)$ – prediction of the reference value at the moment k $+p$, determined at the moment k, $Q_{air}(k+p|k)$ – value of the air flow supplied to the reactor by the aeration system at time k $+p$, determined at time k, H_p – prediction horizon, and w_1, w_2 – weights of the components of the performance functions.

The first component of this function is the error between the predicted output trajectory and the reference trajectory. The second is the cost of the designated controls necessary to complete this trajectory. This cost is related to the operating time of the blowers in the aeration system, and thus the savings associated with air pumping.

The predictive controller allows the constraints of the control system to be implemented, resulting from the necessity to physically implement the values of the control and controlled values.

Table 1
Phase duration in Supervisory Sequential Controller.

Phase	Duration
anaerobic 1	5 h 3 min
filling 1	3 h 38 min
aerobic 1	5 h 21 min
anaerobic 2	3 h 50 min
filling 2	2 h 43 min
aerobic 2	4 h 30 min
anaerobic 3	2 h 7 min
filling 3	23 min
aerobic 3	4 h 53 min
sedimentation	58 min
decantation	31 min
idling	35 min

In the considered case of the DO controller, the set trajectory is determined from the SSC, therefore it should not be limited in any way. The dynamics of the blowers is negligible, so it would be unjustified to impose a limitation on the increase of the control signal. The only limitation resulting from the executive devices is the minimum and maximum power of the blowers installed in the WWTP. By denoting by Q_{air}^{min} and Q_{air}^{max}, respectively, the minimum and maximum values of the inflow intensity realised by the aeration system, a constraint is obtained, which can be expressed by the following:

$$Q_{air}^{min} \leq u\left(k+p|k\right) \leq Q_{air}^{max};\, p = 0, 1, \ldots, H_p \tag{2}$$

where: $Q_{air}^{min} = 0$ [m^3/h], and $Q_{air}^{max} = 5400$ [m^3/h].

The optimisation algorithm uses an estimate of R based on DO measurements. An extended Kalman filter was applied for the estimation.

3.3. Supervisory sequential controller

The simplest implementation of the SSC is a time algorithm with a constant setpoint value for DO. Changes in the reactor phases and their duration are set a priori before the start of the WWTP operation. However, such a solution requires in-depth knowledge of the plant equipment and many experimental tests.

It was decided to implement a supervisory sequential controller that imitates the current reactor operating cycle in the WWTP Swarzewo with phases presented in Table 1.

4. Control results

The proposed nonlinear MPC control system (see Section 3) was examined in simulation tests, based on real data records from the Swarzewo WWTP case study. The Simba commercial simulation package [27] was applied to model the biological processes at the WWTP (ASM2d model). Simba is a toolbox of Matlab environment. The Matlab environment was applied to implement control strategies. The Sequential Quadratic Programming (SQP) solver was used to solve the nonlinear MPC optimisation task. The parameters of the SQP algorithm were as follows: termination tolerance on function value = 1*10^{-5}, maximum number of

Table 2
Values of sewage inflow and levels of pollution.

Scenarios	Inflow [m^3/d]	COD [g O$_2$/m^3]	N_{tot}[g N/m^3]	P_{tot}[g P/m^3]
I	3000 5000 7000	535	55	7.38
II	3000 5000 7000	1070	110	14.75
III	3000 5000 7000	2140	220	29.5

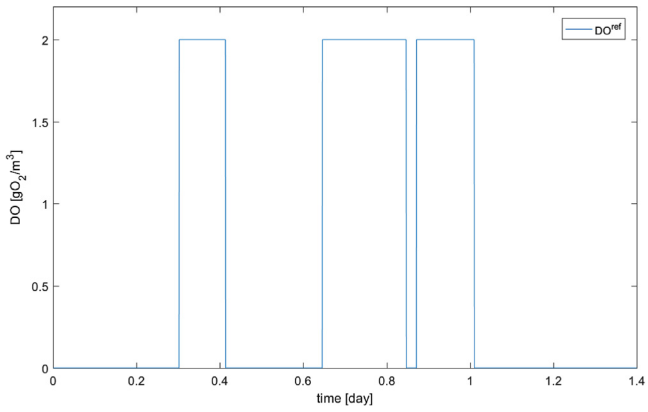

Fig. 5. Trajectory of DO^{ref}.

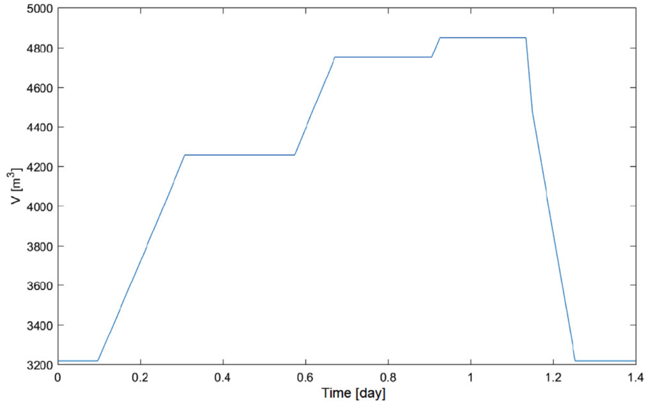

Fig. 6. Filling level of SBR.

iterations = 2000. The calculations were carried out on a Laptop with an i7-9750H in Windows 10 environment.

The tests described in this section were carried out on the basis of three scenarios of the intensity of the sewage inflow and three levels of pollution, which were designed to reflect the conditions in the WWTP in Swarzewo (see Table 2).

During the tests of the nonlinear MPC parameters, a constant trajectory of DO was adopted, as shown in Fig. 5.

The reactor filling level during the operating cycle is shown in Fig. 6. To assess the control quality, integral quality indicators were adopted — Integral Absolute Error (IAE, see (3)) and Integral Square Error (ISE, see (4)).

$$IAE = \int_0^T |e(t)|\, dt \tag{3}$$

$$ISE = \int_0^T (e\,(t))^2 dt \tag{4}$$

Table 3
Influence of the performance function weights change.

Variant	w_1	w_2	IAE	ISE	Q_{total} [m^3]
1	1	0.0000001	1.4592	0.0547	7096.7709
2	1	0.000001	1.4601	0.0547	7096.6340
3	1	0.00001	1.4688	0.0547	7095.5017
4	1	0.0001	1.5554	0.0546	7084.1116
5	1	0.005	13.1352	0.6335	5240.8797

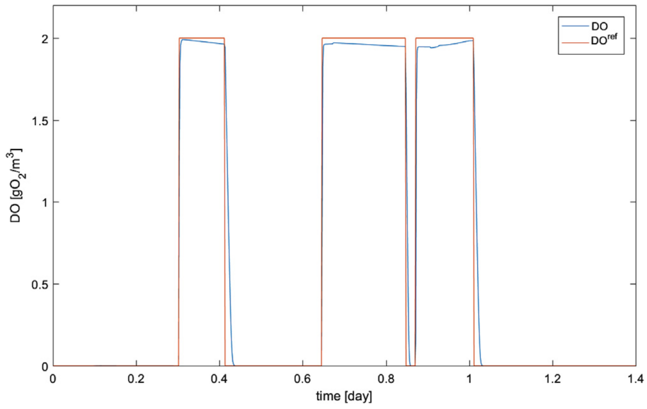

Fig. 7. DO control results — weights.

where: T – simulation time.

The indicator of the control cost is the total volume of air supplied to the reactor, which can be represented by:

$$Q_{total} = \int_0^T (Q_{air}(t))dt \tag{5}$$

4.1. Investigation of the impact of changes in the nonlinear MPC controller

4.1.1. Weights of the performance function

First, the impact of the performance function weights (w_1 and w_2, see (1)) on the quality of control was checked. The performance function given by the relationship has two components. By changing the weights of both components, it is possible to determine which of them has a greater impact on the value of the objective function, and thus on the obtained solution. It was assumed during the research that the weight value $w_1 = 1$ is constant, and the weight value w_2 changes. The results are shown in Table 3.

As can be seen, a high value of w_2 reduces the amount of supplied air due to the increased cost of control, which, however, results in much worse DO control. Reducing w_2 improves the control quality, however only up to a point since further reduction results only in a slight improvement in the quality indicators. For further research, variant 3 from Table 3 was adopted as the best variant of weights. The DO results for the adopted weights are shown in Fig. 7.

4.1.2. Control horizon

The next stage of the simulation consisted of examining the impact of changing the control horizon H_s. The key factor influencing the selection of the control horizon is the dynamics of the DO concentration in the SBR. The sampling time, on the other hand, must allow for satisfactory control while ensuring real computation time. The simulation results for different values of the control horizon are presented in Table 4.

During the simulation tests, the extension of the control horizon significantly influenced the calculation time. The simulations

Table 4
Influence of changes of the control horizon.

Variant	H_s	IAE	ISE	Q_{total} [m^3]
1	2	1.5585	0.0149	7094.5288
2	5	1.4688	0.0547	7095.5017
3	8	1.4677	0.0150	7106.6838
4	10	1.4988	0.0155	7097.5861

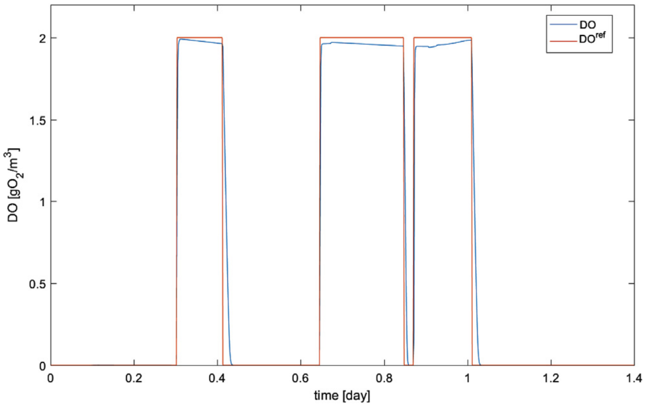

Fig. 8. DO control results — control horizon.

Table 5
Influence of the sampling time changes.

Variant	T_s [min]	IAE	ISE	Q_{total} [m^3]
1	12	–	–	–
2	5	2.3047	0.0226	6975.8251
3	3.33	1.8679	0.0205	7077.4643
4	2.5	1.4688	0.0547	7095.5017
5	2	1.8208	0.0189	7071.2224
6	1.25	1.2105	0.0140	7146.1855
7	1	1.1591	0.0138	7164.0409

for $H_s = 10$ took more than 1.5 h. This indicates that when implementing a hardware controller, the required computing power must be carefully analysed in order to obtain new controls in a finite, satisfactory time. Due to the long simulation time and a small gain in control quality, the remaining tests were carried out for $H_s = 5$. The DO results for the best variant are shown in Fig. 8.

4.1.3. Sampling time

The sampling time, understood as the period of intervention of the predictive controller, was the subject of subsequent tests. The collective results are presented in Table 5.

More frequent nonlinear MPC controller intervention resulted in better control results, however, as with the control horizon, further reduction of the sampling time did not result in any significant improvement. $T_s = 2$ minutes was chosen for further research. The control equipment, programmable logic controller — PLC, available in Swarzewo WWTP, allows for this sampling time.

4.1.4. Model parameter — oxygen respiration rate

The most important parameter affecting the process of aeration is *R*. It refers to the rate of oxygen consumption by bacteria as a result of biochemical reactions. Due to the high cost of measuring the oxygen respiration rate value in a WWTP, an estimate of the oxygen respiration rate value can be used for control purposes. In this case, it is necessary to assume that the assumed oxygen respiration rate value is different from the actual value. The influence of the measurement error on the operation of the control system is presented in Table 6.

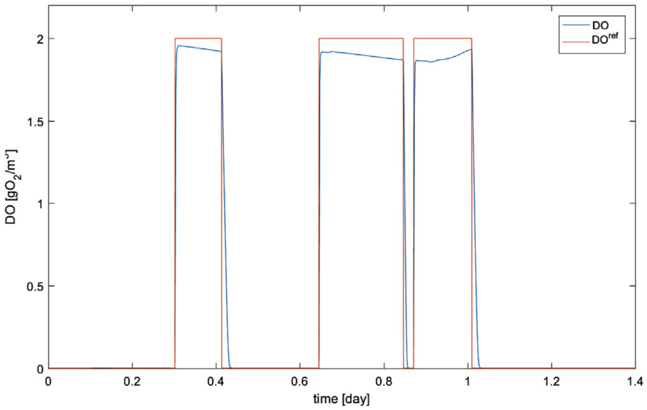

Fig. 9. DO control results — impact of oxygen respiration rate.

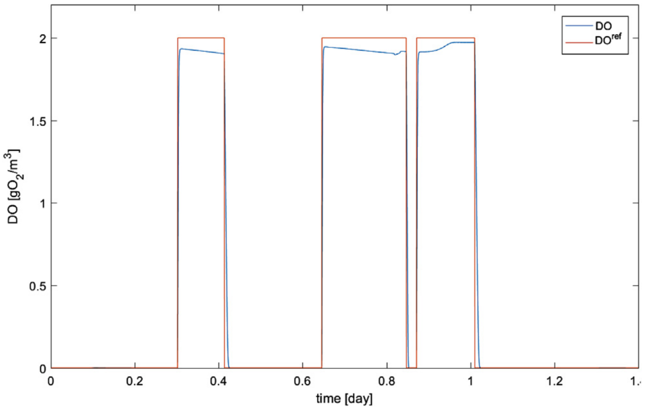

Fig. 10. DO control results — inflow of sewage.

The presented data show that the controller works correctly within the range of the estimation error of approximation 20%. For higher error values, the controller calculates control errors due to the model's incompatibility with the plant. The conducted study proves that information about the oxygen respiration rate value is a key aspect necessary for the proper operation of the control system. Fig. 9 shows the implementation of the DO trajectory for a measurement error of 20%.

4.2. Investigation of the impact of changes in the WWTP inflow scenario

The conditions in which the WWTP works are constantly imbalanced. The intensity of sewage inflows, their chemical composition and temperature are always changing. Therefore, the proposed control system must be ready to work in various conditions. This subsection describes the tests of the predictive controller operation depending on external conditions. The collective results for the scenarios presented in Table 2 are presented in Table 7. The selected implementation of the set trajectory along with the course of the air inflow intensity are shown in Figs. 10 and 11 (for quality 3 and inflow = 7000 m^3/d).

The controller achieves satisfactory results for all scenarios. It can be noticed that along with the increase of sewage pollution, the air intensity necessary to maintain the set DO increases. For the most demanding scenarios, to obtain a satisfactory chemical composition of treated sewage, it is recommended to support biological treatment with chemical treatment.

Table 6
Influence of the oxygen respiration rate error measurement.

Variant	Measurement error of respiration	IAE	ISE	Q_{total} [m^3]
1	-40%	2.6738	0.0159	6948.1853
2	-30%	2.3757	0.0153	6987.2945
3	-20%	2.0756	0.0149	7026.6566
4	0	1.4699	0.0149	7106.1719
5	+20%	1.4194	0.0159	7186.9113
6	+30%	1.7762	0.0168	7227.7539
7	+40%	2.1360	0.0180	7268.9641

Table 7
Influence of sewage inflow.

Quality	Inflow		
	3000 m^3/d	5000 m^3/d	7000 m^3/d
1	IAE: 1.7191 ISE: 0.0224 Q_{total}: 4249.69	IAE: 1.6706 ISE: 0.0218 Q_{total}: 4366.37	IAE: 1.6715 ISE: 0.0218 Q_{total}: 4288.05
2	IAE: 1.5429 ISE: 0.0145 Q_{total}: 6876.29	IAE: 1.4699 ISE: 0.0149 Q_{total}: 7106.19	IAE: 1.4614 ISE: 0.0149 Q_{total}: 7042.37
3	IAE: 1.7212 ISE: 0.0108 Q_{total}: 11850.74	IAE: 1.4744 ISE: 0.01 Q_{total}: 12248.39	IAE: 1.4371 ISE: 0.099 Q_{total}: 12208.95

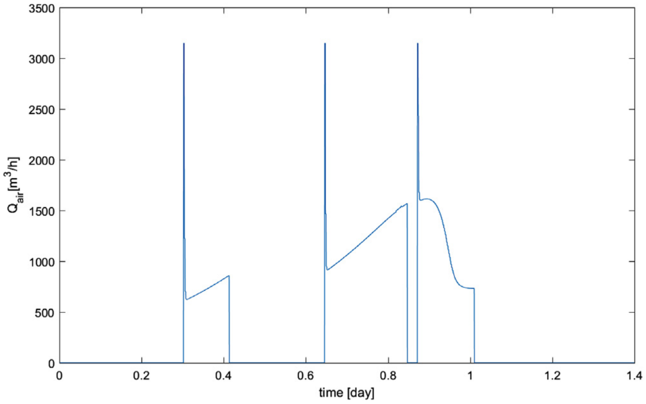

Fig. 11. Air inflow — inflow of sewage.

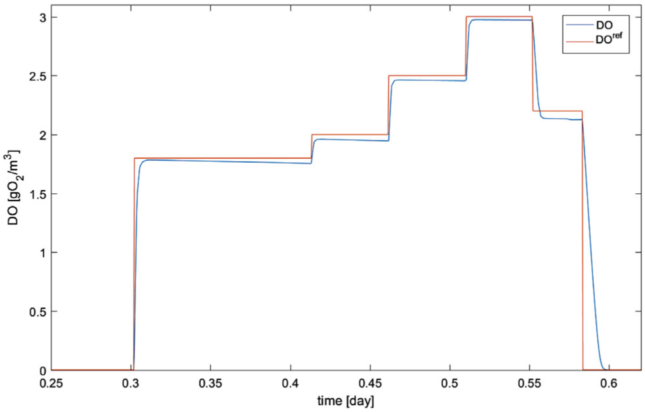

Fig. 12. DO control results — new DO^{ref} trajectory.

4.3. *Investigation of the impact of changes in the trajectory of* DO^{ref}

The main task of the DO controller is to follow a given trajectory. Due to the fact that the level of DO concentration changes due to changes in the operating conditions of the sewage treatment plant, the controller should better reflect any trajectory. The subsection includes tests for several selected runs of a given DO^{ref} level. Fig. 12 shows the first variant of the DO^{ref} trajectory along with the control signal generated by the nonlinear predictive controller. Fig. 13 shows that the controller applies a high-value control signal on every increase of DO^{ref}, it is necessary to reach DO^{ref} as quickly as possible.

4.4. *Investigation of the impact of changes in the supervisory sequential controller*

The adopted control structure (see Fig. 4) consists of two control levels. The first controller is the SSC, which determines the DO^{ref} trajectory. The second one – the DO controller (nonlinear MPC) – is used to determine the optimal trajectory: $Qair^{ref}$. This section contains studies on the influence of superior control on the degree of purification of the wastewater. The scenario used the conditions from scenario 2 (see Table 2) with an inflow of 5000 m^3/h. These conditions are the most common in the Swarzewo WWTP. All previous tests were performed on the SSC described in Section 3.3. For the purpose of these tests, it was decided to use the optimisation supervisory controller from [24]. This controller [24] was based on two optimisation algorithms (stochastic – artificial bee colony and deterministic – direct search algorithm) to optimise the biological processes in the SBR. It allows the control system to operate with a variable DO trajectory and a variable phase length, which results in a variable length of the entire cycle. Simulation results are shown in Figs. 14–16.

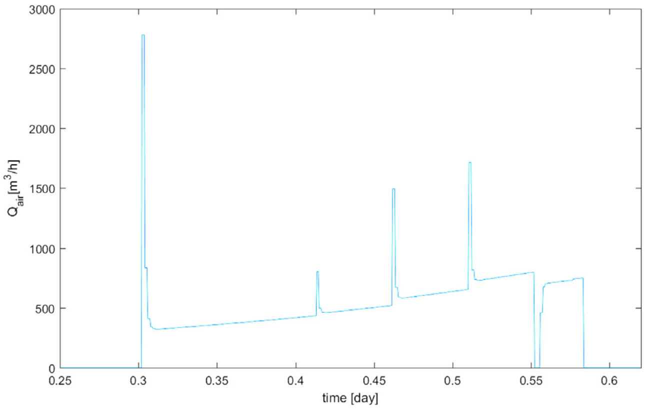

Fig. 13. Air inflow — new DO^{ref} trajectory.

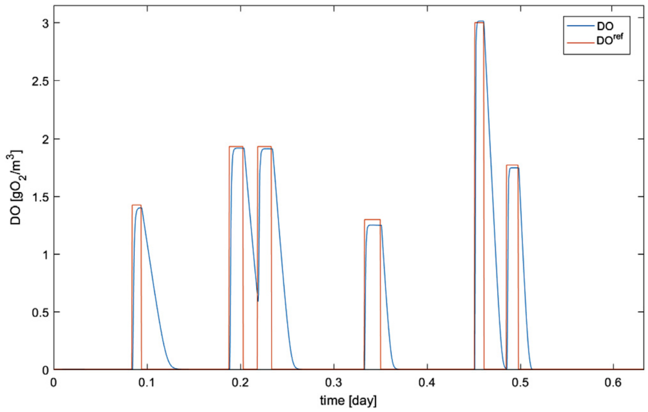

Fig. 14. DO control results — Supervisory Sequential Controller.

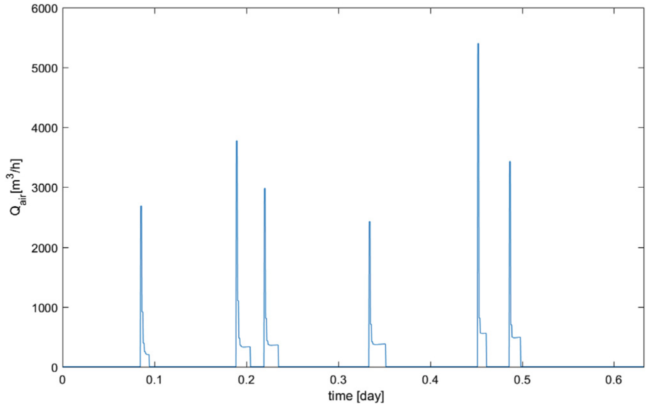

Fig. 15. Air inflow — Supervisory Sequential Controller.

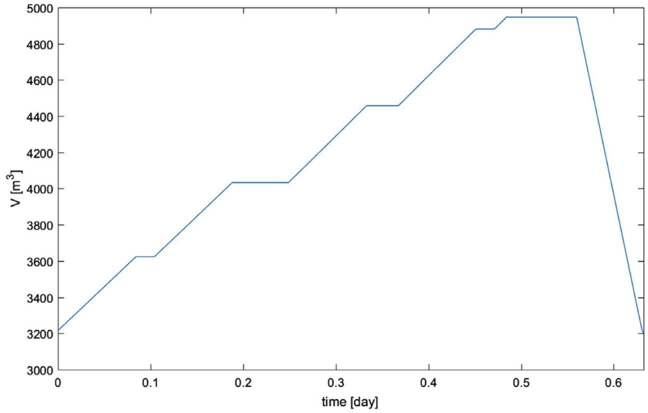

Fig. 16. Filling level of reactor — Supervisory Sequential Controller.

Simulation results show that the optimisation supervisory controller could decrease the duration of the purification process depending on the input conditions. This means that the overall cost will be lower. A variable DO trajectory is necessary to achieve satisfactory results under all biological conditions. Fig. 14 shows the DO trajectory, which is satisfactorily implemented by the proposed controller, even in the case of a sudden decrease in oxygen demand. The consequence of changes in the DO trajectory is a change in the control signal — there are changes in the blower speed. It is worth noting that depending on the change of oxygen concentration, due to cost optimisation, the blowers are switched off for some time and then switched on again.

5. Conclusions

The problem of the design and implementation of a complex control system for an SBR is a common issue in automation. Numerous studies contain various solutions, from classic control systems based on control loops with the use of PID controllers to advanced algorithms aimed at optimising the operation of WWTPs. This proves a wide range of possibilities of shaping the work cycle of the reactor and thus obtaining the desired chemical composition of treated wastewater.

Research on the sewage treatment plant in Swarzewo showed the possibility of improving the quality of the control of biological processes. Therefore, the authors decided to develop their own algorithm for a predictive controller, the main purpose of which is to improve the quality of control.

The designed control system satisfactorily meets the requirements. The conducted simulations have shown that the SBR working with the above strategy can efficiently deal with the highly varying inflow rate while maintaining high treating performance. The predictive controller allows for optimal control of the DO in the reactor within the constraints. Thanks to the future possible implementation of the presented system in the WWTP in Swarzewo, it is possible to increase efficiency while reducing the cost of operation. The proposed solution is also easy to implement, where the only obstacle may be the power of the computing unit.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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