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Evaluation of multiloop chemical dosage control strategies for total phosphorus removal of enhanced biological nutrient removal process

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Abstract−We developed several control algorithms and compare their control performances for controlling the total phosphorous (TP) concentration in wastewater treatment plant, which has strong influent disturbances and the disturbance effects should be removed while maintaining better effluent quality. An anaerobic - anoxic - oxic (AAO) process, which is a well-known advanced nutrient removal process, was selected as a case study, which is modeled with activated sludge model no. 2. Six control strategies for TP control with a polymer addition were implemented in AAO process and evaluated by the plant's performance, where the costs of the dosed chemical were compared among the six controllers. The experimental work showed that the advanced control techniques with feedback, feedforward and feedratio controllers were able to control the TP concentration in the effluent, which must be less than 1.50 g P/m^3 which is the legal limitation, while reducing the necessary chemical cost. The results showed that the best TP removal performance in the effluent TP removal could be achieved by advanced feedback controller with the tuned control parameters, which showed the best effluent quality and control performance index as well as the cheapest cost of chemical dosage among the six TP control strategies.

Keywords: Activated Sludge Model, Chemical Dosage Control, Eutrophication, Feedforward Control, Multiloop Control, Total Phosphorous (TP)

INTRODUCTION

Due to more stringent effluent quality standards in biological wastewater treatment plant processes (WWTP), process systems techniques of modeling, control, monitoring, and optimization have been encountered widely in the last two decades [1-3]. The key control objectives for WWTPs are: (1) to maintain the effluent quality requirements, (2) to maintain the controlled variables at the desired outputs for stabilizing the effects of changing the influent loads and the outward disturbances, and (3) to minimize the energy consumption during the process [4].

Phosphorous is the key important nutrient contributing in the eutrophication of rivers, lakes and surface waters. Removing phosphorous being released from wastewater treatment plants is important in minimizing eutrophication of rivers or surface waters. Polyphosphate accumulating organisms (PAOs) are responsible for enhanced biological phosphorus removal (EBPR). These organisms require a carbon source in terms of chemical oxygen demand (COD) in order to execute the reaction. Therefore, the availability of COD is an important factor when the removal of phosphorus is taking place, particularly when a low influent C/P ratio is present, which is an unfavorable condition. An anaerobic - anoxic - oxic (AAO) process was investigated to combine the denitrifying phosphorus removal potential with denitrification as the carbon source and, therefore, the AAO process was upgraded [5]. Note that phosphate effluent is removed mainly by chemical precipitation, which is expensive and also results in increased sludge production. Further research related to efficient TP control combined with biological treatment is required.

The benchmark simulation model no. 1 (BSM1) was successfully used for modeling the chemical oxygen demand (COD) and biological nitrogen (N) removal process [4,5]. This model achieves acceptable implementation and evaluation of the state-of-the-art control strategies for different predefined weather disturbance scenarios of dry, rain, and storm weather conditions [6]. The performance evaluation of the controllers in the WWTP is a complex activity, especially under the BSM1 simulation environment, which defines several assessment criteria, such as the integral of the absolute error, integral of the squared error, maximum deviation from set points, error variance, limits constraint violations on some concentrations, effluent quality, and operational costs [8-10]. In addition, the BSM1 model does not support the removal of phosphorous from the waste water.

Several recent studies have considered the removal of phosphorus during the wastewater treatment plant process. Gernaey et al. [11] employed a new simulation benchmark model that defines a default plant layout, a biological process model for TP control with detailed model parameters, realistic influent disturbances, and plant performance indices. Liu and Yoo [12] reported that the AAO process can simultaneously remove biological nitrogen and phosphorus in a WWTP with a nitrate cascade controller. Geber et al. [13]

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found that some PAOs are capable of utilizing nitrate, rather than oxygen, as an electron acceptor under anoxic conditions. Therefore, the presence of denitrifying PAOs in an AAO system may relieve the competition for COD between denitrification and EBPR, while bacteria can utilize the same carbon source to remove phosphorus.

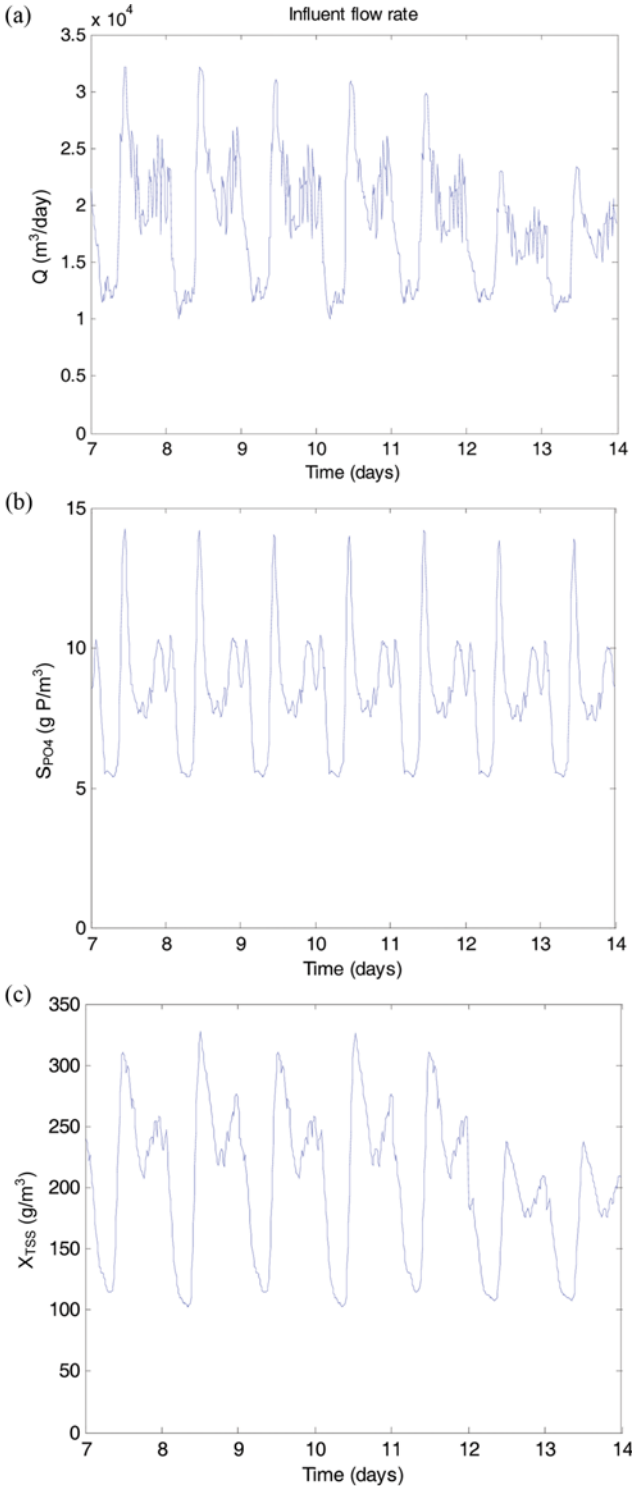

Fig. 1. Influent variations under dry weather conditions: (a) Influent flow rate (Q_{in}), (b) S_{PO4}, and (c) X_{TSS} profiles.

Recent studies have been focused on removing the phosphorus in WWTPs using changes in the biological and chemical dosage.

To date, there has not been a more detailed evaluation of TP control strategies for better effluent results. In this regard, the main purpose of this study is to decrease the TP concentration in the effluent of biological phosphorous removal by the addition of a chemical to the WWTP simultaneously. As shown in Fig. 1, the influents in the WWTP have widely varying disturbances that need advanced control strategies, such as feedforward and feed-ratio controls. However, the addition of chemicals significantly increases the sludge production of the WWTP process as well as the cost. We implemented and evaluated various controller strategies for the removal of the TP concentration. These control strategies were evaluated with control efficiency and economic for TP removal under three disturbances.

The following is an outline of this paper. The introduction sets the motivation for this study. In the materials and methods section, the AAO process and the model with activated sludge model no. 2d (ASM2d) are explained in detail. The TP control strategies and plant performances are also included. Next, the results are evaluated by comparing six TP control strategies with the open loop and closed loop results obtained from the references. Finally the percentage of increase in total phosphorus removal for each control strategy is explained.

MATERIALS AND METHODS

1. Process Description

The AAO process is considered to evaluate the TP control strategy as a case study [6]. This AAO process consisted of seven biological reactors connected in a sequential order which is followed by a secondary settler as shown in Fig. 2. The first two reactors were anaerobic, which were used for phosphorus release. The third and fourth reactors were anoxic, which were used for denitrification process, and the last three reactors were aerobic, where the nitrification of ammonia to nitrate was performed, and also, there is phosphorus uptake in these reactors [3]. Fig. 1 shows the dry weather influent scenario for the influent flow rate, concentration of phosphorus (S_{PO4}), and X_{TSS} profiles, where the dry weather influent conditions were considered for this process.

Fig. 2 shows the schematic representation of the four chemical dosage control strategies in the AAO process: constant dosage, feedback control, feedforward control, feed-ratio control. The nitrate in the anoxic zone was controlled by the internal recycle flow rate, which was connected from the exit of the last aerobic reactor to the first anoxic reactor in Fig. 2. The aerobic zone contains a dissolved oxygen (DO) controller set to the last reactor with a set point value 1. The underflow from the secondary clarifier was divided into two parts. First, sludge from the secondary clarifier was recycled back to the first anaerobic reactor, which was then combined with the influent composition. Second, the sludge that could not be recycled was considered to be the waste-activated sludge, and it was continuously pumped from the bottom of the secondary clarifier. The chemical (here, ferric chloride) was dosed to the last aerobic reactor and the change in the phosphorus concentration was observed [14].

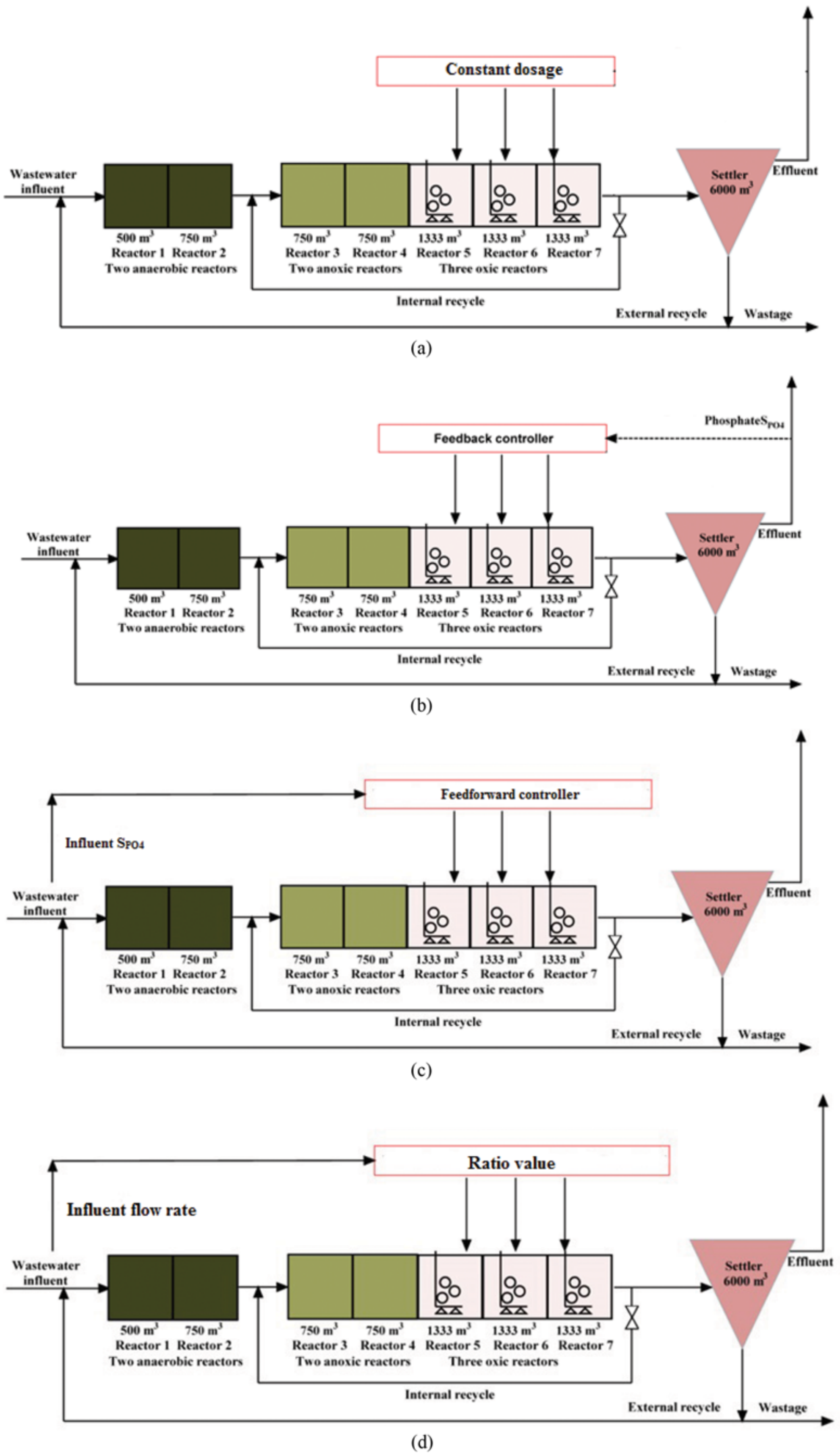

Fig. 2. Schematic representations of the four chemical dosage control strategies in the AAO process for: (a) Constant dosage (b) feedback control; (c) feedforward control; (d) feed-ratio control.

Table 1. Modified ASM2d decay process rate equations for the electron acceptor and dependency of the decay rates [6]

Process	Original decay rate equation	Modified decay rate equation
Decay of X_H	$b_H X_H$	$b_H\ [M_{H,O2}+\eta_{H,NO3,end} I_{H\cdot O2} M_{H,NO3}]\ X_H$
Decay of X_{PAO}	$b_{PAO} M_{P,ALK} X_{PAO}$	$b_{PAO} M_{P,ALK}\ [M_{P,O2}+I]_{P,NO3,end} I_{P,O2} M_{P,NO3}] X_{PAO}$
Decay of X_{PP}	$b_{PP} M_{P,ALK} X_{PP}$	$b_{PP} M_{P,ALK}\ [M_{P,O2}+I]_{PP,NO3,end} I_{P,O2} M_{P,NO3}]\ X_{PP}$
Decay of X_{PHA}	$b_{PHA} M_{P,ALK} X_{PHA}$	$b_{PHA} M_{P,ALK}\ [M_{P,O2}+I]_{PHA,NO3,end} I_{P,O2} M_{P,NO3}] X_{PHA}$
Decay of X_A	$b_A X_A$	$b_A\ [M_{A,O2}+\eta_{A,NO3,end} I_{A,O2} M_{A,NO3}]\ X_A$
With: $M_{P,ALK}=S_{ALK}/(K_{P,ALK}+S_{ALK})$;		
$M_{H,O2}=S_{O2}/(K_{H,O2}+S_{O2})$; $M_{P,O2}=S_{O2}/(K_{P,O2}+S_{O2})$; $M_{A,O2}=S_{O2}/(K_{A,O2}+S_{O2})$;		
$I_{H,O2}=K_{H,O2}/(K_{H,O2}+S_{O2})$; $I_{P,O2}=K_{P,O2}/(K_{P,O2}+S_{O2})$; $I_{A,O2}=K_{A,O2}/(K_{A,O2}+S_{O2})$;		
$M_{H,NO3}=S_{NO3}/(K_{H,NO3}+S_{NO3})$; $M_{P,NO3}=S_{NO3}/(K_{P,NO3}+S_{NO3})$; $M_{A,NO3}=S_{NO3}/(K_{A,NO3}+S_{NO3})$;		

On the other hand, the secondary clarifier was based on the Takacs double exponential settling velocity model [15]. The settling velocity parameters reported by Copp [16] were used in this process. The PAOs with the help of the sludge recycling were sent to the first anaerobic reactor to promote biological P removal and also to save the carbon source. In the process of TP removal, the concentration of nitrate (S_{NO3}) was controlled by the internal recycle flow rate in the anoxic reactors. The higher concentration of S_{NO3} led to higher effluent quality values. The proposed methodology was operated under the assumption that the sedimentation tank had no mixing, which means that it did not undergo any reaction to enhance the P removal. To avoid heavy suspended solids in the effluent, the wastage flow rate (Q_{ws}) was set to a constant value of 400 m^3/day. The concentration of the chemical (metal hydroxide) was fixed at 1,000,000 g/m^3. The chemical was dosed into reactor 7 to control the TP concentration in the effluent. The secondary clarifier, which was divided into ten layers, was non-reactive with a volume of 6,000 m^3, an area of 1,500 m^2, and a depth of 4 m.

2. ASM2d Model

The ASM2d was selected as the base model for describing the phosphorus removal process. In ASM2d, there are 19 state variables (including 9 soluble components and 10 particulate components) and 21 processes. All the variables and processes describe the oxidizing reactions, phosphorus reactions, nitration reactions, and denitrification reactions. Reactions in each bioreactor about 19 state variables follow mass balancing can be seen in Eq. (1):

$$\frac{dZ_k}{dt}=\frac{1}{V_k}(Q_{k-1}Z_{k-1}-r_iV_k-Q_kZ_k) \tag{1}$$

where k is the bioreactor number, Z_k is the state variables, Q_k is the influent, V_k is the volume of the bioreactor, r_i is the observed conversation rates, and i is from 1 to 19. r_i is the core parameter in ASM2d, which reflects the relationship among variables. AAO process is built with Matlab/Simulink, including seven bioreactors, secondary settler and a time-delay unit.

The simulation data of dry weather for 14 days is provided to test the model. The ASM2d model can handle both biological and chemical P removal simultaneously. The growth of phosphorus accumulating organisms (X_{PAO}) in the anoxic and aerobic reactors helped to release the phosphorus in the anaerobic reactor. Therefore, sufficient amounts of X_{PAO} must be present for the biological P removal. The modified ASM2d model was used to compensate the reduction effects of the decay rates for heterotrophs and X_{PAO} under anaerobic and anoxic reactors. This model contained modified equations for biomass decay, which made the biomass decay rates electron acceptor dependent in Table 1 [6]. The modified ASM2d model was used for this process. The modified equations were for the biomass decay, where an increase in sludge production occurred due to a decrease in the biomass decay rates.

3. Chemical Precipitation

Phosphorus removal has become a widely used process by using both the biological and chemical precipitation. When biological TP removal is not sufficient, chemical precipitation is used to eradicate the excess growth of eutrophication. Phosphorus is the key contributing cause for eutrophication, which results in the deterioration of water quality from uncontrolled algae growth. Chemical precipitation is a principle of the physic - chemical process, which involves the addition of divalent or trivalent metal salt to wastewater, causing precipitation of an insoluble metal phosphate that is settled out by sedimentation. The most suitable metal chlorides or sulfates for precipitation are iron and aluminum. Ferric chloride can be reacted with phosphoric acid as shown in Eq. (2) as follows [18]:

$$FeCl_3\cdot 6H_2O+PO_4\rightarrow FePO_4+3Cl+6H_2O \tag{2}$$

Chemical precipitation is a very flexible approach for phosphorus removal and can be applied at several stages during wastewater treatment. There are three types of chemical precipitation. At first, the chemical can be dosed before the primary sedimentation, and the phosphorus removed in the primary sludge is termed as primary precipitation. Second, the chemical can be dosed directly into the aeration reactor of the activated sludge process and the phosphorus is removed in the secondary sludge, and this is termed secondary precipitation or simultaneous precipitation. Finally, the dosage can be followed after the secondary treatment, but this is not generally favored due to high chemical costs and also an additional chemical is created, which is also known as tertiary sludge [18]. Since EBPR was not sufficient enough to remove large amounts of phosphorus in the WWTP processes, simultaneous biological and chemical removal was used. In this study, the chemical was injected into reactor 7, which underwent secondary precipitation.

4. TP Control Strategies

4-1. Feedback Controller

The feedback controller or proportional integral (PI) controller was used to control the effluent phosphorus concentration by manipulating the error between the phosphorus concentration and the desired set point value of 0.50 g P/m^3, which was less than the environmental regulation limit. PI controllers are widely employed in feedback control loops in almost all the industrial control systems due to their simple configuration, robustness, easy implementation, and good performance [19,20]. The PI controller equation is as follows:

$$\text{PI control: } u(t)=u_0+K_c*e(t)+\frac{K_e}{\tau_i}\int e(t)dt \quad (3)$$

where u_0 is the steady state bias value, e(t) is the error, and u(t) is the controller outputs of the proportional integral control. The constants K_c and τ_i in Eq. (3) are the proportional gain and the integral gain, respectively. The two constants K_c and τ_i should be determined under the dynamic conditions of the process where the tuning for parameters are performed for better controller results.

4-2. Feedforward Controller

Although immediate correction to the processes can be made, the controlled variable is not measured [21]. Since WWTPs have a time varying influent (disturbance), a feedforward control would be one solution for TP control. The disturbance variables and their effects are compensated in advance. Feedforward controllers are also widely used advanced control techniques in process control industries, where an exact model is needed. A feedforward control system consists of several process variables in WWTP: the chemical dosage acts as the disturbance signal (G_d), the WWTP process is the process signal (G_p), and the feedforward signal (G_F) is designed by using Eq. (4) as follows:

$$G_F=\frac{G_p}{G_d} \quad (4)$$

Note that two process models of the G_p and G_d should be identified for the implementation of feedforward control.

4-3. Feed-ratio Controller

The ratio controller is used to maintain the ratio of two process variables at a specific value, which is a special type of feedforward controller. The two variables are usually measured in feed-ration control. The flow rates are in parallel streams, of which one of the flow rates is set to a particular value (i.e., set point value), while the manipulated variable (u) and the flow rate, which changes according to the process, are the disturbance variables (d). Therefore, the ratio is given by following Eq. (5) [22]:

$$\text{Ratio}=\frac{u}{d} \quad (5)$$

It is very simple to use and easy to implement in process industries since it does not require a complex model.

5. Process Identification for Controller Tuning

The behavior of the system was identified according to the input-output variation. It is important to tune a parameter for a controller. The process identification justifies the physical aspects of the input to output data of the TP control process. Process identification for the TP control process can be executed and the internal

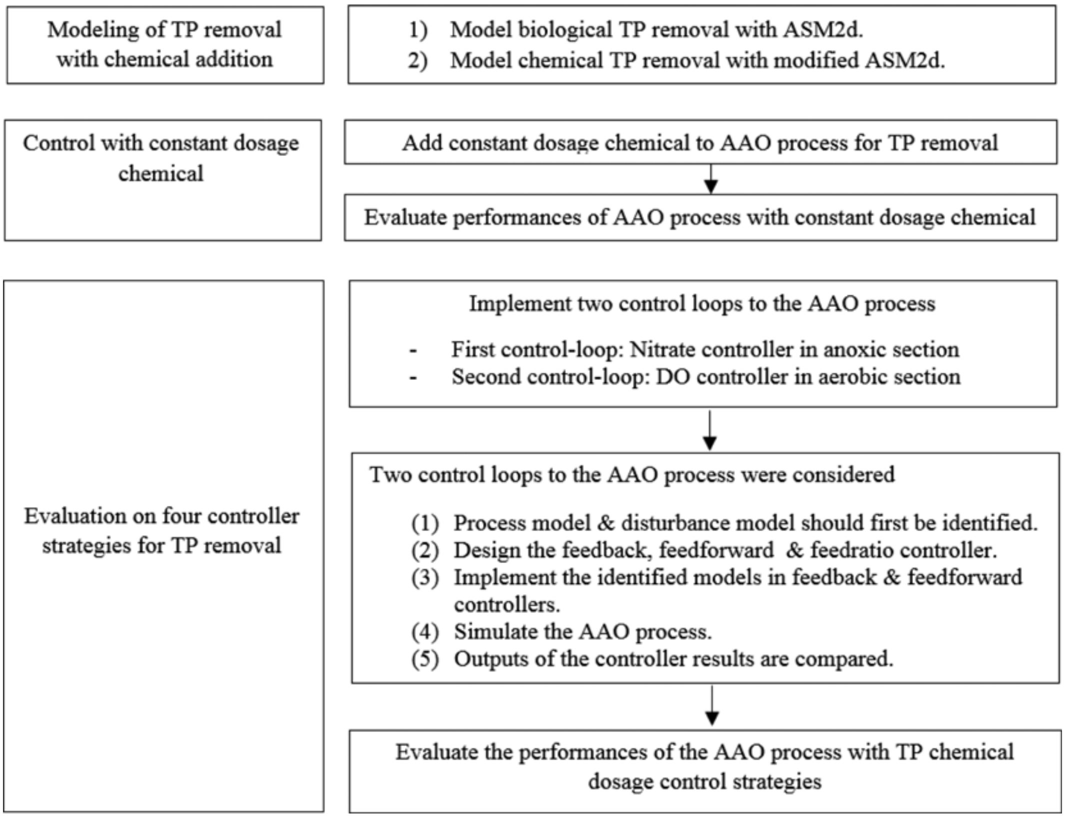

Fig. 3. The proposed framework of the TP chemical dosage control strategies for the WWTP process.

Table 2. Representation of the manipulated, controlled, measured, and disturbance variables for the six TP control strategies

Type of controller	Manipulated variable	Controlled variable	Disturbance variable (measured)
Open loop (C1)	-	Effluent S_{PO4}	-
Closed loop (C2)	Q_{intr} & K_La	Effluent S_{PO4}	-
Constant Dosage (C3)	Chemical flow rate	Effluent S_{PO4}	-
Feedback (C4)	Q_{intr}, K_La, & Chemical flow rate	Effluent S_{PO4}	-
Feedforward (C5)	Q_{intr}, K_La	Effluent S_{PO4}	Influent S_{PO4}
Feed-ratio (C6)	Q_{intr}, K_La, & Chemical flow rate	Effluent S_{PO4}	Influent flow rate

model control (IMC) was used as the tuning rule as developed by Skogestad [19]. Process identification was aimed for both feedback and feedforward control, which is used for controller tuning of the feedback controller and identified the disturbance model in order to implement the feedforward controller.

6. Proposed Method

The proposed framework in Fig. 3 was divided into three parts. First, the modeling part was applied to the AAO process model. Second, a constant dosage of the chemical was applied directly to reactor 7, which reacted instantaneously with the phosphorus present in the reactor and reduced its phosphorus concentration. The plant performance criteria were obtained for this type of control application. Third, advanced TP control algorithm of feedback, feedforward, and feed-ratio were implemented and evaluated. Process identification was performed for the feedback and feedforward controller designs. Table 2 shows the different variables recognized for the six controller strategies. The open loop (C1) did not contain nitrate and dissolved oxygen control loops, and the chemical flow rate was negligible. The closed loop (C2) contained two control loops (nitrate and dissolved oxygen) with a negligible chemical flow rate. The TP control strategies were implemented through the following six controllers: the open loop (C1), closed loop (C2), constant dosage (C3), feedback control (C4), feedforward control (C5), and feed-ratio control (C6). Finally, the plant performance criteria for these six controller strategies were evaluated and compared.

RESULTS AND DISCUSSION

1. Identification of that Control

The process identification was implemented to determine the input-output variation of the TP removal mechanism, which follows the tuning step of the controllers. The excitation input signal for the feedback and feedforward controller process identification were the pseudo random binary sequence (PRBS) and step input signal, respectively. Table 3 shows the performance of both the feedback and feedforward identification modeling for the estimation

Table 3. Process identification results with the feedback and feedforward control

	Estimation data set		Validation data set	
Model	RMSE	R	RMSE	R
PI control	0.6898	0.9708	0.7670	0.9027
Feedforward control	0.7449	0.9657	0.8069	0.9279

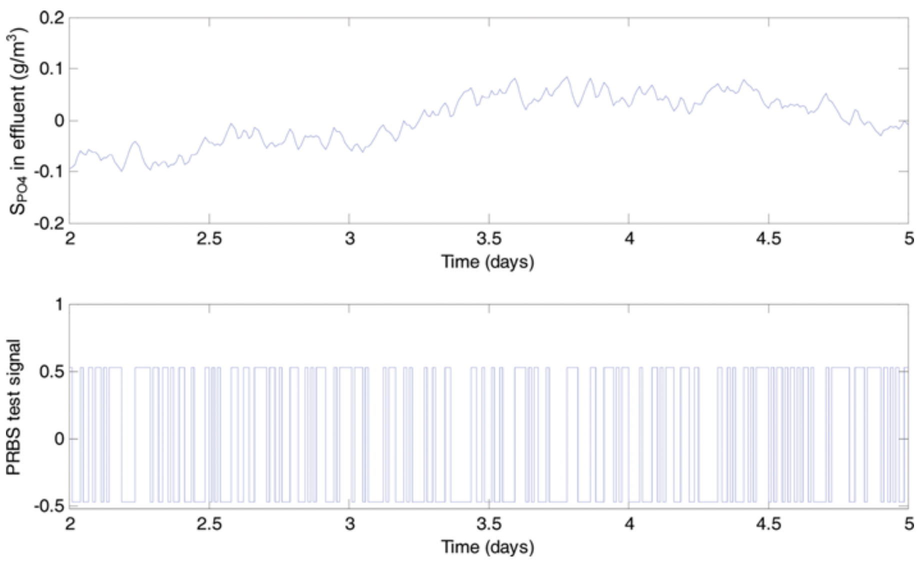

Fig. 4. S_{PO4} concentration and PRBS test signal for identifying the effluent phosphorus concentration dynamics: (upper) S_{PO4} concentration and (lower) added chemical amount with PRBS. Note: The units are normalized scale with mean zero, where the mean values were subtracted from the original data.

data and the validation data with the root mean square error (RMSE) values. RMSE is an absolute measure of fit, whereas the R-squared is a relative measure of fit. RMSE and R are calculated for the training and test data, respectively. In this study, RMSE value of the identification model is too low, which indicates that the model prediction ability is not good. This comes from the highly complex interactions among different variables in the process, while another reason for getting high values of RMSE is due to the presence of system non-linearity. Lower values of R^2 (very close to 1) indicate better fit for the system response. The chemical dosage using the PRBS signal was added at a reactor 7 of the process.

Fig. 4 shows the S_{PO4} concentration and added chemical amount with PRBS test signal for identifying the effluent phosphorus concentration dynamics at reactor 7. The system identification toolbox in the Matlab software was used to obtain the TP process model, where the PRBS gain value was 0.10 and the PRBS sampling time was chosen as 15 mins. Fig. 5 shows the identification results of the feedback and feedforward controller with the fit percentage of the estimation and validation data. The fit percentages for the estimation and validation data in the feedback control in Fig. 5(a) were 97.08% and 90.27%, respectively. To obtain accuracy, the mean values were subtracted from the original data. The continuous time PI controller in the standard form was used in the TP feedback control. Table 4 shows the tuned parameters for the multi-loop feedback controllers of phosphorus and nitrogen implemented in the AAO process. The phosphorus PI controller is implemented in the last aerobic reactor, while nitrate PI controller is in the last anoxic reactor. The Skogestad IMC tuning rule was used for the tunings of each controller. The process model for the PI controller in terms of transfer function G(s) with input U(s) and output Y(s) is shown in Eq. (6):

Table 4. Tuned parameters of PI controllers in the AAO process

PI control parameters	Phosphorus PI controller	Nitrate PI controller [6]
Proportional gain, K_p	−1.50	15,000
Integral time constant, τ_i	0.04	0.05
Anti-wind up time constant, τ_t	0.001	0.03

$$G(s) = \frac{Y(s)}{U(s)} = \frac{-1.5}{0.04s+1} \tag{6}$$

To compare the TP control results, additional two controllers with feedforward and feed-ratio were also implemented. The feedforward controller needs the disturbance model to identify the relationship between influent S_{PO4} and TP concentration of a bioreactor. A step input was added for the influent phosphorus concentration to obtain the disturbance model, since a step increase of influent S_{PO4} concentration typically occurs in the WWTP system. As shown in Fig. 5(b), the fit percentage of the process model for the estimation and validation data of the effluent S_{PO4} were 96.57% and 92.79%,

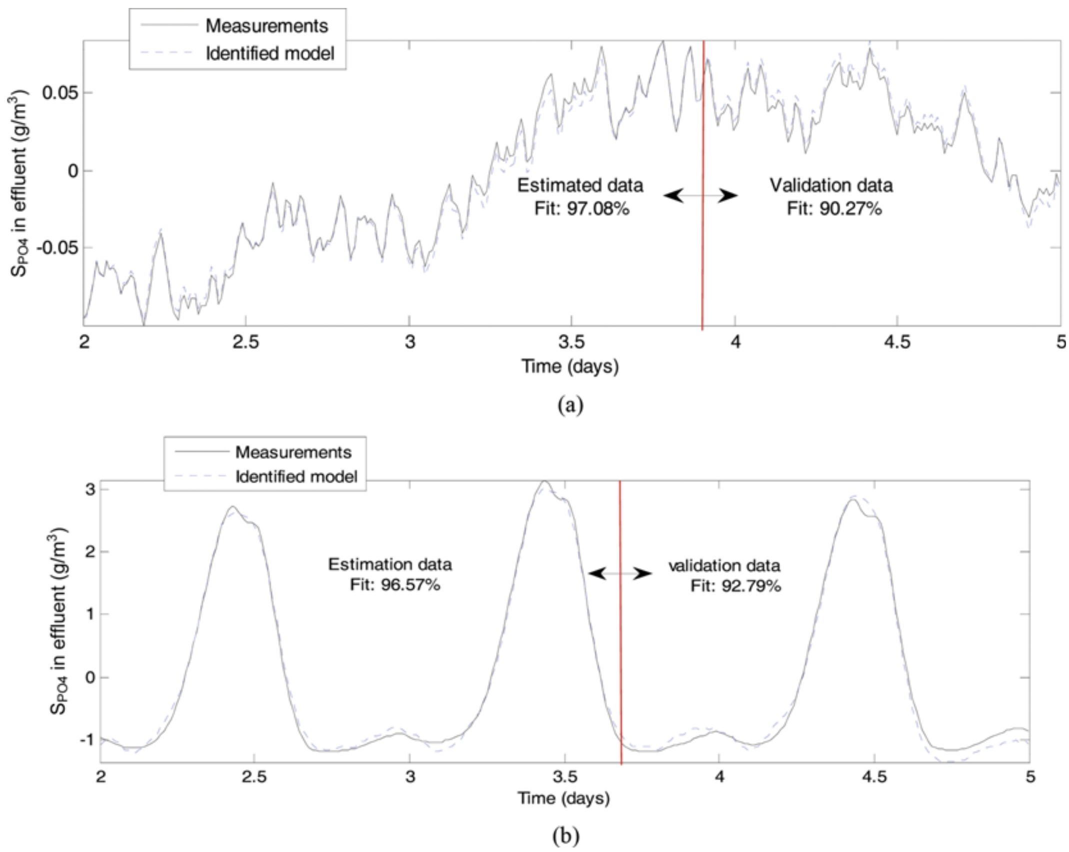

Fig. 5. Process identification results for the measured and estimated data for: (a) Feedback control; (b) feedforward control.

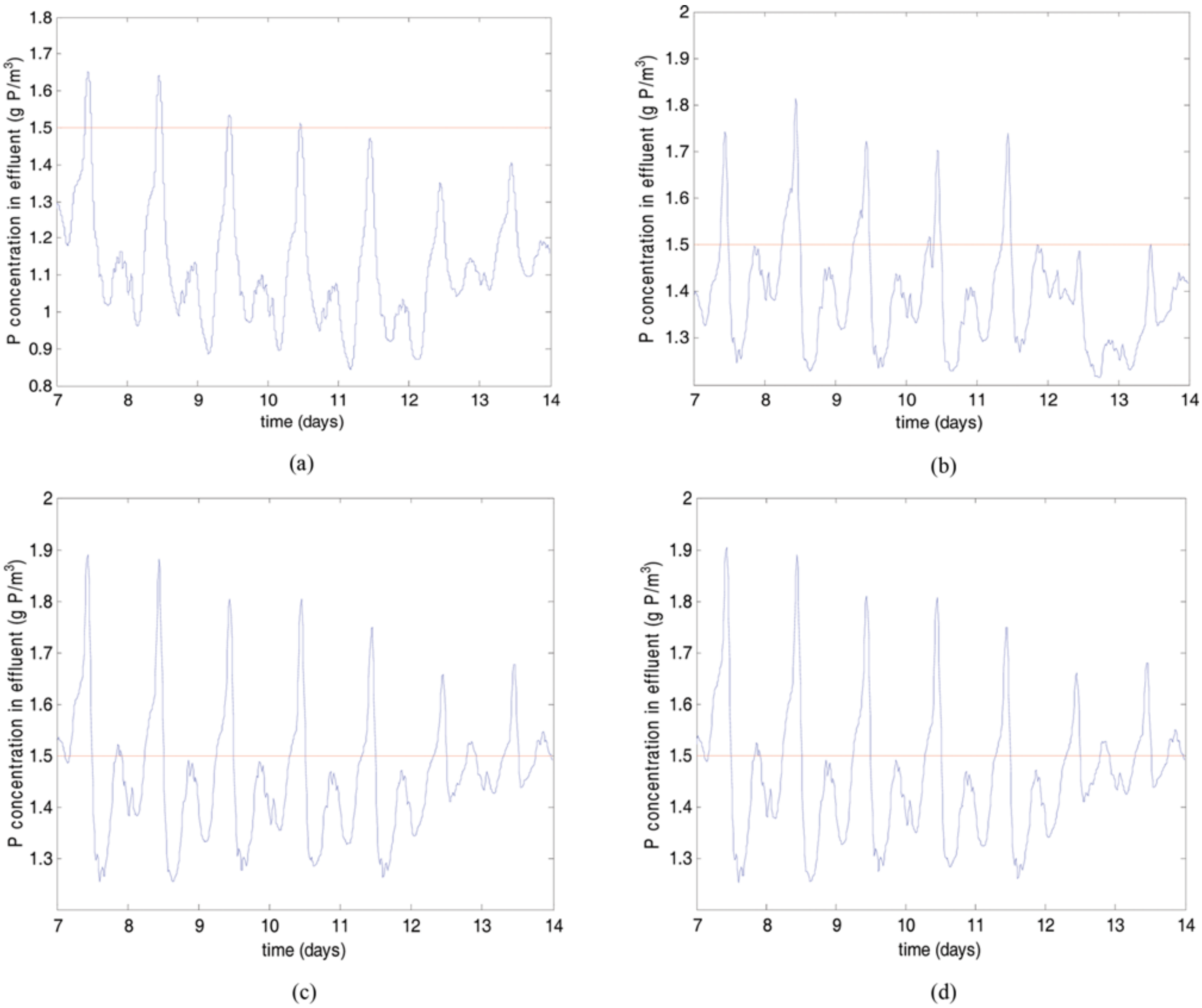

Fig. 6. Control results of the effluent total P concentration with the four controllers: (a) Constant dosage chemical; (b) feedback controller; (c) feedforward controller; (d) feed-ratio controller.

respectively. The feedforward transfer function (G_F) with the fourth order was found along with the chemical added to a reactor 7 to control the effluent phosphorus concentration.

Because the biological P removal was not sufficient in the BSM1 system, a chemical precipitation with the controllers was developed. Fig. 6 shows the control results of the effluent TP concentration (P_{tot}) with four TP control strategies with a set point value of 1.50 g P/m^3, which are constant dosage chemical, feedback controller, feedforward controller, and feed-ratio controller. The six TP control strategies were compared, where the PI feedback controller with IMC tuning parameter showed the highest economic efficiency with better P removal. This result indicates that chemical precipitation can provide better P removal for a feedback controller. On the other hand, the effluent S_{NO3} limit was exceeded due to a higher nitrification capacity in the aerobic reactors, which was also sent back to the anaerobic reactor through the recycle sludge.

For the constant dosage chemical, the flow rates were varied from 0.10 to 1 m^3/day to find the optimum amounts of constant dosage chemical. These flow rates were introduced into reactor 7 and the variation in the effluent phosphorus concentration was observed. Note that a constant chemical flow rate of 0.50 m^3/day was determined for considering the effluent phosphorus concentration with a limiting value of chemical cost. Fig. 6(a) shows that the effluent TP concentration for the constant dosage of chemical is an average value of 1.18 g P/m^3, but the cost of added chemical is also increased with the amount of chemical dosage in Table 5. Compared to the open loop result, the effluent TP concentration was minimized by 42%, but the chemical cost needs to be paid with 485 euro per day. This result represents that the constant dosage of the chemical clearly reduced the TP concentration with the high cost of chemical dosage. In the feed-ratio controller, the mean flow rate of the influent was 18,446 m^3/day. The chemical flow rate that was dosed into reactor 7 was 0.50 m^3/day. Therefore, the ratio value (R) for the control process was given by the ratio of the chemical set point flow rate to the influent mean flow rate. Table 5 compares the average concentrations of effluents controlled by the six TP control strate-

Table 5. Comparison of the effluent average concentrations controlled by the six TP control strategies

Eff. avg. concentrations	Open loop (C1)	Closed loop (C2)	Constant dosage (C3)	Feedback (PI) (C4)	FeedForward (C5)	Feed-ratio (C6)	Units
S_{NH4}	6.25	3.83	6.65	4.00	3.95	3.95	g N/m^3
S_{NO3}	8.05	9.55	7.90	9.56	9.56	9.56	g N/m^3
S_{PO4}	1.16	2.24	0.27	0.49	0.56	0.56	g P/m^3
N_{tot}	15.43	14.52	15.70	14.70	14.66	14.66	g N/m^3
P_{tot}	2.02	3.08	1.18	1.40	1.46	1.47	g P/m^3
COD_{tot}	45.90	45.91	46.01	46.04	46.03	46.04	g COD/m^3
X_{TSS}	15.16	15.08	15.11	15.03	15.04	15.04	g SS/m^3

Note: For the meaning of all acronyms and abbreviations in this table, see the NOMENCLATURE section of this paper

gies, which are the averages effluent concentration for the components of nitrogen, phosphorous and COD. The large variation of effluent concentration with standard deviation results from the disturbance by the influent phosphate concentration, where both the feedback and feedforward control were able to compensate this large size of disturbance. Fig. 6(d) shows that the effluent TP concentration for the feed-ratio controller was similar to the feedforward controller results. It should be that the feed-ratio control was simpler to implement than the feedforward control, since it did not require any model and the manipulated variable was easily adjusted by the ratio of the input flow rate.

2. Plant Performance of the TP Control

Table 5 lists the effluent average concentrations for the six TP control strategies, which are the concentration of ammonia (S_{NH4}), S_{NO3}, S_{PO4}, total nitrogen concentration (N_{tot}), P_{tot}, total COD concentration (COD_{tot}), and X_{TSS}. For a good control strategy in environmental process, the effluent average concentrations were considered to be less from a regulation point of view. All of the effluent average concentrations obeyed the regulation norms with their respective limit values except for the ammonia concentration where the open loop model exceeded its limit value by 56.25% and the constant chemical dosage limits by 21.33%.

Table 6 illustrates the various plant performance criteria which are related to cost and energy consumptions. The addition of a chemical to achieve P removal could result in extra cost. The effluent quality was represented with the cost performance index (CPI). CPI is the summation of effluent quality (EQ), aeration energy (AE), pumping energy (PE) and sludge production (P_{sldg}) costs shown in Eq. (7). The α coefficients in the equation are the operating cost weighting factors [6] are α_{EQ}=50 (euro/year)/EQ; $\alpha_{AE}=\alpha_{PE}$=25 (euro/year)/(kWh/d); α_{sldg}=75 (euro/year)/(kg TSS/d).

$$CPI=\alpha_{EQ}\,EQ+\alpha_{AE}\,AE+\alpha_{PE}\,PE+\alpha_{sldg}\,P_{sldg} \tag{7}$$

The chemical cost is calculated as the product of concentration of metal salt, flow rate of the chemical and cost of metal salt in euro per kg of metal salt shown in Eq. (8), which plays a very important role in the plant performance criteria. In this study, the concentration of chemical is considered as 1,000 g/l and the cost of metal salt per kilogram is 0.97 euro/kg [11,14].

$$\text{Chem cost}=\text{Flow rate of chem}\left(\frac{m^3}{day}\right)*\text{Chem conc.}\left(\frac{g}{m^3}\right)*\text{Cost of metal salt}\left(\frac{euro}{kg}\right) \tag{8}$$

Table 6 also includes plant performances like influent quality (IQ), effluent quality index (EQI), aeration energy (AE), pumping energy (PE) and sludge production (P_{sldg}). The effluent quality index is averaged over the period of observation t_{obs} (d) (i.e., the second week or seven last days for each weather file, here dry weather) based on weighting of the effluent loads of compounds that have a major influence on the quality of receiving water and that are usually included in legislation. It is shown in Eq. (9):

$$EQI=\frac{1}{1000\cdot T}\int_{t_{start}}^{t_{end}}(\beta_{TSS}\cdot TSS_e(t)+\beta_{COD}\cdot COD_e(t)+\beta_{TKN}\cdot TKN_e(t)+\beta_{NO}\cdot NO_e(t)+\beta_{BOD}\cdot BOD_e(t))\cdot Q_e(t)\cdot dt \tag{9}$$

Table 6. Comparison of the TP control performances with the six control strategies

Performance index	Open loop (C1)	Closed loop (C2)	Constant dosage (C3)	Feedback (PI) (C4)	FeedForward (C5)	Feed ratio (C6)	Units
IQ	46,929	46,933	46,930	46,933	46,933	46,933	kg poll·units/day
EQ	7,904	7,949	7,698	7,412	7,421	7,421	kg poll·units/day
AE	3,341	3,515	3,341	3,521	3,520	3,520	kWh/day
PE	389	315	389	314	314	314	kWh/day
P_{sldg}	3,424	3,342	3,404	3,330	3,326	3,326	kg/day
CPI	745,266	743,872	733,451	716,247	716,382	716,371	euro/year
Cost of chemical	0	0	485	441	493	485	euro/day

Note: For the meaning of all acronyms and abbreviations in this table, see the NOMENCLATURE section of this paper

The influent quality is similar to the effluent quality except a number change in the BOD coefficient from 0.25 to 0.65 [16] and is given by Eq. (10):

$$IQ=\frac{1}{1000\cdot T}\int_{t_{start}}^{t_{end}}(\beta_{TSS}\cdot TSS_i(t)+\beta_{COD}\cdot COD_i(t)+\beta_{TKN}\cdot TKN_i(t) \\ +\beta_{NO}\cdot NO_i(t)+\beta_{BOD}\cdot BOD_i(t))\cdot Q_i(t)\cdot dt \quad (10)$$

The aeration energy corresponds to the energy invested in aeration and is calculated from Eq. (11) [23]:

$$AE=\frac{S_O^{sat}}{t_{obs}\cdot 1.8\cdot 1000}\int_{t=7\ day}^{t=14\ days}\sum_{k=1}^{7}V_{as,k}\cdot K_La_k(t)dt \quad (11)$$

The pumping energy is the internal and external flow recycle pumps given by Eq. (12) [24]:

$$PE=\frac{1}{t_{obs}}\int_{t=7\ days}^{t=14\ days}(0.004\cdot Q_{int}(t)+0.008\cdot Q_r(t)+0.05\cdot Q_w(t))\cdot dt \quad (12)$$

The sludge production (P_{sldg}), is calculated from the total solid waste flow from wastage and the solids accumulated in the system over the period of time (seven days) and is shown in Eq. (13) [23-25]:

$$P_{sldg}=\frac{1}{t_{obs}}\Big(TSS\ (14\ days)-TSS\ (7\ days) \\ +0.75\cdot\int_{t=7\ days}^{t=14\ days}(X_{I,w}+X_{S,w}+X_{H,w}+X_{A,w})\cdot Q_w(t)\cdot dt\Big) \quad (13)$$

As shown in Fig. 6 and Table 6, all TP control strategies resulted in considerable improvement in the effluent quality. The result of TP control with constant chemical dose was compared with the results of feedback, feedforward, and feed-ratio controllers. Note that the closed loop results of the effluent nitrate concentration and the effluent TP concentration violated the regulation values. The effluent nitrate concentration for the feedback, feedforward, and feed-ratio controller violated the regulation values ban equal percentage of 6.22%. The feedback controller had the better EQ, PE, CPI and chemical cost (Table 6) when compared to the other five controller strategies [26-31]. From this result, we could justify the need for a plant-wide optimal control strategy because a model predictive control (MPC) is able to eliminate the complexity of the interactions between the control loops in a wastewater treatment system.

CONCLUSIONS

To enhance phosphorus removal and increase the effluent quality standards, four advanced control algorithms of TP control with chemical dosages were evaluated and compared. Compared to the open loop results, the constant dosage resulted in a 41.58% increase in the TP removal, and the feedback, feedforward, and feed-ratio controllers also resulted in an increase in theta removal of 54.54%, 52.60%, and 52.27%, respectively. Because the control algorithms for the improvement of the TP removal and the cost of the chemicals were conflicting, the proper dosing of the chemical in the plant-wide aspect should be determined, which is an on-going research topic.

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NOMENCLATURE

AAO	: anaerobic - anoxic - aerobic process
ASM2d	: activated sludge model no. 2d
AE	: aeration energy
b_A	: decay rate of autotrophic biomass
b_H	: decay rate of heterotrophic biomass
b_{PAO}	: decay rate of phosphorus accumulating organisms
b_{PHA}	: decay rate of organic storage products of X_{PAO}
b_{PP}	: decay rate of stored polyphosphates
BSM1	: benchmark simulation model no. 1
COD	: chemical oxygen demand
COD_{tot}	: total chemical oxygen demand concentration
CPI	: cost performance index
C1	: open loop controller
C2	: closed loop controller
C3	: constant dosage controller
C4	: feedback controller
C5	: feedforward controller
C6	: feed-ratio controller
d	: disturbance variable
DO	: dissolved oxygen
EBPR	: enhanced biological phosphorus removal
EQ	: effluent quality
g	: gram
G_d	: disturbance transfer function
G_F	: feedforward controller transfer function
G_P	: process transfer function
IMC	: internal model control
IQ	: influent quality
K_c	: controller gain
K_La	: oxygen mass transport coefficient
kg	: kilogram
kWh	: kilo watt hour
N	: nitrogen
N_{tot}	: total nitrogen concentration
P	: phosphorus
PAOs	: phosphorus accumulating organisms
P_{tot}	: total phosphorus concentration
P_{sldg}	: sludge production
PE	: pumping energy
PI	: proportional integral
Poll	: pollutants
PRBS	: pseudo - random binary sequence
Q_{in}	: input flow rate
Q_{intr}	: internal recycle flow rate
Q_{ws}	: waste activated sludge
R	: correlation coefficient
RMSE	: root mean square error
SS	: suspended solids

S_{ALK} : bicarbonate alkalinity
S_{PO4} : phosphorus concentration
S_{NH4} : ammonia concentration
S_{NO3} : nitrate concentration
TP : total phosphorus
u : manipulated variable
u_0 : steady state biased value
WWTP : wastewater treatment plant
X_A : autotrophic biomass
X_H : heterotrophic biomass
X_{PAO} : particulate concentration of poly accumulating organisms
X_{PHA} : organic storage products of X_{PAO}
X_{PP} : stored polyphosphate of X_{PAO}
X_{TSS} : particulate concentration of total suspended solids

Greek Symbols

τ_i : integral time

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