Wastewater Treatment Plant Control Strategies

Nobel Ballhysa[1], Soyeon Kim[1] and Seongjoon Byeon[2*]

[1]*Researcher, International Center for Urban Water Hydroinformatics Research and Innovation, Incheon, Korea*
[2]*Principal Researcher, International Center for Urban Water Hydroinformatics Research and Innovation, Incheon, Korea*
[*]*Corresponding author: seongjoon.byeon@gmail.com*

Abstract

The operation of a wastewater treatment plant (WWTP) is a complex task which requires to consider several aspects: adapting to always changing influent composition and volume, ensuring treated effluents quality complies with local regulations, ensuring dissolved oxygen levels in biological reaction tanks are sufficient to avoid anoxic conditions etc. all of it while minimizing usage of chemicals and power consumption. The traditional way of managing WWTPs consists in having employees on the field measure various parameters and make decisions based on their judgment and experience which holds various concerns such as the low frequency of data, errors in measurement and difficulty to analyze historical data to propose optimal solutions. In the case of activated sludge WWTPs, parts of the treatment process can be automated and controlled in order to satisfy various control objectives. The models developed by the International Water Association (IWA) have been extensively used worldwide in order to design and assess the performance of various control strategies. In this work, we propose to review most recent WWTP automation initiatives around the world and identify most currently used control parameters and control architectures. We then suggest a framework to select WWTP model, control parameters and control scheme in order to develop and benchmark control strategies for WWTP automation.

Keywords: Wastewater Treatment Plant (WWTP), Automated Control, Control Parameters, Benchmarking Model, Activated Sludge.

1. Introduction

A Wastewater Treatment Plant (hereafter WWTP) is a complex structure developed in order to treat domestic, industrial, agricultural influent or often a combination of all three. The operation of a WWTP often has the primary objective of ensuring that discharged effluent complies with the local regulations in term of water quality, despite changing influent conditions. In fact, the volume of influent is variable and these variations can follow daily patterns (increased influent rates during certain hours of the day) or change from

one day to another and so is the influent quality with values of suspended solids, biochemical oxygen demand, total nitrogen and phosphorus which can be drastically different from one day to the next. Activated sludge is the most widely used treatment process and focuses on the removal of organic matter and nutrients such as nitrogen and phosphorus by the combined use of aeration (injection of air at a certain flow rate), flocculation and settling. This process requires a specific combination of aerobic, anaerobic and anoxic conditions in order to ensure desired removal of pollutants. For instance, a certain concentration of dissolved oxygen (hereafter DO) is necessary to ensure nitrification (the biological oxidation of ammonia to nitrite and then nitrite to nitrate) while another concentration of dissolved oxygen will be necessary to ensure denitrification (the reduction of nitrate to molecular nitrogen). As a result, a wide range of devices is involved in the activated sludge process, including aeration devices (blowers), mixers, pumps, valves etc. Besides being able to ensure optimal treatment conditions and meeting the regulations for effluent quality, another main concern of WWTP operation is energy use and operation costs. Processes such as mixing, pumping, heating and mostly aeration all require high amounts of energy which eventually leads to high operation costs. The complexity of the treatment model combined with the need for optimization lead several studies to develop automated control strategies. These strategies have in common that they select one or several control parameters for which a target value called "set point" is determined and a modifiable variable which is corrected (automatically and in real time) in order to reach the desired set point. Control strategies are also backed up by data collected from sensors deployed on field such as DO or ammonium concentrations in bioreactors for instance. Initially, control strategies have been developed for a certain WWTP and since the conditions from one plant to another can radically vary, it was often difficult to assess their actual performance. Therefore, replicating a control strategy to another WWTP could lead to poor results in terms of performance. In order to address these issues, the International Water Association (IWA) created a task force to develop standardized mathematical models which would be able to describe the activated sludge treatment process, the anaerobic digestion of sludge and ultimately the whole WWTP. The ASM1 (Activated Sludge Model 1) model was firstly developed in 1987 and further enhanced with parameters modified. For instance, ASM2 published in 1995, included additional processes such as biological phosphorus removal and the relationship between the previously mentioned process and removal of nitrogen. ASM2d published in 1999, contained added description of anoxic and aerobic uptake of phosphorus [1]. The BSM1 (Benchmark Simulation Model 1) model was developed in order to allow benchmarking and evaluation of control strategies. The plant layout described in BSM1 comprises a five-compartment activated sludge reactor including two anoxic tanks followed by three aerobic tanks and a secondary clarifier. The plant described in BSM1 therefore realizes nitrification and pre-denitrification with the objective of biological nitrogen removal, one of the main tasks performed at full-scale WWTPs [2]. A default control strategy is included in the BSM1 model which consists in one controller manipulating the oxygen transfer coefficient to control the DO concentration in the last aerobic tank and one controller manipulating the internal recycle flow rate to control the nitrate concentration in the last anoxic tank. As shown in Figure 1, the BSM2 model [3] proposes a more complex WWTP layout which includes the BSM1 model for the biological treatment of wastewater but adds a primary clarifier, a thickener which collects the wasted sludge from the secondary clarifier, an anaerobic digester which treats the sludge from the primary clarifier and from the thickener and a sludge dewatering unit. Moreover, the ADM1 (Anaerobic Digestion Model 1) model which describes the digestion of sludge has been added to the BSM2 model together with interfaces which convert the variables from the ASM1 model into variables which can be used by the ADM1 model [4].

Table 1. Main characteristics of the BSM1 and BSM2 models

Model	Average Influent Dry-Weather Flow Rate (m³/day)	Influent Average Biodegradable COD (g/m³)	Hydraulic Retention Time (hrs)	Total Tank Volume (m³)
BSM1	18,446	300	14.4	12,000
BSM2	20,648.36	592.53	22	18,900

Table 1 shows some characteristics of the BSM1 and BSM2 models, the plant design average influent dry-weather flow rate has increased from 18,446 m³/day in the BSM1 model to 20,648.36 m³/day in the BSM2 model, the average biodegradable COD in the influent from 300g/m³ to 592.53g/m³ and the total tank volume from 12,000 m³ to 18,900 m³ with a total hydraulic retention time increasing from 14.4 hours to 22 hours. Several options for implementation exist such as simulation software packages including WEST or SIMBA and direct coding options including MATLAB and FORTAN programming languages.
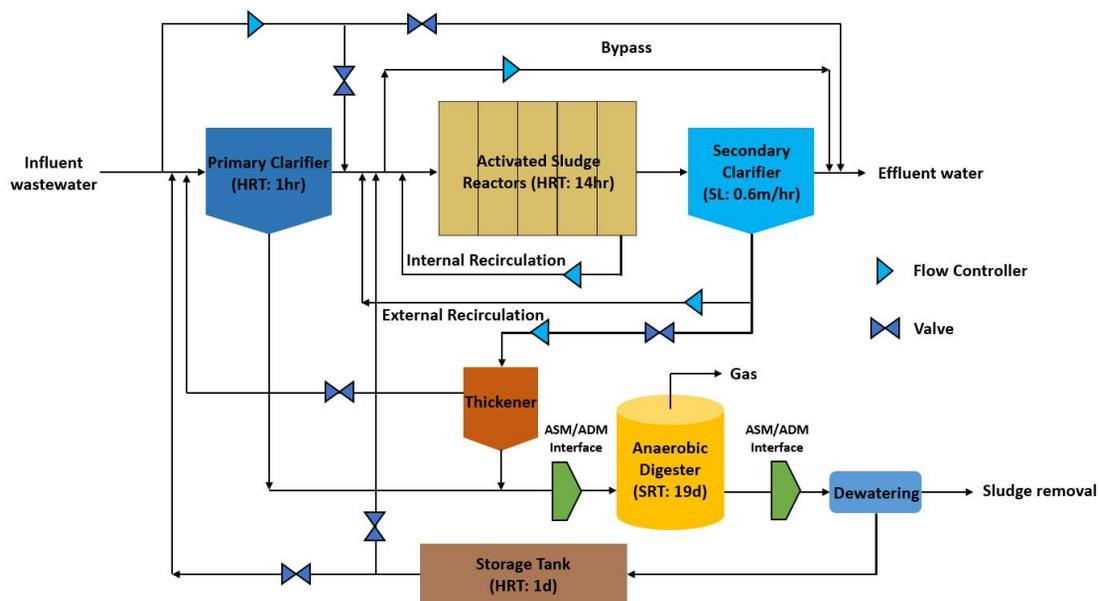
Figure 1. Overview of the BSM2 representation

The simulation of the BSM2 model for evaluation of plant performance is carried out for a period of 364 days which corresponds to a full operation year [5]. However, prior to this simulation, the model needs to be stabilized therefore a constant influent is first input for 200 days. The influent condition files for dynamic stabilization start 63 days before the 1st of January and last for a total of 245 days (63+182). The BSM2 model comes with a Default Closed Loop (hereafter DCL) which uses a PI (Proportional Integral) controller to control the DO set point in the fourth tank (second aerobic tank) to a value of 2mg/L by manipulating the oxygen transfer coefficient of the third, fourth and fifth tanks (K_{La3}, K_{La4} and K_{La5}) as shown in Figure 2 and Figure 3. This default strategy is used as a reference against which the performance of newly implemented control strategies is assessed [6]. A set of performance assessment indexes are available in the BSM2 model which includes the energy consumption from each process (aeration, heating, mixing). The three indices most often

used are the Influent Quality Index (hereafter IQI), the Effluent Quality Index (hereafter EQI) and the total Operation Cost Index (hereafter OCI).
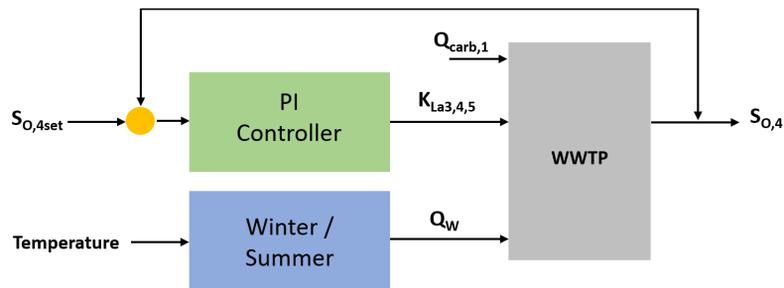

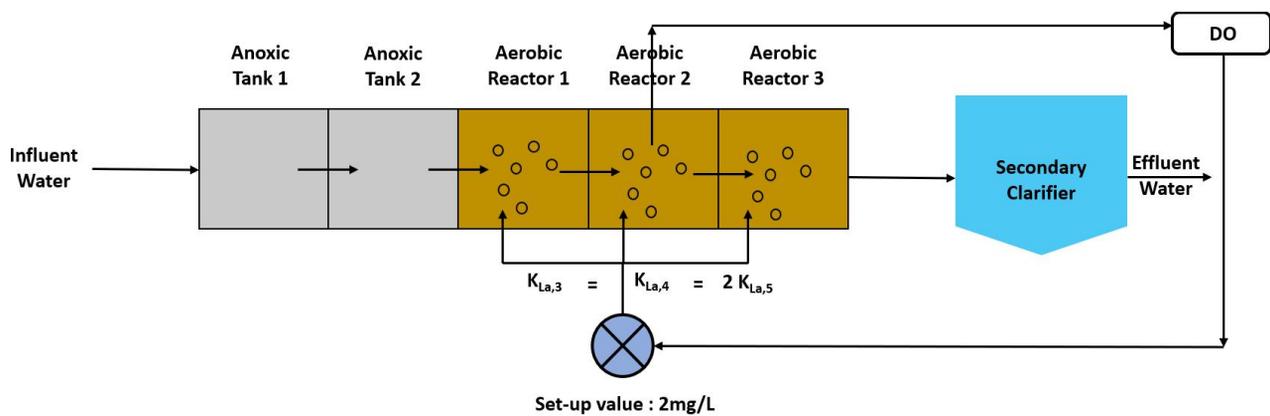**Figure 2. DCL (default closed loop) control strategy (1/2)**

Figure 3. DCL (default closed loop) control strategy (2/2)

2. Control Parameters and Strategies for WWTP

In order to understand the control parameters and strategies used in WWTP automation, we reviewed some of the most recent studies based on models developed by the IWA. As shown in Table 2, some of these studies developed control strategies focusing on the activated sludge treatment only and therefore used the ASM models while others focused on the entire WWTP automation and therefore used the BSM models.

Sanchez et al. [7] considered three control strategies with a set point of 1.5 mg/L for the dissolved oxygen (DO) concentration in the aerobic reactor: classic PI (Proportional Integral) controller, fuzzy PI controller and PI L/A (Logarithm/Antilogarithm) controller. The DO concentration value recorded inside the aerobic bioreactor serves as a feedback for the controller which in turn uses one of the three control schemes to produce an output. The output is converted to a frequency by the frequency converters and defines a corresponding rotation speed for the blower-motors of the aerobic bioreactor, thus having a direct influence on the air flow rate. In order to asses which one of the three control schemes offers the best performance, the considered performance index was the integral of the square error (ISE) and the aeration energy (unit: kWh/d). For both performance indexes, using the PI L/A controller showed lowest values and was thus deemed to be the best option in terms of set point accuracy maintenance and minimization of energy consumption.

Barbu et al. [8] considered the BSM2G model, an updated version of the BSM2 model which allows to evaluate the emissions of CO_2 from the biological treatment process. In addition to the Default Control Loop

(DCL) of the BSM2 model which was used as reference, six control strategies based on combinations of three control actions were implemented and tested. The first control action A1 defines a set point of $1g/m^3$ for the ammonium concentration in the fifth tank (last aerobic tank) and modifies the set point for the S_O controller, therefore using a cascade PI control. The second control action A2 defines a set point of $4,000g/m^3$ for the TSS (Total Suspended Solids) in the fifth tank and modifies the value of the wastage flow rate Q_w, using a simple PI control. The third control action A3 defines a set point of $1g/m^3$ for the nitrate concentration in the second tank (last anoxic tank) and modifies the value of the internal recirculation flow rate Q_a, using a simple PI control. Considering three criteria, Effluent Quality Index (EQI), Total Operational Cost Index (OCI) and Total Greenhouse Gas production (unit: kg CO_2/day), the control strategy S6, which combines the DCL with all three control actions A1, A2 and A3 gives the best trade off reducing EQI index by 11% and the OCI index by 7.7% compared to the DCL.

Luca et al. [9] considered the control of a WWTP which should be deserving a city of 250,000 inhabitants and used the ASM1 model for the activated sludge part and the ADM1 model for the anaerobic digestion part. The modelled WWTP comprises a primary clarifier, seven biological tanks and a secondary clarifier. In the first control strategy S1, the first tank is anaerobic, second and third tanks aera anoxic and the fourth to sixth tanks are aerated. An open loop in which each actuator is set up and controlled to a value corresponding to the design data of the wastewater treatment plant (maximum operating value) is defined. In the second control strategy S2, the first tank is anaerobic, second to fourth tanks anoxic and fifth and sixth tanks aerated. S2 controls several variables: DO concentration in the fifth and sixth aerated biological tanks and nitrate concentration in the fourth tank. The set point for DO in the fifth and sixth tanks is 4mg/L and the set point for nitrate in the fourth tank is 1mg/L. In the third control strategy S3, the first tank is anaerobic, the second and third tanks are anoxic and the fourth to sixth tanks are aerated. The set point for DO concentration in the fourth tank is 0.4mg/L and in the fifth and sixth tanks 2mg/L. The set point for nitrate concentration in the fourth tank is 5mg/L. Control strategy S4 adds to S3 a control for the MLSS (Mixed Liquor Suspended Solids) concentration at the input of the secondary clarifier with a set point of $3,500g/m^3$. Control strategy S5 is the same as S3 except that the DO concentration in the sixth tank is not a constant set point but is modified according to the ammonium concentration of the effluent ($1g/m^3$ for NH_4 and $5g/m^3$ for NO_4). Strategy S5 gave the best results: 7.7% reduction of the EQI index and a significant 54.2% reduction for the OCI index.

Selisteanu et al. [10] studied the possibility to develop a control strategy for the WWTP Calafat in Romania, designed for the treatment of a daily average flow of $8,366 m^3$ and to serve the 29,000 inhabitants of the town of Calafat. The study's aim was mainly to develop an advanced control solution focusing on the activated sludge treatment process with the main objective of maintaining the pollution levels in the effluent at a value which complies with local regulations despite changes in the pollutant load of the influent. The parameters to be controlled are the concentration of pollutant and DO in the aerated tank and the variables which can be modified are the dilution rate and the aeration rate. Three control strategies were considered, an Exact Feedback Linearizing control which considers constant inflow rate and explicit knowledge of all model variables and was used as reference, an adaptive control strategy (in which influent flow rate is assumed to be measurable but growth rate of influent organic load is unknown) and a robust control strategy (in which lower and upper bounds of both influent concentration and influent organic load growth rates are known). All three strategies were tested in real time using data from sensors deployed in WWTP Calafat and showed ability to maintain pollutant at desired levels in a more efficient manner than the reference strategy.

Revollar et al. [11] considered the BSM2 standardized model for implementation and evaluation of WWTP control strategies. They proposed an innovative approach which considers a N/E index (ratio between the

amount of nitrogenated compounds eliminated in the activated sludge treatment process in kgN and the energy required by the entire WWTP to eliminate that amount) as an indicator to assess overall performance of the WWTP and a control parameter to create a control strategy. Firstly, existing control strategies from the BSM2 model were implemented and their performance assessed. Along with the default DO control strategy of the BSM2 model used as reference, three strategies were implemented respectively based on DO and ammonium control. The DO + NO control strategy manipulates the recycle flow Q_a and uses the default DO control scheme of the BSM2 model and a PI control of nitrate concentration in the anoxic tanks (S_{NO2} controller). The ammonium-based control strategy regulates the ammonium concentration in the fifth bioreactor (S_{NH5}) using an external PI loop which computes the DO set point used in the default DO control scheme of the BSM2 model. For this cascade scheme, two different set points are considered, $SP_{NH} = 1g/m^3$ for strict ammonium regulations and $SP_{NH} = 4g/m^3$ for relaxed ammonium regulations. These three control strategies (DO + NO, Cascade $SP_{NH} = 1$ and Cascade $SP_{NH} = 4$) and the DO default were evaluated based on a set of performance indicators including EQI and OCI. A radar plot was computed and the control strategy which allowed to obtain the smallest area for the radar plot was the Cascade $SP_{NH} = 1$ control strategy which was deemed to be the most efficient. Secondly, they proposed a new performance assessment index obtained by modifying existing performance assessment indexes from the BSM2 model. The IQI and EQI indexes which refer to the influent and effluent quality were amended to create the EQN and IQN indexes which compute the same influent and effluent quality but only in terms of nitrogenated compounds. The final index developed, the N/E index is defined as the ratio between the nitrogen removal (IQN – EQN) and the total energy (a sum of aeration energy AE, pumping energy PE, mixing energy ME and heating energy HE). The control strategy based on the N/E index is similar to the cascade control scheme for the regulation of ammonium concentration except that the DO set point is computed in order to optimize energy efficiency (maximize N/E) index. Finally, the Cascade $SP_{NH} = 1$ control strategy is compared against the N/E control strategy using the same approach which consists in minimizing the area of the radar plot based on a set of performance indexes. The results (an overall radar plot area of 2.347 for the N/E control strategy and an overall radar plot area of 2.601 for the Cascade $SP_{NH} = 1$ control strategy) demonstrates the best performance of the newly developed N/E control strategy.

Santin et al. [12] considered the BSM1 model which default control strategy consists of two PI control loops. The first loop controls $S_{O,5}$ by manipulating K_{La5} with a set point for $S_{O,5}$ of 2mg/L and the second loop manipulates Qa to maintain $S_{NO,2}$ at a set point of 1mg/L. The study proposed a two-levels hierarchical control, in the lower level, the PI controllers of the default strategy previously mentioned are replaced by an MPC+FF (Model Predictive Control + Feed Forward) configuration, the set point for $S_{NH,5}$ being given by the higher level instead of being a fixed value of 2mg/L. In the higher level, three different controllers are tested, a MPC, an affine function and a fuzzy control. Three performance criteria are used to assess the efficiency of the proposed strategies: Integral of the Squared Error (ISE) measures the ability of the control strategy to maintain a value corresponding to the set point, the EQI and OCI indexes assess the improvement of effluent quality and operational cost. At the lower level, implementation of the MPC+FF controllers instead of the PI controllers leads to an ISE reduced by 99% which leads to no change in the OCI index but to a 1.1% reduction of the EQI index. For the higher level, using a MPC control shows 1.8% reduction of the EQI index and 0.8% reduction of the OCI index, whereas the Affine Function and Fuzzy controllers show 2.4% reduction of the EQI index and 1.1% reduction of the OCI index.

Drewnowski [13] considered the implementation of an optimized automation system at the Klimzowniec WWTP located in Chorzow, Poland which receive an average influent rate of 25,900 m^3/day (a population equivalent of approximately 200,000 inhabitants). The ASM2d model was chosen to represent the activated sludge process and calibrated with on-site data collected from deployed sensors during a period of six months.

A commercial solution, the PreviSYS/SCADA collects the data in real time from the sensors and carries out mathematical modelling, MPC control being used as a control strategy for treatment optimization. After the model was calibrated, it has been continuously run in order to develop efficient control strategies and offer an overall view of the plant performance in real time. Outcomes from the use of this system include identifying that 40 to 60% of the power consumption at the Klimnzowniec WWTP comes from aeration, and developing a control strategy which allowed 16% energy reduction. Further work, including longer training of the PreviSYS platform and integration of data from more sensors will allow to obtain even more cost-effective aeration systems.

## Table 2. Summary of WWTP control strategy research studies

Study Name	Selected Model	Objective	Selected Control Parameters/Strategy	Results
Revollar et al. (2020)	BSM2	Enhance global plant performance (nitrogen removal and energy consumption)	Cascade PI control of DO and ammonium with DO set point calculated to optimize N/E index	9% global performance improvement compared to SP_{NH} control strategy
Drewnowski (2019)	ASM2d	Optimize and improve energy balance	NH_4 sensor-based MPC	16% reduction of energy costs
Luca et al. (2019)	BSM1	Improve removal of organic substances and nitrogen	Cascade PI control of DO based on effluent ammonium concentration + PI control of nitrate	Improved Effluent Quality (7.7% reduction of EQI index) and reduced Total Operational Cost (54.2% reduction of OCI index) compared to default strategy
Selisteanu et al. (2018)	Modified ASM1	Maintain effluent pollution load values complying with regulations	DO and pollutant concentration / Adaptive Control Scheme and Robust Control Scheme	Effluent Pollution Load complying with regulations for the target WWTP Calafat (Romania)
Barbu et al. (2017)	BSM2G	Improve effluent quality, minimize operational cost and greenhouse gases emissions	DCL (Default Closed Loop) to control DO + S_{NH}, TSS and Q_a controllers	Improved Effluent Quality (11% reduction of EQI index) and reduced Total Operational Cost (7.7% reduction of OCI index) compared to default DCL
Santin et al. (2015)	BSM1	Improve effluent quality, minimize operational cost and energy consumption	Control of DO and Nitrite + Nitrate Nitrogen levels using a Two-Level Strategy: Lower Level: MPC+FF Higher Level: Affine Function and Fuzzy Controller	Improved Control Quality Improved EQI and OCI indices when using Affine Function or Fuzzy Controller compared to MPC

Sanchez et al. (2010)	ASM1	Maintain minimal DO concentration of 1.5mg/L	PI L/A (Logarithm/Antilogarithm) controller to control DO levels	DO concentration maintained closed to target value when WWTP operates at design capacity, 16% energy savings

3. Discussions and Findings

A review of WWTP control strategies modelled and evaluated using the IWA models allows us to identify steps which need to be taken in order to design and implement a new control strategy to allow automated control of an activated sludge WWTP as shown in Figure 4. First of all, the scope of automation shall be chosen depending on whether only the activated sludge treatment (i.e. bioreactors and clarifier) should be optimized or if the entire WWTP operation (including the treatment of sludge generated from the bioreactors) needs to be considered. Depending on the actual constitution of the WWTP for which the control strategy shall be designed, a model with the appropriate level of complexity should be chosen. If direct coding of one of the IWA models is carried out, some processes can be removed or modified accordingly. The BSM2 model proposes a thorough representation of the entire WWTP which includes the activated sludge process and therefore appears the most suitable in a holistic approach.

Secondly, the main objective of the control strategy needs to be defined. Single objectives can be selected such as enhanced removal of nitrogen, DO concentration maintained the closest possible to a defined set point etc. or overall objectives such as reduction of operational costs or greenhouse gas emissions or any combination of single objectives can be chosen. The objective of the control strategy essentially determines the complexity of the control scheme and is therefore of utmost importance. As reviewed, basic control strategies focus on DO concentration in the aerobic tanks of the activated sludge process which is the most often chosen control parameter. The next most common control parameter is the concentration of nitrogen (which can refer to either nitrite, nitrate, ammonium or a combination of one or more of them). A control strategy which controls both DO and nitrogen is expected to contribute to completion of several wider objectives such as improved effluent quality (reduced nitrogen levels) and optimized operation of air-blowers leading to reduced aeration costs and ultimately to reduced overall operation costs. However, depending on the considered performance assessment criteria, unwanted results can be obtained. For instance, choosing a DO set point which allows full denitrification will improve effluent quality (and the associated performance assessment indicator) but also cause increased emissions of N_2O and worsen the WWTP performance from the viewpoint of greenhouse gases emissions. The selected approach should offer the best trade-off between several objectives. Additional control parameters for a fully holistic approach include Total Suspended Solids (TSS), Internal Recirculation Flow Rate (Q_a) or Mixed Liquor Suspended Solids (MLSS).
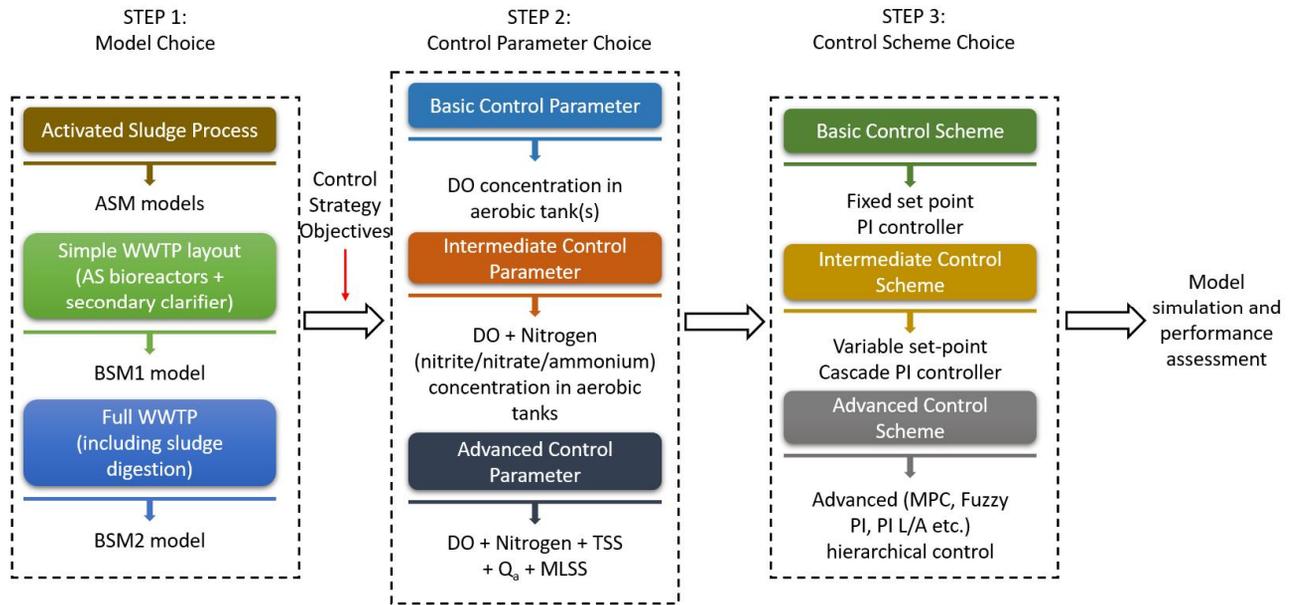
Figure 4. Proposed framework for control strategy design

After choosing the control parameter(s), the last step consists in selecting the controller type and control scheme. The simplest scheme is a PI controller with a fixed set point for the controlled parameter. PI control has proved to be a robust scheme but can cause fluctuations with an important amplitude around the set point. Other mathematical control schemes (such as MPC, MPC + Feed Forward, Fuzzy PI Controller, Affine Function or PI Logarithm/Antilogarithm) have the potential to reduce the error between the set point and the value produced by the control strategy. For instance, the study from Santin et al. showed that replacing a simple PI controller by an MPC+FF scheme reduces the Integral of the Squared Error between the set point and the predicted value by more than 99%, thus greatly enhancing the control quality. Moreover, instead of using a controller with a fixed set point, the use of cascade controllers or hierarchical schemes allows to have a variable set point for a control parameter which can be associated to another variable or even to a performance index. For instance, the study from Revollar et al. developed an improved cascade control scheme for DO in which the set point is not calculated in order to satisfy a fixed concentration of another parameter such as nitrogen but instead varies to allow the optimization of an energy efficiency index which is defined as the ratio between the amount of nitrogenated compounds eliminated and the energy used in the process.

4. Conclusions

In this paper, we reviewed latest initiatives for WWTP automated control in order to identify control parameters and control strategies applied and the efficiency which could be expected. The standardized models from the IWA have been broadly accepted and used throughout the world in order to be able to design and benchmark developed control strategies as well as replicate those strategies to other WWTPs with different characteristics. We propose a framework for design and implementation of WWTP control strategies using IWA models. This framework comprises three steps, selection of the WWTP model based on the complexity of the plant layout and the treatment processes to be described, selection of the control parameters based on the objectives to be achieved and selection of the control scheme according to the desired accuracy for achieving the selected target. Once these steps are completed, the model shall be built and calibrated against field data obtained from a set of sensors deployed in the WWTP and the performance of the developed control

strategies shall be assessed accordingly.

Acknowledgement

References

[1] M. Henze, W. Gujer, T. Mino, and M. van Loosdrecht, "Activated Sludge Models ASM1, ASM2, ASM2d and ASM3," IWA Publishing, Scientific and Technical Report series, 2000
DOI: https://doi.org/10.7236/JIIBC.2005.5.2.56.

[2] J. Alex, L. Benedetti, J. Copp, K.V. Gernaey, U. Jeppsson, I. Nopens, M.N. Pons, J.P. Steyer and P. Venrolleghem, "Benchmark Simulation Model no. 1 (BSM1)"

[3] D. Vrecko, K.V. Gernaey, C. Rosen and U. Jeppsson, "Benchmark Simulation Model No 2 in Matlab-Simulink: towards plant-wide WWTP control strategy evaluation," Water Science & Techology; Vol 54 No 8 pp 65-72, 2006
DOI: https://doi.org/10.2166/wst.2006.773

[4] C. Rosen and U. Jeppsson, "Aspects on ADM1 Implementation within the BSM2 Framework"

[5] J. Alex, L. Benedetti, J. Copp, K.V. Gernaey, U. Jeppsson, I. Nopens, M.N. Pons, C. Rosen, J.P. Steyer and P. Venrolleghem, "Benchmark Simulation Model no. 2 (BSM2)"

[6] I. Nopens, L. Benedetti, U. Jeppsson, M.-N. Pons, J. Alex, J.B. Copp, K.V. Gernaey, C. Rosen, J.P. Steyer and P. A. Vanrolleghem, "Benchmark Simulation Model No 2: finalization of plant layout and default control strategy," Water Science & Technology, Vol 62 No 9 pp 1967-1974, 2010
DOI: https://doi.org/10.2166/wst.2010.044

[7] E.N. Sanchez, V.R. Flores, J. Beteau and S. Carlos, "Automation of an Activated Sludge Wastewater Treatment Plant" in 11th International Symposium on Computer Applications in Biotechnology, Leuven, Belgium, pp 413-418, 2010

[8] M. Barbu, R. Vilanova, M. Meneses and I. Santin, "Global Evaluation of Wastewater Treatment Plants Control Strategies Including CO2 Emissions," IFAC PapersOnLine 50-1, pp 12956-12961, 2017
DOI: https://doi.org/10.1016/j.ifacol.2017.08.1800

[9] L. Luca, R. Vilanova, G.A. Ifrim, E. Ceanga, S. Caraman and M. Barbu, "Control Strategies of a Wastewater Treatment Plant," IFAC PapersOnLine 52-1, pp 257-262, 2019
DOI: https://doi.org/10.1016/j.ifacol.2019.06.071

[10] D. Selisteanu, I.M. Popescu, E. Petre, M. Roman, D. Sendrescu and B. Popa, "Distributed Control Systems for a Wastewater Treatment Plant: Architectures and Advanced Control Solutions," Wastewater and Water Quality, 9, pp 153-181, 2018
DOI: https://dx.doi.org/10.5772/intechopen.74827

[11] S. Revollar, R. Vilanova, P. Vega, M. Francisco and M. Menezes, "Wastewater Treatment Plant Operation: Simple Control Schemes with a Holistic Perspective," Sustainability, 12, pp 1-26, 2020
DOI: https://doi.org/10.3390/su12030768

[12] I. Santin, R. Pedret and R. Vilanova, "Applying variable dissolved oxygen set point in a two level hierarchical control structure to a wastewater treatment process," Journal of Process Control 28, pp 40-55, 2015
DOI: https://dx.doi.org/10.1016/j.jprocont.2015.02.005

[13] J. Drewnowski, "Advanced Supervisory Control System Implemented at Full-Scale WWTP – A Case Study of Optimization and Energy Balance Improvement," Water 11, 2019
DOI: https://doi.org/10.3390/w11061218