Energy saving for air supply in a real WWTP: application of a fuzzy logic controller

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ABSTRACT

An unconventional cascade control system, for the regulation of air supply in activated sludge WWTPs was tested. The dissolved oxygen (DO) set point in the aeration tank is dynamically calculated based on effluent ammonia concentration, following a fuzzy logic based approach. First, simulations were conducted, according to the BSM2 protocol, for a general comparison with more conventional control strategies. It turned out that the effluent quality can be improved to an extent of 7–8%, referring to the EQI parameter. Moreover, the aeration energy requirement can be reduced up to 13%. Subsequently, the system was installed at a full-scale WWTP. While stably complying with the ammonia effluent standard (10 mg/L), excess air supply was prevented: a reduction of the specific power consumption ($kWh/kgCOD_{removed}$) of 40–50% was recorded with respect to the previously installed PID controller (fixed DO set-point).

Key words | activated sludge, cascade control, municipal wastewater, nitrification, simulation, smart control strategy

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INTRODUCTION

In the last decades, the increase of the cost for energy supply and the simultaneous introduction of severe standards for environmental aspects made the topic of the energy employment in the water sector of great relevance. As a consequence, Wastewater Treatment Plants (WWTPs) are facing the issue of the reduction of energy consumption, i.e. operational costs, as well as the need for improving their effluent quality in order to meet restrictive discharge limits.

Energy consumption in WWTPs depends on several factors, such as plant location and size, origin and characteristics of wastewater, flow rate and polluting load inflowing the plant, hydraulic conditions, type of biological process, pumping station, sludge treatment line and energetic efficiency of the employed equipment. For conventional municipal WWTPs, energy costs are in the range 5–10% of the total yearly costs, including both construction and operation: in particular, 60% of the overall energy consumption in a conventional WWTP is related to the biological treatment, mainly to aeration purposes (WEF 2009), followed by the sludge treatment train (about 20%) and the pumping station (about 15%). Some authors report that aeration can account for up to 75% of the total energy usage (Rosso *et al.* 2008).

In order to improve the WWTPs efficiency and to reduce the cost of treatments, the Instrumentation Control and Automation (ICA) were introduced in this sector: the first ICA applications were realized in the 1970s within the activated sludge process for organic matter removal. Many different kinds of controllers were developed and simulated, including rule-based control, fuzzy logic control, linear quadratic control and model predictive control but, in most cases, the full scale application of control strategies is limited to linear controllers, the most common being the Proportional Integral (PI) and the Proportional Integral Derivative (PID) controllers (Olsson 2012; Åmand *et al.* 2013).

The air supply in the biological process was, in general, the most commonly controlled parameter due to its crucial role in the operation of WWTPs. The basic level of aeration control consists of keeping a stable Dissolved Oxygen (DO) concentration, independently from load fluctuations, by manipulating either the air flow rate or the speed/submergence of the mechanical aerators: this result is generally achieved by employing PI or PID controllers. The most frequent problems of DO control at a constant set point are related to the reduced flexibility associated to influent load

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fluctuations (Beltrán *et al.* 2015). The activated sludge treatment is a complex and nonlinear process in which time constants vary in a wide range (i.e., the air flow demand varies over the day, week and year as well as along the aeration tank) and never being in steady-state (Åmand *et al.* 2013); hence, high control performance, by using linear controllers (such as PID), is hardly achieved if a proper tuning is not carried out (see also the 'Results and Discussion' section of the present work, Figure 2).

As an alternative to linear controllers, unconventional control strategies were widely studied. In particular, the controllers based on fuzzy logic have been discussed from the 1980s (Tong *et al.* 1980), and have intermittently returned to favour (Serralta *et al.* 2002; Meyer & Pöpel 2003; Fiter *et al.* 2005; Traoré *et al.* 2005; Yong *et al.* 2006; Han *et al.* 2008), due to the capability of fuzzy logic to provide an intuitive formal representation of the process: indeed, it allows to include operator experience and process knowledge in the controller.

Nevertheless, the publications dealing with fuzzy controllers report mainly either simulation or pilot scale investigations. Simulations are generally related to different plants layout, influent load characteristics, simulation procedures and effluent legislative requirements. Moreover, the performances of the various controllers are evaluated using non-standardized parameters. All these aspects make the systematic comparison of possible alternative solutions very difficult to be performed.

To address this issue, the International Water Association Task Group on Benchmarking of Control Strategies for Wastewater Treatment Plants developed the so called Benchmark Simulation Model-BSM (Gernaey *et al.* 2014). In particular, the Benchmark Simulation Model No. 2 (BSM2) consists of a standard layout that includes a primary clarifier, 5 tanks-in-series for activated sludge (two unaerated tanks followed by three aerated tanks) and a secondary settler for the water line, while the treatment train for the sludge line is composed by a thickener, an anaerobic digester and a dewatering unit. The dynamic influent used for the simulation is generated with a phenomenological model (Gernaey *et al.* 2011). A standardized simulation protocol (simulation period of 609 days and evaluation period of one year) is defined along with an open-loop configuration and a default closed-loop scenario (to be used as reference scenario for the comparison of different control strategies). Moreover, a set of evaluation criteria is identified in order to ensure objective comparison. A detailed description of BSM2 protocol is reported in Gernaey *et al.* (2014).

However, even if software modelling can provide nearly unlimited flexibility and opportunities in control and process development (which is useful in a preliminary phase) there is a gap between the limitations of real applications and the opportunities that a simulation study can offer. Therefore, the need for full-scale validation of each control strategy is well-recognised (Jeppsson 2017). As far as Authors knowledge, the full-scale applications of fuzzy controllers are still scarcely available in the scientific literature: some results are reported but they are not related to DO control in a full-scale municipal conventional activated sludge plant.

The Authors patented the 'Oxy-fuzzy for water' control system. Results of a prototype application on a full-scale plant were previously published (Baroni *et al.* 2006). A first aim of this work was to obtain an objective comparison, still missing, with conventional control strategies, through a simulation phase. This was conducted according to the standardized BSM2 protocol. Moreover, to fill the gap of field validation, a version of the controller at a higher TRL (Technology Readiness Level), than the one previously studied, was applied to a full-scale WWTP. The evaluation carried out was mainly focused on the efficiency of the control system and the energy consumption/cost of treatment.

MATERIALS AND METHODS

The studied controller is composed of two modules: DOSP – Dissolved Oxygen Set Point module and AFR – Air Flow Rate module. The first module (DOSP) receives as inputs the effluent ammonia concentration measured with a 15 min frequency (the highest frequency permitted by the on-line measuring device installed at the full scale plant) and the ammonia variation rate over a period of 30 min (i.e. calculated based on the last 2–3 measured concentrations). By combining these two inputs, it calculates as output the percent variation of the DO set point (every 15 min) with respect to previous DO set point value. The proper DO concentration in the tank is determined in order to ensure that effluent ammonia concentration remains within a predefined range; thus, the DO set point varies dynamically taking into account effective process conditions (nitrification rate and influent load variability). The second module (AFR) regulates airflow (by calculating the percent variation of the valve position, every minute), to guarantee a DO concentration in the oxidation tank as close as possible to the calculated set point. To this aim, it receives as inputs the oxygen concentration measured each second and calculates: (a) the average over one minute, (b) the percent error between the desired and measured DO value, and (c) the variation rate over a period of 12 min. The operation of the controller is thoroughly described in Baroni *et al.* (2006).

Before implementing the innovative controller based on fuzzy logic at full-scale, simulations were carried out in the framework of BSM2 in order to obtain an objective comparison with conventional air supply controller. The free code made available in Matlab/Simulink by Gernaey *et al.* (2014) was used.

The following control strategies for air supply were simulated:

- open-loop BSM2 configuration (OL), i.e. constant aeration with the following fixed default K_La coefficients in the aerobic tanks: 120 d^{-1}, 120 d^{-1} and 60 d^{-1} (Gernaey *et al.* 2014).
- Default closed-loop BSM2 configuration (CL0): a fixed DO set point of 2 mg/L is kept in the intermediate aerated tank (#4), by manipulating K_La_4 with a PI controller. For the other reactors, the same ratios as in the previous scenario are adopted: $K_La_3 = K_La_4 = 2\ K_La_5$ (Gernaey *et al.* 2014).
- Adapted version of the oxy-fuzzy controller (F): a variable DO set point in the third aerated tank (where the effluent ammonia concentration should be measured in a full-scale application) is calculated by the DOSP fuzzy module of the patented controller. The DO concentration is then adjusted by manipulating K_La_5 with a traditional PI controller. Air supply in the other reactors is varied, by calculating the corresponding K_La values, keeping the same ratios as in the previous scenarios. It was not possible to use the AFR module of the complete fuzzy logic controller for adjusting the air flow, because the simulation software does not include tools for describing the physical behaviour of mechanical devices of the air supply system (such as blowers and valves).

The evaluation criteria of the BSM2 protocol were considered (Gernaey *et al.* 2014):

- Effluent Quality Index (EQI) as the weighted average sum of the following effluent concentrations: Total Suspended Solids – TSS, Chemical Oxygen Demand – COD, Total Kjeldhal Nitrogen – TKN, Nitrates and nitrites – NO, Biochemical Oxygen Demand – BOD;
- duration of total nitrogen (18 mg/L) and ammonia nitrogen (4 mg/L) effluent limit violation;
- Operational Cost Index (OCI) as the weighted sum of the costs for aeration energy (AE), pumping energy, sludge production for disposal, external carbon addition, mixing energy, methane production and heating energy.

The WWTP chosen for full-scale implementation is a conventional activated sludge plant (design size 350,000 people equivalent) with the biological treatment divided in three parallel lines. In this plant, the aeration supply accounts for 55% of the whole energy demand, thus an energy saving in this section represents a relevant issue. The traditional DO control strategy is based on the measurement of the DO concentration in the tanks, to be compared with a fixed DO set point, without taking into consideration effective nitrification process performance and the influent load variability. To overcome the limitations of this type of control strategy, the fuzzy-based system was installed in two of the three biological treatment lines (total volume = 25,000 m^3). The air supply system consists of two centrifuge blowers (20,000 Nm^3/h) and fine bubbles diffusers. The plant is not located in a sensitive area, so that the standard for effluent NH_4^+ concentration is 15 mg/L.

The following are the main components of the oxy-fuzzy system for each one of the two lines (the design criteria were the same for both the lines): a $N\text{-}NH_4^+$ on-line probe for effluent ammonia concentration monitoring, two oxymeters placed in the intermediate and outlet sections of the biological reactor, a system for data acquisition and elaboration, the fuzzy controller, an output control decision actuation system that opens/closes the valve to regulate the air flow. A detailed description of the apparatus that makes up the entire control system is reported in Baroni *et al.* (2006).

The first step of the full-scale application consisted in a tuning phase of the patented fuzzy controller. Starting from the original version, through a trial and error process, based on qualitative observation of experimental data, modifications were adopted in terms of rule definition, membership function shaping and timing of the control actions. This process was very important to adapt the system to the case specific characteristics. Moreover it took several weeks, also to assess its behaviour under different conditions.

The full-scale performance of the oxy-fuzzy controller was evaluated by comparing the power consumption for aeration measured during two consecutive months (December and January) of two consecutive years, the first one being referred to fixed DO set point controller and the second one to the oxy-fuzzy controller. The power consumption was normalized over the influent or removed organic load and flow rate.

Indeed, several practical issues have been tackled for the application at the full scale: the choice of the representative sections where to place the OD and ammonia measuring sensors, depending on the hydrodynamic behaviour of reactors; efforts for keeping the sensors efficient by proper maintenance; the need to consider the inertia of mechanical devices (blowers and valves in particular) in the control chain; the presence of limitations of the blowers capacity (both minimum and maximum air flowrate); the necessity to manage critical events (such as power supply interruption, PC or software default, unreliable electric signals due to different kinds of troubles of the measuring devices, etc.); setting a minimum acceptable DO concentration in the aeration tanks to prevent the occurrence of unwanted effects, as, for instance, the deterioration of the sludge settling properties and the increase of N_2O emissions. This last aspect is being widely studied in the recent years (Boiocchi *et al.* 2017; Mannina *et al.* 2019), but was not specifically investigated in the present work.

RESULTS AND DISCUSSION

In the simulated open-loop configuration, total nitrogen and ammonia nitrogen effluent limits (18 mg/L and 4 mg/L) are violated for a period of 0.4 d and 30 d, with a 95th percentile of 15.1 mg/L and 4.7 mg/L, respectively. Dissolved oxygen concentration in the three aerated tanks varies in a wide range (0.3–5 mg/L).

With the implementation of the default closed-loop configuration, total nitrogen and ammonia nitrogen effluent limits are violated for a period of 4.3 d and 1.5 d, with a 95th percentile of 16.8 mg/L and 1.5 mg/L, respectively. The CL0 configuration improves the performance of the plant in terms of ammonia nitrogen with respect to OL scenario. The controlled variable (dissolved oxygen concentration in the second aerated tank) is coherent with the set point with slight oscillations.

The simulation of the fuzzy controller shows the following results in terms of effluent limits violations: total nitrogen and ammonia nitrogen limits are violated for a period of 1.43 d and 3.03 d, with a 95th percentile of 14.83 mg/L and 2.69 mg/L, respectively. The dissolved oxygen concentration in the third aerated tank is coherent with the set point and oscillations are further reduced. As expected, there is a good correspondence between DO concentration in the tank and effluent ammonia nitrogen.

The simulated scenarios present similar performance in terms of BOD_5, COD and TSS effluent limits violations.

Table 1 | Evaluation criteria of the different simulated scenarios: comparison between open loop configuration (OL), default closed-loop configuration (CL0) and fuzzy controller (F)

	EQI [kg/d]	OCI [kWh/d]	AE [kWh/d]
OL	5,661	9,208	4,000
CL0	5,577	9,450	4,225
F	5,186	8,892	3,673

Table 1 reports the results of the three simulated configurations in terms of effluent quality (EQI) and costs (OCI). The cost for aeration energy is specified, being the main item influenced by the implementation of different air supply controller. The plant performance in terms of effluent quality is improved by the introduction of the fuzzy controller to an extent of 7–8%. Moreover, the application of the fuzzy controller allows a reduction of the operating costs of 3.4% and 6% with respect to OL and CL0, respectively. Considering the contribution of the aeration energy, the fuzzy controller reduces the energy consumption in the range 8–13%.

It has to be underlined that the results obtained with the fuzzy system (scenario F) are comparable to those obtainable with a similar cascade control strategy, adopting PID controllers (some tests were conducted during the present study: data not shown). Nevertheless, the fuzzy approach revealed to be user friendly and the controller more efficient

Table 2 | Energy consumption for air supply: comparison between traditional and fuzzy controller in two consecutive months of different years

	Traditional controller	Fuzzy controller
COD_{in} [kg/d]	23,025 23,737	29,953 27,328
$COD_{removed}$ [kg/d]	20,604 20,304	28,070 25,818
Treated flow rate [m^3/d]	75,315 79,572	97,130 83,278
Energy consumption [kWh/d]	12,589 11,705	8,785 9,159
Specific energy consumption [kWh/(p.e.*y)]$^{(*)}$	22 20	12 13
Specific energy consumption [kWh/m^3]	0.17 0.15	0.09 0.11
Specific energy consumption [kWh/kg$COD_{removed}$]	0.61 0.58	0.31 0.35

Average COD mass loadings over the observation period are reported. Daily measurements were carried out (flowrate volume; COD analysis on 24 h composite samples).
$^{(*)}$assumed daily per-capita COD production = 110 g/(p.e*d).

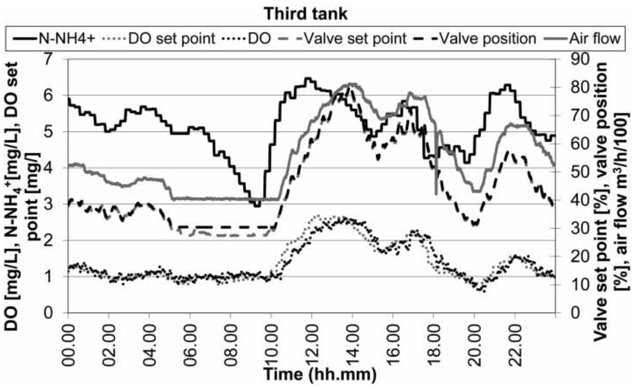

Figure 1 | Typical behaviour of the fuzzy controller installed on the full-scale plant. Trends, over one day, of Dissolved Oxygen (DO) concentration and set-point, N-NH$_4^+$ concentration, valve position (actual and set-point), and air flow.

in stably regulating the plant working conditions, as shown by the real scale application described below.

In the full-scale plant, the controller performance was assessed in terms of both effect on process parameters (efficiency and stability) and energy consumption, with respect to the original configuration.

Figure 1 shows the typical variations of the controlled parameters (DO set point, valve set point, valve position and air flow) over one day. Data refer, as an example, to one of the tanks equipped with the fuzzy controller. Both the tanks, actually, exerted similar behaviour (data not shown). The graph shows that ammonia concentration is stably below the adopted reference safety value of 10 mg/L (the effluent standard being 15 mgNH_4^+/L), and kept in the range 3–6 mg/L. DO and valve position set-points are continuously modified according to the ammonia concentration trend, and the variations of these parameters clearly reflect on the nitrification efficiency. Excess aeration, typical of fixed DO set point systems, is avoided, by reducing the DO set point, when

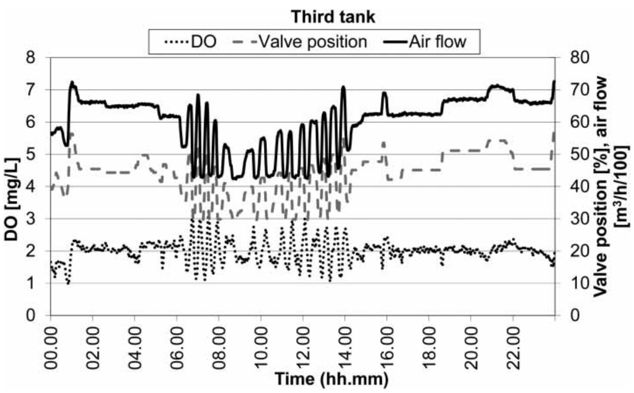

Figure 2 | Example of DO concentration, valve position and air flow trends, with fixed DO set-point (2 mg/L; PID controller), in the full scale plant.

ammonia tends to decrease. Furthermore, the DO concentration and the valve position are always close to their set point, thus exhibiting a high control efficiency.

Moreover, the overall process stabilization was achieved, reducing both the amplitude and frequency of fluctuation of the controlled parameters, with respect to the previous situation: an example of oscillation problems observed with fixed DO set-point (PID controller) is reported in Figure 2.

CONCLUSIONS

In this work, the application of an unconventional fuzzy logic cascade controller for air supply system was tested both at simulation level and at full-scale. Indeed, even if, in the last decades, original controllers have been widely studied at simulation scale, real applications are scarcely reported in the scientific literature.

The oxy-fuzzy controller implemented at full-scale confirmed the preliminary results obtained at simulation level. It showed good control performance, ensuring the required ammonia removal extent. Moreover an improvement of process stability and a promising energy saving were obtained with respect to the traditional fixed DO controller. Simultaneously, a short payback time (less than two years) was estimated for the investment.

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