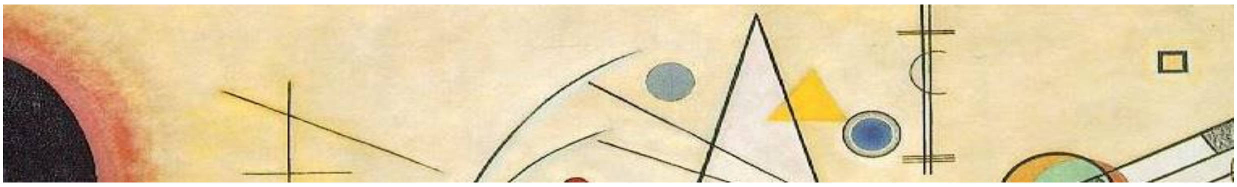

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Artigo

FUZZY DISSOLVED OXYGEN CONTROLLER APPLIED IN ACTIVATED SLUDGE PROCESS

CONTROLE FUZZY DE OXIGÊNIO DISSOLVIDO APLICADO A PROCESSO DE LODOS ATIVADOS

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ABSTRACT: Roughly 80% of waste water treatment plants are based on active sludge technique due to its simplicity and reliability. Under aerobic conditions microorganisms can grow on some organic pollutants present in the wastewater. As such, dissolved oxygen control is paramount in order to save energy, improve effluent quality and achieve high nitrogen removal. However, due to the nonlinearities of bioprocesses, dissolved oxygen (DO) is a challenge in terms of variable control. In Suzano municipal Waste Water Treatment Plant (WWTP) - located in São Paulo Metropolitan area - dissolved oxygen control is conducted based on a set of heuristic rules stablished by skilful operators. Although yielding satisfactory results, staff training is time consuming. Under the light of these facts, this study aimed to develop a fuzzy DO controller applied to activated sludge process. Data collection and implementation of the fuzzy control system were conducted in bioreactors at Suzano WWTP. Three fuzzy inference systems were developed: "aerator number", "aerator speed" and "submergence height". The fuzzy controller was tested and calibrated with a dynamic simulator and implemented as a supervisory controller, yielding positive results. Statistically, dissolved oxygen mean was 1.75 mg/L with a standard deviation of 0.25 mg/L. Based on the results the application of fuzzy logic for DO control in activated sludge process has proven not only viable, but an interesting control option. Fuzzy logic overcame DO non-linearities by translating an empirical knowledge into a linguistic, rule-based controller. It is a promising technique, bringing significant advances, both in treatment performance and energy efficiency.

KEYWORDS: Fuzzy Controller, Dissolved Oxygen Control, Activated Sludge, Waste Water Treatment.

RESUMO: Aproximadamente 80% das estações de tratamento de efluentes (ETE) são baseadas na técnica de lodo ativado devido à sua simplicidade e confiabilidade. Sob condições aeróbicas, os microrganismos podem crescer sob alguns poluentes orgânicos presentes nas águas residuais. Logo, o controle do oxigênio dissolvido é fundamental para economizar energia, melhorar a qualidade do efluente e obter alta remoção de nitrogênio. No entanto, devido incertezas intrínsecas e não linearidades dos bioprocessos, o oxigênio dissolvido é um desafio em termos de controle. Na Estação de Tratamento de Efluente (ETE) municipal de Suzano - localizada na região metropolitana de São Paulo - o controle de oxigênio dissolvido (OD) é realizado com base em um conjunto de regras heurísticas estabelecidas por operadores experientes. Embora produza resultados satisfatórios, o treinamento da equipe consome muito tempo. Diante destes fatos, este trabalho teve como objetivo desenvolver um controlador fuzzy de OD aplicado ao processo de lodos ativados. A coleta de dados e a implementação do sistema de controle *fuzzy* foram realizadas em biorreatores da ETE Suzano. Foram desenvolvidos três sistemas de inferência nebulosos:

“número do aerador”, “velocidade do aerador” e “altura de submergência”. O controlador *fuzzy* foi testado e calibrado com um simulador dinâmico e implementado como controlador supervisório, gerando resultados positivos. Estatisticamente, a média de OD foi de 1,75 mg/L com desvio padrão de 0,25 mg/L. Com base nos resultados, a aplicação da lógica fuzzy para controle de OD em processos de lodo ativado mostrou-se não apenas viável, mas também uma opção de controle interessante. Em relação às estratégias de controle clássicas, a lógica fuzzy superou as não-linearidades do OD ao traduzir um conhecimento empírico em um controlador linguístico baseado em regras simples. É uma técnica promissora na área de controle de OD, trazendo avanços significativos, tanto no desempenho do tratamento quanto na eficiência energética.

PALAVRAS-CHAVE: Controlador Nebuloso, Controle de Oxigênio Dissolvido, Lodos Ativados, Tratamento de Efluentes.

1. Introduction

COVID-19 pandemic was a turning point in many social aspects. One of them was basic sanitation, as the paramount measure against coronavirus infection. Although access to an adequate amount of safe water has always been advocated as a basic necessity. In 2021, for instance, more than 770 million people lack access to safe water and nearly a million deaths were attributed to unsafe water, lack of sanitation or poor hygiene related diseases (GUVEN et al., 2023; WHO, 2021). The World Water Development Report released in 2017 by the United Nations revealed distressful numbers. Globally, over 80% of the wastewater is discharged without treatment. High-income countries treat about 70% of sewage they generate. In contrast, low-income countries treat less than 10% of the generated sewage.

High-income countries invest heavily on cutting-edge wastewater treatment technologies due to water scarcity. Microbial fuel cell is a

technology based on bio-electrochemical processes of bacteria that generates electricity from the degradation of organic material. Only in the past decade this technology was applied in wastewater treatment with interesting results (TSEKOURAS et al., 2022). Membrane bioreactors (MBRs) research emerged from the intensification of the membrane separation technology by incorporating it with the activated sludge process. Although fouling is the main bottleneck of this technology, it is a flexible and viable (AL-ASHEH; BAGHERI; AIDAN, 2021). Nanotechnology is also an emerging field in WWTP. It can be applied to adsorption and biosorption techniques such as carbon based or metal based nanoadsorbents. Nanofilters with almost 100% removal rate of heavy metals from wastewater and photocatalysis are also under studies (JAIN et al., 2021). Low-income countries usually lack financing, technical capacity and infrastructure, resulting in extremely low level of secondary and advanced wastewater treatment. (NIDHEESH et al., 2022) reviewed emerging technologies adopted in WWTP in developing nations. The main challenges faced are the complex nature and the highly volatile composition of the effluent. The main techniques are biodegradation (activated sludge or stabilization lagoons), constructed wetlands (employed in tertiary treatment), membrane systems (such as bagasse, sand, gravel or coal) and chemical precipitation and coagulation processes (specially for heavy metal contamination) (NIDHEESH et al., 2022).

Although Waste Water Treatment (WWT) field is clearly expanding, roughly 80% of the wastewater treatment plants are based on active sludge technique due to its simplicity and reliability (“Wastewater”, 2017). This technique also stands out particularly in situations that require high quality of the treated effluent, with reduced space for unit installation (SPERLING, 2016). Activated sludge system consists of a biological process where microorganisms are suspended in a bioreactor. Under aerobic conditions they can grow on any organic pollutants present in the wastewater (carbonaceous

matter and nutrients). During the formation of a microorganism mass, it can adhere to solid particles, forming macroscopic flakes (known as activated sludge). These flakes are kept in suspension due to mechanical agitation in the bioreactor (DIAS, 1982; GUVEN et al., 2023). This suspension is also called mixed liquor and it is sent to secondary decantation units, where the activated sludge flakes and supernatant liquid (treated sewage) are separated. (VAN HAANDEL; MARAIS, 1999). The supernatant constitutes the effluent of the system, which is discharged into a receiving body or subjected to tertiary treatment (JORDÃO, 2017). When the system is properly designed, and ideal operating conditions are maintained, the organic load reduction can exceed 90%. In general, flakes present high oxygen demand, requiring a supplementary oxygenation system. This can be done by injecting air (air bubble insufflation), or more rarely, pure oxygen into the reactor. Another common method consists of agitating the effluent via superficial mechanical aeration (JORDÃO, 2017). As it can be inferred, dissolved oxygen (DO) control in WWTPs is essential to improve control accuracy, save aeration energy, improve effluent quality (under the lowest energy consumption) and achieve high nitrogen removal.

Dissolved oxygen concentration (DOC) in the reactor depends on the pollutant nature and its concentration in the effluent to be treated. Usually, it is expressed in terms of Biochemical Oxygen Demand (BOD), which represents the amount of oxygen required for the biological degradation of organic matter (SPERLING, 2016). According to (JORDÃO, 2017), it is recommended to keep the DOC in the bioreactor outlet above 0.5 mg/L. In practice, during severe fluctuations in the characteristics of the effluent, this concentration is maintained between 1.0 and 2.5 mg/l, aiming to establish a safe margin to supply any sudden oxygen demand peak. Therefore, due to the extensive uncertainties and nonlinearities – intrinsic to biological processes - DO is seen as a challenge in terms of variable control (AKISUE, 2022).

Li *et al.,* 2022 reviewed the most recent DO control techniques applied to WWTPs. The study classified the control strategies in conventional control, intelligent control and hybrid control. The first group is the most widely used control strategy and it ranges from the classic Proportional-Integral-Derivative control (PID) to a complex Model-based advanced Predictive Control (MPC). Differential equations can be a useful tool to describe the dynamic or kinetic aspects of a system. However, obtaining a mathematical expression that accurately describe the behavior of a bioprocess can be difficult and time consuming (GOMIDE; GUDWIN, 1994; LI; ZOU; JIANG, 2022).

In this context, intelligent control emerged given the complexity of nonlinear time-varying systems. It is comprised of fuzzy logic and neural networks applied to control theory. Fuzzy logic was proposed by professor L. A. Zadeh as a mathematical translation of human brain thinking (ZADEH, 1965). Later, it was adapted for computer digital control techniques. A basic fuzzy logic controller contains fuzzy linguistic variables, defined by linguistic values and associated by fuzzy rules, forming the knowledge base. Fuzzy inference starts by mapping a fuzzy set of input universe according to the membership function in the knowledge base. Then, fuzzy reasoning is carried out based on user-defined fuzzy rules, imitating human thinking. Finally, defuzzification process yield the control output (ZADEH, 1975). Neural network is a learning algorithm that can predict and estimate the system model using only experimental data. The algorithm “learns” by making the output as close as possible to the desired trajectory using mathematical calculations and parameter adjustments. Both conventional control and intelligent control have their own strengths and limitations. Therefore, hybrid control methods combined two or more control methods in order to improve stability and speed (LI; ZOU; JIANG, 2022).

Under the light of these facts, this study aims to develop a fuzzy controller for DO control in an activated sludge process. All the data acquired

for the fuzzy inference system build and its parameter adjustment was provided by Suzano WWTP - managed by São Paulo State Basic Sanitation Company (SABESP). SABESP is the most important sanitation company in Brazil (and one of the largest in the world), supplying 28.4 million people with water and providing sewage collection and treatment services to 25.2 million people in the state of Sao Paulo. In 2021 the company alone was responsible for around 30% of the investments in basic sanitation in Brazil (nearly US$ 1 billion) (“Sabesp Sustainability Report 2021”, 2021). The main steps of the current study were: (I) DO and control actions data collection with time series analysis; (II) development of the fuzzy inference system (and fuzzy set rules) based on expert knowledge in the process; (III) development of a DO simulator to test the fuzzy controller performance and train human operators; (IV) implementation of the DO fuzzy controller in a parallel system as a supervisory controller (although not replacing the human operator) to further test the DO fuzzy controller robustness; (V) comparison of DO results controlled by a human operator and monitored with the fuzzy controller. To the author’s best knowledge, there is a gap regarding fuzzy DO control in activated sludge processes implemented in large scale WWTP such as the ones managed by SABESP.

2. Material and methods

2.1 Data collection

Data collection and implementation of the fuzzy control system were conducted in bioreactors at the Suzano WWTP, located in São Paulo Metropolitan area. Construction of the unit began in 1973 and it was commissioned on May 14, 1982. Treated effluents are released on the left bank of Tietê River (a Class 3 river which, according to the National Water

Agency, allows treated effluent to be discharged on its course). The main operational data design described in Table 1 (SABESP, 2023).

Table 1: Suzano WWTP operational data

Population equivalent capacity (inhabitants)	Lowest flowrate (L/s)	Average flowrate (L/s)	Maximum flowrate (L/s)	Effluent BOD charge (T/day)
670.000	600	1.500	2.000	38,8

Source: SABESP, 2023

The unit was designed anticipating a per capita contribution of organic load equivalent to 58 g BOD/day, with an effluent characterization as presented in Table 2:

Table 2: WWTP effluent characterization

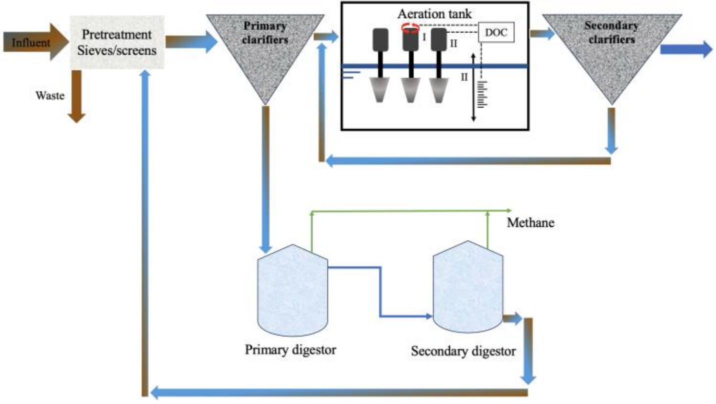
Parameters	BOD (mg/L)	TSS (mg/L)	Domestic influent contribution (%)	Industrial influent contribution (%)
Designed values	300	300	35	65

Source: SABESP, 2023

In Suzano WWTP, the effluents are initially submitted to a pretreatment. It consists of removing objects that could damage the plant or the equipment that will be used during effluent purification processes. First, roughing filtration is carried out. In this phase large and medium-sized solid waste are separated using different screen thickness and sieves. Subsequently, grease and sand particles are removed using desanders and degreasers. The next stage, called primary treatment, is based on the initial separation of solid organic matter from wastewater. The objective is to remove part of the suspended solids. To this end, water is retained for nearly two hours in primary clarifiers where gravity helps to separate these particles. These decanters separate between 25% and 50% of the solids (also known as organics/sludge) in the effluent. The solids sink to the bottom of the tank and are pumped regularly to a sludge digestor or sludge

processing area, where they are dried and hauled away. Chemicals such as coagulants and flocculants can also be added to improve the sedimentation process. During the secondary treatment, treated wastewater is pumped into a secondary clarifier to allow any remaining organic sediment to settle out of treated water flow. This phase is mainly biological and uses bacteria and microorganisms to degrade and eliminate the organic matter. In the WWTP studied, the secondary treatment is based on activated sludge technique, where the water to be treated is left in a tank for several days under varying oxygen conditions (aerobic, anoxic and anaerobic) depending on the required removal requirements. Here, the different types of bacteria inside the bioreactor feed on the organic matter and the nutrients contained in the water. Part of this effluent is returned to the bioreactor to increase the bacterial concentration, help in propagation, and accelerate the breakdown of organic material. The excess is discarded. The water that flows from the secondary clarifier has substantially reduced organic material and should be approaching expected effluent specifications. Additionally, the process is also equipped with an anaerobic treatment subunit for the residues. However, this subunit is not the focus of the present study. A summarized scheme of the process is presented in the Figure 1.

Figure 1: Schematic representation of Suzano WWTP



Source: SABESP, 2023 (adapted)

Monitoring of dissolved oxygen is carried out through optical sensors in the bioreactor. According to the literature, the ideal DOC range in a WWTP activated sludge bioreactor is between 1.0 mg/L and 2.5 mg/L (JORDÃO, 2017). DOC is controlled by manipulating aerator speed (I) and submergence of the rotors (II), in addition to the number of aeration units in operation (III). When DOC gets below 1.0 mg/L threshold, the shift operator follows a heuristic provided by the WWTP operational manual. In the first level of the heuristic, submergence of the rotors is increased. Followed by an increase in the rotational speed. Finally, if DOC is still below the threshold, the operator adds more aerators. Each bioreactor is equipped with 5 aerator units (with at least three operating full time). Aerator speed of each unit operates between 40 to 60 rpm with a submergence height between 20 to 35 cm. In cases of DOC greater than 2.5 mg/l, the logic is inverted as the priority is the reduction of aerators, followed by a reduction in aerator speed and finally a decrease in submergence height.

In order to obtain a comprehensive dataset of different DO scenarios, corresponding to control actions taken by human operators, an operational data collection was carried out from October 2022 to February 2023. In order to coincide with BOD measurements (to evaluate DOC), the number of aerators, their submergence height and aerator speed data were taken every 2 hours between 00:00 to 20:00. This dataset was modelled in a dynamic series of 55 operational scenarios, which was used to define the fuzzy rules and the fuzzy inference system.

2.2 Fuzzyfication of DO system

In activated sludge processes, significant oscillations in dissolved oxygen can be traced in the bioreactor, especially when the characteristics of the effluent are subject to large variations such as in industrial waste. Therefore, an efficient strategy is required in order to ensure the quality of

the treatment. In this context, the application of fuzzy logic becomes interesting as it is a suitable technique to interpret information that carry inaccuracies and uncertainties, translating an empirical knowledge to a convenient mathematical logic.

Fuzzy logic can be defined as a logical system capable of formalizing an approximate reasoning. As opposed to binary logic, in which information can only be classified as true or false, in fuzzy logic each element is assigned a certain degree of membership (a numerical value raging from 0 to 1 - in which 0 indicates complete exclusion and 1 complete membership from its set) (ZADEH, 1965, 1975). Fuzzy control allows modeling of control actions, based on expert's knowledge, instead of classic mathematical deterministic models (HSIAO et al., 1992; LEE et al., 1991). By translating crisp inputs and outputs to fuzzy sets and correlating them using fuzzy rules, it is possible to obtain a robust and precise controller, that can be easily implemented in the processes (GOMIDE; GUDWIN, 1994).

Fuzzy controller development was carried out in a heuristic manner. For this, the elaboration of the rule base and adjustments in the membership functions was carried out according to the fuzzy principle of Mamdani control, using prior knowledge of the WWTP (with MATLAB’s Fuzzy Logic toolbox). Figure 2 shows the fuzzy controller structure (with its inputs and outputs and their respective membership functions). Three separated fuzzy inference systems allowed more flexibility and facilitated the implementation. Each fuzzy system was named after its output variable, “Rotation Speed”, “Aerator Number” and “Submergence height”, all already employed as manipulated variables of the heuristic DO control in the bioreactor. Their linguistic terms were defined based on operational manual instructions (increase, decrease or no action required). The input variables were chosen based on DO control literature (AKISUE, 2022; MONTENEGRO et al., 2020) and data availability. The current number of aerators (their rotation speed and the submergence height) and the current DOC were previously employed as input variables of

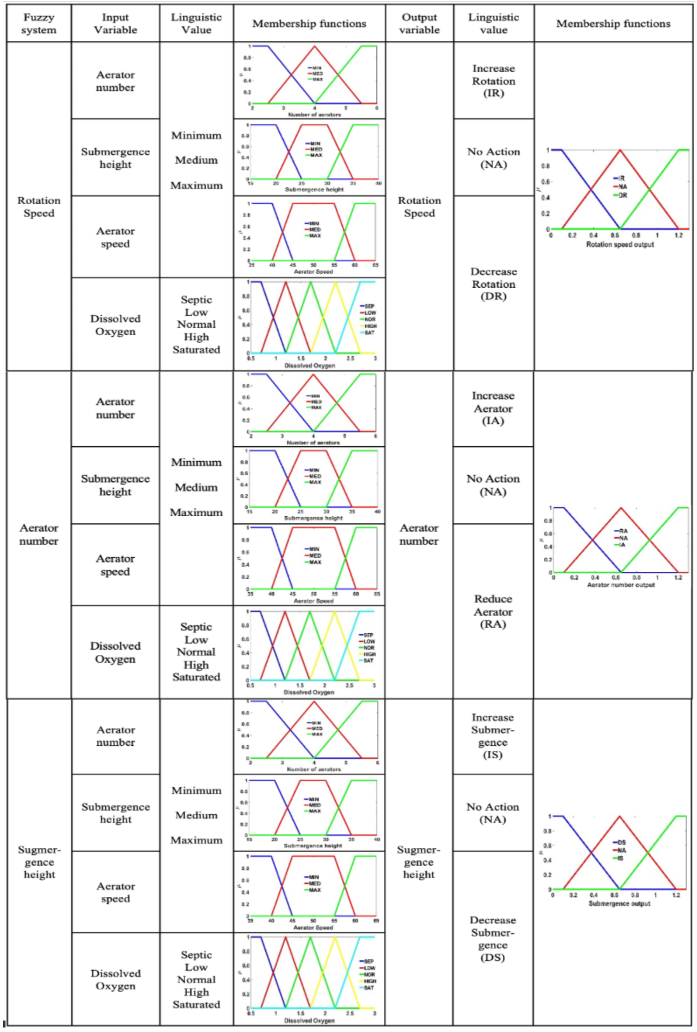
the heuristic controller. Therefore, they were brought in as input variables of the fuzzy controller. Modelling of the input linguistic values were based on three levels: “minimum”, “medium” and “maximum”, characterizing the aerator status. Since DOC was a critical input, it was described by five linguistic values: “Septic”, “Low”, “Normal”, High” and “Saturated”, based on expert’s knowledge and literature review (JORDÃO, 2017; SPERLING, 2016). Denominations were chosen according to operational terms and their ranges were strictly within WWTP internal procedures. Equations 1 and 2 represent the triangular (internal) and the trapezoidal (used mainly on the edges) membership functions.

$$f(x; a, b, c) = \max\left(\min\left(\frac{x-a}{b-a}\right), \left(\frac{c-x}{c-b}\right), 0\right) \qquad (1)$$

$$f(x; a, b, c, d) = \max\left(\min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right) \qquad (2)$$

Values for parameters a, b, c and d, heuristically adjusted, are shown in Table 3.

Figure 2: Summary of the fuzzy controller structure

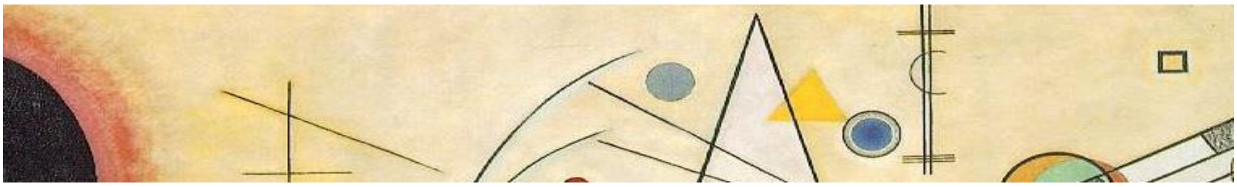


Fuzzy system	Input Variable	Linguistic Value	Membership functions	Output variable	Linguistic value	Membership functions
Rotation Speed	Aerator number	Minimum Medium Maximum		Rotation Speed	Increase Rotation (IR)	
	Submergence height				No Action (NA)	
	Aerator speed				Decrease Rotation (DR)	
	Dissolved Oxygen	Septic Low Normal High Saturated				
Aerator number	Aerator number	Minimum Medium Maximum		Aerator number	Increase Aerator (IA)	
	Submergence height				No Action (NA)	
	Aerator speed				Reduce Aerator (RA)	
	Dissolved Oxygen	Septic Low Normal High Saturated				
Sugmergence height	Aerator number	Minimum Medium Maximum		Sugmergence height	Increase Submergence (IS)	
	Submergence height				No Action (NA)	
	Aerator speed				Decrease Submergence (DS)	
	Dissolved Oxygen	Septic Low Normal High Saturated				

Source: Figure created by the author

Table 3: Parameters of the input membership functions

Membership function	Linguistic Values	Parameters			
		a	b	c	d
Aerator number	Minimum	2.0	2.0	2.5	4.0
	Medium	2.5	4.0	5.5	-
	Maximum	4.0	5.5	7.9	7.9
Submergence height	Minimum	3.2	3.2	20.0	25.0
	Medium	20.0	25.0	30.0	35.0
	Maximum	30.0	35.0	40.0	44.8
Aerator speed	Minimum	33.0	35.0	40.0	45.0
	Medium	40.0	45.0	55.0	60.0
	Maximum	55.0	60.0	65.0	67.0
Dissolved oxygen	Septic	-0.3	0.4	0.7	1.2
	Low	0.7	1.2	1.7	-
	Normal	1.2	1.7	2.2	-
	High	1.7	2.2	2.7	-



Saturated	2.2	2.7	3.8	4.8

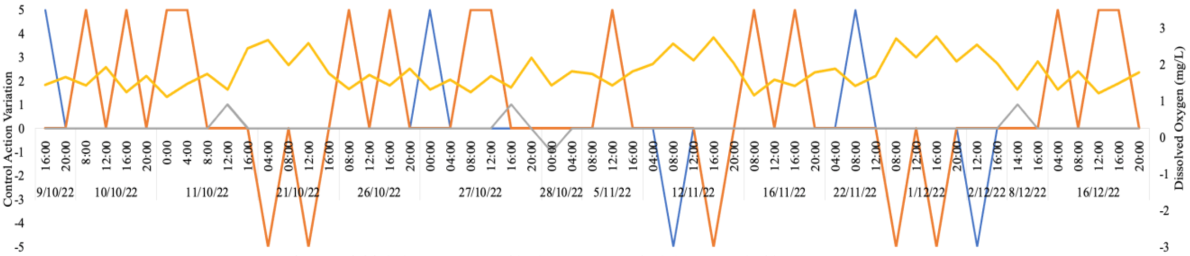
Source: Table created by the author

2.3 Fuzzy simulator

In order to optimize the fuzzy controller and its membership function parameters, a dynamic simulator was built (in Simulink software environment) and calibrated using dynamic data collected at Suzano municipal WWTP. Tests consisted on comparisons between suggested actions by the fuzzy controller and action taken by control experts during the analyzed scenario.

To obtain a comprehensive dataset of 55 different scenarios, an operational timeframe of three months was stablished. In this period variations in submergence height, aerator speed and the number of aerators were monitored roughly every 2 hours, between 00:00 to 20:00. The measurements were classified based on their variation range during dissolved oxygen fluctuations. The dataset is shown in Figure 3.

Figure 3: Historic series of DOC control actions



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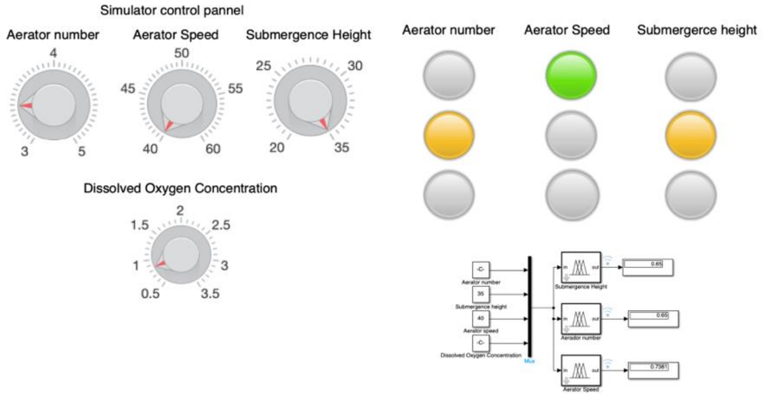
The simulator was design to provide easy access to the main input variables "aerator number" (ranging from 3 to 5 aerators), "aerator speed" (ranging from 40 to 60 rpm), "submergence height" (ranging from 20 to 35 cm) and "dissolved oxygen" (ranging from 0.5 to 3.5 mg/L), manipulated by knobs. Based on operational historic data collected from the WWTP the fuzzy controller yielded suggested control actions, represented by lightbulbs. The green light represents an increase in the designated input variable, yellow light alerts that no action is required and red light represents a decrease in the designated output variable. The clean design was chosen in order to be tangible for any operator to identified and implement the control action after the fuzzy inference. The basic interface of the fuzzy DO simulator is shown in Figure 4.

Figure 4: Fuzzy DOC control simulator



Source: Figure created by the author

2.4 Implementation of the fuzzy DOC controller in activated sludge process

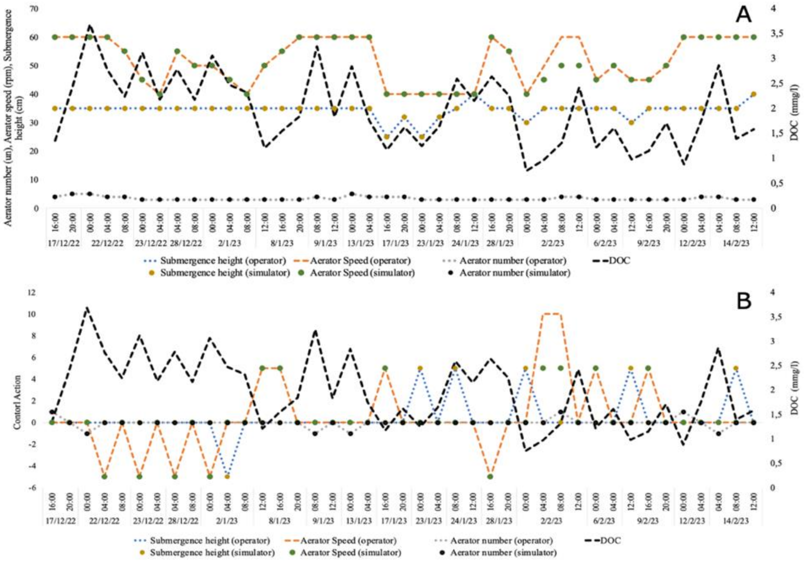
After exhaustive simulation tests and parameter adjustments, the fuzzy DO controller was commissioned in the process – although not directly implemented (replacing the human operator) - but instead, used as a supervisory controller by the operational team in an auxiliary terminal. During testing period fuzzy controller outputs were subjected to expert approval prior to their implementation in the bioreactor system. The WWTP tests were conducted by feeding the simulator with online data. The fluctuations in DOC and the correcting measures were taken at a two-hour interval between 00:00 to 20:00 for 17 days, totaling 41 operational points.

3. Results and discussions

3.1 Simulation results

Prior to the fuzzy DO controller implementation in the system, tests were conducted in the simulator. Several versions were tested in order to find an optimal design, straightforward, clean and easily manipulated by an untrained operator (as shown in Figure 4). Figure 5 shows the main results of the simulation with the dataset based on control actions taken by experienced operator on site.

Figure 5: Simulation results



Source: Figure created by the author

The dotted line represents DOC and control actions dataset generated with the heuristic control by an operator. The dataset was presented to the fuzzy controller in order to assess its responses to DOC fluctuation in real scenarios.

Figure 5 (A) shows the trends of controlled variables (aerator number, aerator speed and submergence height) and monitored DOC. Figure 5 (B) shows the same variables simplified by showing the control actions. As it can

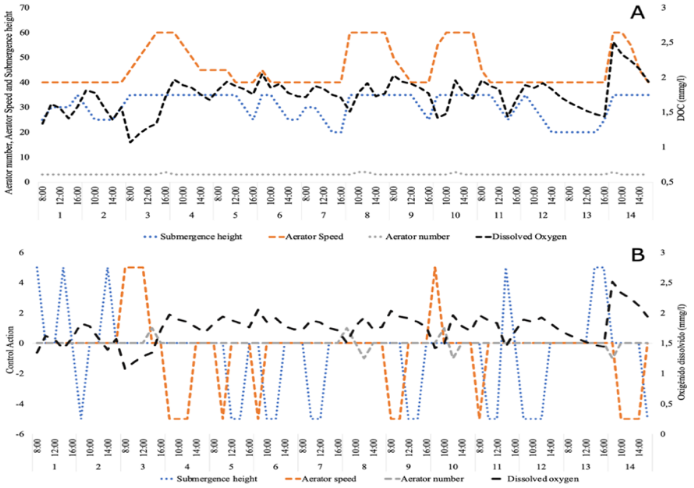
be observed by the overlapping results, under the selected DO scenarios, the fuzzy controlled mimicked almost perfectly the operator reasoning. Sometimes, even presenting a smoother behavior. Due to the effluent characteristics, DOC spiked between 00:00 and 8:00 (in general, almost every day). This period required a robust DO controller to avoid either a DO saturation or a septic state in the activated sludge process. Analyzing the controlled variables there is a tendency of maximizing submergence height in order to control the DO with aerator speed fluctuations. Only during maximum DO threshold value, the number of aerators was altered. Therefore, it can be observed that the heuristic logic satisfactorily controlled DO values within the operational margins. However, the quality of dataset mirrored the experience of the operator. Therefore, the heuristic controller is subjected to performance changes depending on the operator’s experience. Statistically DO mean was 1.97 mg/l, close to the 2.0 mg/L threshold, with a standard deviation of 0.73 mg/L, equivalent to a CV of 37.2%. Due to the heuristic origin of the DO controller the standard deviation value is higher than in Han *et al*., 2019 (0.5 mg/L) and Belchior *et al*., 2012 (0.2 mg/L) that employed a fuzzy neural network MPC control and an adaptive fuzzy control, respectively. Nevertheless, fuzzy logic was able to translate highly non-linear expert’s knowledge to a mathematical computer-based controller.

3.2 Implementation results

Due to the continuous operation of the WWTP and data sensor availability, the fuzzy controller was implemented at line. Hence, it was installed in a parallel system as a supervisory control, yielding actions to be executed by the operator. During the fuzzy controller test, DOC of the bioreactor was monitored to verify the effectiveness of the actions taken. Control dynamic and the robustness of the controller were also evaluated

through the behavior of manipulated variables. The main results are shown in Figure 6.

Figure 6: Implementation results of the fuzzy DO controller



Source: Figure created by the author

Figure 6 (A) shows the trends of controlled variables (aerator number, aerator speed and submergence height) and monitored DOC results. Figure 6 (B) shows the same variables simplified by showing the control actions. The fuzzy DO controller managed to smooth the behavior of monitored variable DO with few peaks. The control actions suggested by the fuzzy controller were approved by a process expert, prior to their implementations, yielding positive results. A reduction in aerator speed fluctuations was observed, whilst an increase in submergence height usage was noted, indicating a reduction in energy consumption. Fuzzy DO controller proved to be robust, avoiding either a DO saturation or a septic state in the activated sludge process. It can be observed that the fuzzy controller achieved interesting results keeping DO values within the operational margins. As opposed to the heuristic controller, that can be subjected, in some extent, to performance changes depending on the operator's experience, fuzzy controller performed according to the best control practice. Therefore, it is not influenced by operator inexperience. Statistically, DO mean was 1.75

mg/L, within the 1.0 to 2.5 mg/L threshold, with a standard deviation of 0.25 mg/L, equivalent to a CV of 14.3%. With the lowest DOC observed during the 14-day period being 1.07 mg/L (3rd day - 08:00) and the highest, 2.51 mg/L (14th day - 08:00). The standard deviation value is consistent with the values found by (HAN; LIU; QIAO, 2019) (0.5 mg/L) and (BELCHIOR; ARAÚJO; LANDECK, 2012)(0.2 mg/L) that employed similar fuzzy-based DO controllers (fuzzy neural network MPC control and an adaptive fuzzy control, respectively). DO control results are also similar to the ones obtained by (PIOTROWSKI; WONIA; WONIA, 2023) that employed a stochastic optimization algorithm for DOC parameters.

These results demonstrate the robustness of the controller, adapting to variations in effluent characteristics (and consequently in DO deviations). Considering the importance of a stable oxygen supplementation to guarantee process performance, it can be stated that the fuzzy controller kept the system operating in optimal conditions with low dispersion and smooth behavior of the manipulated variables. When fuzzy output was confronted with control actions based on expert knowledge of the process, it can be noted that the fuzzy controller yielded compelling DO results (even outperforming the heuristic control) - which highlights the fuzzy logic ability to translate empirical knowledge of the process. During the implementation test, no operator intervention was required in decision-making, attesting the reliability of the fuzzy controller. The system was able to maintain good stability in DOC. During deviations from the ideal conditions, the suggested corrections provided a quick recovery to the DO setpoint value, with smoother behavior of the manipulated variables.

Robustness and reliability are particularly interesting characteristics of the fuzzy controller, considering the simplicity of which the system was implemented and the complexity that would involve a traditional mathematical modeling of the proposed process. The outcomes corroborate the initial expectation of obtaining a more precise and responsive DOC control through fuzzy logic, aiming to avoid metabolic stress and ensuring the energy efficiency of the process.

4. Conclusions

Based on the results presented, it can be stated that the application of fuzzy logic for DOC control in activated sludge process has proven not only viable, but an interesting control option. Regarding the classical control strategies (based on complex equations and mathematical modeling) fuzzy logic overcame DOC non-linearities by translating, successfully, an empirical knowledge into a linguistic, rule-based controller. The possibility of applying linguistic variables, described by terms related to operational jargon, provided a more intuitive and simplified implementation, conveying familiarity to the users. Successful fuzzification is further evidenced by the coherence and effectiveness of the control actions provided by the fuzzy controller and attested by skillful process operators.

The simulator was essential to test the fuzzy controller prior to its implementation in the activated sludge process. Results demonstrate precise control actions suggested by the fuzzy controller when confronted with actions taken by the heuristic controller – sometimes even presenting a smoother behavior of the controlled variables. The fuzzy controller robustness was also tested, expressing positive results. The current version of the simulator can be the first step to a complete simulator to train freshman process operators.

Implementation results demonstrate the effectiveness of the fuzzy controller in maintaining DOC within typical operating ranges with smooth behavior of the controlled variables. When dealing with DOC setpoint deviation, precision of the control actions and the efficiency presented by the fuzzy controller attest for the system flexibility. Overall, DOC peaks presented during the heuristic controller were smoothed (as it can be

attested by a nearly 60% reduction in the CV value). This reduction in DOC fluctuations is particularly interesting in activated sludge processes due to microorganism sensibility to DOC peaks.

Fuzzy logic is a promising and efficient technique in the field of DO control systems in bioreactors applied to activated sludge processes, with potential of bringing significant advances, both in treatment performance and energy efficiency. The control model proposed in the present study provided relevant information regarding DO monitoring and controlled variables behavior. Works based on dissolved oxygen control applied to bioreactors is still timid. Furthermore, the applicability of fuzzy reasoning remains relatively uncharted in the context of effluent treatment. Although further tests are required, the results presented in this research could be a good reference for large scale WWTP of successful application of DO control system in activated sludge processes (such as the ones operated by SABESP).

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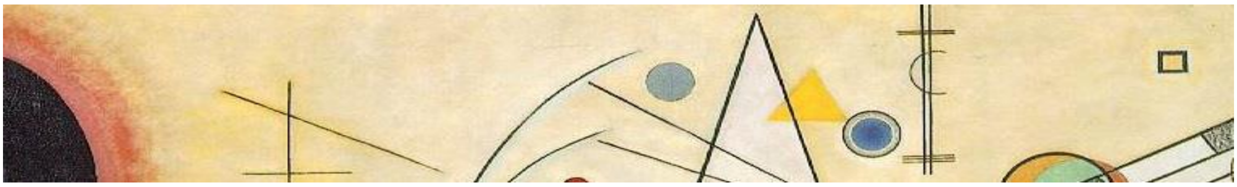

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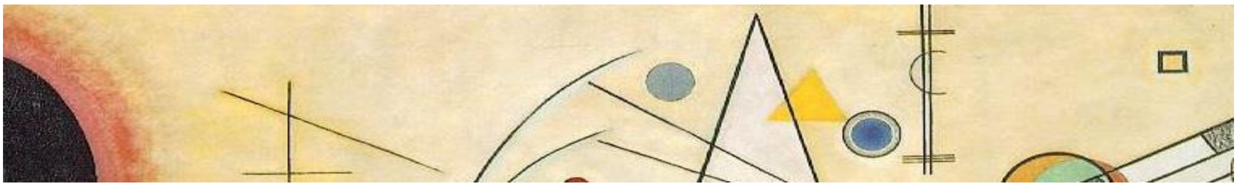

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