Fuzzy Logic-Based Optimization of the Energy Consumption in Wastewater Treatment Plants under Variable Climate Conditions

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***Abstract*— This work proposes the use of a Fuzzy Logic hierarchical controller to address the effect of seasonal variations of temperature and precipitation along the year on the energy consumption of a Wastewater Treatment Plant (WWTP). The proposed strategy also considers the unexpected variations due to climate change effects.**

Keywords—Fuzzy control, Hierarchical control, Wastewater Treatment Plants, Seasonal effects, Climate change

I. Introduction

The operation of Wastewater Treatment Plants (WWTPs) must deal with seasonal variations of influent characteristics and abnormal variations associated with Climate Change. In the current context, where climate change affects influent conditions and stricter regulations are imposed on effluent quality, it is necessary to develop control strategies that explicitly consider climatic effects on wastewater treatment.

The environmental performance of typical Urban WWTPs depends on the appropriate operation of the activated sludge process (ASP). ASP is a biological treatment that takes place in reactors that exhibit anoxic and aerobic conditions followed by a settler. Nitrification to convert ammonium to nitrates occurs in the aerobic conditions, where Dissolved Oxygen (DO) is the controlled variable. These nitrates are transformed in N_2, through denitrification, in anoxic conditions. Several Urban WWTPs include a sludge line, where an anaerobic digester is used to stabilize the sludge of the ASP and to produce biogas. Biogas is used as a source of energy in a cogeneration process. Furthermore, modern WWTPs have implemented renewable energy sources as photovoltaic (PV) cells to improve the energetic efficiency of the plant [1].

Seasonal variations of the climatological conditions produce slow and lengthy changes of the influent temperature, while faster changes are produced by diurnal variations of temperature and domestic and industrial discharges. Wastewater temperature has a strong impact on treatment and energetic efficiency of the plant. The biochemical reactions that take place in the biological processes of the WWTP are temperature sensitive, temperature also affects the energy consumption and the heating requirements of digester [2].

The effect of seasonal variations of temperature is addressed adjusting the Solids Retention Time (SRT). The denitrification slow down due to temperature effects can be attenuated by carbon addition. On the other hand, the elimination of ammonium compounds in the presence of flowrate and load disturbances is regulated adjusting Dissolved Oxygen (DO) set-point. The influent flowrate and pollutants load depends on population activities, precipitations, sewer management, and industrial discharges [3]. The amount of pollutants determines both the treatment effort required and the amount of chemicals needed.

It is important to notice that control movements for regulation of DO and SRT involves energy consumption and carbon additions increase the use of chemicals in the plant. Temperature, influent flow and load disturbances affected by climatic conditions are the main drivers of these control movements. In the case of WWTPs that include cogeneration and photovoltaic cells, the climate conditions also affect the availability of self-generated energy.

This work proposes the use of a hierarchical fuzzy logic-based control to address the interactions between seasonal and unexpected variations of temperature and precipitations, ASP treatment performance and energy consumption in an Urban WWTP. The study focuses on WWTPs that employ the Nitrogen Removal Activated Sludge Process (N-Removal ASP) with DO control and external carbon source (chemicals addition) in the anoxic zone to facilitate denitrification, as is described by Benchmark Simulation Model (BSM2) plant [3] considering a reference period of 365 days.

II. Methods

The BSM2 simulation environment describes the plant layout (Fig.1), the simulation model, the influent profile, and the evaluation protocol. The BSM2 influent model includes dry periods, periods of precipitation and variations of load (IQI_{in}) and influent flow rate (Q_{in}) associated with human activities, as well as temperature variation. The BSM2 represents a WWTP comprising two operating lines: the water line and the sludge line (Fig. 1). The water line includes a primary settler and N-Removal ASP, and the sludge line includes anaerobic digestion, thickening units, and dewatering units together with a storage tank [3].

The N-Removal ASP takes place in a system of five bioreactors (Fig.1). The reactors 1 and 2 are anoxic but perfectly mixed. Reactors 3, 4 and 5 constitute the aerobic zone, where aeration system maintains the DO concentration required for nitrification. The default control strategy considered in the BSM2 plant is typically used in real practice. In this control strategy, the DO of the reactor 4 is kept at a set-point (DO_{SP}= 2 g/m^3). The Solids Retention Time (SRT) is regulated employing a timer control of the waste flow (Q_w), and a external carbon source (Q_{carb}) is added at a fixed flow rate to the anoxic reactors.

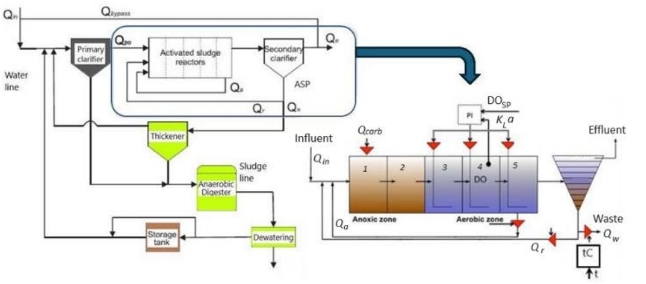

Fig. 1. BSM2 plant layout

The BSM2 platform provides a performance assessment protocol. The performance indicators considered in this work are: the Effluent Quality Index, EQI (kg/d) and the Influent Quality Index, IQI (kg/d), that measures the total pollution load of the effluent and the influent, respectively, in the operation period. The pollutants considered are: total Nitrogen (TNe), ammonium (S_{NHe}), nitrates (S_{NOe}), total Chemical Oxygen Demand (COD_e), total Suspended Solids (TSSe) and Biological Oxygen Demand ($BOD5_e$). Another indicator is the Energy Consumption (E_{total} kWh/d), that measures aeration, pumping energy and mixing energy.

The limits of pollutants in the effluent considered in the BSM2 model are: TNe$\leqslant$18 gN/m^3, $S_{NHe} \leqslant 4$ gN/m^3, $COD_e \leqslant 100$ gCOD/m^3. The volume of received wastewater (m^3) is used as a functional unit to compute Influent Quality (IQI/Q_{inav}), Effluent Quality (EQI/Q_{inav}) and Energy Consumption (E_{total}/Q_{inav}) with respect to average influent flowrate in the evaluation period (Q_{inav}).

This work builds upon the results from the previous study of Revollar et al. (2025). There, BSM2 is used to formulate and test a Temperature Driven Control Strategy (TDCS) that adjusts the main control drivers of the plant to mitigate the strong effect of temperature on treatment efficiency and to deal with disturbances in the influent flow. The strategy focused on the improvement of N-Removal efficiency for temperature variations between 10ºC and 20ºC. A variable influent pattern given by population activities with moderated variations respect to the nominal value was considered. The TDCS vary DO set-point, carbon addition Q_{carb} and wastage flow Q_w, depending on temperature (14ºC is a critical limit) and influent flowrate (90% percentile of Q_{in}). These control movements were selected after a comprehensive study of the effect of control actions on plant behaviour at different temperatures considering variations on influent flow and load.

In the present study, seasonal variations of rainfall are included in the study. TDCS manages the control actions to optimize the effluent quality and energy consumption at different climatic scenarios. The knowledge can be incorporated in a hierarchical fuzzy controller able to select the appropriate operational variables that maximize the efficiency of the plant in terms of Effluent Quality (EQI and violations of S_{NHe} and TN_e) and Energy Consumption. Furthermore, the information about the availability of PV energy can be also integrated in the Fuzzy TDCS.

Fig, 2 a) shows the variations of influent temperature (T), flow (Q_{in}) and load (IQI) between July and January, considering 10 days average values. Figure 2 b) shows the effect of these variations on Energy Consumption (E_{total}) and Effluent Quality (EQI), using the default BSM2 control strategy. The hierarchical fuzzy control (Fig.2 c)) uses the T, Q_{in} and IQI information to compute the corresponding on DO set-point, carbon addition Q_{carb} and wastage flow Q_w according with the fuzzy rules based on TDCS knowledge and the fuzzy sets defined for these variables. The possibility to increase the DO set-point is influenced also by the availability of PV energy.

This information, considering the full year climatological scenarios, complemented with a model for PV energy production can be used to determine the appropriated fuzzy rules to develop the hierarchical controller. Some of the fuzzy sets, based on TDCS knowledge, are: Q_{in} (Average, High, Peak), IQI (Low, High), T(Below 12ºC, 12-14ºC, Above 14ºC), PV availability (Available, no available), DO set-point (1.8mg/l, 2mg/l, 2.2mg/l, 2.4mg/l, 2.6mg,l), Q_w (250 m^3/d, 300 m^3/d, 375 m^3/d, 450 m^3/d), Q_{carb} (2m^3/d, 3m^3/d). Some of the preliminary fuzzy rules are:

If T>14ºC, Q_{in} average then DO set-point is 1.8 mg/l, Q_w is 450 m^3/d and Q_{carb} is 2m^3/d.

If T<(12-14) ºC, Q_{in} average then DO set-point 2 mg/l, Q_w is 300 m^3/d, Q_{carb} is 3 m^3/d.

If T<14ºC, Q_{in} Peak and PV no available then DO set-point is 2.2 mg/l, Q_w is 250 m^3/d, Q_{carb} is 3m^3/d.

If T<14ºC, Q_{in} Peak and PV available then DO set-point is 2.6mg/l, Q_w is 250 m^3/d, Q_{carb} is 3m^3/d.

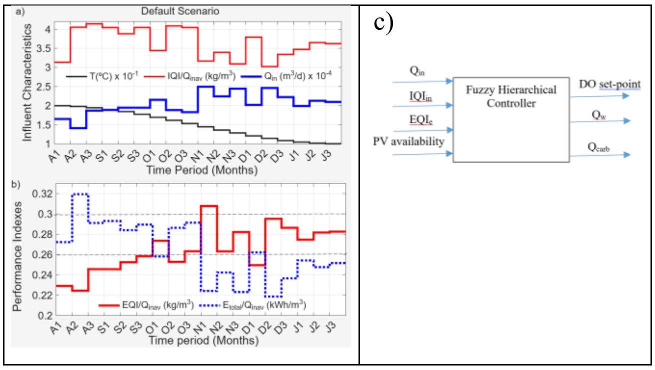

Fig. 2. Simulation results. Effect of influent variations on Performance inficators considering 10 days average values (Ai-August, Si-September, Oi-October, Ni-November, Di-December, i (weeks):1 to 3)

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