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Improving process performance in wastewater treatment plants using an intelligent environmental decision support system

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Abstract: The objective of this paper is to present the simulation results of implementing and intelligent environmental decision support system (IEDSS) to overcome the limitations of the manual control at the wastewater treatment plant (WWTP) of Vall del Ges (North-East, Spain). The proposed IEDSS integrates online information with knowledge management techniques and aims to reduce the pollution load leaving the plant, at the same time that keeps the operational costs at minimum. To this end, a fuzzy logic engine (FLE) controls the effluent nitrate and ammonium concentration manipulating both aeration and internal recycle flow respectively. The results show significant savings in terms of operational costs and a slightly enhancement of the nitrification/denitrification (N/D) efficiency improving the overall nitrogen removal.

Keywords: wastewater treatment; modelling; fuzzy logic; control; intelligent environmental decision support system (IEDSS).

1. INTRODUCTION

Upgrading or optimisation of biological nutrient removal (BNR) is a common issue in existing wastewater treatment plants (WWTP). The variability in quality and quantity of the influent, the dynamics of the biological processes and the limited knowledge of the physical-chemical and biological interactions that take place in the biological reactor make the nitrification/denitrification (N/D) process complex and therefore difficult to control. The even more widespread use of on-line sensors over the last decades, the automation of a number of operations and progress in automatic control technology have enabled real time process information and thus significantly improved automatic control of the N/D process in the majority of the medium- and large-sized treatment plants [Olsson et al., 2005]. The majority of feedback automatic controllers are based on the data provided with indirect variables such as dissolved oxygen (DO) or the oxidation-reduction potential (ORP) (e.g. Jung Kim et al., [2005]). However, an adequate knowledge of N/D process performance requires data about ammonium, nitrates, sludge retention time or even respiration rates to be monitored. Much of the latter data, however, is obtained with some delay after taking samples and analysing specific parameters in the laboratory. This fact limits automatic controllers when certain disturbances in the process occur due to the influent (e.g. toxic events) or to operational problems (filamentous bulking or incomplete denitrification). In addition, the majority of small plants (less than 2000 inhabitant equivalents, IE) typically do not contain even a small part of the instrumentation found in large plants, so that the knowledge, experience and reasoning processes of the human expert continues being of crucial importance.
N/D process control involves high reliability of the process performance in any operational situation and in real time, minimizing the impact on the water body and generating minimal operating costs. This can be only achieved if more and better information from automatic analysers is integrated with typically human characteristics such as analytical capacity, interpretation and the reasoning skills of a treatment process expert. Literature already provides some examples where automatic analysers of nutrients or suspended solids enable new control structures to be designed and implemented to optimize nitrogen removal (e.g. Ayesa et al., [2006]). On the other hand, some authors propose control strategies based on changes of aeration volume to improve the biological nitrogen removal in full-scale plants [Thomsen et al., 1998] and by simulation [Samuelsson et al., 2002].

Nevertheless, there are still very few examples of the use of tools based on expert knowledge and human reasoning models to improve the full-scale WWTPs control. These tools are based on principles of Artificial Intelligence (AI), the branch of computer science concerned with creating or mimicking intelligent behaviour or “thought” in computers. Among those that have recently generated great expectations, Intelligent Environmental Decision Support Systems (IEDSS) for environmental problems stand out [Poch et al., 2004]. These systems are computer programs that attempt to emulate the human capacity to solve problems as if they were experts. The core of the IEDSS incorporates reasoning models used to infer the state of the process. The models used involve the integration of statistical and AI models (e.g. Rule-Based or Fuzzy Logic Systems) with mathematical models (e.g. Activated Sludge Models, ASM) and with advanced control algorithms.

This paper illustrates (via simulation) a successful application of an IEDSS to ease the integration of online information with knowledge management techniques to overcome the limitations of the current manual control in the WWTP of Vall del Ges. The existing mode of operation is based on an open loop regime making the plant non-capable to handle with process disturbances. The final aim of the IEDSS is to reduce the operational costs and slightly enhance the N/D efficiency, therefore keeping both environmental and financial cost at minimum. To this end, a fuzzy logic engine (FLE) controls the effluent nitrate and ammonium concentration manipulating both aeration and internal recycle flow respectively. The paper is organized as follows: First of all, the facility under study is described detailing the design and operating characteristics. Then, the development of the deterministic model and of the new IEDSS, especially the reasoning core (fuzzy-logic engine and rule-based system), are described. Next, the simulation procedure and evaluation criteria used are briefly introduced. Finally, the simulation results of the IEDSS implementation in the WWTP of Vall del Ges are presented and discussed.

2. METHODS

2.1. Environmental System under study

The WWTP of Vall del Ges (North-East, Spain) is designed to remove biologically organic carbon and nitrogen. The large number of industries nearby makes chemical precipitation the most suitable technology to achieve a relatively low concentration of phosphorus in the effluent. It was constructed in 1993 for a design capacity of 42000 IE but it receives only 30,000 IE with an average flow rate of 4800 m$^3$·d$^{-1}$, and an organic and nitrogen load of 1946 kg COD·d$^{-1}$ and 167 kg N·d$^{-1}$ respectively. Figure 1 shows the dynamic profile of influent COD, BOD5 and TKN together with the influent flow and the temperature during the studied period. The studied WWTP is depicted in Figure 2. The water line comprises a pretreatment with sand and fat removal units followed by an activated sludge system. The latter has an Orbal configuration (see for example Metcalf & Eddy, [2003]) with three concentric channels (ASU1, 2 & 3) of 3370, 2607, and 1843 m$^3$ and the aeration is transferred through surface rotors. The external channel has 6 rotors that remain idle because it is used as the anoxic zone of the treatment. The inner and the middle channels are aerobic with an average DO concentration of 0.6 and 1.5 g·m$^{-3}$ respectively. The aerobic zone presents 8 rotors (four in each channel) but working in pairwise fashion because there are only 4 engines. Finally, two secondary settlers are followed, with a circular area of 628 m$^2$ and a total volume of 2370 m$^3$. 

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The current control of aeration is based on setting time intervals and thus switching the aeration ON and OFF. An internal recirculation ($Q_{\text{intr}}$) links the inner (ASU3) and the external (ASU1) channels with a constant flow of 23760 m$^3$·d$^{-1}$. Also, there is an external recirculation ($Q_r$) from the bottom of the settlers to the external channel (ASU1) with a constant value of 4320 m$^3$·d$^{-1}$, and the wastage flow rate is 12m$^3$·h$^{-1}$. A DiaMon analyser is providing on-line data for the effluent ammonium and nitrate but is not linked to any type of automatic control.

$Q_W = 12$ m$^3$·h$^{-1}$

Secondary settler = 2370 m$^3$

$Q_r = 4320$ m$^3$·d$^{-1}$

$Q_{\text{intr}} = 23760$ m$^3$·d$^{-1}$

ASU1 = 3370 m$^3$

ASU2 = 2607 m$^3$

(0.5 – 1 g·m$^{-3}$)

ASU3 = 1843 m$^3$

(1.2 – 2 g·m$^{-3}$)

AEROBIC ROTORS

ANOXIC ROTORS

Figure 1. Influent wastewater flow and components dynamic profile

Figure 2. Representation of the studied WWTP
2. 2. Deterministic model of the WWTP of Vall the Ges

The model is calibrated following the Unified Calibration protocol proposed by the IWA Task Group of Good Modeling Practices (www.modeleau.org/GMP_TG). This calibration protocol involves several steps: i) project definition, ii) data collection and reconciliation, iii) model set-up, iv) calibration and validation and, v) simulation and result interpretation.

Project definition: The main goal of this study is to obtain a deterministic model that allows comparing the performance of the Vall del Ges WWTP when the proposed IEDSS is either included or not.

Data collection and reconciliation: One year historical data was collected for the influent and effluent characteristics, as well as the operating parameters. Two measuring campaigns (of one day length each) were also carried out to check the quality of the data and proceed with the data reconciliation. In this sense, phosphorus mass balances were conducted with the aim of determining the proper sludge retention time. All these data were also used for influent wastewater characterization, which was based on the STOWA protocol (Hulsbeek et al. 2002). Finally, a hydrodynamic study (tracer test) of the WWTP was conducted.

Model set-up: The complete model of a WWTP is based on the hydraulic, oxygen transfer, biokinetic, settling and sensor models. The results of the tracer test came up with the structure of 3 anoxic reactors (ASU31=ASU32=ASU33=1123 m³) for the external channel, and 2 aerobic reactors (ASU2=2607 m³ and ASU1=1843 m³) for the middle and inner channels. Aeration capacity was modelled as the mass transfer coefficient (KLa), and its value was obtained adjusting the experimental concentration profiles of DO in the liquid phase. The biological model ASM1 [Henze et al., 2000] was used. The effect of temperature on the kinetics was also considered in the model implementation using the Arrhenius equation. Regarding the settling model, the double exponential settling velocity of Takács et al. [1991] was selected as a fair representation of the settling process with a ten layer discretization. Sensor models were also implemented for effluent ammonia and nitrate to emulate the performance of the DiaMon analyser. These sensor models include response time, sample & hold, noise, measuring range as described in Rieger et al., [2003].

Calibration and validation: The simulations are carried out using the MatLab-simulink environment. Dynamic simulations were preceded of steady state simulations. This ensures and eliminates the bias due to the selection of the initial conditions for the dynamic results. Steady state was reached simulating 100 days with constant influent flow and concentrations and using default values at 15°C for the kinetic and stoichiometric parameters [Copp 2002]. Next, a dynamic influent of 332 days was simulated considering that i) for the days without influent concentrations data the mean value between the previous and next day was taken or in some cases the mean values for the whole period, and ii) the daily dynamics in the influent flow were applied based on percentages of the mean flow (according to Metcalf & Eddy, [2003] values). Figure 3 shows a good fit between the experimental and simulated values and the dynamics are properly described, so the model is ready for evaluation of the IEDSS’s performance. The observed mismatches are not relevant for accomplishing the objectives of the study. They are related to the nature of the data used to carry out the simulation i.e incomplete, ambiguous and uncertain.

2. 3. Fuzzy Logic Engine and Rule-Based System

The IEDSS is based on a FLE and integrates knowledge management techniques and online information. The IEDSS controls the effluent nitrate and ammonium concentration (input variables) manipulating both aeration and internal recycle flow (output variables). The effluent nitrate and ammonium signals coming from the DiaMon analyzer are used as input variables of the IEDSS. Historical data of effluent ammonium and oxidized nitrogen were analyzed in order to define the membership functions of the FLE. Both ammonium and oxidized nitrogen range from 0 to 10 gN·m⁻³ and they are distributed into 3 labels of concentrations (Low, Normal and High). The membership functions are trapezoidal for low and high labels and triangular for the Normal label.
Aeration ($K_{L,a}$) and internal recycle flow are the output variables. The $K_{L,a}$ ranges from 0 to 80 $d^{-1}$. Thus, 0 and 80 represents when the four rotors are switched OFF and ON respectively. The intermediate values are associated to different working and speed combinations of rotors. On the other hand, the internal recycle flow ranges from 0 to 31680 $m^3 \cdot d^{-1}$. Both aeration and internal recycle flow ranges are subdivided into three labels (low, medium and high) in the definition of the output triangular membership functions.

Information and good practices from the experts working in the WWTP are the sources to construct the knowledge base including IF-THEN rules that link the values of the input and the output variables. The mapping between the inputs (fuzzification) and the outputs (defuzzification) is carried out following the mandami approach. The fuzzy toolbox of Matlab-simulink is used to develop the FLE. The graphic representation of the decision matrix can be found in Figure 4 for the aeration (left) and recycle flow (right) respectively.
Thus, on the one hand, when the effluent ammonium nitrogen is high the desired control action would be increasing the aeration flow in order to improve nitrification. High dissolved oxygen concentration in ASU2 & 3 favours the growth of the autotrophic bacteria in charge of nitrification process. On the other hand, when the effluent nitrate nitrogen is high, the control action would be increasing the internal recycle flow in order to improve denitrification. High internal recycle flow increases the quantity of nitrate going from ASU3 to ASU1 and potentially usable for anoxic growth of heterotrophic bacteria. On top of the IEDSS a RBS is developed to check the quality of the data before being introduced into the FLE. This RBS checks the measuring range for the ammonia and oxidized nitrogen values. When implementing the IEDSS in full-scale this will be complemented with other methods e.g. control charts described in Thomann et al., [2002].

2.4. Simulation Procedure and Evaluation criteria

The model described in section 2.2 is used for evaluating the IEDSS performance. The simulations are conducted for the 332 days using dynamic conditions. Hence, it is possible to evaluate long term performance of the system. A set of evaluation criteria, defined by the IWA Task Group on benchmarking strategies and described in Copp [2002], is used to test the proposed IEDSS in the Vall del Ges WWTP. In this case the selected criteria are the effluent quality index (EQ), the aeration energy cost (AE), and the pumping energy cost (PE).

3. RESULTS

This section summarizes the simulation results and shows the plant performance comparing the current manual mode of operation with the proposed IEDSS. It is organized in the following way: Firstly the effluent quality is quantified averaging the concentration of the different pollutants leaving the plant. Secondly, both approaches are compared in terms of operation costs and effluent quality indices. Finally, the behaviour of the system using the IEDSS is shown under dynamic conditions demonstrating its adaptation to different plant perturbations i.e. changes in the influent load, effect of the temperature.

Table 1 presents the averaged effluent concentrations when the proposed IEDSS is either included or not. The plant is in both cases operating close to the effluent optimum conditions and complies with the limits set by the European Directive (91/271/EEC). However, one can notice that the alternative with the IEDSS is marginally better than the other in terms of enhancing N/D, which is one of the goals of the study. Organic matter and solids are not a big issue here since the concentrations are much lower than the legislation limits.

Table 1. Simulated effluent concentrations (average of the 332 days simulation)

<table>
<thead>
<tr>
<th>EFFLUENT CONCENTRATIONS</th>
<th>Without IEDSS</th>
<th>With IEDSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>average total N (g·m⁻³)</td>
<td>7.38</td>
<td>6.28</td>
</tr>
<tr>
<td>average total COD (g·m⁻³)</td>
<td>37.35</td>
<td>37.81</td>
</tr>
<tr>
<td>average TSS (g·m⁻³)</td>
<td>6.72</td>
<td>6.73</td>
</tr>
<tr>
<td>average BOD5 (g·m⁻³)</td>
<td>0.61</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Figure 5 (top and middle) shows the dynamics of the manipulated variables according to the defined response surfaces and the decision matrixes (see Figure 4). Regarding aeration, K_L_a fluctuates between 13 and 67 d⁻¹, with an average value of 26 d⁻¹, which is lower than the open loop value of 40 d⁻¹. The internal recycle flow ranges from 3376 to 27997 m³·d⁻¹, with an average value of 19106 m³·d⁻¹. Again, this value is lower than the open loop constant value of 23760 m³·d⁻¹ used for manual mode of operation, indicating that savings could be achieved.

Also, Figure 5 (bottom) shows the dynamic profile of the total nitrogen in the effluent with and without IEDSS. Nitrification efficiency is enhanced when using IEDSS because the
rotor provides the necessary oxygen and thus overcoming the apparent limitations of the plant running in an open loop regime in front of the plant perturbations e.g. decrease of the autotrophic activity during the winter periods because of the temperature. Further, the control of internal recycle improves the denitrification rates in the anoxic section, maximizing the conversion of nitrogen nitrate to nitrogen gas. Thus, the effluent total nitrogen is lower during almost the whole studied period when using the IEDSS. However, it is important to point that for days 180 and 290 the FLE is not capable to keep effluent nitrogen concentrations at the desired values. These periods are characterized for having a step increase in the influent nitrogen concentration but not a significant increase in the BOD (see Figure 1). Hence, although the control action is to increase the internal recycle, there is not enough organic carbon in the influent (the BOD/TKN ratio is less than 3) to be used as electron donor to denitrify the entire arriving nitrogen nitrate.

![Figure 5. Effect of the IEDSS on $K_L a$, internal recycle flow and effluent total nitrogen](image)

The performance of the IEDSS is also assessed by the calculated performance indices presented in Table 2. An improvement of 10% is observed for the EQ index when implementing the IEDSS. Nitrogen ammonium and nitrogen nitrate are the pollutants with the highest impact on water body and for this reason they are weighted the most in the EQ calculation. In terms of economic objectives, it is important to point out the reduction of the operational costs that the implementation of the controller supposes. The aeration and the pumping energy costs are reduced by 37% and 14% respectively. Assuming a value of 0.12€/kW-h, the savings would be around 19000€·year⁻¹.

<table>
<thead>
<tr>
<th>PERFORMANCE INDICES</th>
<th>Without IEDSS</th>
<th>With IEDSS</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effluent Quality (EQ) (Kg pollution units·d⁻¹)</td>
<td>918</td>
<td>828</td>
<td>-10</td>
</tr>
<tr>
<td>Aeration energy cost (AE) (kW-h·d⁻¹)</td>
<td>1137</td>
<td>718</td>
<td>-37</td>
</tr>
<tr>
<td>Pumping energy cost (PE) (kW-h·d⁻¹)</td>
<td>135</td>
<td>116</td>
<td>-14</td>
</tr>
</tbody>
</table>
As a final remark, forthcoming work will be conducted for full-scale implementation of the IEDSS. Then, the limitations of the IEDSS performance due to model assumptions and deviations between measurements and model variables will be investigated.

4. CONCLUSIONS

This paper has presented the advantages of implementing an IEDSS to overcome the limitations of the current manual control of the WWTP of Vall de Ges. The proposed IEDSS integrates on-line information with knowledge management techniques and reduce the pollution load leaving the plant at the same time that keeps operational costs at minimum. Additionally, it must be pointed out a reduction of the operation costs in terms of aeration and pumping energy and the slightly improvement of the overall nitrogen removal. This is mainly due to a better adaptation to the different process disturbances (e.g. changes in the influent load, temperature...) using the knowledge extracted from both the experts and the deterministic simulations.

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