(S39) Energy efficient WWTPs: simulation and validation of a decision support system through modelling

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Abstract

Mathematical modelling has been tested as a decision support system to management of a biological WWTP, aimed at optimizing energetic efficiency. A conventional activated sludge plant has been studied and the ASM1 mathematical model has been implemented, calibrated and validated, by using West® 2012, DHI software. Optimal operating strategies, under different operating conditions, such as variable influent loading, have been defined. Also, indicators concerning energy efficiency and effluent quality have been defined and quantified.

Keywords

WWTP simulation, modelling, EDSS, effluent quality, energy efficiency

INTRODUCTION

Wastewater treatment plants (WWTPs) must ensure effluent quality standards under variable influent loading and different operating conditions. Olsson (2006) showed that the use of appropriate instrumentation, control and automation (ICA) tools may improve energy and depurative efficiency up to 30%. To this aim, mathematical models are frequently used for the simulation of biological processes (Gernaey et al., 2004) and several advanced control strategies have been designed using both model based (Demey et al., 2001) and soft computing techniques, such as artificial neural networks and fuzzy logic (Ruano et al., 2010).

Dynamic simulation of WWTPs based on mathematical models offers several benefits, such as the predetermination of organic matter and nutrient removal efficiency for different scenarios, such as, for example, substantial changes of influent loading and quality. Simulations have been performed on a pilot-scale, continuous-flow conventional activated sludge (CAS) plant, fed on real wastewater, aiming at achieving the maximum energy efficiency under different loading conditions. The experimentation is part of a wider project, coordinated by ENEA (section UTVALAMB IDR - Water Resource Management, based in Bologna) in collaboration with the multi-utility Hera SpA (Bologna) and Politecnico di Milano, aiming at developing automation and control of WWTP based on simple, cheap and reliable probes, measuring dissolved oxygen, pH and redox potential. These indirect signals will be used to implement PI controllers (and, in the near future, fuzzy-logic based controllers) acting on air flow and internal and external recycle flow-rates.

MATERIALS AND METHODS

Pilot plant

Figure 1 and 2 show a schematic and the front view of the pilot plant, located inside the area of the municipal WWTP in Trebbo di Reno (Bologna). The plant is composed of a pre-denitrification tank (95 L), an oxidation tank (162 L), a secondary sedimentation tank (85 L). Mechanical equipment includes a stirrer, a variable-flow blower connected to a fine bubble membrane diffuser, three peristaltic pumps: one is used for influent loading (460 l/d), and the other two for internal (760 l/d) and external (430 l/d) recycle flows. The plant was fed with real wastewater, taken downstream of the full-scale micro-screen and was provided with probes to measure pH, ORP, NH_4^+-N, NO_3^--N in the anoxic tank and pH, ORP, DO,

NH_4^+-N, NO_3^--N and TSS in the aeration tank. Data are acquired and stored by a data logger stand-alone dataTaker DT 80, at a frequency of 1 per minute.

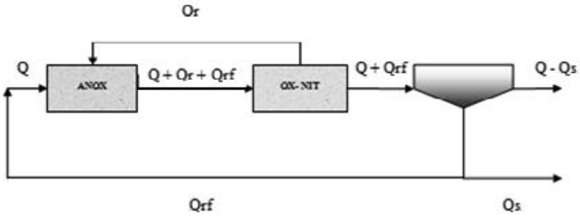


Fig. 1: CAS *block diagram*

Fig. 2: *pilot plant front view*

Modeling and respirometry

The ASM1 dynamic model of the plant has been implemented in WEST DHI 2012 (Vanhooren et al., 2003), following the protocol defined in Petersen et al. (2002). Respirometric tests for biomass and wastewater characterisation were carried out with M.A.R.TIN.A (Multiple Reprogrammable TitratioN Analyser) (Artiga et al., 2005), a titration biosensor that allows to measure the bacterial activity in sludge samples, at constant DO and pH (thus, it is a pH and DO-stat titration).

Analyses

Wastewater was sampled at a frequency of 1 sample/h by an automatic sampler, ISCO 6712. Six data sets of 24 h were collected and the daily variability has been expressed as arithmetic means and 95% confidence range. DO, pH and ORP were continuously measured by two modular multi-parameter measuring systems WTW IQ SENSOR NET. Occasionally, COD, ammonium, nitrate, nitrite and TKN have also been measured by chemical analyses according to Standard Methods (APHA, 1995).

RESULTS

Simulation and control logic implementation

The kinetic parameters measured with respirometric tests are reported in Table 1, while Table 2 and Table 3 report the calibrated parameters concerning the anoxic and the aerobic tank, respectively.

Parameter	Test 1 value (20°C)	Test 2 value (20°C)	Default value in WEST (20°C)
$\mu_H[d^{-1}]$	4.44	6.03	6
Ks[mgCOD/l]	0.95	0.99	20
$b'_H[d^{-1}]$	0.63	-	0.62
$\mu_A[d^{-1}]$	0.74	0.8	0.8
K_{NH}[mgN/l]	0.21	0.41	1

Table 1: kinetic parameters

Parameter	Starting value	Calibrated Value	Confidence interval (95%)
K_X	0.02	0.008	+/- 3.381 E-007
K_{NO}	0.5	0.2	+/- 4.174 E-006
K_h	2	5.79	+/- 1.296 E-004
η_h	0.4	0.85	+/- 3.119 E-005

Table 2: parameters calibrated for the anoxic tank

Parameter	Starting value	Calibrated Value	Confidence interval (95%)
i_{XB}	0.086	0.108	+/- 2.314 E-005
i_{XP}	0.06	0.0001	+/- 4.387 E-008
k_a	0.08	0.04	+/- 4.67 E-005
k_h	3	2	+/- 4.25 E-004

Table 3: parameters calibrated for the aerobic tank

Improvements of water quality in the tanks and in the effluent were evaluated with different control strategies and the corresponding simulation results are shown in Figures 3 and 4.

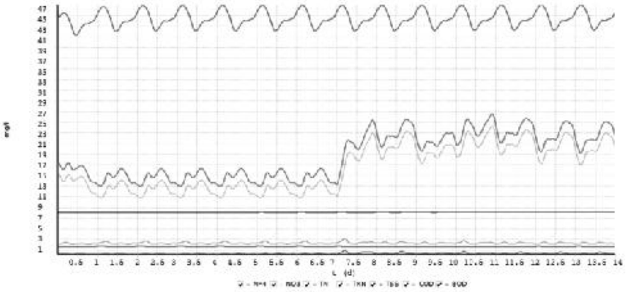


Fig 3: pollutant concentration in effluent (*open loop simulation)*

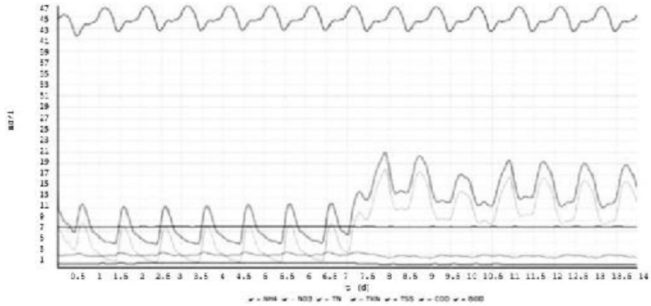


Fig 4: pollutant concentration in effluent (*cascade control simulation)*

Fifteen control logics have been defined and simulated (Di Cosmo, 2012). One of the most significant is the cascade control of dissolved oxygen in the aerobic tank. The implementation of the cascade controller with DO variable minimizes aeration requirements, thus improving energy savings (Yoo and Liu, 2011).

If the ammonia concentration is too high, then DO set-point increases and vice versa. Normally, one sets the minimum and maximum rate of change of the DO set-point; however optimization may push the value of ammonia set-point up, but below ammonia effluent allowable concentration limit for discharge. A first PI controller fixes the ammonia set-point at 1 to 1.5 mg/l while the second PI controller has a variable DO set-point with a hysteresis cycle between 0 to 2.5 mg/l as a function of NH_4^+-N concentration in the aerobic tank. This allows setting the aeration so that the nitrification process produces the maximum allowable effluent ammonia concentration, while effluent nitrate concentration is reduced consequently (Figure 4). The parameters of the controllers used are shown in Tables 4 and 5.

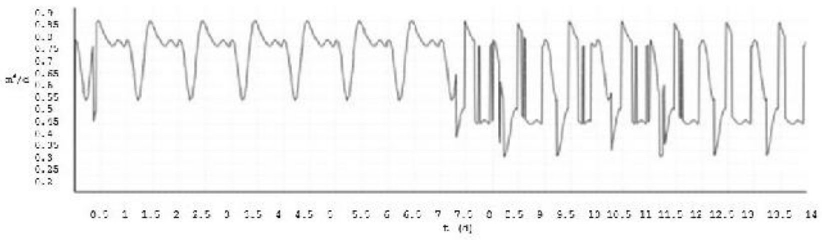
Controller Type	**PI**	**Unit**
Proportional Gain (K_p)	250	$m^3(g(-COD))^{-1}d^{-1}$
Integral time constant (t_i)	10	minutes
Controlled variable	S_0 in aerobic tank	
Set point	2-1-0.5	mg/l
Manipulated Variable (VM)	K_La	d^{-1}
VM max value	300	d^{-1}

Table 4: parameter for *Oxygen PI controller*

Controller Type	**PI**	**Unit**
Proportional Gain (K_p)	-10	$m^3(g(-N))^{-1}d^{-1}$
Integral time constant (t_i)	50	minutes
Controlled variable	S_{NH} in aerobic tank	
Set point	1.5-1	mg/l
Manipulated Variable (VM)	y_s controller DO	mg/l

Table 5: parameter for ammonia *PI controller*

This controller is also associated with the variation of internal and external recirculation, maintaining a constant proportion with the influent flow-rate. A further analysis involved the use of a strategy to support critical transitional phases, during which nitrate may build up in the anoxic tank, for example when internal recirculation is too high compared to the available biodegradable carbon, adversely affecting the denitrification process. The modulation of the internal recirculation flow allows stabilizing nitrate concentrations in the anoxic tank around a set point of 2 mg/l. An ON | OFF controller sets the internal recirculation flow rate to the 80% of the influent flow rate, if measured nitrate (SNO3) increases over the set point, else it increases it to 165%. Figure 5 displays the flow profile of the internal recirculation and the values of nitrate in the anoxic tank, with a set-point around a value of 2 mg/l.



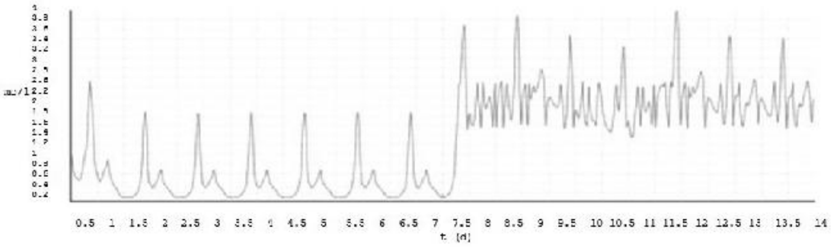


Fig. 5: *Trend of the internal recirculation flow (in m^3/d, above) and corresponding trend in the concentration of nitrate in the anoxic tank (in mg/l, below).*

The results show that these strategies can improve both energy savings and effluent quality. Following the Benchmark approach (Copp, 1999) several indicators have been considered and calculated (Figure 6). First of all, the Effluent Quality Index and the percentage, over time, when total nitrogen exceeded the effluent threshold value established for sensitive areas. The latter was tested as an evaluation index, because the facility is not located in a sensitive area. The calculation included the value of kLa in the aeration tank within 14 days of simulation, as this parameter is related to the intensity of aeration and, hence, to the power used by the air-blowers. Energy costs have been evaluated at a price of 0.14 €/kWh, with an oxygen transfer rate of 1.8 kgO/kWh.

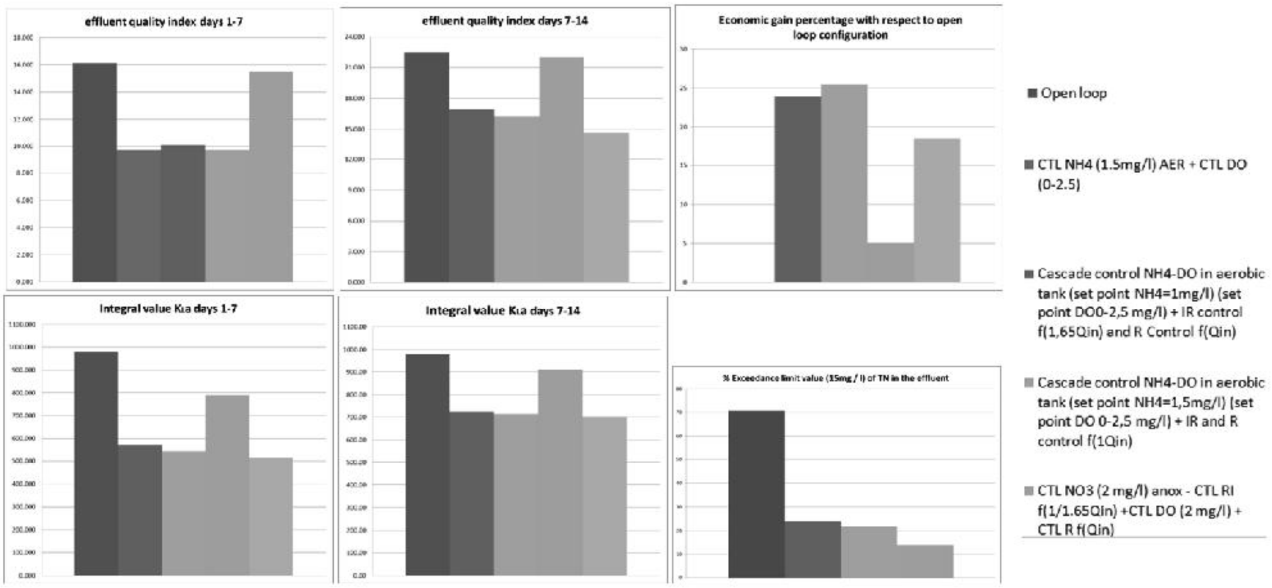


Fig. 6: *Results of the economic evaluations using different qualitative control strategies.*

CONCLUSIONS

The adverse effects of the very high daily variability of the wastewater characteristics on the performance of the biological processes in the WWTP could be counteracted by control strategies In particular, the NH_4-DO cascade control proved very efficient in improving the energy and quality performance of the biological processes when nitrate is measured in the anoxic tank as the controlled variable and this is associated with an active control of the internal recirculation.

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