

Dynamic air supply models add realism to the evaluation of control strategies in water resource recovery facilities

Pau Juan-García, Mehlika A. Kiser, Oliver Schraa, Leiv Rieger and Lluís Corominas

ABSTRACT

This paper introduces the application of a fully dynamic air distribution model integrated with a biokinetic process model and a detailed process control model. By using a fully dynamic air distribution model, it is possible to understand the relationships between aeration equipment, control algorithms, process performance, and energy consumption, thus leading to a significantly more realistic prediction of water resource recovery facility (WRRF) performance. Consequently, this leads to an improved design of aeration control strategies and equipment. A model-based audit has been performed for the Girona WRRF with the goal of providing a more objective evaluation of energy reduction strategies. Currently, the Girona plant uses dissolved oxygen control and has been manually optimised for energy consumption. Results from a detailed integrated model show that the implementation of an ammonia-based aeration controller, a redistribution of the diffusers, and the installation of a smaller blower lead to energy savings between 12 and 21%, depending on wastewater temperature. The model supported the development of control strategies that counter the effects of current equipment limitations, such as tapered diffuser distribution, or over-sized blowers. The latter causes an intermittent aeration pattern with blowers switching on and off, increasing wear of the equipment.

Key words | aeration control, ammonia-based aeration control, dynamic aeration system model, energy optimisation, full-scale

Pau Juan-García
Atkins,
(The Hub) 500 Park Avenue, Aztec West,
Almondsbury, Bristol, BS32 4RZ,
UK

Pau Juan-García
Mehlika A. Kiser
Lluís Corominas (corresponding author)
Catalan Institute for Water Research (ICRA),
Scientific and Technological Park of the University
of Girona,
Emili Grahit 101, Girona 17003,
Spain
E-mail: lcorminas@icra.cat

Oliver Schraa
Leiv Rieger
inCTRL Solutions Inc.,
7 Innovation Dr., Suite 107,
Dundas ON L9H 7H9,
Canada

INTRODUCTION

Water resource recovery facilities (WRRFs, formerly wastewater treatment plants) are among the main consumers of energy in a municipality. Aeration energy consumption typically accounts for around 50% of a facility's total operating costs (Olsson 2012). The WRRF aeration system is therefore an important target for reducing municipal energy demands. Classic energy audits identify opportunities to reduce energy use, typically based on the average energy consumption of unit processes, which may include benchmarking with similar plants or comparison against key performance indicators. However, significant saving potential lies in the adaptation of operational parameters to the variability of

wastewater characteristics and loads and the changing wastewater temperature by using tailored process control strategies. More meaningful energy audits should therefore use dynamic models that integrate the treatment process, mechanical equipment, and a detailed description of the applied control strategies.

The use of dynamic mechanistic models to reduce energy consumption in WRRFs is common in the wastewater field, normally carried out using a combination of experimental work and modelling studies. Such optimisation often includes the implementation of a new control strategy, as seen in works of Corominas *et al.* (2006) and Thornton *et al.* (2010). Recent studies have been published on control system design (Rieger *et al.* 2016; Odriozola *et al.* 2017); yet current studies use simplified aeration system models that include oxygen transfer and oxygen

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

doi: 10.2166/wst.2018.356

demand, but assume ideal air supply and distribution with no equipment constraints. Not including these constraints such as blower, valve, or diffuser limitations can hide extra costs or even mask the inability of a control strategy to reduce energy consumption. Oftentimes, optimisations carried out with simplified aeration models overestimate the potential for energy savings by 5 to 10%, due to missing equipment constraints (Schraa *et al.* 2017).

Recent research focused on more detailed models of the aeration system and its energy consumption (Schraa *et al.* 2015; Alex *et al.* 2016; Amerlinck *et al.* 2016; Amaral *et al.* 2017). Within this context, the work of Schraa *et al.* (2015, 2017) uses a fully dynamic model for the piping network, which recalculates the system curve based on the changing pressure drops throughout the system. Dynamically simulating the air distribution system enables the possibility of troubleshooting analyses, and evaluating the components and limitations of the system for different optimisation options and load and temperature scenarios. Hence, integrated models can be used to find solutions for energy and process optimisations that are more realistic and tailored to a specific facility.

In this study, the advanced aeration system model developed and implemented in SIMBA# (Schraa *et al.* 2015, 2017) was used to carry out a model-based process performance and energy audit of the Girona WRRF (Spain), with the aim of reducing energy consumption while maintaining effluent quality. The Girona WRRF's 2013 energy consumption record shows that 63% of the plant's energy consumption was due to aeration. The existing DO control system has already been optimised by the plant operators by trial and error, but it was hypothesised that further optimisation using the dynamic air supply model would lead to extra energy savings and an improved dynamic response to disturbances (i.e. load peaks, temperature variation, operational settings).

The objective of this study was to model the dynamic interactions between process performance, aeration system equipment, controller settings, and energy consumption, to gain understanding of the limitations of the current operating approach. After assessing the current performance (Base Case SC0), three different optimisation scenarios have been selected: SC1 ammonia-based aeration control (ABAC) (Rieger *et al.* 2014), SC2 optimisation of the air distribution system, and SC3 installation of a smaller blower. The optimisation scenarios were compared for three different temperature variations and a stress test in the form of an ammonia peak. This is the first published application of the aeration system model library developed by Schraa *et al.* (2015, 2017) at a full-scale WRRF.

MATERIALS AND METHODS

Plant layout and operation

The Girona WRRF receives an average of $55,000 \text{ m}^3 \cdot \text{d}^{-1}$ of domestic and industrial wastewater, and has the capacity to serve 275,000 population equivalents. The plant is a conventional activated sludge system in a five-stage Bardenpho configuration. Even though such a configuration is designed for biological removal of nitrogen and phosphorus, chemical phosphorus removal is currently practised at the WRRF. Legislation allows the discharge of a total nitrogen concentration of $10 \text{ mg} \cdot \text{L}^{-1}$ (measured as 24-hour composite samples).

The biological stage consists of two parallel treatment lanes. Each lane has a total volume of $14,360 \text{ m}^3$ split into seven zones, of which four are aerated, as shown in Figure 1. Sludge is wasted from the return activated sludge (RAS) streams and is anaerobically digested. Reject water from the centrifuges is sent back to the headworks of the facility. A first analysis showed that the load profile of the plant – including nitrogen and phosphorus – is heavily dependent on the schedule of the reject water, which varies depending on the usage of the sludge dewatering centrifuges. On average, the reject water represents up to 11% of the incoming nitrogen load and 0.5% of the phosphorus load. Although this is seen as a significant optimisation potential, optimising reject water dosage was not evaluated in this study due to the absence of buffer tankage.

The aeration system consists of a main blower and two support blowers that service a main header, which splits into two header pipes, each controlled by an automatic valve, and followed by four manual zone valves (Figure 1). The list of air supply equipment can be found in Table 1. The reactors are aerated using fine-bubble membrane disc diffusers. The sensors for on-line measurements of dissolved oxygen (DO) are currently placed at the end of the biological reactors (AER4). The air supply (blower set) is controlled by the average DO of both lanes by varying the speed and guide vanes of the blowers (Figure 1: Signal). The DO measurement in each lane is used to manipulate the positions of the automatic main header valves. Table 2 shows an overview of the number of diffusers, valve diameter and settings of each aerated reactor.

The WRRF in its current form has been in operation since 2008. Since then, operators have been manually optimising the aeration system by adjusting the manual valves in each lane and changing the location of the DO sensors. The manual valves for AER1 and AER2 have been adjusted

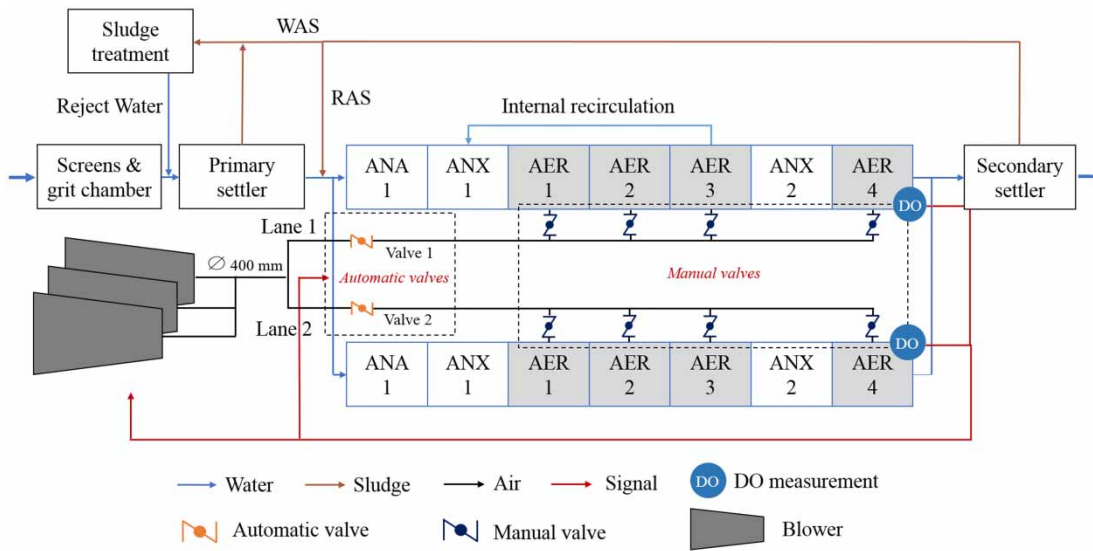


Figure 1 | WRRF configuration and aeration system. ANA: anaerobic, ANX: anoxic, AER: aerobic, WAS and RAS: waste and return activated sludge respectively.

Table 1 | List of air supply equipment modelled (technical specifications and SIMBA# model parameters)

Equipment	Brand	Num. units	SIMBA# parameters
Blower	Turbo-compressor ABS HST 9000 Sulzer	1 (2 standby)	Efficiency curve, surge curve, max. and min. airflow
Automatic valves	Butterfly, centred axis. Belgicast	2	K_v values, max. and min. airflow, fitted with a quadratic equation
Manual valves	Butterfly, centred axis. Belgicast	8	K_v values, max. and min. airflow, fitted with a quadratic equation
Diffusers	ABS Nopon disc diffuser system PIK 300	2,280	number of diffusers per grid, pressure drop and SOTE ^a curves, submergence, oxygen transfer parameters
Pipes	Measured in on-site visits	2 lines (8 reactors)	K (i.e. resistance) factors, pipe roughness, length, diameter, fittings

^aStandard oxygen transfer efficiency.

by the operators to reduce airflows to the first two aerated reactors. Whereas this improves the balance of the incoming load with the air supply (using a DO signal from AER4), it also leads to increased aeration system pressure drops.

The DO sensor was finally placed in AER4, with a DO setpoint of 2 mg O₂·L⁻¹. Measurements from the SCADA

system and DO probes temporarily installed by ICRA show that this results in concentrations around 1–2 mg O₂·L⁻¹ in reactors AER1 and AER2, and very low DO concentrations (0.5–1 mg O₂·L⁻¹) in reactor AER3.

Girona WRRF model

A model was built following the recommendations of the IWA *Guidelines for Using Activated Sludge Models* (Rieger et al. 2012a) and using the advanced modelling platform SIMBA#. First, mass balances on total suspended solids, chemical oxygen demand (COD) and total phosphorus were conducted to verify that no gross errors were present in the data. The model was built using SIMBA#'s in-house activated sludge model ASM-INCTRL, and a

Table 2 | Number of diffusers, pipe diameter and valve setting on each aerated reactor

Reactor	Diffusers (#)	Valve diameter (m)	Valve opening (%)
AER1	480	0.25	0.325
AER2	366	0.2	0.45
AER3	180	0.15	1
AER4	144	0.15	1

simplified anaerobic digester model developed by the Institut für Automation und Kommunikation (ifak 2017). To build the layout of the aeration system, mechanistic models were used for each actuator in Table 1. The air distribution system includes blowers, pipes, fittings, valves, and diffusers. The piping system is modelled using the Darcy–Weisbach equation with the friction factor calculated using the Swamee & Jain (1976) equation. The pressure rise across blowers and pressure drops across valves and diffusers are calculated using polynomial functions based on airflow rate, which have been calibrated using the manufacturer-supplied data. More information on the aeration system models can be found in Schraa *et al.* (2015). Aeration control was accounted for by means of continuous feedback using proportional-integral or proportional-integral-derivative (PID) control algorithms. To model the behaviour of the automatic valves, a control algorithm was implemented that fixes the valve position of the lane with the highest oxygen requirement at 70% open and allows the other valve to vary to adjust the required airflow; 70% is the maximum valve opening currently set in the SCADA system.

After building the model, a steady-state calibration was conducted to match the sludge production (using full-scale data from January until December 2015). Dynamic calibration was executed by using real dynamics from a period between the 7th and the 13th of December 2015. It comprised a period of dry weather data, with detailed flow measurements (every 15 min) and daily nutrient measurements (one sample per day). Hourly concentration dynamics were incorporated by scaling an hourly ammonia profile gathered in February 2016 to the measured daily composite measurements. For the dynamic calibration period, DO concentrations from reactors AER1 and AER4 were used, as well as measured blower airflow, system header pressure, and valve positions. The calibration effort focused

on influent fractionation and the physical characteristics of the plant and its equipment instead of adjusting biokinetic parameters, which should improve the validity of the predictions. A list of the calibrated parameters is provided in Table 1. The goodness of fit of the airflow during the calibrated week can be seen in Figure 2 and will be discussed in the results section ‘Base case SC0: current operation’.

Scenario analysis

Several options were evaluated in the virtual plant to reduce energy consumption while maintaining or even improving effluent quality. The options were grouped into three cumulative scenarios of increasing financial investment. An overview of the optimisation options and the scenarios is shown in Table 3. To guarantee the robustness of the control strategies, all scenarios were stress-tested by an artificial ammonia peak, which increased the influent ammonia concentration from the average ($\sim 40 \text{ mg N}\cdot\text{L}^{-1}$) to $80 \text{ mg N}\cdot\text{L}^{-1}$ for 4 hours, starting on the eighth day of the simulation. Variations in ammonia loading are commonplace in the treatment plant, and the peak is the maximum concentration registered in the plant’s historical data.

SC1. Ammonia-based aeration control (ABAC)

This refers to a cascade controller where ammonium as primary loop modifies the DO setpoint in the secondary loop. Following the implementation described in Rieger *et al.* (2014), an ammonia probe measures the ammonia concentration in the last aerated reactor (AER4). The ammonia measurement adjusts the DO setpoint through a PID controller, in a range of $0.1\text{--}2.5 \text{ mg O}_2\cdot\text{L}^{-1}$. The DO sensor is moved from AER4, where it was in the Base Case (SC0), to AER2, in the middle of the main aerated reactors where

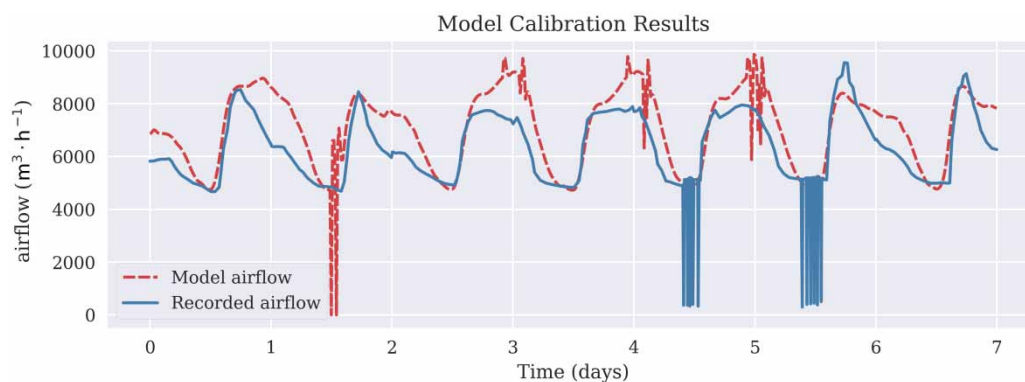


Figure 2 | Comparison of airflow results obtained from 1 week of real data and the modelled Base Case (SC0). Days 6 and 7 correspond to a weekend. Fast decreases around days 1.5, 4.5 and 5.5 correspond to the blower on-off behaviour.

Table 3 | Summary of optimisation options and scenarios (SC)

	Ammonia-based aeration control (ABAC)			+ Aeration system upgrade		+ Blower downscaling	
	DO probe	ABAC	Fixed valve at 100% open	Optimised pipe and valve sizes	Diffuser distribution	Downscaled blower	Blower scheduling
SC0	AER4						
SC1	AER2	X	X				
SC2	AER2	X	X	X	X		
SC3	AER2	X	X	X	X	X	X

most of the load is being removed. To reduce the pressure drop, the valve in the lane that has more air requirement is fixed at 100% open, and the valve in the controlled lane is set to operate between 20% to 90% open.

SC2. Aeration system upgrade

To improve the airflow distribution in the system, the number of diffusers was optimised and redistributed as follows: from 480 to 360 in AER1, from 366 to 360 in AER2, from 180 to 360 in AER 3, and from 144 to 230 in AER4. A second optimisation step was to adapt the diameter of the pipes that feed AER3 from 0.15 to 0.2 m to minimise the pressure drops and improve air distribution. The valves feeding these pipes, which were designed for a maximum airflow of $1,194 \text{ m}^3 \cdot \text{h}^{-1}$ were re-sized to allow for up to $2,111 \text{ m}^3 \cdot \text{h}^{-1}$. These values are the result of a sensitivity analysis of diffuser distributions and iterative simulations to assess the design.

SC3. Blower downscaling

This scenario addresses the problem of not being able to turn down the blower set to match the requested air demand at minimum load conditions. It includes the previous strategies, plus replaces one of the blowers with a lower capacity blower: TDS Turbo compressor type ABS HST 9000 to type ABS HST 6000. This reduces the lower limit of the aeration system's airflow rate. The blower scheduling was adapted to the new configuration, and simulation results showed that this setup was not prone to surge of the smaller blower.

To assess the performance of each scenario, the model was first initialised by a steady-state simulation with the scenario's conditions for 100 days, and then dynamically simulated for 11 days including an ammonia peak on day 8 at 10 a.m.

RESULTS AND DISCUSSION

The first results are for the Base Case (SC0) and have been used to calibrate and diagnose the current shortcomings of the plant. The subsequent three scenarios are presented and the results of the optimisation strategies are discussed below. Finally, the effects of temperature in each scenario are discussed, and an optioneering assessment is performed to evaluate the strategies from an economic point of view.

Base Case SC0: current operation

The model describes the airflow dynamics of the system, as illustrated in Figure 2. It also captures the behaviour of the blower overshooting 1–2 times per week on average, and the oscillatory on/off behaviour. A better fit of the blower overshooting would be possible if real hourly measurements for nutrients and COD at the inlet of the reactor were used. The support blower starts 2–3 times a week during peak moments and runs for short periods, even though this is not accurately captured by the SCADA system recordings (days 5–7). The importance of the effect of delayed ammonia peaks during the weekends' nutrient profiles is appreciated in the delayed airflow curve (days 6–7).

System shortcomings

The blowers are controlled based on the average DO of the last reactor of the two lanes and operate with a fixed DO setpoint of $2 \text{ mg O}_2 \cdot \text{L}^{-1}$. The DO probe location in the reaeration reactor (AER4) is outside of the internal nitrate recycle loop (AER1–3 to ANX1) and therefore is somewhat disconnected from the main aeration stage and will therefore miss some of the system dynamics. To minimise pressure drops due to both control valves closing when the minimum blower capacity is reached, the control algorithm fixes the valve in the lane with more oxygen

requirement at 70% open, while the valve in lane 2 is controlled to redistribute the air between the two lanes.

The facility has been designed with diffuser tapering and manual control valves to each of the individual aeration grids. The header pipes and the valve diameters decrease in diameter from 0.25 m to 0.15 m. With all manual valves completely open, the highest airflow would therefore be delivered to the first aerated zone and then diminish with each successive zone. To compensate for the mismatch between airflow and load, the airflow distribution has been adjusted by the operators by setting the first two manual valves on the reactor's grid to be partially open, at 32.5% and 45% of the total opening capacity respectively. Consequently, the reactors with the highest airflows have a high pressure drop which results in increased system air pressure requirements – the system usually operates at 1,650–1,800 mbar.

The loss of control authority leads to an oscillation of the oxygen concentrations in reactors AER1–3, and the response of the plant to stressors is slowed down as the only sensor is located at the end of the lane (and after an anoxic zone). The minimum blower turn-down is above the minimum airflow requirements during low load periods. So, with the current control algorithm, the blower switches on and off intermittently when the load is low for extended

periods of time. This reduces the blower life and creates instabilities in the DO concentration.

The Base Case scenario displays periods of insufficient DO concentrations throughout the reactors (Figure 3(b): Base Case SC0); AER4 maintains the setpoint, except during peak loading. Reactors AER1 and AER2 vary around 1–3 mg O₂·L⁻¹, depending on the load, and AER3 is lacking airflow capacity as can be seen from the DO concentration. Although most of the COD and ammonia load is treated in AER1 and AER2, the aeration capacity is not sufficient to maintain an acceptable DO concentration in AER3. Only at low load situations does the DO in AER3 increase to around 1 mg O₂·L⁻¹, which limits the ability of the plant to fully realise its nitrification capacity.

Overall, the Base Case (SC0) results in an energy consumption in the biological reactors of about 0.2 kWh·m⁻³ of treated wastewater. This is at the low end of typical ranges, which are between 0.13 and 5.5 kWh·m⁻³ (Enerwater 2015); however, the system is unable to maintain the DO setpoint during influent peaks. In low load situations, the blower turn-down limitation forces the air control valves to close as much as possible, which results in the blowers working against an increased system pressure and therefore reduced efficiency. Another effect of having

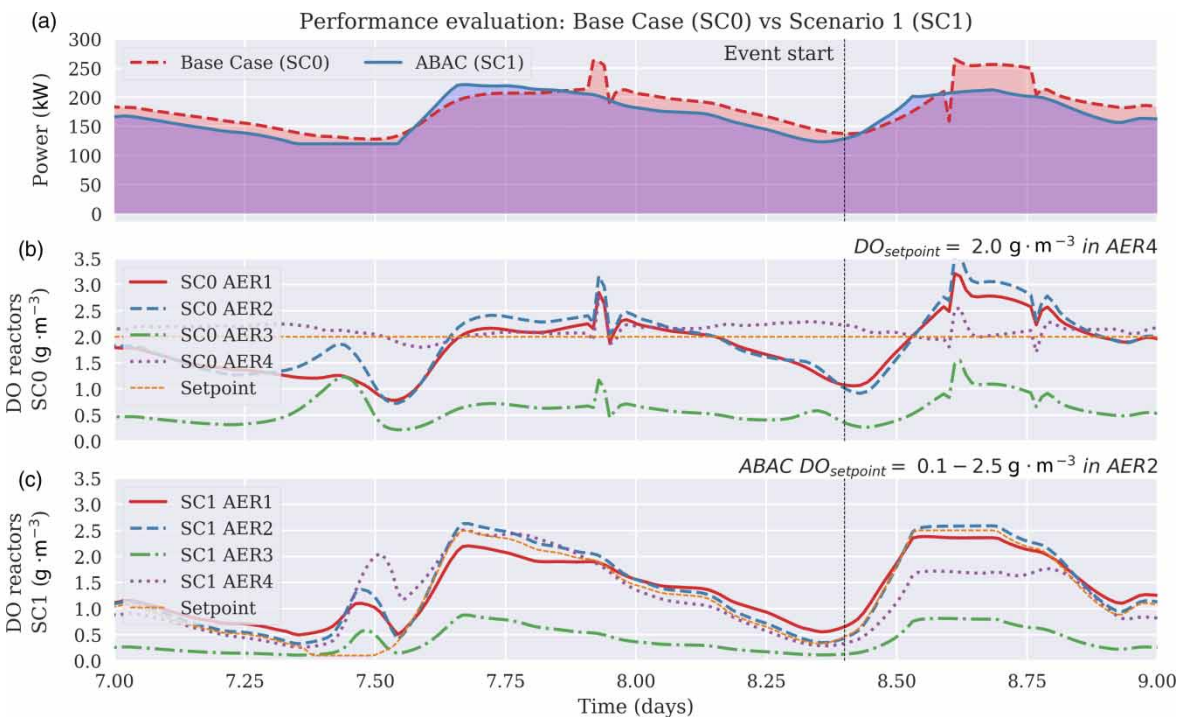


Figure 3 | Performance evaluation of Scenario SC1 over the Base Case (SC0). (a) Power consumption; (b) oxygen profiles across reactors in Lane 1 for the Base Case; (c) oxygen profiles across reactors in Lane 1 for Scenario SC1.

AER1 and AER2 at high DO concentrations to compensate for low DO in AER3 is a higher energy consumption, as oxygen transfer is more efficient at low airflow rates and low DO concentrations (Rosso et al. 2005).

Model-based evaluation of the optimisation scenarios

Scenario SC1: ABAC

The implementation of ABAC results in both energy savings of up to 7% and improved controller response. Savings are obtained by the DO setpoint varying between 0.1 and 2.5 mg O₂·L⁻¹, increasing the airflow when higher ammonia loads enter the reactor, and saving aeration power otherwise. The system's improved reaction to ammonia peaks can be appreciated in Figure 3(b) and 3(c). Right after the 'Event start' mark, the ABAC controller reaches a high DO concentration faster than the Base Case, despite having a lower DO setpoint before the event. The ability of the ABAC controller to increase the DO setpoint up to 2.5 mg O₂·L⁻¹ instead of 2 mg O₂·L⁻¹ at peak load conditions allows the aeration system to draw more capacity in moments of need.

By controlling the oxygen supply to maintain a minimum ammonia concentration in the effluent of 1 mg·L⁻¹, the load is distributed over the entire reactor causing a

more balanced oxygen demand. As can be seen in Figure 3(c), the DO profile is now more uniform across reactors, which indicates that the load is more equally distributed. Nevertheless, AER3 still presents a critical limitation in reaching the required DO concentration (Figure 3(c): SC1 AER3), and the turn-down capacity of the blower is reached in low load periods (day 7.5), which causes short spikes in the DO concentration.

Despite the improvements with the ABAC scenario (SC1), the manual valves in reactors AER1 and AER2 must remain partially closed to compensate for the flawed airflow distribution generated by the tapering. Figure 4(a) shows that the ABAC controller is properly working and reacts quickly to the measured ammonia most of the time. However, at low load situations the minimum blower turn-down prevents the system from maintaining the low DO concentrations requested by the ammonia controller. The DO controller (Figure 4(b)) works well until the ammonia controller is limited; then the DO concentration spikes in the lane with the fully opened valve. The valve control (Figure 4(c)) shows that the automatic valve in lane 2 closes to regulate the airflow. Yet, the valve in lane 1 must be fixed at 100% open to prevent the blowers working against closed valves. This would reduce blower efficiency and may lead to blower surge. After this in-depth analysis of the controller and actuator performance, the two main

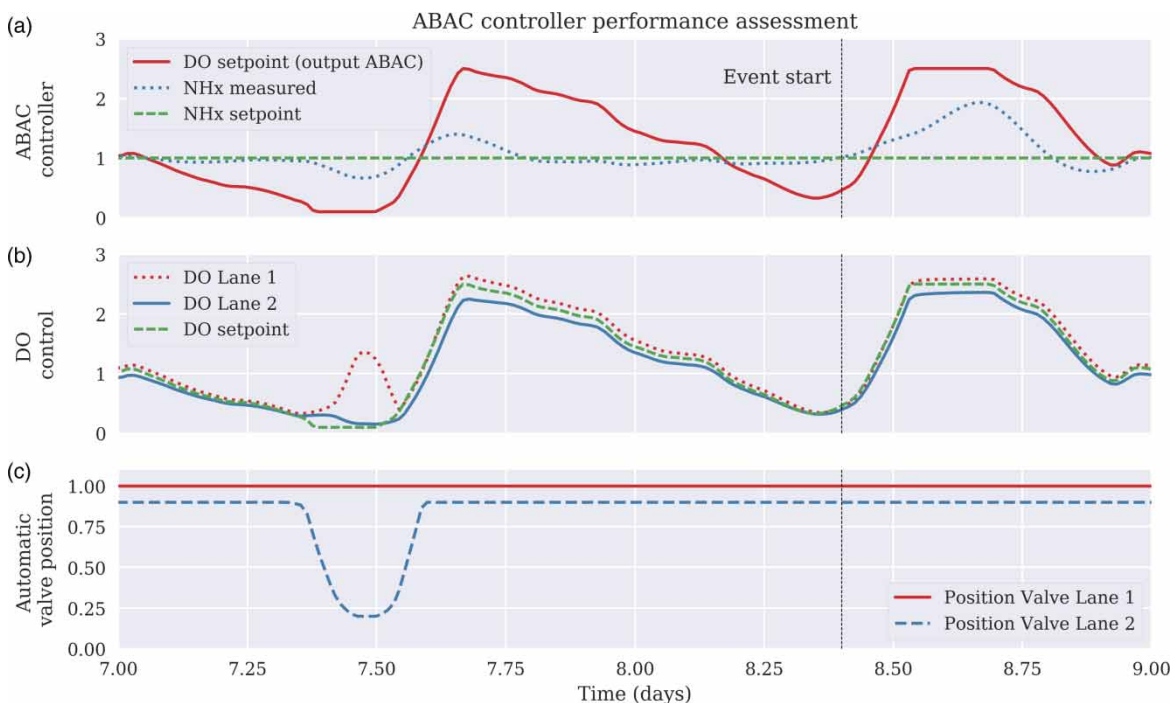


Figure 4 | ABAC performance evaluation in Scenario 1. (a) Input–output signals (ammonia (NH_x) in mg N·L⁻¹, DO in mg O₂·L⁻¹); (b) oxygen profiles of each lane; (c) valve position in % 0–1.

system constraints can be identified: (1) the airflow distribution and (2) the minimum blower turn-down. Overall, the model confirms the benefits of ABAC reported in other studies (Amand et al. 2013).

Scenario SC2: aeration system upgrade

Scenario SC2 upgrades the aeration system to overcome airflow limitations in reactor AER3 by (i) reducing the number of diffusers in the first two reactors, (ii) increasing the number of diffusers in the last two reactors, and (iii) re-sizing the pipes and valves, as described in Table 3. According to model predictions, this allows the plant to operate with the manual valves fully open, which translates into reduced system pressure. Although some form of diffuser tapering still exists, the limitation of delivering air to AER3 has improved, and the reactor can now reach higher DO concentrations (Figure 5(b)). The airflow distribution changes were simulated and analysed (see Supplementary information, Figure S1, available with the online version of this paper). The diffuser distribution has been calculated with respect to the current loading patterns but could change if the loading patterns were to change significantly over time.

The model predicts that improving the airflow distribution would increase energy savings up to 12%, due to several reasons. Firstly, reducing the system pressure allows the blowers to supply the same airflow with less energy consumption. Secondly, by increasing the nitrification capacity in AER3, there is more nitrite and nitrate being recirculated to the anoxic reactors; thus more organic matter is removed anoxically instead of aerobically. This NO_x was previously being produced in AER4, and thus its oxidising capacity was lost. The improvement in

denitrification activity can be seen in Figure 6, which shows the ratio of kWh per kg NH_x-N removed and total nitrogen removed. Both nitrification and denitrification become more efficient with each scenario, which translates to less blower usage (Figure 5(a)) and reduced effluent concentration of total nitrogen. Finally, a more balanced load allows the plant to run with a lower DO setpoint overall, which increases the oxygen transfer driving force.

The only remaining constraint was the minimum blower turn-down. Upgrading the aeration system further lowered the air demand during low peak periods. However, the blower can only decrease its capacity to 40% of the full capacity of one blower, which is already over the minimum air demand. The turn-down capacity of the blower is reached in low load periods, which causes DO spikes in low peak periods in reactors AER3 and AER4 (Figure 5(b)).

There are three main solutions to this problem. The first one is to implement intermittent blower operation, using advanced control based on effluent ammonia as in Rieger et al. (2012b). The second solution is to implement a blow-off valve, and the third solution is to replace the main blower by a smaller one. In this study we have explored the third solution, as it is considered the most efficient in terms of design.

Scenario SC3: blower downscaling

The last scenario solves the minimum blower turn-down limitation by downscaling the main blower. The virtual system now has a lower minimum airflow, which results in energy savings at low peak periods (Figure 7(a) and Figure 8) and improves the DO profile across the reactors (Figure 7(b)). The system dynamics are also smoother.

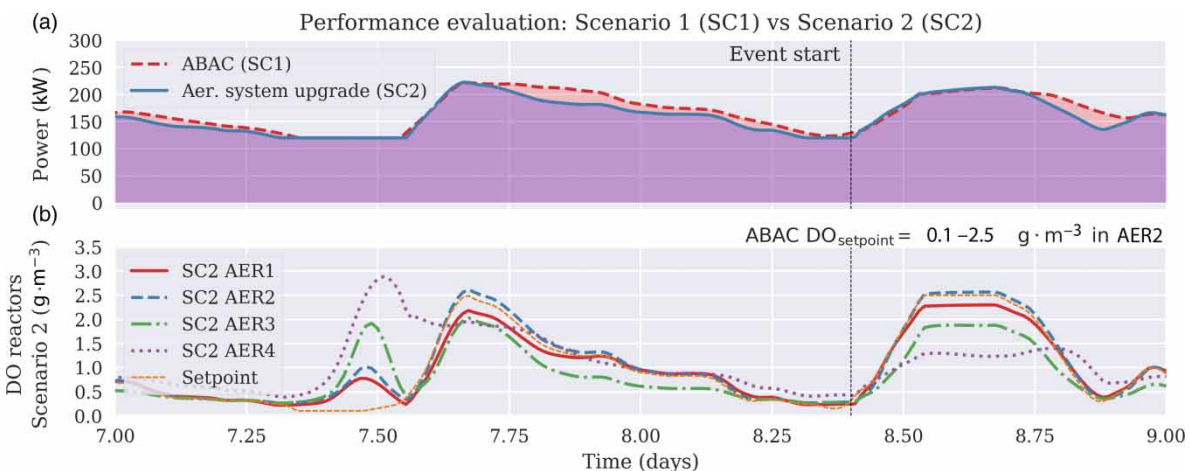


Figure 5 | Performance evaluation of Scenario SC2 over Scenario SC1. (a) Power consumption; (b) oxygen profiles across reactors in Lane 1 for Scenario SC2.

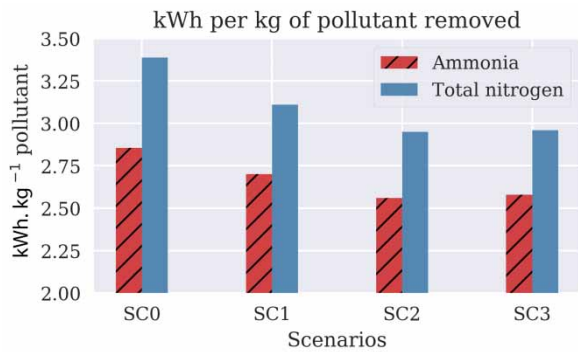


Figure 6 | kWh consumed per kg of ammonia/total nitrogen removed in each scenario.

Influence of temperature

The calibration data used for the Base Case is from December 2016, which had a recorded average temperature of

16.5 °C. As the temperature in the WRRF varies between 15 °C and 25 °C the effect of temperature on energy savings was evaluated for the different optimisation options (Figure 8).

Figure 8(a) shows the energy consumption of the blowers in each scenario for each temperature. All scenarios are more energy-efficient as the temperature increases, both in terms of raw energy savings and kWh per pollutant removed (Figure 6). This is mainly due to increased bacterial activity, which allows the reactor to be run at a lower suspended solids concentration compared to winter (where it needs to be raised up to 4,000 mg·L⁻¹) and lower DO setpoint. The Base Case at 25 °C consumes 8% less energy than at 16.5 °C.

Figure 8(b) shows the percentage of savings of each scenario and each temperature with respect to the Base Case at the same temperature. Results show that not every

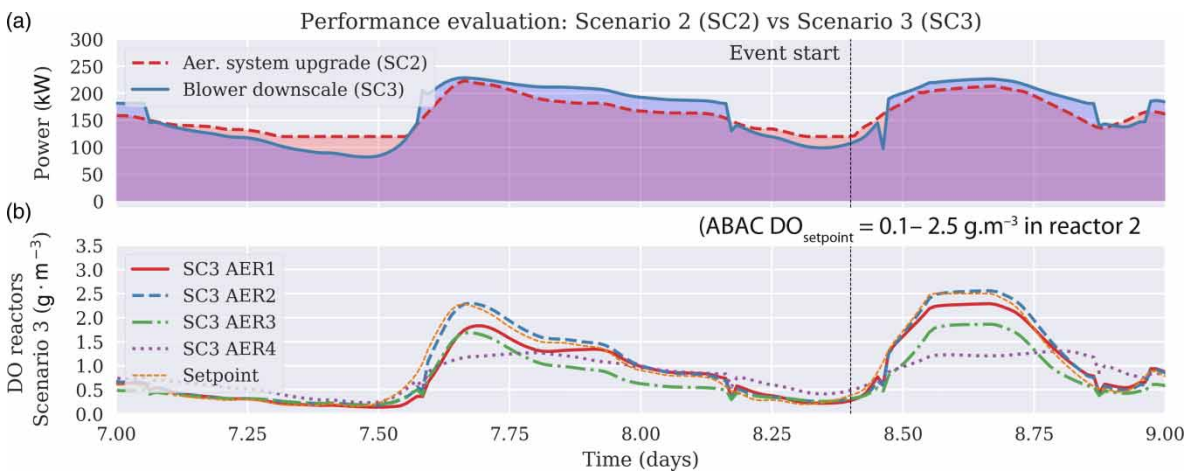


Figure 7 | Performance evaluation of Scenario 3 over Scenario 2. (a) Power consumption; (b) oxygen profiles across reactors in Lane 1 for Scenario 3.

Energy reduction at different temperatures

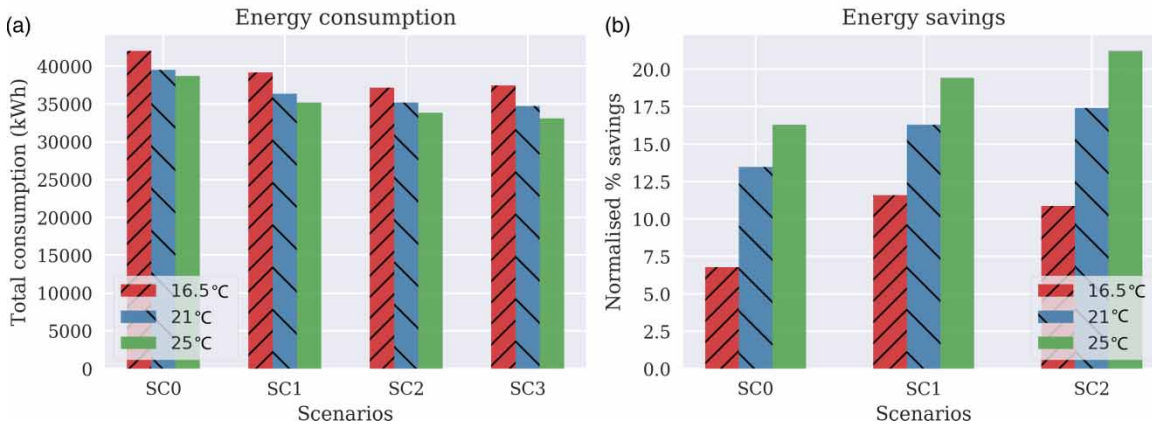


Figure 8 | Energy consumption and the percentage of energy savings of each scenario compared to the Base Case at three different temperatures. (a) Weekly aeration energy consumption. (b) Per cent savings, normalised to the savings of the Base Case at the given temperature.

scenario behaves similarly with temperature changes. Upgrading the aeration system (Scenario 2) shows less savings variation across temperatures, whereas the ABAC (Scenario 1) is significantly more efficient at high temperature. Downscaling the blower (Scenario 3) provides no increased savings at low temperature, but is more efficient at high temperatures when the minimum capacity of the blower is reached more often. This shows the trade-off between flexibility and energy savings. The perfect design would be running several 'small' blowers in a wider capability range, allowing maximum process modularity and improving energy savings.

Optioneering assessment

Table 4 summarises the results for the tested scenarios, considering the effluent quality and system response to ammonia peaks. Return of investment (ROI) for each enhancement has been calculated using the following equation:

$$\text{ROI} = \frac{\text{Investment cost}}{\text{Savings per year} - \text{Maintenance cost per year}}$$

Investment cost and maintenance is calculated as follows: (i) maintenance costs for the ABAC controller during a 10-year period amount to €25,000·yr⁻¹, (ii) energy price used to calculate savings is considered to be €0.1·kWh⁻¹, (iii) cost of piping, valves and installation is estimated at €52'000 (values obtained from a personal communication with the consultancy Banc Bedec (ITeC)), (iv) blower cost estimated at €155,000 (obtained through a personal communication based on recorded data from the Belgian water utility Aquafin).

Results indicate that Scenarios 1 and 2 are recommended as valid optimisation options to save energy. Replacing a blower needs to be evaluated based on a

cost-benefit analysis; however, this highlights the importance of designs including low load scenarios, and the cost of over-sized equipment. Results on mean effluent ammonia and total nitrogen show that the Base Case was not making use of the plant's full denitrifying capacity, which is improved when aeration is optimised.

The ammonia stress test is generated in a low-load period, and thus the DO setpoint set by the ammonia controller, right before the ammonia peak, was at the lower end of the range. This is the most disadvantageous moment for the ABAC system to receive an ammonia peak. Still, all scenarios handled the ammonia peak and maintained effluent quality (Table 4, NH_x peak).

CONCLUSIONS

A model-based audit of the energy and treatment performance has been carried out for the Girona WRRF. The goal was to evaluate energy reduction strategies by understanding the relationships between process performance, aeration equipment, control and energy consumption, using a dynamic air distribution model together with a process model and a control system model. Prior to the audit, the plant's aeration system was already controlled and considered to be optimised following a trial-and-error approach by operators. Using the model, a set of strategies was designed which reduced energy consumption by 12–21%, while improving effluent quality. Furthermore, in the simulated scenario with no equipment limitations, the DO profile is the same across reactors and follows the DO setpoint in all aerated tanks, and the aeration system can respond more rapidly to disturbances and draw more aeration capacity when needed.

This study highlights the importance of considering equipment constraints when designing control strategies. Often the system constraints are hidden as they cannot or are not measured, such as the positions of the manual

Table 4 | Summary of modelled cases and performance obtained

Scenario description ^a	Energy savings (%) ^b	Effluent NH _x daily average (g N·m ⁻³)	Effluent NH _x peak (g N·m ⁻³)	Effluent TN mean (g N·m ⁻³)	Return of investment (years)
SC0: Base Case	–	0.59	1.19	6.85	–
SC1: ABAC	6.8–16.3	0.99	1.40	6.22	0.88
SC2: Aeration system optimisation	11.6–19.4	0.98	1.29	6.20	6.29
SC3: Blower downscaled	10.8–21.2	1.02	1.33	6.12	15.64

^aScenarios are cumulative. Each new scenario includes the optimisation options of the previous scenario.

^bThe range of savings for each scenario is calculated over the Base Case for each temperature.

valves, or the effect of pipes and valves sizing. The mechanistic dynamic air supply model accurately represents the current system, showing airflow distribution and pressure drops as they occur in the plant. This enables in-depth analysis of the aeration together with the treatment performance and the control system, diagnosing the main bottlenecks in the existing aeration system (i.e. the piping size, diffuser distribution and blower minimum turn-down).

ACKNOWLEDGEMENTS

The authors would like to thank Trargisa S.A. for providing the data and feedback on the WRRF of Girona, the funding from the EU project R3water (contract no. 619093), the Ministry of Economy and Competitiveness for the Ramon y Cajal grant for Lluís Corominas (RYC-2013-14595) and for the REaCH project (CTM2015-66892-R). ICRA was recognised as a consolidated research group by the Catalan Government with the code 2017024_SGR17-19_ICRA-TECH. This work has been supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 642904 – TreatRec ITN-EID project.

REFERENCES

- Alex, J., Rieger, L. & Schraa, O. 2016 Comparison of advanced fine-bubble aeration control concepts with respect to energy efficiency and robustness. In: *Proceedings of WEFTEC 2016, New Orleans*, pp. 136–147.
- Amand, L., Olsson, G. & Carlsson, B. 2013 *Aeration control – a review*. *Water Sci. Technol.* **67** (11), 2374–2398. doi:10.2166/wst.2013.139.
- Amaral, A., Schraa, O., Rieger, L., Gillot, S., Fayolle, Y., Bellandi, G., Amerlinck, Y., Mortier, S., Gori, R., Neves, R. & Nopens, I. 2017 *Towards advanced aeration modelling: from blower to bubbles to bulk*. *Water Sci. Technol.* **75** (3), 507–517. doi:10.2166/wst.2016.365.
- Amerlinck, Y., De Keyser, W., Urchegui, G. & Nopens, I. 2016 *A realistic dynamic blower energy consumption model for wastewater applications*. *Water Sci. Technol.* **74**, 1561–1576. doi:10.2166/wst.2016.360.
- Corominas, L., Sin, G., Puig, S., Traore, A., Balaguer, M., Colprim, J. & Vanrolleghem, P. A. 2006 *Model-based evaluation of an on-line control strategy for SBRs based on OUR and ORP measurements*. *Water Sci. Technol.* **53**, 161–169. doi:10.2166/wst.2006.120.
- Enerwater 2015 *Deliverable 2.1. Study of Published Energy Data. H2020-EE-2014-3-MarketUptake*. Available at <http://www.enerwater.eu/download-documentation/> (accessed 15 May 2017).
- ifak 2017 *SIMBA Portal*. Available at <https://simba.ifak.eu/> (accessed 11 May 2017).
- Odriozola, J., Beltrán, S., Dalmau, M., Sancho, L., Comas, J., Rodríguez-Roda, I. & Ayesa, E. 2017 *Model-based methodology for the design of optimal control strategies in MBR plants*. *Water Sci. Technol.* **75**, 2546–2553. doi:10.2166/wst.2017.135.
- Olsson, G. 2012 *Water and Energy: Threats and Opportunities*. IWA Publishing, London, UK.
- Rieger, L., Gillot, S., Langergraber, G., Ohtsuki, T., Shaw, A., Takacs, I. & Winkler, S. 2012a *Guidelines for Using Activated Sludge Models: IWA Task Group on Good Modelling Practice*. Scientific and Technical Report No. 22, IWA Publishing, London, UK.
- Rieger, L., Takács, I. & Siegrist, H. 2012b *Improving nutrient removal while reducing energy use at three Swiss WWTPs using advanced control*. *Water Environ Res.* **84** (2), 171–189. doi:10.2175/106143011X13233670703684.
- Rieger, L., Jones, R. M., Dold, P. L. & Bott, C. B. 2014 *Ammonia-based feedforward and feedback aeration control in activated sludge processes*. *Water Environ Res.* **86** (1), 63–73. doi:10.2175/106143013X13596524516987.
- Rieger, L., Alex, J. & Schraa, O. 2016 *Model-supported design, testing, and implementation of process control strategies*. In: *Smart Water Utilities: Complexity Made Simple* (P. Ingildsen & G. Olsson, eds). IWA Publishing, London, UK, pp. 221–226.
- Rosso, D., Iranpour, R. & Stenstrom, M. K. 2005 *Fifteen years of off-gas transfer efficiency measurements on fine-pore aerators: key role of sludge age and normalized air flux*. *Water Environ. Res.* **77** (3), 266–273.
- Schraa, O., Rieger, L. & Alex, J. 2015 *A comprehensive aeration system model for WRRF design and control*. In: *Proceedings of WEFTEC 15, Chicago, Illinois, USA*.
- Schraa, O., Rieger, L. & Alex, J. 2017 *Development of a model for activated sludge aeration systems: linking air supply, distribution, and demand*. *Water Sci. Technol.* **75** (3), 552–560. doi:10.2166/wst.2016.481.
- Swamee, P. & Jain, A. 1976 *Explicit equations for pipe-flow problems*. *Journal of the Hydraulics Division (ASCE)* **102** (5), 657–664.
- Thornton, A., Sunner, N. & Haeck, M. 2010 *Real time control for reduced aeration and chemical consumption: a full scale study*. *Water Sci. Technol.* **61**, 2169–2175. doi:10.2166/wst.2010.971.

First received 16 February 2018; accepted in revised form 2 August 2018. Available online 30 August 2018