Effect of sensor location on controller performance in a wastewater treatment plant

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ABSTRACT

Complete mixing is hard to achieve in large bioreactors in wastewater treatment plants. This often leads to a non-uniform distribution of components such as dissolved oxygen and, hence, the process rates depend on them. Furthermore, when these components are used as input for a controller, the location of the sensor can potentially affect the control action. In this contribution, the effect of sensor location and the choice of setpoint on the controller performance were examined for a non-homogeneously mixed pilot bioreactor described by a compartmental model. The impacts on effluent quality and aeration cost were evaluated. It was shown that a dissolved oxygen controller with a fixed setpoint performs differently as a function of the location of the sensor. When placed in a poorly mixed location, the controller increases the aeration intensity to its maximum capacity leading to higher aeration costs. When placed just above the aerated zone, the controller decreases the aeration rate resulting in lower dissolved oxygen concentrations in the remainder of the system, compromising effluent quality. In addition to the location of the sensor, the selection of an appropriate setpoint also impacts controller behavior. This suggests that mixing behavior of bioreactors should be better quantified for proper sensor location and controller design.

Key words | activated sludge process, compartmental modeling, instrumentation, mixing, process control

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INTRODUCTION

The discharge of treated wastewater and the disposal of sludge from treatment plants treating domestic or industrial wastewater are subject to regulations imposed by the authorities. The main focus of wastewater treatment plants (WWTPs) is to reduce the biochemical oxygen demand (BOD), chemical oxygen demand, and nutrients in the effluent discharged to natural waters, meeting the discharge regulations. WWTPs are designed to function as 'microbiology farms', where bacteria and other microorganisms (activated sludge) are fed with wastewater containing organic waste. Aeration plays a vital role in a wastewater treatment process and its purpose is twofold. First, oxygen must be dissolved in wastewater in sufficient quantities to support the biological activities associated with BOD reduction and nitrification. Second, the contents of the tank must be sufficiently mixed to keep the wastewater solids in suspension and uniformly mixed during the treatment. Wastewater plants are typically operated at least 1–2 mg/L dissolved oxygen (DO) to ensure enough aerobic process conditions. This is required for effective BOD removal, maximal rates of nitrification, and a reduction in the volume of sludge remaining after wastewater treatment.

Like any other process, wastewater treatment systems need to be operationally and cost-effectively optimized, and aeration is one of the most energy-intensive operations associated with the treatment process. Up to 60–65% of the total energy consumption is used for the activated sludge part of the treatment plant, i.e. for the stirring and aeration systems (Bischof *et al.* 1996; Duchène *et al.* 2001; Rieger *et al.* 2006). This shows the importance of proper design and operation of such systems, and it thus indicates the need for an optimized control strategy.

The increasing demands on effluent quality at lower operational costs have promoted the development of new technologies and the implementation of control concepts to improve the overall performance of WWTPs (Olsson &

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Andrews 1978; Olsson *et al.* 2005; Olsson 2012; Fikar *et al.* 2005). Here, on-line sensors are used to gather process information, and action is undertaken depending on the system's state (feedback control). Full-scale applications have shown the feasibility of automatic control in aeration systems, chemical dosage, and recycle flows (Oennerth *et al.* 1996; Ingildsen *et al.* 2002; Devisscher *et al.* 2002; Olsson *et al.* 2005). Dynamic simulation studies have also been used to compare the performance of different control strategies (Zhao *et al.* 1995; Spanjers *et al.* 1998; Corominas *et al.* 2006; Stare *et al.* 2007; Flores-Alsina *et al.* 2008; Machado *et al.* 2009) or to evaluate them before full-scale implementation (Ayesa *et al.* 2006). Plant-wide operation has also been introduced to take into account the interactions between the processes (Gujer & Erni 1978; Lessard & Beck 1993; Jeppsson *et al.* 2007; Nopens *et al.* 2010). In this regard, the location of sensors has also been discussed (Waldraff *et al.* 1998), but these studies often have to do with the development of observers whose results are used as input to controllers.

Controllers for WWTPs are typically designed based on process models that approximate the mixing by a tanks-in-series (TIS) approach. In the TIS approach, the mixing behavior of the whole reactor is modeled as a number of completely mixed continuous stirred tank reactors considering the flow in only one direction. This approach can only account for some back-mixing by maintaining the liquid longer in the system by adjusting the back-mixing rate (Le Moullec *et al.* 2010a). Hence, at most, sensor locations in the advective flow direction (1D) can be considered, whereas in reality these might not represent the overall reactor behavior. Therefore, sensors should be placed in those regions that are a good approximation of the reactor behavior. Considering a higher number of tanks (to some extent) can better predict the overall behavior of the reactor. However, a small number of tanks is usually chosen small for computational load reasons, and all the tanks are considered completely mixed. However, in this way they average out local variations occurring in the other two dimensions. In reality perfect mixing never occurs because only a portion of the reactor is directly aerated and oxygen is transferred to the rest of the reactor through advective transport (air bubble flow along with the liquid flow). The effectiveness of this advective transport mainly depends on reactor design and induced hydrodynamics of the system (Jin *et al.* 2006). Mass transfer between air and water occurs depending on the local concentration gradient and inter-phase resistance. Therefore, inefficiently mixed reactors possess fewer mixed regions or even completely dead zones resulting in a non-uniform environment. Thus, in conclusion, the TIS approach is unable to take into account the reactor inhomogeneity. This drawback of TIS modeling implies its limitation for evaluating the effect of sensor location on the controller performance.

Computational fluid dynamics (CFD) has emerged as a useful tool which allows more accurate evaluation of local phenomena such as mixing (Le Moullec *et al.* 2010b; Cockx *et al.* 2001; Glover *et al.* 2006; Wang *et al.* 2009; Laborde-Boutet *et al.* 2009; Brannock *et al.* 2010b). Furthermore, biokinetics and CFD have been integrated to understand the system in more detail (Le Moullec *et al.* 2010a, b, 2011). However, CFD is computationally very intensive for a complex system such as a WWTP. Therefore, an intermediate solution between TIS approaches and CFD modeling, called compartmental modeling (CM), has been used in previous studies (Gresch *et al.* 2009; Alvarado *et al.* 2012; Le Moullec *et al.* 2010a, b). A CM consists of a number of compartments C_i of volume V_i configured in more than one dimension, in which a recirculation flow Qr_i from compartment C_{i+1} to C_i occurs, along with the forward flow. It has been concluded that this approach reduces the computational requirements and improves the hydrodynamic predictions by taking recirculation flows into account and by modeling the flow in all three dimensions.

The main driver for choosing the location of on-line sensors is easy accessibility for maintenance and installation. Whether the sensor is located in a place that severely deviates from the average behavior in the monitored process is usually not considered. However, since this local value provides the input to the controller, it directly impacts its behavior and success. This contribution illustrates the impact of sensor location in an aerated bioreactor of a WWTP on the process performance by using a compartmental model derived from CFD predictions.

MATERIALS AND METHODS

The compartmental model used in this study is borrowed from the study of Le Moullec *et al.* (2010a, b), who developed it for a pilot plant reactor and based it on a CFD model. The reactor was a pilot gas/liquid channel reactor with a very long length compared to its height and width (Le Moullec *et al.* 2010b, 2011) and thus leading to water flow along the length of the reactor. The total length of the reactor was 3.6 m with a rectangular cross-section of 0.18 m width and 0.2 m height. One side of the walls was fitted at the bottom with stainless steel tubes in which 1 mm holes were present every centimeter for air sparging. The mixed liquor was recycled at the inlet keeping a recycle ratio of 4. A 0.88 m^3 settler was used to clarify the mixed liquor and to produce sludge which was also recycled at the reactor inlet keeping a recycle ratio of 1. As the biological kinetics involved in the reactor are well represented by Monod equations with apparent reaction orders higher than zero, the pollution removal efficiency depends on the hydrodynamics (Levin & Gealt 1993).

Compartmental modeling

Compartmental modeling describes the reactor as a network of spatially localized compartments. Compartments are chosen on the basis of process knowledge and CFD results. The configuration of the compartments is based on the determination of homogeneous physical–chemical properties within a given tolerance. Shape, number, and connectivity of these compartments are determined on the basis of the following parameters:

- The distribution of gas fraction, i.e. extent of mixing.
- The liquid velocity field to compute flow rates.
- Liquid turbulence characteristics (k and ϵ). A previous study (Le Moullec *et al.* 2010b) has shown that the dispersion coefficient along the reactor is mainly dependent on these characteristics.

As the studied system was a channel reactor, flow remains invariant along the length. Thus, the reactor could be split into just six slices of equal size along the length. It was obvious from the design of the reactor and also observed from the velocity and turbulence profiles of the CFD studies that air rises along the side of the wall and causes recirculation in the reactor. This recirculation creates dead zones in the middle and in the corners of the reactor. Hence, the reactor cross-section was divided into four different zones on the basis of flow dynamics. For clarity, each zone is labeled as gas rich zone (GR), recirculating liquid zone (RL), corner zone (CR), and center zone (CN) (Figure 1(a)).

These labels are accompanied by the numbers 1–6, where 1 represents the first slice at the reactor entrance and 6 is the last zone near the outlet. This eventually resulted in a total of 24 compartments, i.e. four zones in each of the six slices (Figure 1(b)). All compartments are coupled through bidirectional fluxes. The model was implemented in the modeling and simulation platform WEST (http://www.mikebydhi.com) and used the BSM1 dry weather influent with dynamic diurnal effects (Gernaey *et al.* 2014). To study the effect of sensor location, controller performance was evaluated in terms of both aeration cost and effluent quality.

Model configuration in WEST

The compartmental layout in the WEST simulation platform is shown in the Appendix (available online at http://www.iwaponline.com/wst/071/525.pdf). It consists of a network of 24 reactors, where each reactor represents one compartment in which reaction conditions are created. Each compartment also has inter-compartmental connections for respective convective and exchange fluxes. Convective fluxes in principle are the flow rates due to the main flow patterns (determined by velocity profiles through CFD) of fluid in the reactor. Exchange fluxes are calculated based on the turbulent characteristics of the flow along with the main flow. The reactors in this layout are distributed in a network of four rows which represent each of the four zones in a slice, i.e. GR, RL, CR, and CN. The top row represents GR reactors which account for 30% of the total reactor volume. These compartments are directly aerated as air is being pumped in these regions. All remaining compartments do not have direct aeration. However, oxygen can be transferred to these reactors by convective or recirculation flows (i.e. through liquid transport terms). The second row from the top represents RL compartments which account for 50% of the total reactor volume. The inlet and outlet of the reactor are present in RL1 and RL6 compartments, respectively. The third and fourth rows, respectively, represent the corner and central dead zone compartments. Connections coming out of a reactor are accompanied by flow splitters to divide the flow between forward flow and recirculation fluxes. It can be seen that flow out of each GR (except GR6) reactor is partially sent back to the respective RL zones, i.e. from GR1 to RL1 and partially forwarded to GR2. Similarly, in RL compartments, part of the flow is sent back as an exchange flow to the respective GR compartment, i.e. from RL2 to GR2. CR and CN, being dead zones, do not exchange flow with other compartments through convective transport. For the GR6, CR6, and CN6 compartments all flows are directed toward the RL6 compartment and finally out of the reactor. Effluent from the reactor is carried to the secondary clarifier before discharge. Two recycle streams, one from reactor effluent and the other from the underflow of the secondary clarifier, are sent back to combine with the inflow to RL1.

The biological kinetics model chosen for this study is the ASM1 model (Henze *et al.* 1987, 2001) for the biological modeling of all reactors. This model is frequently adopted to simulate or predict performances of biological reactors.

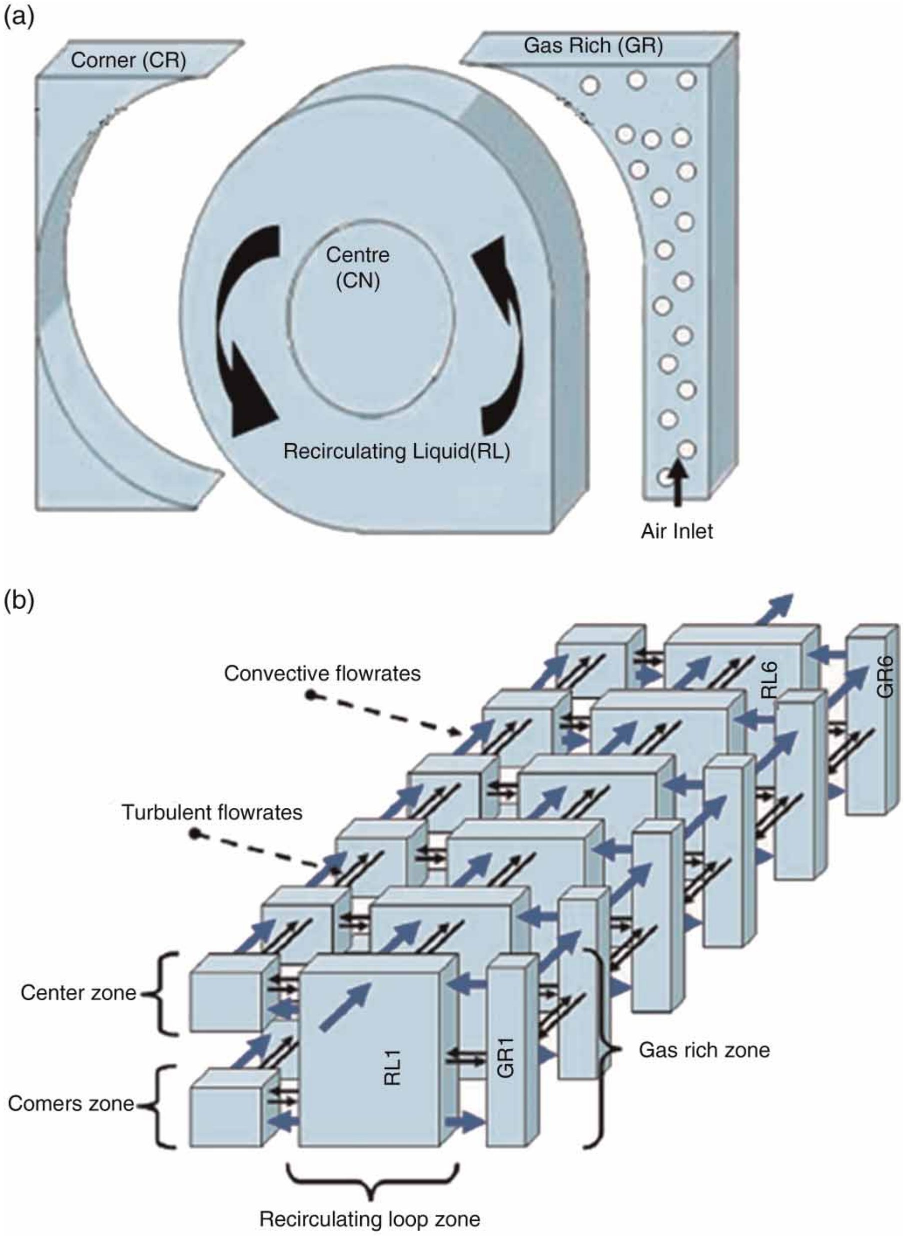

Figure 1 | (a) Cross-sectional compartments (Le Moullec *et al*. 2010a, b). (b) Compartmental model layout.

It is suitable to simulate carbon oxidation, nitrification, and denitrification in the aerobic and anoxic zones of activated sludge reactors. It considers 12 different components and eight kinetic processes. The default values were used for all stoichiometric and kinetics parameters.

Simulations set-up

The PI controllers for maintaining the DO at a certain level were implemented in the WEST simulation platform. Two sets of simulations were performed: first, the controller configurations were fixed and the sensor location was changed; second, the controller settings were varied, i.e. DO setpoint, at two different locations. All other parameters and influent composition remained the same for all simulations. Steady-state conditions were achieved by running the simulation for 100 days. Subsequently, the controller was implemented for dynamic inflow conditions for 28 days.

RESULTS AND DISCUSSION

Simulations with varying sensor location

For the first set of simulations, a PI controller was implemented and fed with the signal of a DO sensor placed in different compartments, i.e. GR1, GR3, GR6, RL6, and CR6. These locations were selected based on the fact that usually DO is measured near the bioreactor outlet and at the water surface (easy access for maintenance). Controller settings (controller gain 200 and reset time 0.1 h) were kept fixed for each sensor location in order to only evaluate the impact of the location. The setpoint for DO concentration was chosen as 1.5 g/m^3 according to common industrial practices (Olsson 2012). The effluent regulations in BSM1 impose constraints for effluent BOD, NH_4-N, and total nitrogen, respectively, at 10 g/m^3, 4 g/m^3, and 18 gN/m^3 (Gernaey *et al.* 2014). Effluent quality in terms of BOD, ammonia, and DO in the effluent was simulated in the final compartment, named RL6, as this is the actual outflow of the reactor.

The effect of sensor location on effluent quality and aeration cost per day is shown in Figure 2. The aeration cost only includes the energy requirements for aeration. It is evident from the figure that when the sensor is placed in the GR compartments where aeration is actually taking place, BOD and ammonia concentrations in the effluent are quite high. Indeed, the aerated GR compartments have higher DO concentrations as compared to other compartments to which oxygen is transferred only by advection. The DO setpoint is easily reached and leads to local higher values of DO in the GR compartments. As a result, the controller reduces the aeration rate to bring the DO level back to 1.5 g/m^3, which leads to much lower DO levels in the other not directly aerated compartments. It can be seen in Figure 2 that the DO level in the effluent is as low as 0.03 g/m^3 in the cases where the sensor was located in GR1, GR3, and GR6. This of course explains the higher BOD and NH_4 levels in the effluent for these cases because lower reaction rates occur due to the low DO levels. Changing the location of sensor between GR1, 3 and 6 did not result in significantly different behavior due to similar aeration conditions in these compartments. For this particular reactor, this behavior indicates that there is no significant effect of inlet and outlet location as long as the sensor is placed in the aeration zone.

When the sensor was placed in the RL and CR zones with relatively low DO values, the controller kept on increasing aeration (within the blower specs) to achieve the setpoint. In these poorly mixed zones, the setpoint was hard to reach and the maximum capacity of aeration had to be imposed in order to reach the setpoint. The DO concentration in the effluent was 1.1 g/m^3 resulting in good effluent quality in terms of ammonia removal but at very high aeration costs. The DO concentration in GR zones was found to be as high as 7 g/m^3.

Simulations with varying setpoint

This analysis led to a second set of simulations for obvious control optimization by changing the setpoint to higher values when the sensor is placed in GR zones or lowering it when placed in RL zones. A higher setpoint for GR zones will eventually result in increased aeration and better oxygen transfer to other zones, whereas a lower setpoint in the RL zone will cause a decrease in aeration and thus lower costs.

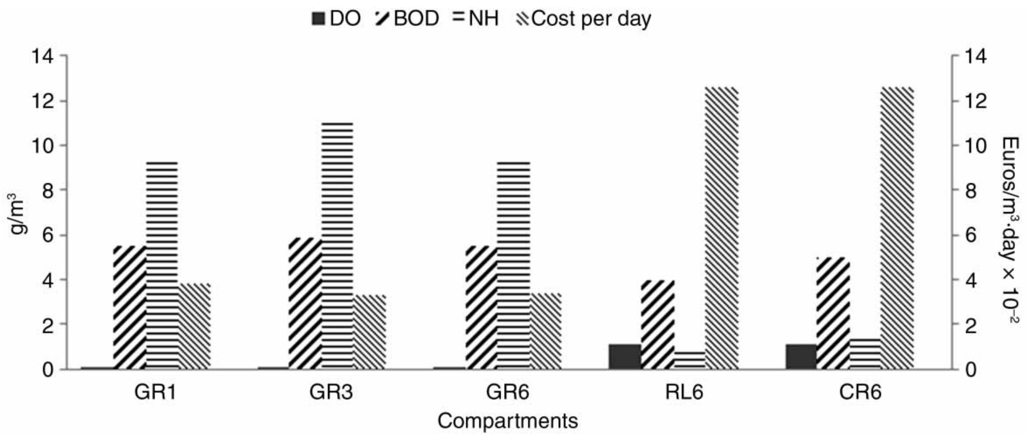

Figure 2 | Average effluent quality and aeration cost per day with a fixed DO setpoint of 1.5 g/m^3.

Three different setpoints were applied in both the GR6 and RL6 compartments. In the GR6 compartment, the setpoint was increased from 1.5 to 2 and 2.5 g/m^3. In contrast, the DO setpoint in the RL6 compartment was reduced from 1.5 to 1 and 0.5 g/m^3. The results in terms of average effluent quality and cost of these six simulations are summarized in Figure 3 (RL6-1.5 corresponds to the sensor being placed in the RL6 compartment with a DO setpoint of 1.5 g/m^3).

It can be observed that increasing the DO setpoint in the GR zones causes an increase in aeration and better oxygen transfer to the other compartments resulting in lower BOD and ammonia concentrations in the effluent, however at higher aeration cost. The gain from 1.5 to 2 g/m^3 is larger than from 2 to 2.5 g/m^3 (Figure 3). This observation leads to the conclusion that increasing the setpoint in aerated zones (e.g. GR compartments) will not linearly increase the effluent quality. However, decreasing the DO setpoint to 1 g/m^3 in RL zones resulted in lower aeration costs while maintaining good effluent quality. It can be seen that further reducing the setpoint to 0.5 g/m^3 caused significant decrease in aeration costs but effluent quality significantly decreased as well. It should be noted that the aeration cost in the case of RL6-0.5 is still two and a half times higher compared to GR6-2.5. The increase in cost relative to DO in the effluent can be seen in Figure 4.

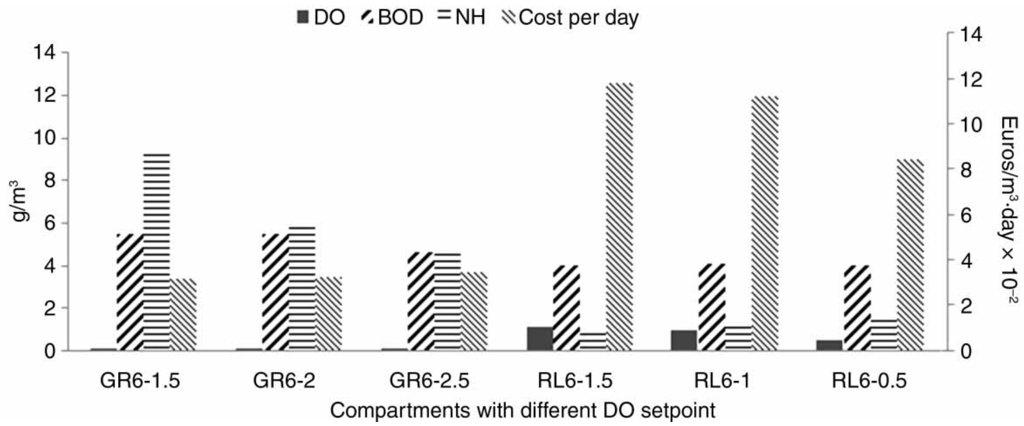

Figure 3 | Effluent quality and aeration cost per day with varying DO setpoints.

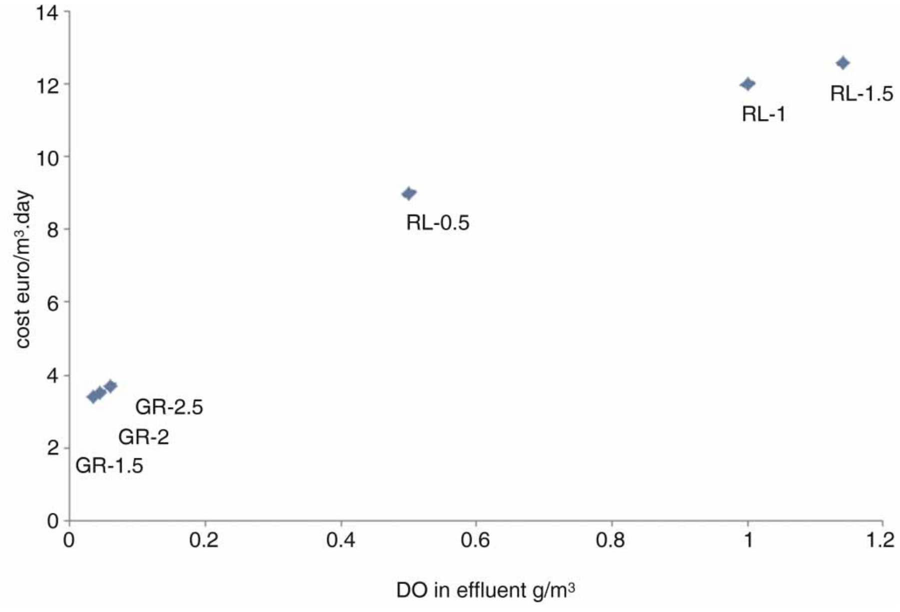

Figure 4 | DO in effluent vs cost for different setpoints in GR and RL zones.

It shows the level of DO in the effluent and the corresponding cost for aeration for all different setpoints in RL and GR compartments. The figure shows that only the cases RL-0.5 and RL-1 result in actual effluent DO levels equal to the controller's setpoint. In all other cases, effluent DO failed to reach the actual setpoint in the effluent either due to bad mixing or physical limitations of the aerators (i.e. in RL-1.5).

Simulations with NH_4-DO control

In addition to the above mentioned set of simulations, an NH_4-DO cascade control strategy was also applied to investigate its impact on the effluent quality. In this control strategy an NH4 controller selects the setpoint of a DO controller which directly controls the aeration rate (Zhang *et al.* 2008). A fixed setpoint of $2\,g/m^3$ was used for ammonia, while the DO controller gets its setpoint as an input from the ammonia controller. Both ammonia and DO probes were placed in the GR6 compartment. To achieve the desired setpoint of ammonia, a higher DO level is required which leads to higher aeration in GR compartments. Thus, it resulted in lower BOD and higher DO concentrations in the effluent. A comparison in terms of DO, BOD, and ammonia dynamics between DO control and NH_4-DO cascade control can be seen in Figure 5. It should be noted that in both cases, steady state solution was achieved before applying controllers. Therefore, starting points for both DO and NH_4-DO simulations were the same. It can be inferred that the cascade control partially corrects the bad sensor location resulting in improved effluent quality and DO concentration.

CONCLUSIONS AND OUTLOOK

For the complex mixing behavior of full-scale reactors, TIS models usually used to develop controllers are not very

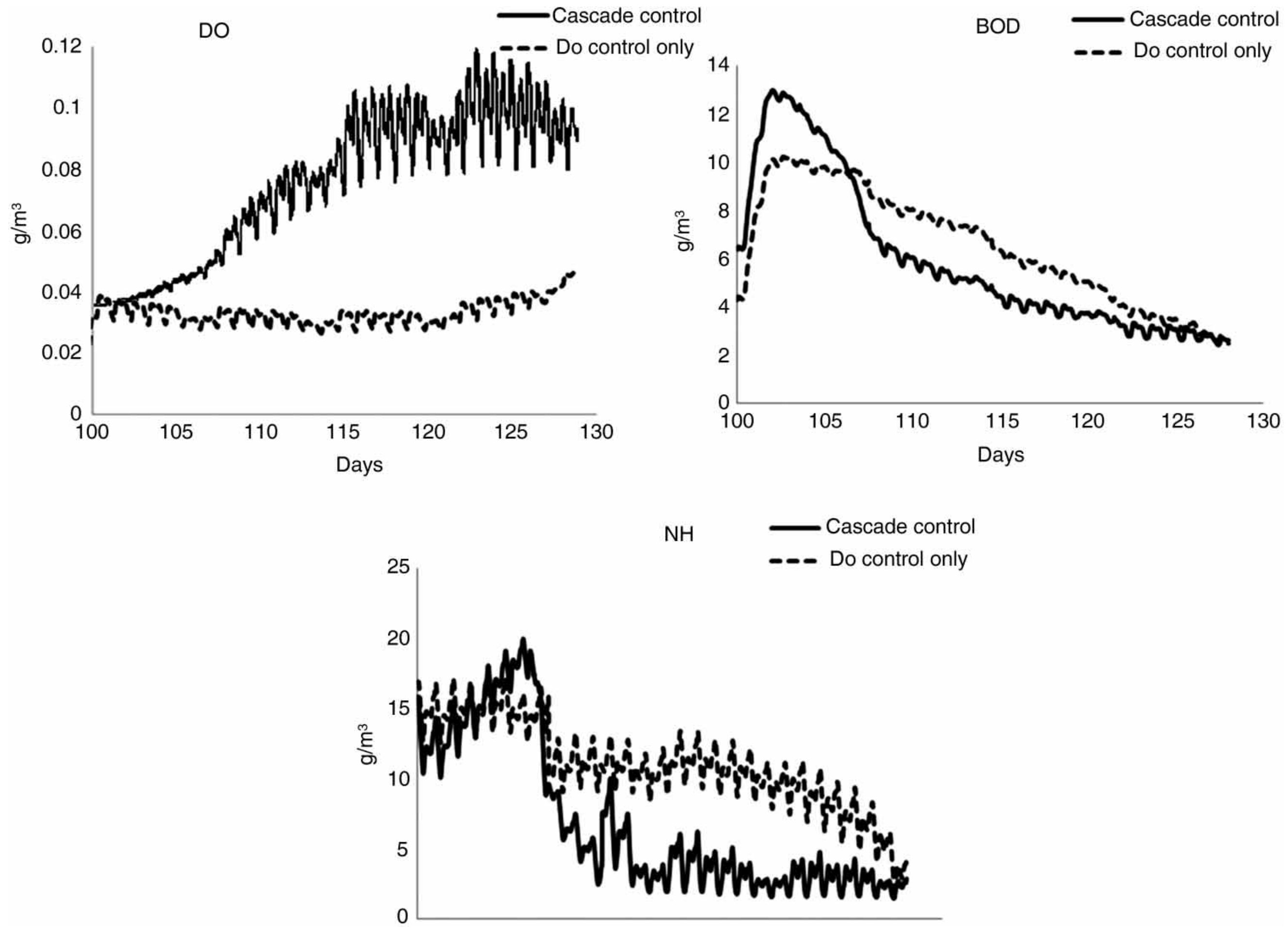

Figure 5 | DO, BOD, and NH dynamics for DO control and NH_4-DO cascade control.

realistic because they severely oversimplify real mixing behavior. It is shown that knowledge of process hydrodynamics can be useful in deciding the appropriate location of sensors. A compartmental model that refines the mixing behavior of a pilot reactor illustrated clearly that in order to achieve cost-effective DO control the sensor location and setpoint are important. Hence this should be embedded in a control design protocol. Another path forward is to redesign reactors and embedded aerators to better achieve completely mixed conditions. However, it must be ensured that such new design does not lead to reduced process efficiency or increased construction costs.

It should be noted that the compartmental model used in this study was fixed. In reality, the mixing behavior of a plant will significantly vary when the influent flow rate changes. This can be accounted for by making the exchange fluxes between compartments functions of the influent flow rate. Hence, this study should be regarded as a first proof of principle study with regard to mixing impact on controller design.

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