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Dynamic control of nutrient-removal from industrial wastewater in a sequencing batch reactor (SBR), using common and low-cost online sensors

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Abstract

On-line control of the biological treatment process is an innovative tool to cope with variable concentrations of chemical oxygen demand (COD) and nutrients in industrial wastewater. In the present study we implemented a simple dynamic control strategy for nutrient-removal in a sequencing batch reactor (SBR) treating variable tank truck cleaning (TTC) wastewater. The control system was based on derived signals from two low-cost and robust sensors that are very common in activated sludge plants, i.e. oxidation reduction potential (ORP) and dissolved oxygen (DO). The amount of wastewater fed during anoxic filling phases, and the number of filling phases in the SBR cycle were determined by the appearance of the "nitrate knee" in the profile of the ORP. The phase length of the subsequent aerobic phases was controlled by the oxygen uptake rate (OUR) measured online in the reactor. As a result, the sludge loading rate (F/M ratio), the volume exchange rate (VER) and the SBR cycle length adapted dynamically to the activity of the activated sludge and the actual characteristics of the wastewater, without affecting the final effluent quality.

Keywords: activated sludge, phase-length control, biological nutrient removal, oxygen uptake rate, nitrate knee, moving ORP slopes

INTRODUCTION

The sequencing batch reactor (SBR) represents a flexible process for biological wastewater treatment. In general, the SBR operation consists of a series of phases, i.e. fill, react, settle and draw, with a fixed length irrespective of fluctuations in wastewater strength and microbial activity (Yang *et al*. 2010). This may result in a highly inefficient operation, especially in the case of industrial wastewater with variable wastewater characteristics (Eckenfelder *et al.* 2009). Large safety factors are therefore applied in the design phase of industrial plants to guarantee an effluent quality within the discharge limits. As a result, wastewater treatment in many facilities is often not very (energy-) efficient (Marsili-Libelli *et al*. 2008). By introducing on-line control strategies, the wastewater treatment process may adapt itself dynamically to the varying influent conditions (Olsson *et al*. 2005). Such an approach offers great potential to save energy and time.

Real-time dynamic control significantly enhanced the flexibility and efficiency of the SBR process for biological removal of chemical oxygen demand (COD) and nitrogen, by adapting the length of the aerated and anoxic phases in the SBR cycle (e.g. Puig *et al*. 2005; Marsili-Libelli 2006). A large diversity of control strategies have been proposed for real-time operation of SBR processes, varying from simple direct control algorithms to intelligent monitoring systems (Yang *et al*. 2010; Zanetti *et al*. 2012). In the current study, we focus on low-cost control systems using characteristic patterns in the profiles of two of the most common and robust online sensors applied in activated sludge treatment plants, i.e. dissolved oxygen (DO) and oxidation reduction potential (ORP). During aerated phases, the SBR acts a full-scale respirometer, where the end of the exogenous oxygen-consuming biological reactions, i.e. COD oxidation and nitrification, is indicated either by a break point in the DO curve or by low values of the oxygen uptake rate (OUR) (Johansen *et al*. 1997; Casellas *et al*. 2006; Puig *et al*. 2006). During anoxic phases, the end of the denitrification reaction is indicated by a significant drop in the ORP value, the so-called "nitrate knee" corresponding to the disappearance of nitrate, and the transformation from denitrifying to more reduced anaerobic conditions (Pavselj *et al*. 2001; Puig *et al*. 2005). The detection of the nitrate knee is based on changes in the relative ORP profile and represents a more reliable approach than control based on absolute ORP values (Yang *et al*. 2010; Won and Ra 2011).

These "simple" strategies have mostly been applied for treatment of domestic wastewater, while reports on industrial implementations are limited, e.g. for treatment of swine wastewater, slaughterhouse wastewater and wastewater from a wood factory (Andreottola *et al*. 2001; Mauret *et al*. 2001; Won and Ra 2011). The aim of the present study is therefore to expand the field of industrial application of dynamic SBR processes. The specific case-study presented here deals with complex nitrogen-containing wastewater originating from tank truck cleaning (TTC) activities, where the wide range of transported cargo results in wastewater with a highly variable composition (De Schepper *et al*. 2010; Dries *et al*. 2013).

METHODS

Reactor Set-up and Operation

A lab-scale SBR (total volume = 20 L, volume after discharge = 12 L) was set-up to treat the real variable wastewater originating from a small TTC company active in the harbor region of Antwerp, Belgium. The SBR was inoculated with the activated sludge originating from the full-scale wastewater treatment of the TTC company. Prior to the start of the dynamic operation (described below), the SBR was operated during about 2 months using fixed cycle times to acclimate the sludge to the laboratory conditions and to investigate the sensor signals used for the real-time control strategy. During the subsequent dynamic SBR operation, which lasted about 80 SBR cycles, 54 different TTC wastewater batches were fed to the reactor. The average composition of these influent batches is shown in Table 1.

Table 1 Average composition of the TTC wastewaters fed to the lab-scale SBR, during the experimental period.

Parameter (unit)	Min.	Max.	Avg. ± SD	%CV
Total COD (mg/L)	1024	3000	2078 ± 409	20
Filtered COD (mg/L)	962	2696	1864 ± 388	21
NH_4-N (mg/L)	57	194	115 ± 30	26

The full-scale activated sludge plant of the TTC company is a conventional step-feed SBR treating 200 m³ of wastewater per day, operated in 24h-cycles consisting of several aerobic/anoxic sequences. In the lab, SBR operational cycles consisted of the following steps: (1) an aerated idle phase (fixed at 30min), (2) repeated sequences of anoxic filling followed by aerobic react phases, each with a dynamic duration (see below), (3) an endogenous aerobic phase (fixed at 2h), (4) a post-denitrification anoxic mixing phase (fixed at 2h) followed by 5min aeration to remove nitrogen gas bubbles, (5) settling (fixed at 2h) and discharge (15min). The endogenous aerobic and post-denitrification phases were included to ensure low N concentrations in the final effluent (Puig *et al*. 2006). Approx. 4 L wastewater was fed to the reactor during each cycle, divided over 3 to 5 anoxic filling phases, depending on the result of the control strategy. The flow rate of the feeding pump was set at 1L/h. The mixed liquor suspended solids concentration (MLSS) was about 6 g/L. The sludge retention time (SRT) was kept at about 40d by wasting mixed liquor daily from the reactor. The reactor was operated at room temperature.

The lab-scale SBR reactor was equipped with the following online sensors from Hach-Lange connected to a SC1000 transmitter: pH, ORP, luminescent dissolved oxygen (LDO) and NITRATAX sc (nitrate UV sensor). Process operation was controlled by a Siemens PLC connected to I/O modules from WAGO Kontakttechnik. The operator interface, including visualization of sensor signals and the process control settings, was programmed using LabView software (National Instruments). The logging frequency of the ORP and DO sensors was set to 15s and 10s respectively.

Real-time control strategy

Figures 1 and 2 show diagrams with the real-time control strategy for the aerobic and anoxic phases in the SBR operation, respectively. The principle of the control strategy is illustrated in Figure 3 for a typical SBR cycle.

During aerated steps, on/off-DO control was operated between DO levels of 2 and 3 mg/L. The OUR was calculated online as the descending slope of the DO values during air-off periods, using least-square linear regression analysis (e.g. Puig *et al*. 2005). After a minimum aeration time (30min), the length of the aerobic phase was based on a combination of (1) the absolute value of the OUR, and (2) the difference between two consecutive OUR values (Fig. 1). The end of the aerobic processes, being either nitrification or COD oxidation, was indicated by a "low" OUR value of 15 mg O_2/L.h in combination with a "small" difference between consecutive OUR values of less than 1 mg O_2/L.h (this is illustrated by arrow "a" in Fig. 3). The applied threshold OUR value corresponded to a biomass-specific OUR (SOUR) of approx. 2 mg O_2/g MLSS.h, which can be considered as an endogenous respiration rate (Eckenfelder *et al.* 2009).

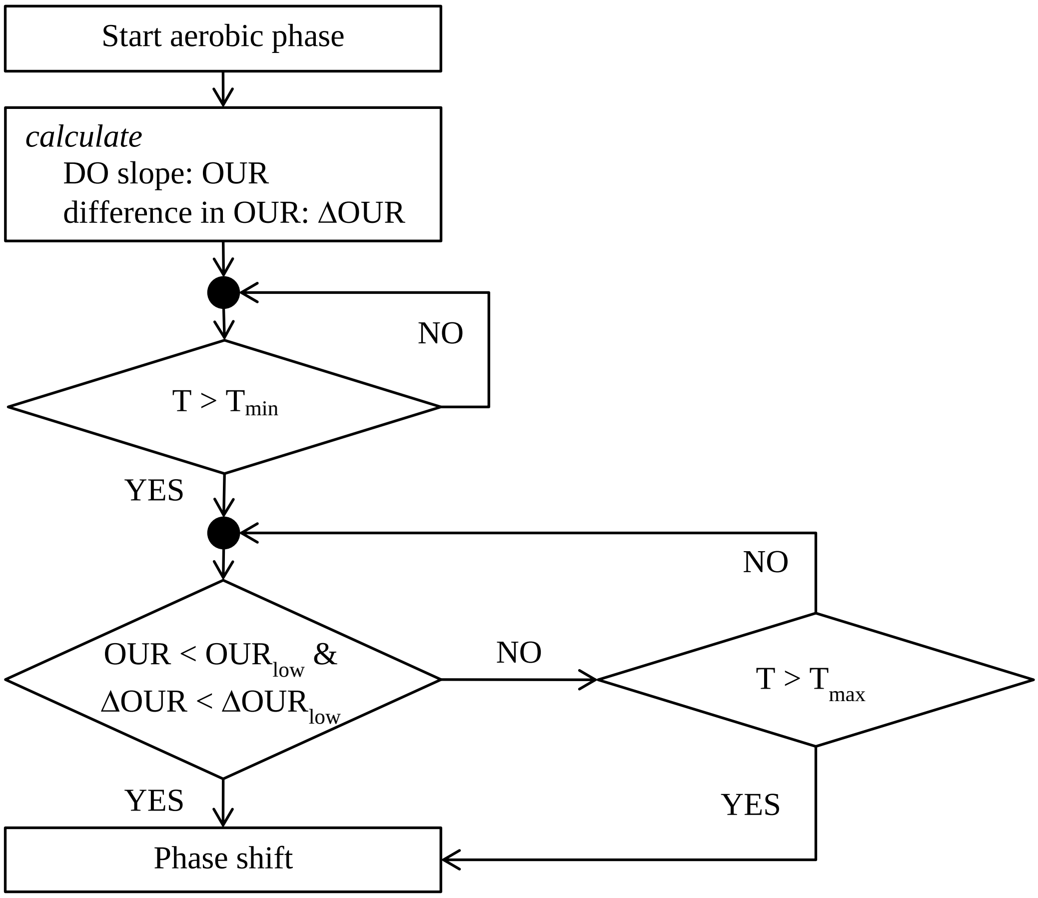

Figure 1 Real time control strategy for duration control of the aerobic phase; OUR_{low} = 15 mg O_2/L.h; ΔOUR_{low} = 1 mg O_2/L.h; T_{min} = 30min; T_{max} = 10h.

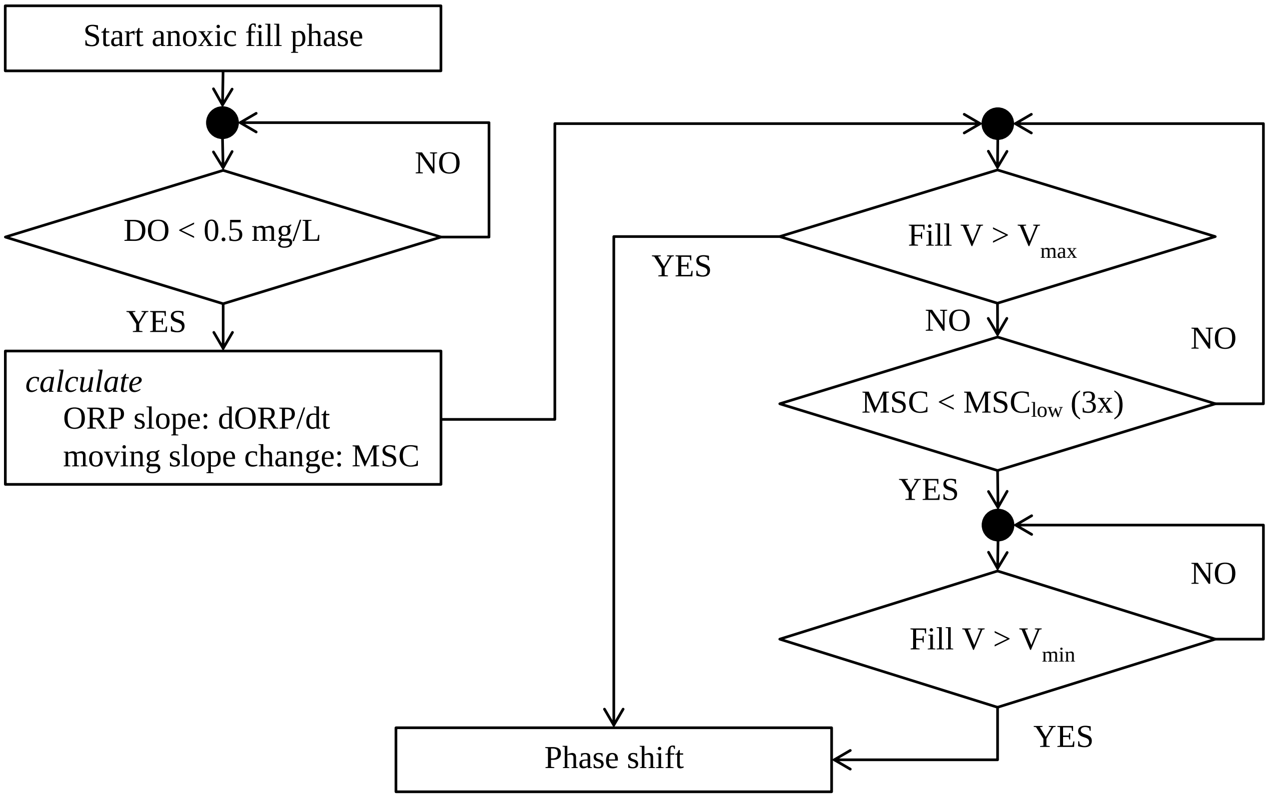

Figure 2 Real time control strategy for duration control of the anoxic fill phase; MSC_{low} = -50%; V_{min} = 0.8 L; V_{max} = 1.6 L.

The duration control of the anoxic filling phases was based on the on-line detection of the "nitrate-knee" in the ORP profile (Fig. 2). To this end, moving ORP vs. time slopes were computed, using linear regression based on 6 ORP measurements. A significant negative change in the ORP slope, corresponding to a sharp decrease of the ORP indicated the complete removal of nitrate and the end of the denitrification process (arrow "b" in Fig. 3). Anoxic phase-length control was initiated when DO levels fell below 0.5 mg/L to avoid disturbances of the ORP profile by residual oxygen (Pavselj *et al*. 2001; Casellas *et al*. 2006). After a minimum amount of wastewater (= 0.8 L) was fed to the SBR, the anoxic filling phase was terminated whenever 3 consecutive ORP slope changes of less than a threshold value of -50% were detected, or when a maximum amount of wastewater (= 1.6 L) was fed to the reactor (Fig. 2). After the subsequent aerobic phase, a new anoxic filling phase was only initiated if the total volume already fed in the SBR cycle was less than 3.8 L. Since the volume of wastewater added in each filling phase varied between a minimum of 0.8 L and a maximum of 1.6 L (Fig. 2), the number of filling phases ranged from 3 to 5, and the total volume of wastewater added in each SBR cycle ranged from 3.8 L to 5.4 L. In contrast to previous research, this control strategy thus not only affected the duration of the anoxic phases, but also the amount of wastewater added in each phase and the number of filling phases.

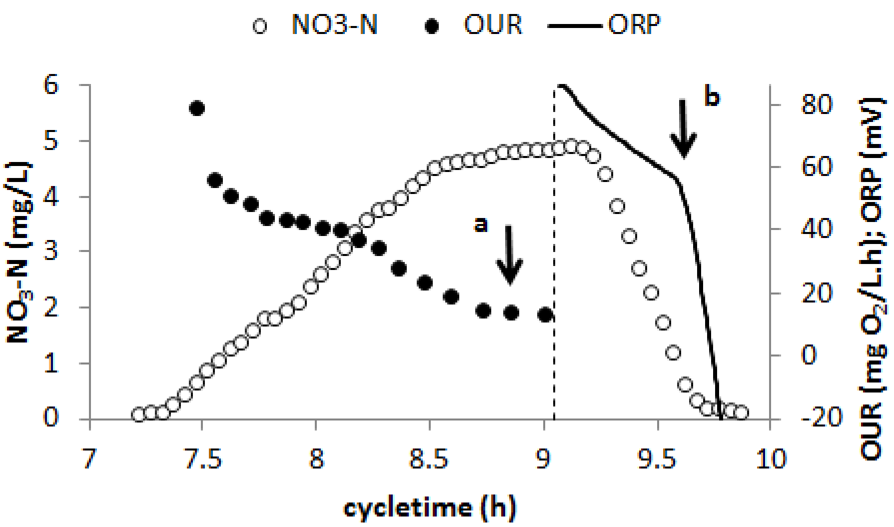

Figure 3 Online nitrate (NO_3-N), OUR and ORP profile for a typical aerobic/anoxic sequence in a cycle of the SBR operating in step-feed mode; the vertical dashed line indicates the shift from the aerobic to the anoxic phase; the arrows a and b designate detectable endpoints for the nitrification and denitrification reactions respectively.

Analyses

Total chemical oxygen demand (COD) and filtered COD (after filtration over a 0.45 µm glass fiber filter) were determined using micro-COD tubes (Hanna Instruments, Belgium). Ammonium (Nessler method), and nitrate (cadmium reduction method) concentrations were determined with standard cuvette tests. MLSS was measured gravimetrically after three consecutive centrifugation/washing cycles to remove the dissolved salts, and drying overnight at 105°C.

RESULTS and DISCUSSION

The lab-scale SBR was fed with the variable ammonia-containing TTC wastewater described in Table 1, and operated dynamically during 80 cycles. Throughout this experimental period, high

COD and nitrogen removal efficiencies were recorded (Fig. 4 and Fig. 5). Effluent COD and nitrogen (N) concentrations were well below Flemish discharge limits for TTC companies, i.e. 500 mg COD/L and 60 mg N/L, at all times (Table 2).

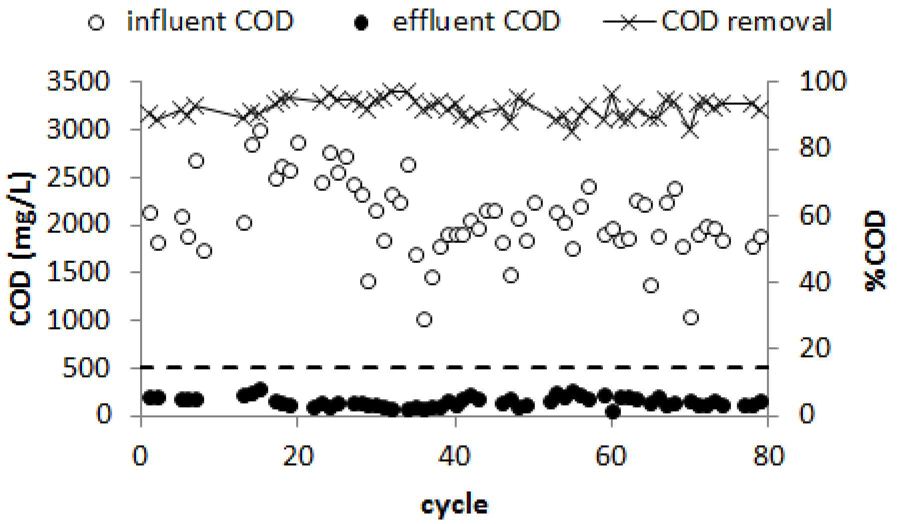

Figure 4 Evolution of influent and effluent COD concentrations and relative efficiency of COD removal from real TTC wastewater in the dynamically operated lab-scale SBR; the horizontal dashed line indicates the discharge limit for COD (500 mg/L).

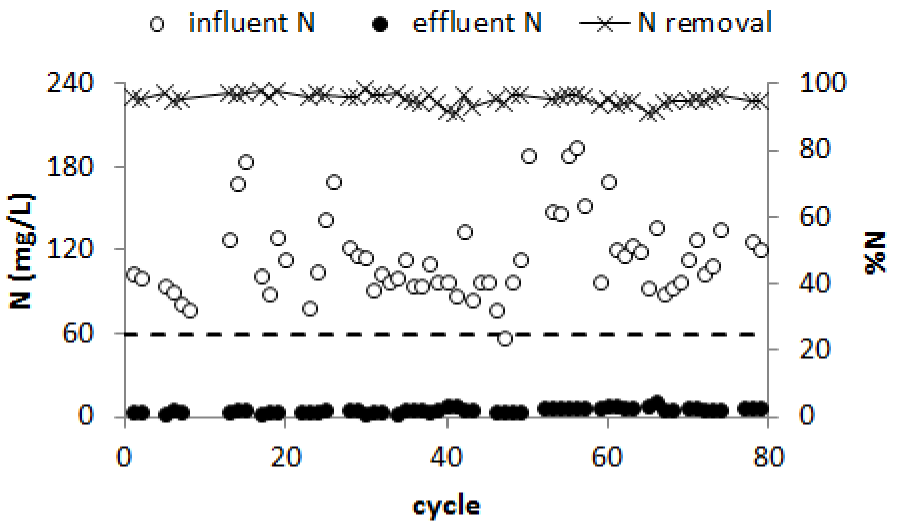

Figure 5 Evolution of influent and effluent N concentrations and relative efficiency of total N removal from real TTC wastewater in the dynamically operated lab-scale SBR; the horizontal dashed line indicates the discharge limit for total N (60 mg/L).

Aerobic oxidation and anoxic denitrification endpoints (illustrated in Fig. 3) were detected successfully in all cycles (results not shown). Previous research reported that the failure to detect denitrification endpoints was mostly due to incomplete denitrification caused by the absence of sufficient biodegradable COD in the influent (Poo *et al*. 2006). In our case, the COD/N ratio in the influent wastewater varied from 9 to 33, implying that there was always enough internal COD present for complete denitrification. The low NO_3-N concentrations measured in the effluent confirm this explanation (Table 2).

Table 2 Average effluent quality and performance of the dynamic SBR treatment process.

Parameter (unit)	Min.	Max.	Avg. ± SD	%CV
Effluent COD (mg/L)	63	283	153 ± 50	33
Effluent NH_4-N (mg N/L)	0.8	7.2	3 ± 1	42
Effluent NO_3-N (mg N/L)	0.7	4.2	2 ± 1	37
COD removal (%)	85	97	92 ± 3	3
N removal (%)	91	98	95 ± 2	2

Activation of the real-time control strategy resulted in variable aeration and anoxic phase lengths as reported by a number of researchers (Yang *et al*. 2010). In these previous studies however, the anoxic phases typically consisted of 2 parts, i.e. a relatively fast filling stage with fixed duration followed by a dynamically controlled anoxic stage without filling (e.g. Casellas *et al*. 2006; Puig *et al*. 2006). In our work the anoxic react phase consisted completely of a filling stage, and we applied a relatively slow filling rate as typical in full-scale SBR installations. As a result, the control strategy not only affected the anoxic phase lengths, but also the amount of wastewater fed during each anoxic phase and the number of filling steps in each cycle. The latter represents an innovative approach not reported before, leading to a true dynamic process (Fig. 6 and Table 3).

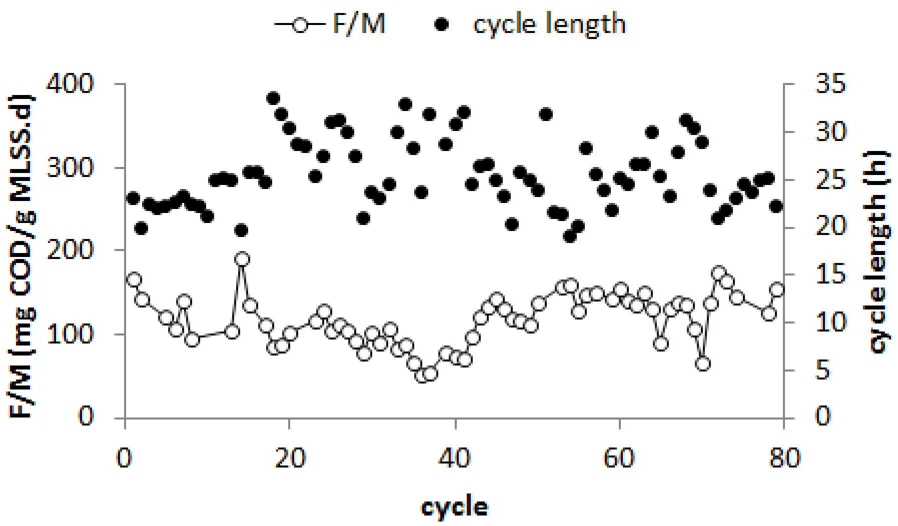

Figure 6 Evolution of the sludge loading rate (F/M ratio) and total cycle length during 80 cycles in the lab-scale SBR dynamically operated in step-feed mode with real variable TTC wastewater.

In the dynamically operated lab-scale SBR, the average COD sludge loading rate (F/M-ratio), nitrogen loading rate (NLR) and volume exchange rate (VER) were more than two times higher than in the full-scale plant operated using a fixed 24h-cycle, while the total cycle length was only about 7% longer (Table 3). Although care should be taken when comparing lab results with full-scale data, these observations suggest that the operational capacity of the full-scale SBR could improve significantly by implementing real-time control strategies: the same amount of wastewater can be treated in a considerably smaller SBR and/or in a significantly shorter period of time in the existing SBR. In any case, real-time control results in a major reduction in unnecessary aeration time and in the associated operational energy costs (Won and Ra 2011).

Table 3 Average operational characteristics of the dynamic SBR treatment process, in comparison to average values for the full-scale SBR.

Parameter (unit)	Min.	Max.	Avg. ± SD	%CV	Full-scale
F/M (mg COD/g MLSS.d)	52	191	119 ± 31	26	50

NLR (mg N/g. MLSS.d)	3	14	7 ± 3	40	3
VER (%)	23	30	26 ± 1	4	12.5
Cycle length (h)	19	34	26 ± 4	14	24

On-line ammonium and nitrate sensors and analyzers are available on the market today, and they can be applied for direct real-time control of biological nutrient removal processes (e.g. Wiese *et al*. 2006; Melidis *et al*. 2014). These instruments are however expensive and require intensive servicing (Marsili-Libelli *et al*. 2008; Yang *et al*. 2010; Amand *et al*. 2013). The cost for an online UV-based nitrate sensor and/or a reliable automated ammonia analyzer range from 15 000 to 20 000 euro each (this is the sensor/analyzer cost only, not including the maintenance costs nor the transmitter), which is significantly higher than the low cost of an industrial ORP sensor of about 200 euro. These numbers illustrate that direct on-line nitrogen monitoring is not a realistic option for control of small wastewater treatment plants in small enterprises, as in the case presented here.

CONCLUSIONS

The result of the dynamic control strategy applied in the current study is a SBR cycle with variable length and variable sludge loading rate, depending on the characteristics of the wastewater (such as nitrogen content) and the activity of the sludge (as indicated by the OUR). Importantly, the implementation of the real-time control strategy had no adverse impact on the efficiency of the biological treatment of TTC wastewater.

The results of the present study indicate that on-line control based on common and cheap sensors is a robust way to implement dynamic processes in industrial activated sludge plants, leading to significant improvements in operational capacity. Moreover, dynamic SBR cycles may play a decisive role in novel mitigation strategies to minimize nitrous oxide (N_2O) emissions from activated sludge plants. Recent finding by Rodriguez-Caballero *et al*. (2015) indeed indicate that the SBR cycle configuration, i.e. the length of aerated and anoxic phases, influences the N_2O emissions.

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