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Application of online instrumentation in industrial wastewater treatment plants – a survey in Flanders, Belgium

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Abstract A survey regarding online instrumentation and control was conducted among 90 companies managing their own biological wastewater treatment plant in Flanders, Belgium. In this study, all types of online instrumentation have been found suitable for automatic process control. However, its integration in general process control as well as in nitrogen removal and chemical dosing control appeared to be rather limited. Only dissolved oxygen and pH sensors were widely applied, being present on 96% and 69% of the plants, respectively. Widespread process integration is mainly obstructed by the fact that companies, especially small and medium-sized, still do not regard wastewater treatment as a full-fledged part of the production process. Operators often lack technical expertise in this domain and tend to be skeptical towards automated control mechanisms. In addition, the price of online instrumentation is still perceived as too high, in particular at smaller companies. Lastly, the design of the existing wastewater treatment plant does not always allow for real-time control. Certain measures such as operator training, monitoring of energy and chemical consumption and reduction of instrumentation costs are essential for a widespread application of online process control in future years. Additionally, water reuse can create an important incentive.

Keywords ICA; industrial wastewater treatment; online instrumentation; process control

Introduction

The implementation of stricter regulations on effluent discharge has created new challenges in wastewater treatment. Whereas in the past often only organic carbon removal was required, nowadays stringent effluent standards demand for extensive nutrient removal as well. As a result, process complexity has increased in the last decades. Moreover, treatment plants have to perform at high removal efficiencies to meet discharge limits at all times. Constantly complying to these high treatment standards is not straightforward since the flow rate and composition of the incoming wastewater are continuously varying, especially in an industrial setting (Bianco *et al.* 2011).

To better cope with these requirements, online monitoring and control of the wastewater treatment process is gaining more and more importance. The process integration of online measurements provides several advantages. Not only does it allow for a more stable plant operation, it also results in a decrease of energy demand, chemical use and other operational costs. The use of online instrumentation increases with increasing process variation and process complexity. Indeed, Olsson (2012) identified process disturbances as the key reason for instrumentation, control and automation (ICA).

In the last decades, a lot of effort is put in the development of new and reliable online instrumentation. 'Simple' online sensors for measuring, e.g., the flow rate, temperature, pH, dissolved oxygen (DO) and suspended solids (SS) are nowadays widely implemented in wastewater treatment (Jeppsson *et al.* 2002). In addition, more complex online sensors and analyzers to measure total organic carbon (TOC), ammonium (NH_4^+), nitrate (NO_3^-) and phosphate (PO_4^{3-}) are becoming less expensive, expanding their application range. An overview of such online measuring equipment for wastewater treatment processes is presented in Vanrolleghem & Lee (2003).

As Jeppsson *et al.* (2002) stated, the sensors as such are no longer the bottleneck for the implementation of online control in wastewater treatment. In this research, the application of online instrumentation in industrial wastewater treatment plants was investigated and possible barriers limiting its widespread implementation were identified.

Data regarding full-scale industrial wastewater treatment are scarce in scientific literature. Therefore, in this study the application of online instrumentation in 90 companies managing their own biological wastewater treatment plant in Flanders, Belgium, was investigated. Flanders is a highly industrialized region that is characterized by a high population density and a low per capita water availability. For these reasons, it is of paramount importance that industrial wastewaters are thoroughly treated before being discharged into the environment.
Firstly, a general description of the studied plants will be given. Then focus is put on the process integration of online measurements in the biological treatment compartment. An overview of the installed sensors is presented and their use for process monitoring and control is identified and discussed. To conclude, key reasons hindering the implementation of online instrumentation in industrial wastewater treatment are indicated.
As such, this study provides a unique view on the current performance of industrial wastewater treatment plants in a region where water quality is an important concern.

Methods

A (non-exhaustive) survey, which included a site visit, was carried out between September 2016 and May 2018 in 90 companies in Flanders managing their own biological wastewater treatment plant. The participating companies were reached through various federations in Flanders (including the federation for food producing companies, breweries, industrial laundries, chemical companies, textile companies, environmental coordinators) and wastewater treatment technology providers to assure a high diversity in the industrial activities of the surveyed companies.

First, a general description of each individual wastewater treatment plant was inquired. In this respect, companies were asked which pollutants (i.e., organic compounds, nitrogen and phosphorus) had to be removed from their wastewater to meet discharge limits and which biological treatment system had been installed to this purpose. Presence of a pretreatment, posttreatment and/or sludge treatment step was questioned, as well as if the effluent was completely discharged or (partly) reused.

Furthermore, surveyed companies were asked to what extent the performance of the plant was monitored. The availability of a designated operator responsible for daily follow up was assessed as well as the frequency of influent and effluent monitoring and the regular evaluation of energy and chemical consumption of the treatment plant. Additionally, operators were queried about incoming flow rates, loads, removal efficiencies and the main problems encountered when managing the plant.

Finally, focus was put on online monitoring and control of the biological treatment step. Companies were asked which sensors were installed and if they were integrated in process control, implemented for monitoring only or perhaps not used at all. As for process control, a distinction was made between online instrumentation for automatic and for manual control. The former implies that the sensor is used for automatically controlling the process, such as the pumping rate of an acid/base dosing pump, whereas the latter requires the intervention of an operator, e.g., for adjusting the waste sludge rate manually.

Results and Discussion

General description of surveyed plants

In 2016, there were 345 industrial biological wastewater treatment plants operational in Flanders (Flemish Environment Agency 2016). Food processing companies accounted for 50% of these plants, including meat (17%), vegetable (10%), general food (7%) companies, breweries (7%), dairy firms (5%) and bakeries and chocolate factories (3%). Other plants were installed at chemical (20%), tank cleaning (9%), textile (6%), waste processing (5%), pharmaceutical (2%) companies and industrial laundries (1%).

In the presented survey, 90 (26%) of the operational biological treatment plants in Flanders were covered. Of all companies included in the survey, 48% can be considered as small and medium enterprises (SME) as they had less than 250 employees. Figure 1 gives an overview of the industrial activities of the companies at which the plants were operational. Most enterprises were food processing companies (56%), especially active in the meat and vegetable processing industries. Other food processing companies included in the survey were general food producing plants, bakeries and chocolate factories, breweries and dairy firms. Next to food processing, the study investigated chemical (19%), textile (8%), waste processing (7%), tank cleaning (4%), pharmaceutical (4%) and industrial laundry (2%) enterprises.
These numbers indicate that the distribution of the industrial activities covered in the study was similar to those of all companies in Flanders operating a biological wastewater treatment plant.

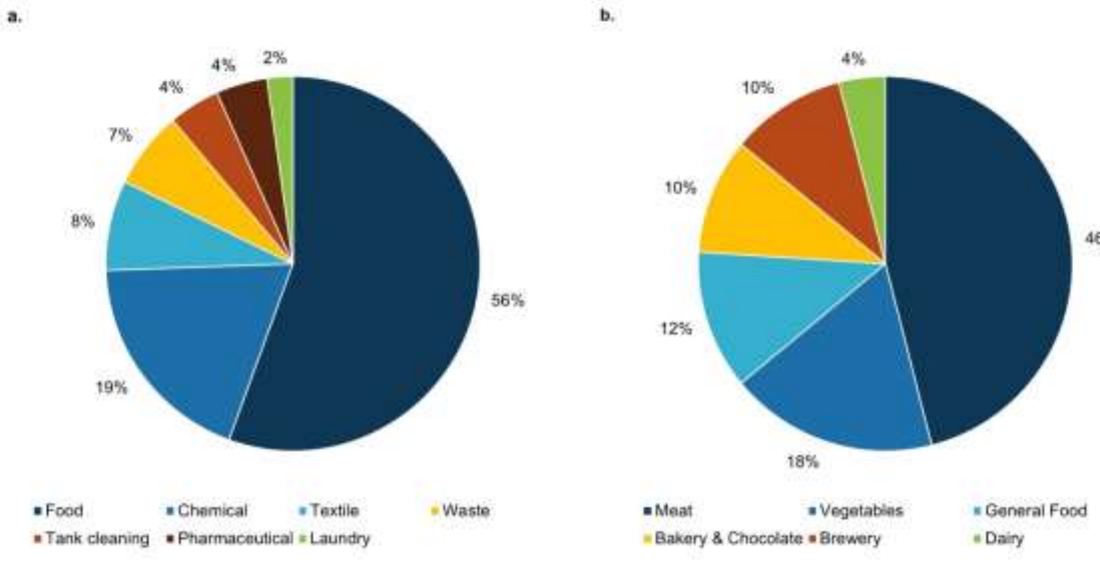

Figure 1 Overview of industrial activities involved in the survey (a. all industries, b. food processing companies).

Table 1 represents a general overview of the different plants involved in the study. Most companies (99%) had to remove organic compounds, expressed as chemical oxygen demand (COD), from their wastewater, whereas nitrogen and phosphorus removal was not always required (it was required in 64% and 42% of the cases, respectively). In those companies, nutrient removal due to biological assimilation was sufficient to meet effluent discharge limits. Moreover, the addition of a nitrogen (e.g., urea) and phosphorus source (e.g., phosphoric acid) was required in 20% and 27% of the treatment plants, respectively. As for phosphorus removal, it must be noted that none of the plants included a treatment step for enhanced biological phosphorus removal. The removal of phosphorus was achieved by conventional biological assimilation and physicochemically, i.e., by the addition of chemicals such as iron chloride or aluminum chloride. It was noted that especially the wastewater from meat and vegetable processing companies demanded nutrient removal.

In 72% of the industrial plants a pretreatment step was installed, such as a physicochemical (FC) (mainly dissolved air flotation) or an anaerobic (upflow anaerobic sludge blanket (UASB) reactors) treatment step. Other pretreatment systems included lamella separators, fat & grease traps, grit chambers, pre-settlers etc. Some plants were equipped with a combination of these pretreatment steps. As for the biological treatment compartment, the conventional activated sludge with settler (CASS) and sequencing batch reactor (SBR) systems were most present. Other biological treatment systems included the conventional activated sludge with flotation unit (CASF), UNITANK® and membrane bioreactor (MBR) systems. Of all plants, 31% were accommodated with a posttreatment step, mainly sand (26%) and activated carbon (10%) filters, and 64% were equipped with a sludge dewatering facility. Most enterprises were discharging all of their wastewater, whereas only 28% of the companies reused part of their effluent in the production process, e.g., for cleaning purposes. In several companies, reuse of the effluent required further treatment such as ozonation and chlorination. The highest percentage of enterprises with reuse was seen at vegetable processing companies (56% of companies). However, water reuse as a food ingredient was not encountered.

It must be noted that not all companies had data available on the treatment performance of their wastewater plant. Out of the 90 companies covered in the survey, 4% did not follow up the volume of water to be treated daily. Furthermore, several influent parameters were never measured: COD was never measured in 33% of the companies, SS in 75%, total nitrogen (TN) in 39% and total phosphorus (TP) in 47%. Also, 23% of the surveyed companies did not measure the sludge concentration in the biological reactor. Effluent concentrations were at least monitored yearly in all companies discharging to surface water, since this is imposed by the Flemish government (VLAREM II, art. 4.2.5.2.1 1995).

As for the consumption of chemicals and energy, the lack of data was even more pronounced. Only 23% of the enterprises dosing iron chloride for phosphate removal knew the specific iron chloride dose applied. Moreover, only 23% and 17% of the surveyed companies monitored the energy consumption of respectively the total wastewater treatment plant and the biological treatment step.

Due to this lack of monitoring, companies are usually unaware if discharge limits are continuously met. However, in Flanders, companies discharging to surface water are audited only once a year by the government, during a short measurement campaign of a few consecutive days. In this way, fines are generally avoided and companies do not feel obliged to monitor their wastewater treatment plant more frequently.

Table 1 General overview of the number and type of industrial wastewater treatment plants covered in the survey.

		Meat		**Vegetable**		**Other Food[a]**		**Chemical**		**Textile**		**Other[b]**		**Total**	
# of plants		23		8		18		17		7		16		90	
		#	%	#	%	#	%	#	%	#	%	#	%	#	%
Removal	COD	23	100	9	100	18	100	17	100	7	100	15	94	89	99
	N	21	91	9	100	6	33	7	41	4	57	11	69	58	64
	P	16	70	9	100	6	33	5	29	1	14	1	6	38	42
Pre-treatment	FC	16	70	0	0	8	44	7	41	0	0	7	44	38	42
	UASB	0	0	7	78	2	11	0	0	0	0	0	0	9	10
	Other	5	22	6	67	5	28	10	59	0	0	8	50	34	38
Biological treatment	CASS	2	9	7	78	5	28	8	47	6	86	2	13	30	33
	CASF	7	30	0	0	1	6	2	12	0	0	3	19	13	14
	SBR	14	61	2	22	5	28	2	12	0	0	8	50	31	34
	UNITANK	0	0	0	0	4	22	4	24	1	14	0	0	9	10
	MBR	0	0	0	0	3	17	1	6	0	0	3	19	7	8
Posttreatment		3	13	7	78	1	6	5	29	3	43	9	56	28	31
Sludge dewatering		15	65	5	56	13	72	13	76	4	57	8	50	58	64
Reported problems	None	9	39	5	56	3	17	3	18	3	43	5	31	28	31
	Foam	3	13	1	11	8	44	5	29	2	29	4	25	23	26
	Settling	6	26	1	11	7	39	9	53	3	43	6	38	32	36
	Discharge limits	12	52	4	44	11	61	9	53	2	29	6	38	44	49
	Odor	1	4	0	0	1	6	4	24	0	0	0	0	6	7
Reuse		5	22	5	56	3	17	4	24	1	14	7	44	25	28

[a] other food companies include general food processing companies, dairy factories, bakeries and chocolate producing enterprises and breweries

[b] other companies include waste processing, tank cleaning, industrial laundry and pharmaceutical companies

Table 2 provides an overview of the overall plant performances. The reported removal efficiencies were comparable to those of municipal wastewater treatment plants (Gallego *et al*. 2008; Kumar *et al.* 2010; Özkan *et al.* 2012; Zorpas *et al.* 2010). Remarkable is, however, that only 31% of the surveyed companies declared to never have difficulties managing their treatment process. Of all surveyed companies, 49% reported having difficulties meeting effluent discharge limits for at least one parameter at all times. Especially sludge bulking and foaming are commonly known as important operating problems, resulting in poor plant performance (Jenkins *et al.* 2003), which was confirmed in this survey: 36% and 26% of the companies reported problems with sludge settling and foaming, respectively.

Table 2 Overview of the flow, influent load and removal efficiencies of the surveyed companies.

Parameter	Range	Mean	Median
Flow (m^3/d)	7 - 18250	1060	326
COD load (kg COD/d)	33 - 25240	3612	1197
COD reduction (%)	31.3 – 99.8	94.2	97.8
SS load (kg SS/d)	1 - 29200	2955	136
SS reduction (%)	30.5 – 99.8	89.2	97.6
TN load (kg TN/d)	1 - 1170	122	43
TN reduction (%)	32.5 - 98.4	86.9	92.2
TP load (kg TP/d)	0 - 484	33	4
TP reduction (%)	0 - 99.8	87.2	92.9

Dissolved oxygen and nitrogen removal control

Sensors

Obviously, the dissolved oxygen concentration is an important parameter for process control of the biological wastewater treatment. Sufficient oxygen is required for the biological decomposition of organic compounds and the conversion of ammonia (Metcalf & Eddy 2003). However, since the aeration system is the main energy consumer (Rosso *et al.* 2008), aeration control is of paramount importance in terms of energy savings. Nowadays, most aeration systems are therefore equipped with controllers for adjusting the oxygen concentration in the aerobic reactors. Based on a survey in 13 European countries, Jeppsson *et al.* (2002) concluded that this control system was by far the most common type of real-time control applied in wastewater treatment plants. A more recent overview of aeration control can be found in Åmand *et al.* (2013).

The development of nitrogen sensors/analyzers allows for an extension of the conventional DO control by continuously determining the amount of oxygen required for nitrogen removal. For instance, Ingildsen *et al.* (2002) reported aeration energy savings of 5 to 15% in a full-scale pre-denitrification plant by controlling the dissolved oxygen setpoint based on online ammonium measurements.

Next to nitrogen sensors/analyzers, the implementation of sensors measuring the oxidation reduction potential (ORP) is gaining more attention as a control parameter for nitrogen removal as well. The end of denitrification is indicated by a change in the ORP profile, known as the 'nitrate knee' (Dries 2016). Furthermore, the end of nitrification can be identified by a change in the first order derivative of the pH value, called the 'ammonia valley' (AI-Ghusain *et al.* 1994). Therefore, a dual control strategy based on both the pH and ORP profile can be set up for nitrogen removal (Kim & Hao 2001). This control strategy has mainly been investigated in sequencing batch reactors and intermittently aerated continuous systems (Tanwar *et al.* 2008; Won & Ra 2011), but its implementation has been studied in continuous reactors as well (Ruano *et al.* 2012).

Figure 2a provides an overview of sensors used for DO and nitrogen removal control (i.e., DO, ORP, NH_4^+ and NO_3^-) in the biological reactor of the surveyed plants. The number of DO sensors is given as a percentage of all companies, whereas the other sensors are given as a percentage of plants in which nitrogen removal is required (58 companies, see Table 1). Almost all plants (96%) were equipped with a DO sensor, but the application of online ORP, ammonium and nitrate instrumentation was much less prevalent. Their use in process control is shown in Figure 2b.

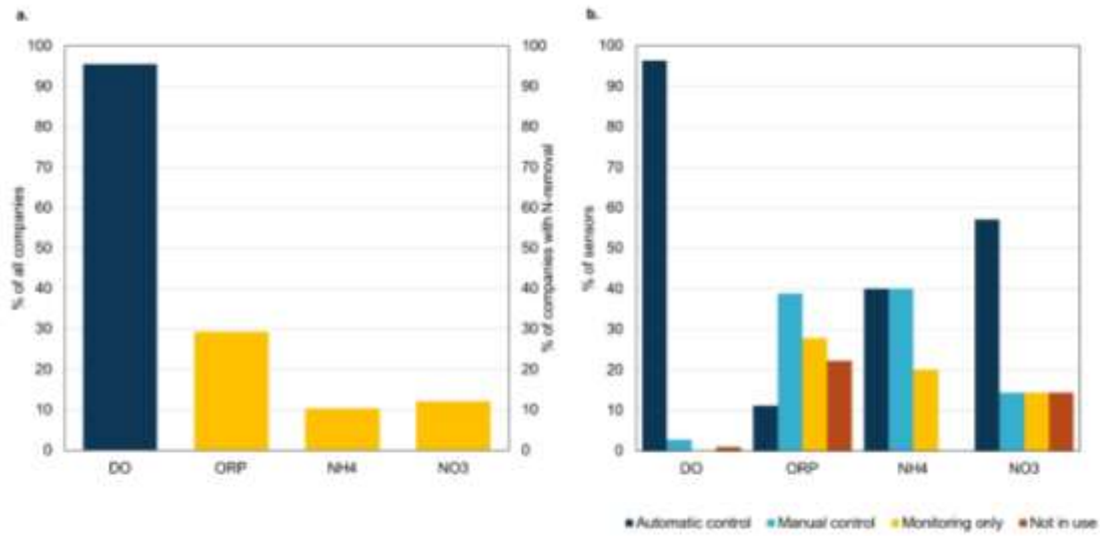

Figure 2 Overview of presence (a.) and use (b.) of online instrumentation installed on the wastewater treatment plants for dissolved oxygen and nitrogen removal control. In the left-hand figure, the number of DO sensors is given as a percentage of all companies, whereas the ORP, NH_4^+ and NO_3^- sensors are given as a percentage of plants in which nitrogen removal is required. In the right-hand figure, all sensors are expressed as a percentage of the total number of sensors.

The total number of DO sensors installed was 112. Almost all these sensors (96%) were implemented for automatic DO control. The implemented control mechanisms were either frequency controllers (54%) or on/off controllers (46%), depending on the aeration system. Next to automatic control, 3 of the sensors were used for manually setting the aerators and 1 sensor was not used at all.

As for nitrogen removal, there were respectively 17, 5 and 7 sensors/analyzers installed for measuring the ORP, ammonium concentration and nitrate concentration in the biological tank. More specifically, there were 2 analyzers with a gas-sensitive electrode and 3 sensors with an ion-selective electrode in use for the online measurement of the ammonium concentration. Out of the 7 sensors for measuring the nitrate concentration, 4 were based on UV absorption and 3 sensors made use of an ion-selective electrode.
Only 2 (11%) ORP sensors automatically controlled the nitrogen removal process (aeration or carbon source dosing control). There were 7 sensors (39%) in use for manual control, whereas a striking 50% of the sensors available were not integrated in process control.
Out of the 5 ammonium analyzers, 2 were used to automatically control the aeration, 2 of the analyzers were used for manually setting the aeration and 1 was used for monitoring only. As for the nitrate sensors, 3 of them were applied to automatically control the aeration, whereas 1 was used for an automatic control of the nitrate recirculation flow. In addition, 1 nitrate sensor was used for manually adjusting the aeration, 1 was used for monitoring only and 1 was not in use.

Besides, there was 1 ammonium analyzer positioned in the effluent, which was used for automatically controlling N-source dosing in the biological compartment.

Aeration systems

The aeration was provided by surface aerators, submerged aeration systems and fine bubble aerators in 24%, 41% and 46% of the industrial wastewater treatment plants, respectively (some plants had two different aeration systems). Although surface aerators are the least efficient aeration systems regarding oxygen transfer of the three systems (Metcalf & Eddy 2003), they are still widely implemented in industrial wastewater treatment, often for reasons other than oxygen transfer efficiency (e.g., price, ease of installation and cool down effect).

Data on energy consumption were rather limited: only 10 plants with COD removal and 5 plants with N removal had energy data available. Consequently, no conclusions could be drawn with regard to the energy efficiency of the aeration systems implemented in the surveyed plants.

The energy consumption for all 15 plants was 2.11 ± 1.22 kWh per m^3 of treated water. This energy consumption is much higher than the energy required in CAS installations treating municipal wastewater in Flanders (0.3 kWh/m^3), as reported by Fenu *et al*. (2010). However, this is to be expected since the pollutant loads of industrial wastewaters are much higher as well. The energy consumption in plants with only COD removal ranged from 0.73 to 1.69 kWh/kg COD, with a mean value of 1.22 ± 0.34 kWh/kg COD. As for plants dealing with COD and nitrogen removal, the energy consumption varied between a minimum and maximum of 0.66 and 4.04 kWh/kg O_2, respectively. In the latter case, the energy consumption was expressed as oxygen required for COD removal and for nitrogen removal, i.e., nitrification (+4.57 kg O_2/kg N) and denitrification (-2.86 kg O_2/kg N), yielding a net oxygen requirement of 1.71 kg O_2/kg $N_{removed}$.

Chemical dosing control for phosphorus removal

The development of phosphate analyzers has greatly improved the control of chemical dosing for phosphate removal. By continuously determining the amount of iron chloride required for phosphate precipitation, excess chemical consumption and sludge production can be avoided (Devisscher *et al.* 2002).

In this survey, 7 out of the 38 industrial wastewater treatment plants requiring phosphorus removal were equipped with an online phosphate analyzer. In these 7 companies, phosphate was precipitated by the addition of iron chloride in the biological tank. All analyzers took samples from the biological tank or from the effluent. Iron chloride dosing was done automatically in 6 of the plants, whereas the analyzer was used for manually controlling iron chloride dosing in 1 plant. In addition, there were 2 analyzers installed that were used for controlling P-source dosing in the biological tank.

In theory, 1 mole Fe^{3+} is needed to precipitate 1 mole of orthophosphate. However, the iron chloride consumption per amount of phosphorus to be removed in the surveyed companies ranged from 1.00 to 3.91 mole Fe^{3+}/mole P, with a mean value of 1.91 ± 0.93 mole Fe^{3+}/mole P. It must be noted, however, that data on iron chloride consumption were only available in 8 out of the 35 plants dosing iron chloride for phosphorus precipitation (the other 3 companies requiring phosphorus removal where dosing polyaluminumchloride).

pH control

Of all treatment plants, 69% were equipped with a pH sensor (Figure 3a). Their use in process control is shown in Figure 3b. In total, there were 85 pH-sensors installed on the plants (some plants had more than one pH-sensor). Of these 85, 26 (31%) were installed on the influent flow to the biological treatment compartment, 47 (55%) in the biological tank and 12 (14%) on the effluent. It appeared that mainly the sensors installed in the influent were used for an automatic pH correction (65% of the sensors), whereas this was rather limited for the sensors present in the biological tank (21%) and in the effluent (8%). The sensors positioned in the biological tank were generally used for monitoring (40%) or not used at all (34%). Operators reported that pH control was usually not required because of limited pH variations in the biological tank. pH sensors that were placed in the effluent were mainly used for monitoring before discharging (92%).

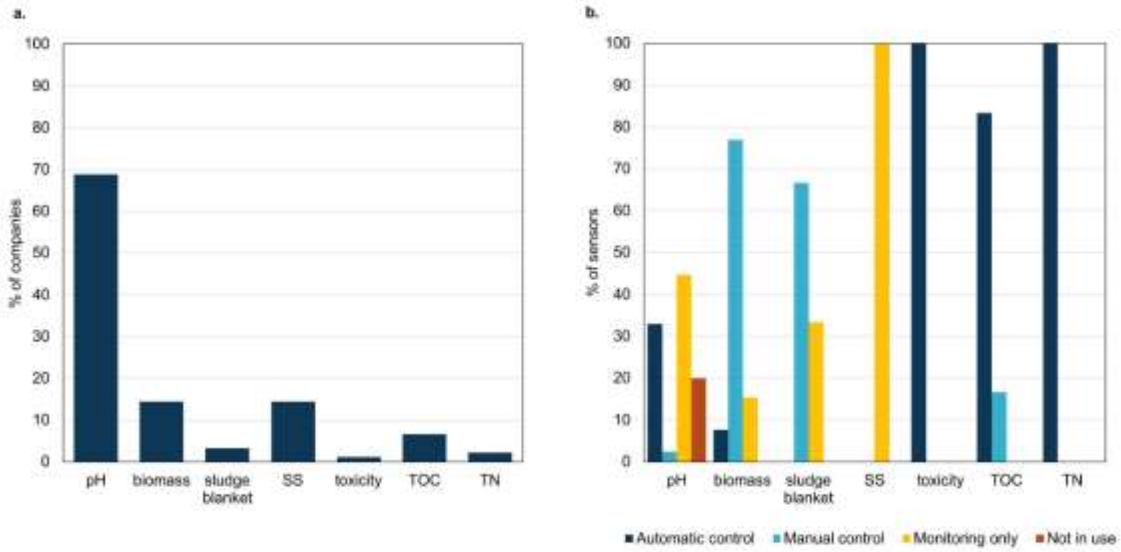

Figure 3 Overview of presence (a.) and use (b.) of online instrumentation installed on the wastewater treatment plants for pH control, sludge concentration/level control and other online instrumentation.

Sludge concentration/level control

Online instrumentation that is implemented for this purpose, includes sensors to measure the biomass concentration, the sludge level and the concentration of effluent suspended solids.

Of all treatment plants, 14%, 3% and 14% were equipped with a sensor to measure the biomass concentration, the sludge level and the concentration of effluent suspended solids, respectively. Their presence and use are shown in respectively Figure 3a and Figure 3b. As for sludge related parameters, 13 online sensors were installed in the biological tank for determining the biomass concentration and 3 sensors were applied in the settler to measure the sludge blanket. These sensors were mainly (77% and 67%, respectively) used for manually setting the sludge waste flow rate.

There were 14 sensors installed for online measurement of the effluent suspended solids concentration, which were all used for monitoring the effluent quality before discharge.

Other online instrumentation

Other online instrumentation included online analyzers for measuring the toxicity, the total organic carbon concentration (TOC) and total nitrogen concentration (TN). The principle of the toxicity measurement is based on the respiration rate of the sludge. When the respiration rate drops significantly

after exposure to an influent wastewater sample in comparison to a reference sample, the microorganisms are inhibited, implying that the influent is slowly biodegradable or even toxic (Oviedo *et al.* 2009).
It must be noted that all of these analyzers were installed at industrial wastewater treatment plants of large companies. Their presence and use are shown in Figure 3a and Figure 3b, respectively.

There were respectively 1, 5 and 2 online analyzers installed for measuring the toxicity, TOC and TN concentration, all located in the influent stream. All these measurements automatically controlled the flow rate of the incoming wastewater to the biological treatment compartment. As for the toxicity analyzer, the flow rate of toxic influent was reduced automatically to avoid microbial inhibition. The TOC and TN analyzers controlled the flow rate so that a constant load was maintained and overload of the system was avoided.
Furthermore, there was 1 TOC analyzer installed in the effluent, which was used for manual control of carbon-source dosing in the biological tank.

Reasons limiting the implementation of online monitoring and control

Although online monitoring and control allows for maintaining high treatment performance at the lowest operational costs, its implementation in industrial wastewater treatment plants in Flanders was found to be rather limited. Based on this survey, following key factors hindering its widespread application could be indicated.

One, if not the most, important reason was that wastewater treatment is not seen as a core activity of the production process. Companies still consider it as an inevitable operational cost, which is often small in comparison to those of the production unit. As long as discharge limits are met and fines are avoided, no use is seen in investing time and money to upgrade the wastewater treatment plant.
As wastewater treatment is no core business, treatment performance is hardly monitored. Operators are commonly only technically educated and, in many companies, no sufficient training regarding wastewater treatment processes is provided. This lack of knowledge is especially the case in small and medium sized enterprises. Besides, since every industrial treatment plant has its own specific characteristics, process knowledge is usually built up through years of experience by individual operators. Often this operational experience is not properly recorded. In addition, during site visits it became clear that operators are rather skeptical towards implementing automated control strategies. They are concerned that measurement errors will lead to process disturbances and therefore prefer manual control. The importance of the ‘human factor’ was also pointed out by Rieger & Olsson (2012).

Secondly, efficient control strategies ask for reliable measurements. All types of online instrumentation have been proven to be adequate for automatic process control. However, reliable measurements require thorough maintenance and calibration. In a striking 28% of the companies maintenance of the sensors was insufficient, leading to unreliable measurements. This poor maintenance was often attributed to either lack of time or operator unawareness of the measurement errors and the need for maintenance.

In addition, it was commonly reported, especially by smaller enterprises, that online instrumentation prices are still too high. Indeed, in this survey, only large companies were equipped with the more expensive online measurements such as TOC, nitrogen and phosphorus analyzers.
As operational costs of the treatment plant are often small in comparison to those of the production process, profits are negligible. A cost-benefit analysis will only show limited benefits in this case, such that the investment cost is considered too high or the return on investment too long. In smaller

companies, however, when effluent discharge limits are regularly exceeded, an incentive for process optimization is created.
Finally, in some cases the existing wastewater treatment plant is just not designed for real-time control. Jeppsson *et al.* (2002) state that this is probably the most fundamental barrier. Indeed, conducting this survey, it was often noticed that the actuator (e.g., the blower) could not be optimally controlled because of its design (mostly over-dimensioned).

According to the authors, following measures are essential for a widespread application of online instrumentation and control on industrial wastewater treatment plants in future years.

- **Operator training**: only when operators fully understand the wastewater treatment process, they will recognize the benefits of online process control and the necessity of sensor maintenance. In smaller companies, where dedicated wastewater treatment personnel is more sparse, operation of the treatment plant might be outsourced to external service providers.
- **Data on energy and chemical consumption**: as became clear during this survey, many companies lack data on energy and chemical consumption of the wastewater treatment plant. When there is no data available, it is difficult to quantify savings. In many companies, the return on investment is positive. However, since companies lack data and straightforward calculation tools to quantify the savings, the extent remains unclear.
- **Reduction of online instrumentation costs**: in companies with limited discharge volumes, the investment cost of more expensive online instrumentation such as TOC and nutrient analyzers is often considered too high, especially if the cost is expressed as €/m^3. Therefore, a more widespread implementation of online control, in large as well in small and medium-sized companies, demands for a reduction of instrumentation costs.
- **Proof of alternative control strategies based on low-cost sensors**: the implementation of control strategies based on low-cost sensors offers an interesting alternative for the more expensive instrumentation, especially in companies with limited discharge volumes. The performance of control strategies for, e.g., nitrogen removal based on low-cost sensors such as DO, ORP and pH sensors on lab-scale installations has been proven in the past (Dries 2016; Ruano *et al.* 2012; Tanwar *et al.* 2008; Won & Ra 2011). However, there is a need for proof-of-concept of these strategies on full-scale industrial wastewater treatment plants.
- **Regulation**: nowadays, companies discharging to surface water in Flanders are audited only once a year by the government, during a short measurement campaign (few days). If the compliance with discharge limits would be checked more frequently, the need for continuously meeting effluent limits would increase even further. Hereby, an extra incentive for online wastewater treatment control would be created.
- **Integrating online control in the design phase**: in some cases, the wastewater treatment plant was not designed for online control strategies. It is therefore crucial that real-time control is integrated in the design phase of the plant.

In addition, water reuse might be an important incentive for ICA in future years. Indeed, some of the surveyed companies (including SME) did show an interest in reuse of wastewater in their production process to reduce water bills or because the supply of fresh water had been restricted by the government. In Flanders, the price of fresh water ranges from 1 to 4 euro per m^3. For water reuse, it becomes even more important that an excellent water quality is assured at all times. Moreover, since water reuse allows for a reduction of freshwater expenditures, the implementation of online instrumentation becomes economically feasible, even at companies with limited discharge volumes.

Conclusions

A survey on process monitoring and control was conducted among 90 companies managing their own biological wastewater treatment plant in Flanders, Belgium. Apart from dissolved oxygen (available in 96% of the wastewater treatment plants) and pH (69% of the plants), the integration of online instrumentation for general process control as well as for nitrogen removal and chemical dosing control appeared to be rather limited.

Based on this research, the principal barriers limiting the widespread application of online instrumentation and control in industrial wastewater treatment plants can be summarized as follows.
First and foremost, wastewater treatment processes are still not considered as a core activity of the production process, especially in small and medium sized companies. This lack of engagement results in a lack of well-trained operators who are therefore often rather skeptical towards implementing new control mechanisms and are unaware of the importance of sensor maintenance.
Secondly, since operational costs of the treatment system are low in comparison to those of the production process, savings are negligible as well. Because of this, investment costs are generally considered too high, certainly in smaller companies where profits are limited.
Lastly, the design of the existing wastewater treatment plant did not always allow for real-time control.

According to the authors, following measures are essential for a widespread application of online instrumentation and control on industrial wastewater treatment plants in future years.

- Operator training
- Availability of data on energy and chemical consumption
- Cost reduction of online instrumentation
- Proof of alternative control strategies based on low-cost sensors
- Law enforcement
- Integrating online control in the design phase

In addition, water reuse might be an important incentive for ICA in future years.

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