Process auditing and performance improvement in a mixed wastewater–aqueous waste treatment plant
Maria Cristina Collivignarelli, Giorgio Bertanza, Alessandro Abbà and Silvestro Damiani

ABSTRACT
The wastewater treatment process is based on complex chemical, physical and biological mechanisms that are closely interconnected. The efficiency of the system (which depends on compliance with national regulations on wastewater quality) can be achieved through the use of tools such as monitoring, that is the detection of parameters that allow the continuous interpretation of the current situation, and experimental tests, which allow the measurement of real performance (of a sector, a single treatment or equipment) and comparison with the following ones. Experimental tests have a particular relevance in the case of municipal wastewater treatment plants fed with a strong industrial component and especially in the case of plants authorized to treat aqueous waste. In this paper a case study is presented where the application of management tools such as careful monitoring and experimental tests led to the technical and economic optimization of the plant: the main results obtained were the reduction of sludge production (from 4,000 t/year w.w. (wet weight) to about 2,200 t/year w.w.) and operating costs (e.g. from 600,000 €/year down to about 350,000 €/year for reagents), the increase of resource recovery and the improvement of the overall process performance.

INTRODUCTION
The performance of wastewater treatment plants (WWTPs) is often a significant issue, mainly due to technical and operational deficiencies. In many cases, structural upgrades are applied in order to solve plant problems: this approach often involves high capital costs, sometimes without effect. However, it is important to provide management actions, firstly through intensive monitoring aimed at: (i) complying with the effluent discharge limits, (ii) calculating the removal yields of pollutants, (iii) providing information on the health of the biomass, (iv) maintaining the correct operating parameters. Afterwards, experimental tests (both at laboratory and in-situ scales) should be conducted with the aim of identifying any weaknesses and optimizing the process. In this regard, the methodological approach reported by Sorlini et al. (2015) for drinking water treatment facilities may also be suggested for WWTP performance optimization, thus leading to increasing the pollutant removal efficiency and simultaneously reducing the operating costs.

This approach is particularly important in the case of municipal WWTPs with a significant industrial input. The characteristics of industrial wastewater change not only according to the manufacturing sector, but also within the same sector. This aspect is more pronounced for industrial than municipal wastewater, that usually maintains qualitative and quantitative homogeneous characteristics (Oller et al. 2013). Moreover, in the case of plants that receive an additional load of aqueous waste, this aspect is even more crucial. Aqueous waste can be treated in typical WWTPs (Renou et al. 2008), or in dedicated plants, typically after a series of chemical-physical pre-treatments, such as coagulation, flocculation, neutralization and advanced chemical oxidation (De et al. 2006; Gonzàles et al. 2008; Martins et al. 2011; Covinich et al. 2014; Hermosilla et al. 2014; Mohapatra et al. 2014; Muruganandham et al. 2014; Collivignarelli et al. 2015a, 2015b). Also, the plants that treat aqueous waste clearly differ from conventional systems in that they
receive many different influent streams (with a consequent variability of qualitative and quantitative characteristics) and are equipped with many processes (chemical and biological) variously interconnected.

The treatment of aqueous waste commonly requires advanced chemical (Oller et al. 2010; Bustillo-Lecompte & Mehrvar 2016; Klancar et al. 2016) and biological (Oller et al. 2010; Collivignarelli et al. 2014, 2015a) processes and often their combination (Bertanza et al. 2011; Ganiyu et al. 2015; Bustillo-Lecompte & Mehrvar 2016; Dehghani et al. 2016), particularly when the effluent quality must meet the standards for discharge into surface water bodies (Brucculeri et al. 2005; Castro et al. 2014; Collivignarelli et al. 2014; Collivignarelli et al. 2015a, 2015b).

This case study highlights how, through careful and smart management (achieved by adopting monitoring plans and performing experimental tests), it is possible to maximise the treatment capacity of a plant.

MATERIALS AND METHODS

Treatment plant description

The plant studied (in northern Italy) is divided into three operating units (OUs), as shown in Figure 1. Operating unit 1 (OU I) encompasses all the initial operations on both aqueous waste and sewage. In particular: industrial aqueous waste is received by truck, weighed, analytically checked and stored; urban aqueous waste, delivered by truck as well, is weighed and mechanically pre-treated (coarse grilling, uplift, fine grilling, sand/oil separation, sieve and pre-treated sand storage); sludge delivered (by truck) from other WWTPs is weighed; urban sewage undergoes the same mechanical pre-treatments as the urban aqueous waste.

Operating unit 2 (OU II) consists of: chemical/physical treatment of aqueous waste (coagulation with FeCl₂; neutralization with Ca(OH)₂; flocculation with anionic polyelectrolyte dosage; sedimentation and chemical/physical sludge extraction), biological activated sludge treatment of the pre-treated aqueous waste + sewage mixture (pre-denitrification, oxidation-nitrification with air insufflation, final sedimentation and sludge extraction, and disinfection) and receiving water body discharge. The activated sludge process consists of two main lines (called ‘line 1’ and ‘line 2’), divided in turn into secondary lines also operating in parallel.

Finally, operating unit 3 (OU III) provides the treatment of the sludge produced in the previous compartments and consists of: thickening (one, with cationic polyelectrolyte dosage, for the treatment of the biological sludge; one for the chemical/physical sludge), mechanical dewatering (two separate units for the treatment of the biological and chemical/physical sludge, respectively) and sludge storage.

Analytical methods

Chemical oxygen demand (COD), total nitrogen (TN) and ammonia (NH₄⁺) were measured at the inlet of the plant. At the outlet of the plant, BOD₅, COD, NH₄⁺, total suspended solids (TSS) and volatile suspended solids (VSS) were measured. COD and NH₄⁺ were also measured at the inlet of OU II.
Ammonia uptake rate (AUR) tests were carried out on the sludge leaving the oxidation-nitriﬁcation process, three times a week, in order to analyse the nitrifying bacteria activity. All samples were analysed according to official standard methods.

OPERATING CONDITIONS BEFORE IMPROVEMENTS

Operating unit I (waste inlet)

Daily monitoring (lasting approximately one year) showed that the weekly volume of aqueous waste, subjected to the pre-treatments, had a signiﬁcant variability, from a minimum of 360 to a maximum of 2,350 m³/week. The same evaluation can be done for the load of COD at the outlet of the pre-treatment station, ranging from 7,000 kg/week to about 55,000 kg/week.

Finally, the COD removal efﬁciency was variable, but typically greater than 30% with peaks of over 70%.

Operating unit II (activated sludge process)

Table 1 shows the inﬂuent loads of COD and ammonia to the activated sludge process, highlighting the contribution due to urban sewage. The inﬂuent loads refer to the above-mentioned monitoring year, divided into quarters. As we can see the latter is much less signiﬁcant than the total, whereas the contributions of aqueous waste and sludge are very signiﬁcant.

Instead, the daily average concentrations of inﬂuent COD and BOD₅ were quite low and only in the 4th quarter were the discharge limits were occasionally exceeded; TSS concentrations were signiﬁcantly lower than the regulatory limit, while TN concentrations were generally quite low (<20 mg/L), even if very high values were sometimes observed. Ammonia showed inﬂuent concentrations lower than the discharge limit (15 mg/L), despite the peaks recorded in the inﬂuent. Finally, for nitrate and nitrous nitrogen, very low concentrations were observed, due to the high efficiency of the denitriﬁcation process.

The average removal yield of the organic substances was, for each investigated period, greater than 90% while the ammonia average removal yield showed a progressive decline; the lowest value was obtained in the last quarter, corresponding to an increase in the F/M ratio (0.18 kgCOD/(kgTSS*d)): Figure 2(b).

Even the results of the AUR tests carried out on sludge from both oxidation-nitriﬁcation lines (Figure 2(a) highlights the average trend of the two lines) showed that the lowest values occurred precisely in the last quarter of plant operation (October–December). The decrease of AUR values could be due both to a higher organic load value (with the reduction of the nitrifying bacteria fraction) and to the presence of inhibiting substances in the aqueous waste.

We must note, however, that after the ammonia inﬂuent peaks the normal working conditions were re-established quickly: this means that the nitrifying biomass was not inhibited, but, more likely, a temporary overload of ammonia nitrogen and/or organic matter occurred.

Before the improvements, the average AUR value was equal to 0.80 mg NH₄⁺/(g VSS*h); based on this data, the average ammonia quantity that could be nitriﬁed can be estimated at 850 kg NH₄⁺/day, by assuming a biomass concentration of about 7 kg VSS/m³ (operation data) in the oxidation-nitriﬁcation tank, a temperature of 20 °C and a suitable supply of oxygen. However, considering the effect of the temperature on the nitriﬁcation rate and the loads ﬂuctuating during the day, but especially the organic nitrogen contribution, a safer value can be assumed as the nitriﬁcation capacity of the plant, say around 500 kg NH₄⁺/day. This value was indeed often exceeded during the monitoring year and, in particular, in the last quarter.

Criticalities pointed out and ﬁrst improvements made

The analysis of the performance of the plant allowed the identiﬁcation of a series of critical issues.
In Table 2 all the critical issues are listed for each OU, along with the actions suggested for troubleshooting.

As an example, the simplification of the OU I pre-treatments phase is described. Before the year of monitoring, the industrial aqueous waste was pre-treated, in the OU I, with a Fenton process (with a very large dosage of reagents). The performance of Fenton and OU II clari-flocculation (coagulation + flocculation + sedimentation) was tested at the laboratory scale, using aqueous waste suitable for full-scale treatment. The tests (data not shown) highlighted that clari-flocculation, alone, produced aqueous waste suitable for OU II treatments. For this reason, the Fenton process has not been used anymore.

OPERATING CONDITIONS AFTER IMPROVEMENTS

Operating unit I (waste inlet)

After the improvements, the weekly volume of aqueous waste fed to the plant was maintained at an average of below 2,000 m³/week in the first five months of the year, with considerable variability (from a minimum of 270 to a maximum of 2,010 m³/week). Starting from June, this trend definitely settled mostly above 2,000 m³/week (about 300 m³/day). Indeed, in the last days of the week (Saturday and Sunday), the flow rate was reduced in order to empty the storage tanks, by Monday morning, as gradually as possible.

Table 2 | Critical issues and related troubleshooting actions

<table>
<thead>
<tr>
<th>Critical issues</th>
<th>Troubleshooting actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPERATING UNIT I</td>
<td></td>
</tr>
<tr>
<td>Massive use of reagents → high costs for reagent purchase and sludge disposal</td>
<td>Optimization of the reagent assay</td>
</tr>
<tr>
<td>Oily emulsions</td>
<td>Suspension of oily emulsions</td>
</tr>
<tr>
<td>Waste treatment line very detailed and complex</td>
<td>Simplification of the plant layout</td>
</tr>
<tr>
<td>N_{TOT} detection failure in waste → no optimal control of the load input to the biological sector</td>
<td>Checking programme of the input wastewater</td>
</tr>
<tr>
<td>OPERATING UNIT II</td>
<td></td>
</tr>
<tr>
<td>Raising of NH₃ output (often exceeding the limits)</td>
<td>Regulation of waste supply</td>
</tr>
<tr>
<td>O₂ concentration in the nitrification tanks often very high (7 mg/L)</td>
<td>Resetting of the air supply system</td>
</tr>
<tr>
<td>Several supplementary maintenance interventions on the blowers</td>
<td>Resetting of the air supply system</td>
</tr>
<tr>
<td>Air diffusion system in the tanks significantly different</td>
<td>Removal of sand deposits</td>
</tr>
<tr>
<td>Presence of sand in the sand separation and denitrification tanks</td>
<td>Descaling of the lift pumps</td>
</tr>
<tr>
<td>Presence of scales in the wastewater initial lift pumps</td>
<td></td>
</tr>
<tr>
<td>OPERATING UNIT III</td>
<td></td>
</tr>
<tr>
<td>Moderate concentration of dry matter in the biological sludge</td>
<td>Identification of the optimal reagent</td>
</tr>
<tr>
<td>Need for maintenance/replacement of the filterpress cloths</td>
<td>Replacement of the filterpress cloths</td>
</tr>
<tr>
<td>Thickener in precarious structural conditions</td>
<td>Proposals for a new thickener</td>
</tr>
<tr>
<td>High production of chemical sludge</td>
<td>The reduction of the use of reagents led to a decrease of sludge production</td>
</tr>
</tbody>
</table>
The effluent COD load from the pre-treatment station was variable, as well as the influent one, ranging from about 8,000 kg/week to about 37,000 kg/week. The COD average load measured from June to December was equal to 27,740 kg/week (equivalent to about 33,000 PE). Supposing the weekly load was distributed over seven days, the maximum value was 5,400 kg COD/day. Finally, the COD removal efficiency also showed some variability, but was usually close to 50%, with peaks of over 70%.

The ammonia load also showed a variable trend, with values ranging between 240 and 1,000 kg/week. The yearly average load was equal to 583 kg/week, and an average of 641 kg/week was measured in the period June–December.

### Operating unit II (activated sludge process)

Table 3 shows the influent loads of COD and ammonia to the activated sludge process, highlighting the contribution of urban wastewater.

The analysis of average daily effluent concentrations (data not shown) showed that the discharge limit of COD and BOD$_5$ were exceeded only occasionally, at the beginning of the year. The effluent concentration of TN was generally quite low (<20 mg/L). The concentration of ammonia, after a critical phase at the beginning of the year, remained stable and very low (<1.5 mg/L).

### COMPARISON OF THE PERFORMANCE BEFORE AND AFTER THE ACTIONS WERE TAKEN

#### Operating unit I (waste inlet)

**Received waste volumes and fed pollutant loads**

Figure 3 shows that, after the improvements were adopted, the total quantity of treated waste increased, thanks to the introduction of stricter and more detailed waste acceptance protocols and the execution of respirometric and jar tests on the waste suitable for the OU treatments. If waste was received during the whole year with the same frequency adopted during the 2nd semester, the total quantity could be estimated to exceed 100,000 m$^3$.

As shown in Figure 3, the treated waste volumes increased after the improvements were adopted. As a consequence, the average COD load also increased, as reported in Figure 4(b). Conversely, the ammonium nitrogen load reduced due to careful selection of the incoming waste (Figure 4(a)). If waste was received during the whole year with the same frequency adopted after the improvements, the NH$_4$ load could be estimated to exceed 600 kg/week and the COD load could be estimated to reach about 60,000 kg/week.

#### Residual concentration and load after pre-treatment

The effluent COD concentration from the pre-treatment station was lower after modifying the operation procedures, despite the increase of the volumes of treated waste and the influent COD load. This result was achieved thanks to the optimization of the pre-treatment station and to a more careful selection of the waste received. Conversely, ammonia remained stable.

The effluent COD load remained almost the same, but with smaller fluctuations, compared to the previous...
situation. Moreover, despite the treatment of a larger quantity of waste and the reduction of the reagent consumption (described below), the COD removal yields were higher, thanks to the application of very accurate and rigid waste acceptance protocols already mentioned. However, the increase of the effluent ammonia load could be due to lower extent of removal by uncontrolled stripping, as a consequence of the lower pH during the pre-treatment stages (always lower than 12).

Reagent consumption and sludge production

The reagent consumption is shown in Figure 5: a remarkable reduction was achieved, notwithstanding the greater amount of treated waste. This target was achieved thanks to the determination of the optimal dosages through jar tests and the utilization of pure reagents instead of recovered ones (obtained from industrial by-products), as was the situation before improvements were made. Moreover, the reagent consumption is expected to decrease further if waste were received during the whole year with the same frequency adopted after the improvements. The lower dosage of reagents also yielded reduced chemical sludge production.

Operating unit II (activated sludge process)

Influent pollution load

Figure 6 shows that the COD average influent load to the biological phase was lower compared to the one before the modifications were implemented (7,280 kg/day instead of 8,130 kg/day). This was the consequence of the lower effluent COD load of the waste pre-treatment station. Conversely, the ammonia load was slightly higher (340 kg/day instead of 308 kg/day), again as a direct consequence of the modified performance of the waste chemical/physical treatment station upstream.

Final effluent

During the two years of observation, the COD average concentration detected in the effluent (lower than 90 mg/L) did not show relevant variations. However, in the first months after the implementation of the improvements, anomalous situations were recorded, clearly shown by the peaks measured. Similar considerations can be applied to ammonia which was, on average, lower after the improvements (4.8 mg/L instead of 6.8 mg/L), but occasionally with high peaks.
Sludge production

The biological sludge production was reduced to half after the introduction of the improvements: from 4,000 t/year w.w. (wet weight) down to about 2,200 t/year w.w. Several factors affected this outcome: the reduction of the influent load to the biological plant; the greater sludge dewatering efficiency achieved thanks to the optimization of the filterpress; the lower amounts of residual chemicals in the pre-treated waste stream (the dosage in the pre-treatment stage was reduced).

Operating costs

The simplification of OU I layout and the identification of optimal reagents in the OU III (as reported in Table 2) led to considerable savings, as shown in Figure 7. If waste was received during the whole year with the same frequency adopted after the improvements, the savings could be increased further.

CONCLUSIONS

The aim of this work was to show how modifications to the operation procedures of a WWTP can yield important and valuable results. The work was carried out over more than one year (through a large number of technical inspections of the plant, the acquisition and processing of operational data and the execution of experimental tests), and was structured in the following phases: state-of-the-art evaluation (plant performance and operating costs), identification of critical issues, implementation of numerous actions and, finally, verification of the improvements achieved thanks to the modifications adopted.

Despite the quantity of treated aqueous waste increasing (from 70,000 m³/year to about 80,000 m³/year) after the modifications were implemented, thanks to the introduction of stricter and more detailed waste acceptance protocols, the effluent organic load of the pre-treatment station remained almost the same (from about 9,000 kg/day down to about 8,000 kg/day). This means that the COD removal yield increased; moreover, thanks to the simplification of the plant layout and the utilization of pure reagents, the consumption of chemical reagents drastically decreased, with consequent benefits in terms of chemical sludge production.
As a consequence of the modifications adopted in the pre-treatment compartment, the average COD load fed to the biological plant was reduced (from 8,100 down to about 7,300 kg COD/day) while the COD and ammonia nitrogen concentrations in the final effluent remained the same. The biological sludge production was significantly reduced. As a final outcome, the operating costs were reduced by 35% on average (considering the cost for reagent purchase and for biological and chemical sludge disposal), mainly due to the lower reagent consumption and sludge production.

In conclusion, the example described in this paper shows how the rigorous application (over a significant period of time) of an assessment procedure, based on careful monitoring and the execution of experimental tests, is a key factor in the improvement and process performance and the reduction of operating costs. The advantages of this approach are particularly evident in the case of complex facilities where many different kinds of wastewater have to be treated.

REFERENCES


First received 26 July 2017; accepted in revised form 20 November 2017. Available online 30 November 2017