ABSTRACT

During the retro-fitting of a civil wastewater treatment plant it is important to note that all structures of existing plants can be used in order to control investment costs. The article discusses the upgrading of a plant (from 80,000 to 120,000 PE) that was originally constructed for the biological removal of carbon. The water line of this plant was adapted for the use of the alternate oxic-anoxic process through which the biological removal of nitrogen can also be achieved. The article discusses the effects of the adaptation of the plant in regards to: results achieved by using the nitrogen balance, the gravitational behaviour of the biomass, the energetic consumption and the disposal of sludge. Since the plant was upgraded, it runs at a specific volume that varies from a minimum of 55 L/PE during the summer, and a maximum of 82 L/PE during the winter, that is, it guarantees the nitrification of 62-70% of incoming nitrogen. The denitrification process is accomplished not only simultaneously with nitrification in Carousel® basins, but also during the anoxic phases occurring in an automatically controlled alternate oxic-anoxic basin. This allows for the denitrification of 71 to 85% of denitrifiable nitrogen as well as the operation of the plant with a specific energy consumption of 80-90 Wh/PE d. This consumption is less than 25% of the consumption of plants of equal size using the pre-denitrification-nitrification process.

KEYWORDS: alternate cycles, denitrification, phosphorus removal, wastewater treatment.
necessary to know the physical-chemical properties of the sewer water and in particular the carbon (COD) to nitrogen (Ntot) ratio in the incoming wastewater. If the quantity of carbon that supports the process is not sufficient, specific technologies have been developed in order to fully use the incoming carbon. These are: the elimination of the primary sedimentation tank or the fermentation of primary (Isaac et al.; 1995; Lotter et al.; 1992) or biological (Kristensen et al.; 1992a) sludge.

If the COD/Ntot ratio in the sewer network is too low it is necessary to introduce carbon from an external renewable source. In this case a sustainable development, from both an environmental and an economic point of view, is made up of organic fraction of municipal solid waste (OFMSW), which can flow through the sewer network to the wastewater treatment plant after passing through the sink garbage grinder disposal.

Even though the use of the sink garbage disposal is widely diffused (England, North America, Australia), the Legislative Decree 258 forbids its use in Italy. An alternative, however, is the AF-BNR-SCP (Cecchi et al.; 1994; Battistoni et al.; 1998°, 2001a) process, where the given OFMSW is partly used with fermentation.

In the 1990s the scientific world updated the processes of biological nutrient removal of which, the mechanistic and kinetic aspects are well known (Beccari et al;1999). Today the problem resides in choosing one of the available solutions. That is, the one which is better both in regards to the characteristics of the network as well as in regards to minimizing investment costs.

In the specific case of Carousel® plants, the best process is that which uses the alternate oxic-anoxic process in a single reactor, also defined as continuous SBR (sequencing batch reactor). Of the available technologies, the following are the most common: the Abj ICEAS®, which has global presence for small (20,000 m$^3$/d) and large (750,000 m$^3$/d) sized plants and the continuous SBR, which are common in Europe (Wilderer 2001).

These approaches involve the best theoretical and practical solution regarding the most reliable energy saving system. In particular, there are two methods of approach: the process that runs at various volumes allowing the management of the cycle length to be based on time and the process that runs at a constant volume for which it is necessary to have remote and local controlled automatisms in order to adapt the process to the variety of mass and hydraulic loads. The attempt to individualize the automatism in both pilot plants (Paul et al.,1998) and existing plants (Battistoni et al., 1999b-c; Wacheux 1996; Charpentier1992; Zipper ,1998) has caught the interest of many researchers. Such interest demonstrates the fact that also in Europe a problem has been recognised and now, there are many applications of the process in actual Italian plants (Amoruso 2001, Battistoni 2000c-2001).

The article presents three years of observation of the Viareggio civil wastewater treatment plant. This plant, in which the water line was originally constructed using Carousel® basins, was upgraded, without the addition of new materials, to run using the alternate oxic-anoxic process in a single reactor with automatic local control. The article also discusses the experimental effects on the plant’s performance regarding biological nutrient removal, the production of sludge and the consumption of energy. The objective of the study is to demonstrate that existing plants, both old and new, can be upgraded without elevated costs.

**METHOD AND MATERIALS**

The treatment plant was checked using average samples collected over a 24-hour period, twice a week. The samples were collected from various sections of interest throughout the plant and the physical-chemical characterisation was carried out using standard methods (A.P.H.A. - A.W.W.A. 1992). The measurement of RBCOD in the incoming water was verified with each average sample taken during a 24-hour period (Mann et al. 1993). The analysis of the solid flow was carried out once a month on the mixed liquor of the biological process according to the Keinath methodology (1989). The measurement of the kinetic constant of nitrification was carried out periodically using the biomasses of an alternate oxic-anoxic process basin according to the Kristensen methodology (1992b).

**RESULTS AND DISCUSSION**

The evolution of the plant
The Viareggio civil wastewater treatment plant was built in 1974. The water line follows a simplified flow scheme (Fig. 1) in which, after pre-treatment (fine screening and grit removal), the biological removal of carbon and the aerobic stabilization of waste activated sludge, are brought into effect. All of this occurs without primary sedimentation. This type of process configuration suffers two critical conditions are: the reduced volume of Carousel® basins allocated for the biological process and the elevated hydraulic surface loadings that force the secondary clarifiers to work. In particular, the main dimensions of the plant (Tab. 1 Phase A) demonstrate how with the mass loading during summer (120,000 PE) and with that during winter (80,000 PE), the specific volumes of Carousel® basins are 28 and 42.5 L/PE respectively. Therefore, its reliability for the removal of any nitrogen is greatly reduced.

The secondary clarifiers run in critical circumstances because when in dry weather conditions, the hydraulic surface loading is 18 m$^3$/m$^2$d and reaches 1.12 m$^3$/m$^3$h during the peak flow rate in dry weather, while in the maximum flow rate of rain the hydraulic surface loading can reach 2.2 m$^3$/m$^2$h. The operational function of the basins is further worsened by a 1.9 m hydraulic head on the weir that can cause the leakage of solids even if the clarifiers are working with a sludge blanket of minimal height.

For this reason, the plant was progressively upgraded changing the original purpose of the available structures in order to support the biological processes. The following phases demonstrate the evolving path of the plant:

Phase A: from 1/8/98 to 31/7/2000; characterised by the stability of the specific volumes of the process in which a primary clarifier was used in order to contain hydraulic overflows during peak dry and wet weather conditions, in a way so that probable/possible leaks of solids from the primary sedimentation were contained/prevented.

Phase B1: from 1/9/2000 to 31/8/2001; the aerobic stabilization was converted into the biological process, and the primary clarifier into an alternate oxic-anoxic process in a single reactor. In this way the specific volumes during the summer and winter changed to 55 and 82 L/PE respectively.

Phase B2: from 1/19/2001 to 31/12/2001; in which the electromechanical device of the oxic-anoxic basin was substituted in order to allow for the lowest possible energy consumption. An anaerobic sludge waste digester was added to the sludge line. In this way the specific volume remained unaltered, but due to higher stabilization of the sludge from the outgoing treated water, there were additional incoming loads of nitrogen due to the feedback by the anaerobic supernatants in the sludge line.

For this reason, the plant sustained a gradual transformation of the water and sludge lines until they conformed to those seen in Fig. 2.
During the three years of observation of the plant (1998-2001), the characteristics of the incoming water and the mass loadings remained basically unchanged. The characteristics are typical of a mixed network that is predominantly civil. In fact, there are only a few factories with agro-industrial production. The mass loadings confirm both the seasonal difference for a touristic location in the area as well as a dimension almost equal to that of the project. The population served by the plant, calculated on the basis of carbon (105 g COD/PE) fluctuates from 75,000 to 95,000 PE during the winter and reaches 103,000 PE during the summer. Calculated on the basis of nitrogen (12 g Ntot/PE), however, the plant dimension is reduced because the COD/Ntot ratio in the sewer network is irregular in respect to the ratio in large sized Italian plants (Beccari 1999), but retains its seasonal characteristics.
From the characteristics of the influent, an elevated and fluctuating COD/Ntot ratio is noted (Tab 3.). The ratio seldom reaches values lower than 7.5, the minimum value for the denitrification of nitrogen (Kristensen 1992a). This can be attributed to the industrial districts linked to the sewer network. The data of readily available COD (RBCOD) reveal an optimal situation because the RBCOD/COD ratio fluctuates between 0.20 and 0.26, which is above the average value in European sewer networks (0.15-0.20). It is therefore confirmed that no problems exist concerning the limitation of the substrate if the nitrification of nitrogen is enhanced in the water line.
The performance of the plant is graded on the base of the of nitrogen mass balance (Tab. 4) calculating not only the traditional yields of nitrification (En) and denitrification (Ed) (expressed in reference to the total incoming nitrogen), but also the performance of the nitrification related to both the nitrificable nitrogen (Enn) and the denitrification related to denitrificable nitrogen (Ed). These parameters allow for better understanding of the process, that is, what is actually accomplished in respect to the potential determined by operative SRT (sludge retention time), and therefore by the biological sludge waste. In particular, during Phase A, it was necessary to run the plant using low SRT values, and therefore with reduced concentrations of biomass in the Carousel® basins (max 5 kg/m³), in order to limit the negative impact on the operational function of secondary clarifiers. Obviously, the minimal presence of autotrophic biomasses limited nitrification without a change in plant performance during the summer and winter periods.
With the increase of available volume (from phase A to phases B1 and B2), it was possible to run the plant at higher values of SRT, and therefore increase its performance for the removal of nitrogen, until values that ensure the safest plant operation were reached. The confirmation of this comes from the experimental verification of the kinetic constant of nitrification, which, with some changed in SRT values, increases progressively from 0.25 to 0.065 kg NH₄-NOₓ/kgMLVSS (Fig. 3). A prompt confirmation of higher performance is demonstrated, obviously, by the different concentration of nitrogen in the effluent (Fig. 4). From phase B1 to phase B2, substantial differences in performance are not demonstrated as the operational volumes and the parameters remained unchanged. In phase B2, however, the performance was achieved with minimal waste of energy.

Fig. 3 Increase of the standard velocity of nitrification at 20°C
The impact on the gravitational behaviour of the biomasses

The gravitational behaviour of the biomasses was studied by analysing (once a month) the gravitational solid flux. During the 8 month observation period (October 2000-May 2001), the plant sustained a temperature excursion of 10°C which is not the maximum range as in this case the warmest months of the year were not observed. In this period (Fig. 5), the gravitational solid flux curve remains at a constant minimum from December to March. After March, though, a gradual increase is noted.

A criterion for evaluating the quality of the gravitational solid flux can be derived by comparing the maximum flow of the biomasses in the Viareggio plant, expressed in Kg TS/m² h, to the current maximum flow of other plants that use various configurations of the process. In this way, the range of factors that influence the behaviour of the biomasses (filamentous micro organism development, the effect of the temperature, etc.) is synthesized.

The experimental results (Tab.5) demonstrate how at minimum temperatures of the process, the gravitational solid fluxes are low. The processes that do not use primary sedimentation have elevated gravitational solid fluxes. Even though it uses a mixed water line consisting of the alternate oxic-anoxic process and Carousel® basins, the Viareggio plant has biomasses with gravitational solid fluxes equal to or more than the flows found in the biomasses of predenitrification-nitrification plants. Therefore, no change in gravitational behaviour results by using processes that adopt oxic-anoxic phases or by using the simultaneous nitrification-denitrification process.

Obviously, the actual impact of this gravitational solid flux on the available structures can be evaluated on the basis of state point analyses (Ekama 1977), but this is not related to the effect of the process on the biomasses because the state point analysis gives indications regarding the performance of existing structures.
Fig. 5 Analysis of the gravitational solid flux

Tab. 5 Maximum gravitational solid fluxes in various plants

<table>
<thead>
<tr>
<th>P.E.</th>
<th>TYPOLOGY</th>
<th>T min</th>
<th>Fg Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>60,000*</td>
<td>DN</td>
<td>12,0</td>
<td>2,5</td>
</tr>
<tr>
<td>60,000**</td>
<td>DNWP</td>
<td>12,0</td>
<td>5,8</td>
</tr>
<tr>
<td>2,500*</td>
<td>Alternate cycles</td>
<td>12,0</td>
<td>2,5</td>
</tr>
<tr>
<td>700</td>
<td>Alternate cycles</td>
<td>12,0</td>
<td>2,5</td>
</tr>
<tr>
<td>Viareggio</td>
<td>Alternate cycles and Carousel</td>
<td>14,0</td>
<td>6,2</td>
</tr>
</tbody>
</table>
The impact on sludge production

With the upgrading of the plant, the production of sludge sustains a gradual decrease (Tab.6). In particular from phase A to phase B1 a decrease of 15% (from 675 to 570 t/month) is noted. This is explained mainly by the higher SRT values adopted because of the higher available volume (see Tab.4). From phase B1 to phase B2, comparing winter seasons, a subsequent decrease of 42-47% is obtained given due to both the higher SRT levels as well as the steady state condition of the mesophilic anaerobic digester.

Tab. 6 Sludge production (values expressed in t/month)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Winter Period</th>
<th>Summer Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>01/01/00  06/30/00</td>
<td>07/01/00  09/31/00</td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>728</td>
</tr>
<tr>
<td>B1</td>
<td>10/01/00  06/30/01</td>
<td>07/01/01  09/30/01</td>
</tr>
<tr>
<td></td>
<td>570</td>
<td>450</td>
</tr>
<tr>
<td>B2</td>
<td>10/01/01  12/31/01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>310</td>
<td></td>
</tr>
</tbody>
</table>

The precise representation of the monthly production of sludge cakes (Fig.6) allows for an analysis of the main detail of evolution of the production with the phases, even though an increase in the dry content when anaerobically stabilized biological sludge waste is dewatered.

The introduction of the anaerobic digester in 2001 brings about a temporary phase that does not allow for the use of disposed sludge in 2001 in the quantities in which it was used last year. It is possible, however, to extrapolate the reduction of sludge, calculated comparing homogeneous periods both before and after the anaerobic digester conforms to a steady state condition, in order to foresee the upcoming quantities of sludge cake. As a result, in 2002 a global production of about 4,500 t in comparison with the 7,900 of 2000 corresponds to a savings of about 207,000 Euro.

Fig. 6 Monthly sludge production (2000-2001)

The impact on the energy consumption

The energy consumption of the plant was evaluated in terms of specific consumption per PE (Wh/PE d), calculated on the basis of the incoming mass loads, in order to allow for comparison to the literature (Balmer 1994). The experimental results demonstrate how the upgrading of the plant brings about an increase of energy consumption (from phase A to phase B1) of about 48% during the winter and about 18% in the summer. With the installation of a low energy consumption device, the increase in consumption is reduced (27% in the winter) to values that are clearly lower than those found in the literature regarding plants of equal size (100-200 Wh/PE d)
Tab. 7 Specific and absolute energy consumptions

<table>
<thead>
<tr>
<th>Phase</th>
<th>Winter Period</th>
<th>Summer Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>01/10/99 30/06/00</td>
<td>01/07/00 31/09/00</td>
</tr>
<tr>
<td>A</td>
<td>71</td>
<td>83</td>
</tr>
<tr>
<td>B1</td>
<td>105</td>
<td>98</td>
</tr>
<tr>
<td>B2</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

In particular, the consumption from phase A to phase B2 changes from 71 to 90 Wh/PE. If it is considered that it is a comprehensive consumption of the sludge line and excludes pumping, the consumption of energy is 25% less than that of plants that use the prenitrification-nitrification process. Therefore, the alternate oxic-anoxic process in a single reactor allows for considerable savings, as has already been demonstrated in similar plants (Battistoni 1999-2000).

The role of alternate cycles in a single reactor

The oxic-anoxic process in a single reactor is vital for both the performance and for the reduction of energy consumption of the water line despite the treatment of only a fraction of the mass entering the plant, which is equal to the fraction of the basin volume in respect to the water line. The power installed into the Carousel® basins amounts to 80% of the total power even if the volume amounts to only 66%. This corresponds to energy consumption equal to 100% of the power installed into the Carousel® basins versus 65% of that in the alternate oxic-anoxic process basin. That is, 87% of the consumption is allotted to the Carousel® basins where as the remaining consumption, 13%, is allotted to the alternate oxic-anoxic process basin. This is explained not only by operation of the machines at low energy efficiency, but also by carrying out various processes. In fact, a control of the process in the alternate oxic-anoxic process basin allows for the automatic variation of the duration of the oxic and anoxic phases in relation to the variation of loads. On the contrary, in Carousel® basins, the lack of automatism availability leads to continuous occurrences of nitrification and subsequently nitrification and denitrification occurring simultaneously, in relation to the fact that the oxygen supply is respectively higher or equal to that of the demand. Therefore the occurring process depends considerably on the incoming loads.

An example of a different trend of the processes can be seen on the basis of DO (dissolved oxygen) and ORP (oxidation reduction potential) markers. In Fig.8 the following is represented: first, the scenario of the alternate oxic-anoxic process basin markers during a day without precipitation where the process carries out 11 cycles, each of which consists of an aerobic phase and an anoxic phase, of which the durations are varied and automatically carried out, and second, the maximum value of the dissolved oxygen varies in relation to the incoming loads, with reduced values during dry weather conditions. The average duration of the aerobic phase is 65% of the cycle time. The average duration of the anoxic phase, though, is briefer (35%).
In the case of wet weather conditions, a minimum of incoming mass loading is verified despite the hydraulic overflow. The system of the process control responds by adequately increasing the anoxic phase. This is achieved through the over-aeration of the preceding aerobic phase through the minor reduction of ORP due to the limited availability of substrate for denitrification. During a wet day (for example 15/11/2001), the process carries out 11 additional cycles, but the average duration of the aerobic phase is 51% of the total time (Fig.9). The duration of single cycles is represented in Fig.9. In this way, the automatism allows for a reduction of energy consumption (51% versus 65% in dry weather conditions) and a guarantee of the process in that it avoids unnecessary over-aeration and incomplete denitrification.

Carousel® basin 2 (Fig.10) was studied during the same day shown in Fig.9, where typical and constant DO values are registered. In particular it is possible to see an over-aeration in the first few hours or the day due to low incoming loads and subsequently an anoxic phase together with an increase of incoming loads. Therefore the simultaneous nitrification denitrification process (DO<0.5 mg/L) is guaranteed only during some parts of the day, and it is not guaranteed during the periods of over-aeration. In the case that there is a decrease in loading during wet periods further over-aeration occurs, which causes a decrease in performance of the process and also causes unnecessary waste of energy (see Fig.10 1,000-1,200 min.).

Phosphorus removal

It is known that the alternate oxic-anoxic process in a single reactor (Battistoni 2001) and the SBR (Chang 1996, Danesh 1997) process can favour the growth of accumulating phosphorus biomasses (BPA), and therefore bring into effect the biological removal of phosphorus. In reality, the processes are not structured with aerobic and anaerobic phases dedicated to the preferential development of the BPA. For this reason, only a partial removal is reached. In the test plant the incoming phosphorus has an average concentration that fluctuates (Tab.8) from 3 to 5 mg/L with peak daily averages that reach 10mg/L. In the outgoing flow, the total phosphorus maintains values lower than 2.0 mg/L even though the PO4-P is considerably lower due to there are medium-high concentrations of suspended solids (TSS 25 - 40 mg/l) because of the secondary clarifiers. During the various phases considered it is always demonstrated that in the summer time the outgoing Ptot is higher than that during the winter. This fact could be attributed not only to a higher concentration of incoming Ptot, but also to the scarcity of oxygen which generates prolonged anaerobic conditions and the release of accumulated phosphorus in the BPA.
Experimental evidence of the presence of BPA is found in the feedback flow of anaerobic supernatants. In the B1 and B2 phases, the anaerobic supernatants contain PO4-P fluctuating from 70 to 90 mg/L. That is equal to a mass loading that varies from 32 to 42 Kg/d of PO4-P and corresponds to a 22-56 percentage of the incoming phosphorus mass loading. Such an elevated presence of PO4-P is certainly caused by the phosphorous release from the BPA during the thickening of the biological sludge waste with Imhoff tank sludge (Phase B1) and during anaerobic digestion.
Tab. 8 Influent and effluent phosphorus

<table>
<thead>
<tr>
<th>Phase</th>
<th>Period</th>
<th>Ptot in (mg/l)</th>
<th>Ptot out (mg/l)</th>
<th>SST (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>average</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>A</td>
<td>winter</td>
<td>3.9</td>
<td>0.8</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>summer</td>
<td>4.8</td>
<td>2.1</td>
<td>10.2</td>
</tr>
<tr>
<td>B1</td>
<td>winter</td>
<td>2.8</td>
<td>1.1</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>summer</td>
<td>3.2</td>
<td>2.9</td>
<td>6.8</td>
</tr>
<tr>
<td>B2</td>
<td>winter</td>
<td>3.0</td>
<td>2.2</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>summer</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A detailed analysis of the phosphorus can be achieved based on Fig.11 which shows daily incoming and outgoing values of the plant.

Fig. 11 Influent and effluent phosphorus

CONCLUSIONS

The experimental work carried out at the Viareggio civil wastewater treatment plant allowed for the study of various themes relating to the performance obtained through progressive upgrading. The following are the main conclusions:

- it is possible for plants that adopt a carbon-only removal process to carry out the upgrading of the water line with the continuous SBR process or with the alternate oxic-anoxic process in a single reactor;
- using this strategy, modification of the plant is less invasive because it allows for the use of existing plant structures;
- the alternate oxic-anoxic process in a single reactor is equipped with remote and local controlled automatism. Therefore, for basins that run at a constant volume, it allows for the upgrading of the duration of each oxic and anoxic phase in relation to the incoming loads. This method avoids unnecessary over-aeration and incomplete denitrification;
- the coupling of Carousel® basins and alternate oxic-anoxic process basins is a solution in which specific energy consumption is 25% lower than the energy consumption that is well-established in the literature;
the gravitational behaviour of the biomasses produced in the water line is equal to or better than that of similar sized plants with similar water line flow schemes even if these plants use the prenitrification-denitrification process;

in every plant it is possible to operate with higher SRT values, and therefore at a lower $Y_{obs}$ value: this permits reduction of the sludge production;

The process achieves the biological removal of phosphorus even if not in large quantities. During the winter the process allows the plant to conform to the limit of $P_{tot} = 2$ mg/L in the effluent, while during the summer it is necessary to assist the process by using chemical precipitation.

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