CONTROLLED VARIABLES SELECTION FOR A BIOLOGICAL WASTEWATER TREATMENT PROCESS

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Abstract: This paper considers control structure selection for a biological wastewater treatment process, with emphasis on identifying controlled variables that contribute to minimize economic costs. This is achieved according to the self-optimizing procedure proposed by Skogestad (2000). The aim is to demonstrate how, with simple considerations on the control structure design, the efficiency of a wastewater treatment plant can be improved, minimizing operational costs in the plant, while keeping it running optimally and satisfying the effluent requirements.

Keywords: Self-optimizing control, Cost function, Activated sludge

1. INTRODUCTION

In the last decades, environmental water protection has gained an increasing public awareness, which is also reflected in more strict effluent concentration requirements and regulations. This has, in turn, considerably increased the necessity of efficient and reliable Waste Water Treatment Plants (WWTPs) that have to face an important challenge arising from both regulation fulfillment and cost aspect of plant operation. These regulations hence give rise to both technical and economical problems since most of the existing plants have to undertake major upgrading, particularly for nutrient removals. In addition to plant improvements attained through the adoption of new equipment technologies, the application of careful considerations on control systems is required to achieve the improved benefits in practice. In particular, since inside a biological WWTP, the Activated Sludge Process (ASP) is the most common used technology to remove organic pollutant from wastewater, we focus our attention on this process.

In the literature, ASP optimization has been studied by several authors in different ways. For instance, Chachuat et al. (2001) investigate the optimal sequence of aeration and non-aeration time for a small ASP and Samuelsson et al. (2005) studied the impact of different nitrate cost functions on the location of the cost optima. Gillot et al. (1999) defined an objective cost function in order to standardize the cost calculation procedure integrating both investment, fixed and variable operating costs. Vanrolleghem and Gillot (2002) proposed an economic index including weighted investment and operating costs used to evaluate the transferability of control strategies to different situations. A methodology to estimate costs and benefits of online control for WWTP is developed by Devisscher et al. (2006).

In this work, it is shown how optimal operation can be achieved in practice by designing the control structure appropriately. In other words
the constrained optimization problem is translated into the proper operation in the ASP process. Controlled variables are the important link between layers in the hierarchic control structure and there are many issue involved. First, we should control the active constraints (which are optimal from an economic point of view in terms of minimizing the cost). Second, we need to find controlled variables associated with the unconstrained degrees of freedom. This is the issue of self-optimizing control. We are looking for the controlled variables for the ASP which when kept constant, indirectly achieve optimal operation in spite of disturbances. In order to trade them off against each other in a systematic manner we follow the control structure design proposed in (Skogestad, 2000).

2. ACTIVATED SLUDGE PROCESS

We consider the ASP in the TecnoCasic WWTP located in Cagliari (Italy), reported in (Mulas, 2006), and schematically represented in Figure 1. Here, the bioreactor consists of an anoxic (pre-denitrification, \(p\) in the following) followed by an aerobic (nitrification, \(n\) in the following) zone. To maintain the microbiological population, the sludge from the settler is recirculated into the anoxic basin, while the sludge concentration is kept constant by means of sludge withdrawn from the settler.

The ASP layout has the following characteristic features:

- Biological treatment reactor (2000 \(m^3\)), with an anoxic zone followed by an aerobic zone. The aeration is obtained with fine pore air diffusers located at the bioreactor bottom. A Dissolved Oxygen (DO) controller maintains the oxygen concentration at 0.09 \(gO_2/m^3\), in the anoxic zone and at 4 \(gO_2/m^3\), in the aerobic one.
- Non-reactive secondary settler with a surface of 707 \(m^2\) and 4 \(m\) depth.
- Recycled flow, \(Q_r\), from the secondary settler to the front end of the plant at a constant flow rate of 7000 \(m^3/d\).
- Waste flow, \(Q_w\), intermittently pumped from the secondary settler underflow.

Furthermore, the average influent conditions for the considered plant are reported in Table 1.

### Table 1. Influent nominal conditions for the considered plant.

<table>
<thead>
<tr>
<th>Influent Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent Flow rate (Q_{in})</td>
<td>6152 ([m^3/d])</td>
</tr>
<tr>
<td>Influent Chemical Oxygen Demand (COD_{in})</td>
<td>221 ([gCOD/m^3])</td>
</tr>
<tr>
<td>Influent Total Suspended Solids (TSS_{in})</td>
<td>46 ([gSS/m^3])</td>
</tr>
<tr>
<td>Influent Nitrate (S_{NO}^{in})</td>
<td>0.22 ([gN/m^3])</td>
</tr>
<tr>
<td>Influent Total Kjeldhal Nitrogen (TKN_{in})</td>
<td>22 ([gN/m^3])</td>
</tr>
<tr>
<td>Influent Ammonia/TKN ratio (f_{NH}^{in})</td>
<td>0.36</td>
</tr>
</tbody>
</table>

The bioreactor is represented by means of the Activated Sludge Model No. 1 (Henze et al., 1987), while the secondary settler representation is obtained with the Takács model (Takács et al., 1991); these models are coupled together in a Matlab/Simulink (R14) environment. Furthermore, in order to take into account the not ideal fluodynamic in the ASP, the biological reactor is formed with six different zones: three anoxic which represent 1/3 of the total volume and three aerated zones, corresponding to the remaining volume.

3. OPERATIONAL OBJECTIVES

In order to run a WWTP economically, costs such as pumping energy and aeration energy should be minimized; nevertheless, the discharge concentrations to recipients should be kept at acceptable level. Hence, the operational objectives includes not only the cost function to be minimized but also the constraints at which it is subjected and the disturbances that may occur in the plant.

3.1 Cost Function

Economically speaking, the overall cost in a wastewater treatment plant is highly dependent
on the wastewater system itself and it can be divided into manpower, energy, maintenance, chemical sludge treatment and disposal evaluated on a time basis. Therefore, an inventory has to be made of the different costs so that individual importance of each term is determined. In this work, the following partial costs are considered:

- Pumping costs due to the required pumping energy ($E_P$ expressed in kWh/d);
- Pumping costs due to the required aeration energy ($E_A$ expressed in kWh/d);
- Sludge disposal costs ($C_D$ expressed in €/d).

In order, to express the partial costs we adopt the following notation. It is a good practice to maintain the DO level between 1.5 and 4 gO$_2$/m$^3$, as a further increase does not improve operation, but increases aeration costs considerably. On the other hand, in the anoxic zone a lower aeration is needed in order to satisfy only the mixing requirements.

Furthermore, we know that the nitrate consumption in the last predenitrification zone ($S_{NO}^{p,3}$) should be between 1 and 3 gN/m$^3$ when internal recirculation is present (Olsson et al., 2005), which is not the case in the considered plant. We verified that $S_{NO}^{p,3}$ between 0.75 and 1 gN/m$^3$ can assure a good behavior in the anoxic zone. This awards to not excessive air consumption in the aeration zones.

In addition, the constraints related to the optimal operation of the secondary settler have to be considered. It is also important to prevent the loss of sludge solids in the effluent in order to guarantee the required degree of treatment. Hence, we consider an index that is able to represent the sludge behavior such as the Food to Microorganisms ratio (F/M). According to the literature (Metcalf and Eddy, 1991), it must not exceed certain level as summarized in Table 2.

### 3.3 Disturbances

One of the major reasons for control is the presence of disturbances, and compared to most other process industries a wastewater treatment plant is subject to very large disturbances. In order to give a representation of the system behavior when disturbances occur, the nominal average circumstances are augmented by 20% (Table 3).

<table>
<thead>
<tr>
<th>Constant $Q_{in}$</th>
<th>Variable $Q_{in}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_1$: COD$_{in}$ + 20%</td>
<td>$d_4$: $Q_{in}$ COD$_{in}$ +20%</td>
</tr>
<tr>
<td>$d_2$: TKN$_{in}$ + 20%</td>
<td>$d_5$: $Q_{in}$ TKN$_{in}$ +20%</td>
</tr>
</tbody>
</table>

Table 3. Disturbances.

Two different situations are considered. The case with constant influent flow rate $Q_{in}$ ($d_1$, $d_2$, $d_3$), from a practical point of view, it may happen if there is a large equalization basin before the ASP. For disturbances $d_4$, $d_5$ and $d_6$ also a 20% change in $Q_{in}$ is included.

### 4. MANIPULATED VARIABLES AND DEGREES OF FREEDOM

In order to define the number of Degrees Of Freedom (DOF) for optimization, $N_{opt}$, we must identify the number of degrees of freedom for control,
If we look at the schematic representation of that plant in Figure 1, we note that there are only few variables that we can manipulate; this is quite common in a biological wastewater treatment plant, (Olsson and Newell, 2002). However, there is potential to make a better use of the existing manipulated variables.

From Figure 1, we observe that there are 7 valves, but we identify only 4 degrees of freedom for control because the levels in the aeration tank and in the secondary settler need to be controlled at constant values (they are actually self-regulating) and because the influent flow rate is a disturbance and not a manipulated variable. It should be noted that inventory of sludge in the secondary settler should be controlled, but since the inventory has a steady-state effect, this does not affect the number of degrees of freedom. We assume that the DO concentration in both anoxic and aerobic zones are constant at the setpoint values by the airflow controllers meaning that we have two remaining degrees of freedom. In the following two different cases are examined:

- **CASE1**: we assume that: 1) there is no disturbance in the influent flow rate $Q_{in}$ and 2) $Q_r$ is constant. There is then one controlled variable left to select.

- **CASE2**: we want to select two controlled variables. An objective is to check if fixing $Q_r/Q_{in}$ is a good policy, which is the common practice in most wastewater treatment plant, in the case where also disturbances in $Q_{in}$ are considered. In this case, there are two remaining DOF.

### 5. OPTIMIZATION PROCEDURE AND CANDIDATE CONTROLLED VARIABLES

As the beginning of the optimization procedure, we examine the existing operating conditions for the considered plant and we notice that aeration is responsible for 99% of the total cost. Therefore, the first attention focuses on the pumping cost for the aeration and on the DO controller present in the WWTP. A preliminary optimization was carried out to find the setpoint values for the DO concentration in both controlled anoxic and aerobic zones. The results are reported as "improved" in Table 4 and we can observe a remarkable cost reduction with respect to the existing initial condition.

Now, we can go a step further in the self-optimizing procedure and propose the candidate controlled variables. According to Skogestad (2000), these should be easy to measure and control, but sensitive to changes in the manipulated variables and their optimal value should be insensitive to disturbances. The following candidates are suggested:

- Sludge Retention Time, SRT [d];
- Food to Microorganisms ratio, F/M [gCOD/gSS/d];
- Effluent ammonia, $S_{NH}^{eff}$ [gN/m$^3$];
- Mixed Liquor Suspended Solids, MLSS [gSS/m$^3$];
- Nitrate in the last anoxic zone, $S_{NO}^{3}$ [gN/m$^3$].

The used setpoint values for these variables (Table 5) are the average of various operation points.

<table>
<thead>
<tr>
<th>SRT $^{sp}$</th>
<th>F/M $^{sp}$</th>
<th>$S_{NH}^{eff}$ $^{sp}$</th>
<th>MLSS $^{sp}$</th>
<th>$S_{NO}^{3}$ $^{sp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.77</td>
<td>0.74</td>
<td>0.17</td>
<td>1482</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 5. Setpoint values used for the candidate controlled variables.

With regard to CASE1, we optimize the system with respect to one possible manipulated variable, $Q_w$, with constant values $Q_r/Q_{in}$ fixed at its optimum value found with the optimization procedure. Using oxygen concentration values at constant setpoints, as reported in Table 4, it allows us to investigate the steady state process behavior at nominal conditions and different $Q_w$.
In Figure 2, the operating variables behavior at different \( Q_w \) is shown with fixed \( Q_r/Q_{in} \), \( DO^{p-sp} \) and \( DO^{n-sp} \) (with values from Table 4). In this way, we can define an operating region for this particular situation. In fact, we note that the operative constraints are respected for \( Q_w \) ranging between 60 and 100 \( m^3/d \) and that in this region we expect costs of 1400-2000 €/d (Figure 2f).

In CASE2, we optimize with respect to two manipulated variables: \( Q_w \) and the ratio \( Q_r/Q_{in} \) with fixed \( DO^{p-sp} \) and \( DO^{n-sp} \) as reported in Table 4. We investigate the process behavior using the operating space diagrams, which are contour plots of an output variable against the manipulated variables as reported in Figure 3. We note that the constraints are satisfied only for 40 < \( Q_w < 100 \) \( m^3/d \) and for a \( Q_r/Q_{in} \) ratio ranging from 0.5 and 1.5. The total cost is not actually dependent on variations in the recycle ratio \( Q_r/Q_w \) whereas it decreases as the wastage flow rate increases (Figure 3f).

![Figure 3](image1)

Fig. 3. Effect on change on \( Q_w \) and \( Q_r/Q_{in} \) with constant \( DO^{p-sp} \) and \( DO^{n-sp} \).

In Table 6, all considered control configurations are reported with the associated minimum singular value. The controlled variable sets corresponding to the larger minimum singular value (\( C \)) are preferred. From these, we remark that the configurations from \( c_{5} \) to \( c_{14} \) take into account \( Q_r/Q_{in} \) and \( Q_w \) as inputs which means that two controller loops are involved. Configurations from \( c_{1} \) to \( c_{4} \) consider the recycle ratio fixed at the optimum, assuming this is a good self-optimizing variable, and the SRT, F/M, \( S^3_{NH} \) and MLSS controlled by \( Q_w \). We note that the best configurations with a large minimum singular value are \( c_{1} \) and \( c_{4} \) which are made fixing \( Q_r/Q_{in} \). We then expect that those configurations are the best also in an economic point of view, but for sake of completeness, we investigate also \( c_{9} \) and \( c_{14} \). In this case, the acceptable loop pairing leads to the following control configurations:

- control SRT (or MLSS) by manipulating \( Q_w \);
- control the nitrate concentration in the last anoxic zone, \( S^3_{NO} \), by manipulating the ratio \( Q_r/Q_{in} \).

We note that the candidate controlled variables involve SRT and MLSS. We know that keeping the SRT a constant setpoint value implies to hold the nitrification capacity of the sludge (measure of the maximum nitrification rate) at a constant level, and especially when the flow rate and load are not constant this should be allowed to develop in the system as a result of an increase influent (Ölsson et al., 2005). Also for this reason, we expect that the configurations regarding mixed liquor suspended solid measurements will be preferable.

Having defined the candidate controlled configurations, we investigate the different situations in order to select the one that contribute to minimize the cost in the plant.

### 6. CONTROLLED VARIABLES SELECTION

We here consider in detail the actual cost for the considered configurations. From Table 7, it is clear that for disturbances \( d_1 \), \( d_2 \), and \( d_3 \) the cost is considerably reduced and it is possible to omit further saving if a MLSS controller is implemented in the ASP.

Also when the influent flow rate is not constant (\( d_4 \), \( d_5 \), and \( d_6 \), the best way to operate is to fix the ratio \( Q_r/Q_{in} \) and control the MLSS concentrations by means of the waste flow rate \( Q_w \). It follows that the recycled sludge pump will change \( Q_r \) on the basis of influent flow rate measurements, assuring an appropriate amount of biomass in the system.

In both situations, with and without flow rate disturbances the adjustment of waste activated
sludge flow is based on MLSS measurements and on the ratio between the recycled sludge and the influent flow rate, proving that even if the $Q_w$ is usually a small fraction of the influent flow, a careful control may have a significant effect on the performance of an activated sludge system.

Eventually, the open loop behavior is also reported; this is a poor policy to adopt, but it is frequently used and is a good reference to understand how the system can be improved by applying controller.

### 7. CONCLUSION

In this paper, the control design of an ASP in a biological wastewater treatment plant is studied from a process economic point of view. The self-optimizing procedure gives a clear chance to obtain a cost-efficiently controlled process, respecting the effluent requirements as well as the operative conditions. Two different plant situations have been studied. In one case the influent flow rate is considered constant whereas the same flow rate is varying in the second case. In both situation, the best configuration ($Q_r/Q_m - MLSS$) involves the mixed liquor suspended solids controlled by the waste flow and keeping the recycle ratio fixed.

### REFERENCES


