# ADVANCED CONTROL OF AN INDUSTRIAL EQUALIZATION SYSTEM

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## Abstract

This paper illustrates the modeling and the control of the equalization system of a full scale industrial wastewater treatment plant. The structure of the system is very specific and a number of difficulties are pointed out and then solved using an optimal controller associated with a fuzzy based supervisory system. Simulation results are presented and evaluated.

## 1 Introduction

Any industrial wastewater treatment facility is subject to variations in the influent flow rate as well as in the influent waste concentration. Equalization systems are thus used either to overcome the operational problems caused by flow rate and load variations, to improve the performance of the downstream processes or to reduce the size and cost of the plant. In fact, equalization system objectives simply consist of the attenuation of both flow rate and concentration variations so that constant - or nearly constant - flow rates and concentrations are achieved before being introduced in the treatment plant [math1].

From an engineering point of view, these control objectives appear to be challenging. First, wastewater treatment processes suffer from a systematic lack of reliable sensors and actuators. One reason is that only little money is available since these processes do not produce any added value products. As a consequence, very little information is available for control and one has to optimize the number of hardware systems we need to fulfill the control objectives. In this paper, the actuators are a set of three controllable pumps.

However, as pointed out above, one of the control objectives is to limit output flow rate variations. Thus, the control problem is challenging in the sense that part of the regulation requirements involves actuators themselves. A third point to be pointed out is that the control includes a number of constraints (physical constraints on the pumps, volumetric capacity of the system, functioning range...).

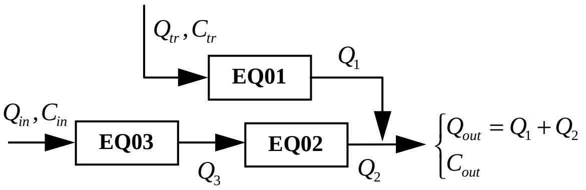
The wastewater treatment facility under interest has to deal with a very dynamic influent : both flow rate, waste concentration and, consequently, loading rate vary. This is the reason why there are three equalization tanks at the treatment plant. Two of them have a working volume of 1400 $m^3$ and one has a working volume of 800 $m^3$. In the near future, a 34% increase in the loading rate is expected. In this case, a complete equalization of the flow rate would require an additional working volume of approximately 3600 $m^3$ (graphically determined [metc1]). An extra basin of considerable volume would thus be necessary, but one should keep in mind that the soluble waste concentration and thus the loading should be equalized as well.

The paper is organized as follows. First, the system and the overall control strategy are presented. After this, a first principles model of the equalization system is derived. An optimal controller together with a fuzzy based supervisory system are then designed and simulation results based upon real data collected on the process over a two months period are presented. Finally, some conclusions and perspectives are drawn.

## 2 Problem statement

The equalization system under interest consists of three equalization tanks interconnected by pumps and pipes as shown in Figure 1. Tanks EQ01, EQ02 and EQ03 have a working capacity of respectively 800, 1400 and 1400 $m^3$. The tank EQ01 is reserved to handle highly concentrated wastewater (discharged from trucks). In the following, pumps $Q_1$, $Q_2$ and $Q_3$ are assumed to be controllable while the influent flow rate ($Q_{in}$) and the truck discharge ($Q_{tr}$) are considered as unmeasured input disturbances with known mean values.

A preliminary study showed the potential of using a control approach to significantly reduce flow rate and load variations [decl1]. Indeed, regarding the characteristics of the equalization system with respect to the influent flow rate and the Total Organic Carbon (TOC) concentration, it is not satisfactory to simply damp them without any control strategy.



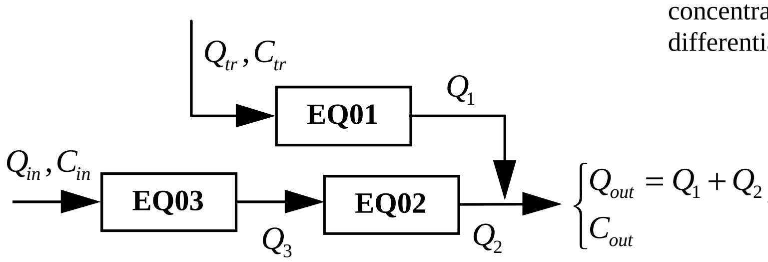




***Figure 1*** *: Configuration of the equalization system*

The idea of the control law to be implemented can then be summarized as follows. First, notice that the mean value of the flow rate coming into and going out of EQ01 is about 1 $m^3$/h. It is relatively small compared to the flow rates delivered by pump $Q_2$ (from data collected over a two months period, their mean values are about 100 $m^3$/h). Second, the water discharged into the calamity tank EQ01 has a significantly higher TOC concentration than the water entering the process through $Q_{in}$. As a consequence, the major idea of the proposed control strategy is to manipulate the controllable pump $Q_2$ in order to adjust the output flow rate (control objective 1) and to use $Q_1$ to regulate as much as possible the output TOC concentration (control objective 2). In other words, the control has a decentralized structure and the system modeling was divided into two sub-systems, the first one describing what happens in EQ01 while the second one is concerned with the interaction between EQ02 and EQ03.

Clearly, the control problem can be defined as a regulation problem in the presence of unmeasured input disturbances. In other words, we face an input disturbance attenuation problem. Indeed, the control objectives can be summarized as follows :

- Regulation of the output flow rate $Q_{out} = Q_1 + Q_2$
- Regulation of the output TOC concentration $C_{out} = \dfrac{C_1 Q_1 + C_2 Q_2}{v_{1o} Q_1 + Q_2} = \dfrac{Num}{Q_{out}}$

with $Num = C_1 Q_1 + C_2 Q_2$ while $C_1$, $C_2$ and $C_3$ are the TOC concentrations in EQ01, EQ02 and EQ03 respectively.

If $C_1$ is considered as an external disturbance, and assuming that the output TOC $C_{out}$ is measured on-line, it is straightforward that the control objective 2 can be fulfilled in acting on the system through $Q_1$ and $Q_2$.

Now, in order to better go through its analysis, the equalization process is being to be modeled.

# 3 First principles modeling and control design

According to first principles and defining the state of the system to be composed of the volumes $V_1$ to $V_3$ and the concentrations $C_1$ to $C_3$, it is straightforward to establish the differential equations that govern the system as :

$$\begin{cases} \dfrac{dV_1}{dt} = Q_{tr} - Q_1 \\ \dfrac{dV_2}{dt} = Q_3 - Q_2 \\ \dfrac{dV_3}{dt} = Q_{in} - Q_3 \end{cases} \tag{1a}$$

$$\begin{cases} \dfrac{dC_1}{dt} = \dfrac{Q_{tr}\left(C_{tr} - C_1\right)}{V_1} \\ \dfrac{dC_2}{dt} = \dfrac{Q_3\left(C_3 - C_2\right)}{V_2} \\ \dfrac{dC_3}{dt} = \dfrac{Q_{in}\left(C_{in} - C_3\right)}{V_3} \end{cases} \tag{1b}$$

Notice that the part of the non linear model (1) describing the evolution of the volumes is linear. However, this part is unstable. One of the control objectives would then be to stabilize the volumes.

At this step, several strategies were examined, keeping in mind that the "optimal" strategy would be the simplest one in terms of computation and implementation. One solution would have been to implement an extended Kalman filter (assuming that the external disturbances can be considered as white noises) to reconstruct the concentrations on-line and extract necessary information for a reconstructed state feedback. However, keeping in mind the industrial characteristic of the work and regarding the decoupled structure of the system described in Figure 1, it was rather decided to use the simple control system structure described in Figure 2 in splitting the regulator into two complete decentralized parts :

- A Linear Quadratic state feedback (LQ controller referred as controller 1) using a second order system involving the state $x_1^T = \left(V_2 \quad V_3\right)$ and the control vector $u_1 = \left(Q_2 \quad Q_3\right)^T = G\left(V_2 \quad V_3\right)^T$ in order to stabilize $V_2$ and $V_3$. In weighting $Q_2$ very much with respect to $Q_3$, it can be expected the variations of $Q_2$ to be negligible compared to those of $Q_3$.

- A simple Proportional-Integral controller[1] (PI controller referred as controller 2) for computing $Q_1$ as a function of the output waste TOC concentration which is measured on-line.

Then, on one hand, the new optimal controller 1 objective will simply focus on limiting the control action $Q_2$ while stabilizing $V_2$ and $V_3$. On the other hand, notice that limiting this control action can be seen as satisfying the control objective related to the regulation of the output flow rate $Q_{out}$ (given that $Q_1$ is negligible with respect to $Q_2$). The structure of the global controller, consisting in the association of the controllers 1 with the controller 2 is shown in Figure 2.

The state feedback gain matrix $G$ of the controller 1 is computed by minimizing :

$$J = \int_{t_0}^{t_f} \left( y^T Q_y y + u^T R u \right) d\tau \qquad (2)$$

The solution to the minimization problem of (2) subject to a linear dynamical structure is well known and does not present any difficulty (see for example [ande1]). In order to implement the global controller, we simply discretize them with a one hour sample time to obtain the general implementable following form as :

$$\begin{cases} u(k) = Gx(k) \\ Q_1(k) = PI(C_{out}(k)) \end{cases} \qquad (3)$$

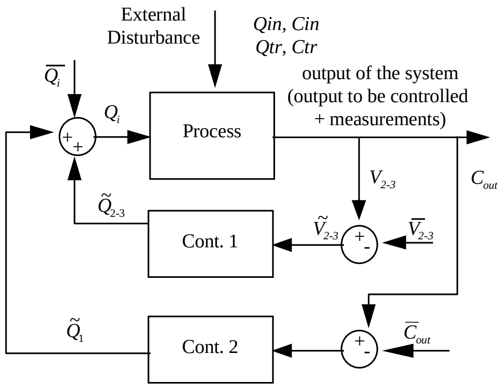



***Figure 2 :*** *Configuration of the control system*

***Remark :*** Notice that the degree of freedom of the controller 2 is relatively small. Indeed, controller 2 aims to regulate the output concentration using $Q_1$. However, regarding the structure of the system, the output flow rate is the sum of $Q_1$ and $Q_2$! Thus, it has no sense to very well regulate $Q_2$ with controller 1 and then "cancel" that good regulation with controller 2 to buffer the output TOC concentration. As a consequence, when choosing this strategy, we have to limit the effect of the controller 2 and constrain $Q_1$ to stay within pre-specified bounds that are not affecting $Q_2$ very much...

# 4 Necessity of a supervisory system

In fact, it appears that the proposed control scheme exhibits good results when part of the states of the system (i.e., the volumes) are far enough from their constraints (i.e., low and high volume limits) [harm1]. In other words, the control scheme gives good performance but only when the three tanks are not full or empty. In these two extreme situations (volumes full or empty), the control system misses the necessary degree of freedom to buffer the flow rate and the TOC output concentration. In fact this comes from a problem of ability of the control algorithm to fulfill the control objectives. Again, let us consider the two following extreme cases.

On the one hand, assume that the input flow rate is significantly higher than $\overline{Q_i}$ for a long period of time. without an intelligent system, it is obvious that, after a given time, tanks will overflow. In this case, it is then necessary to increase $\overline{Q_i}$. Now, assume that the input flow rate is significantly smaller than $\overline{Q_i}$ for a long period of time. In this case, it is quite obvious that the $\overline{Q_i}$ values have to be decreased.

In order to overcome this difficulty, we thus added to the general previously presented control strategy a fuzzy-based supervisory system. This supervisor determines the operating point around which the process has to operate in order to avoid saturation of the volumes. The inputs of the fuzzy supervisory system consist of both volumes $V_2$, $V_3$ and their derivatives $\dot{V}_2$, $\dot{V}_3$ to take into account their rate of variation. The output of this system then adjusts $\overline{Q_2}$ and $\overline{Q_3}$ in order to avoid the saturation of $V_2$ and $V_3$.

The structure of the global controller is then depicted in Figure 3. Each input variable is qualified into fuzzy values as presented in Figure 4.

[1] Notice that it is the "responsability" of controller 2 to stabilize $V_1$.

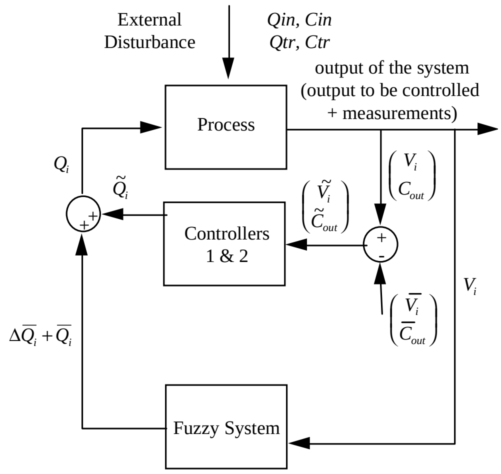



***Figure 3 :*** *Configuration of the control system*

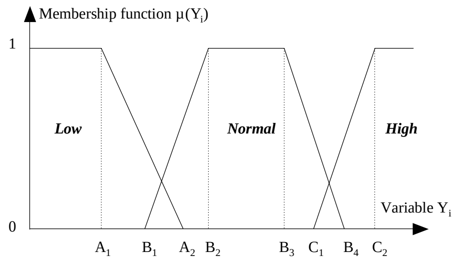



***Figure 4 :*** *Fuzzification scheme of the variables*

After several tests, it was decided to use the tuning parameters given in Table 1 :

***Table 1 :*** *The tuning parameters for the fuzzification of the variables*

| | $A_1$ | $A_2$ | $B_1$ | $B_2$ | $B_3$ | $B_4$ | $C_1$ | $C_2$ |
|---|---|---|---|---|---|---|---|---|
| $V_1$ | 50 | 250 | 200 | 350 | 550 | 700 | 650 | 800 |
| $V_2$ | 100 | 600 | 100 | 600 | 900 | 1400 | 900 | 1400 |
| $V_3$ | 100 | 400 | 100 | 350 | 1100 | 1400 | 1150 | 1400 |
| $\Delta Q_1$ | -3 | 0 | -4 | -2 | 2 | 4 | 0 | 3 |
| $\Delta Q_2$ | -60 | -40 | -60 | -15 | 15 | 60 | 40 | 60 |
| $\Delta Q_3$ | -40 | 0 | -40 | -10 | 10 | 40 | 0 | 40 |

It can be noticed that the number of classes for each input has been limited to three. Indeed, because of the number of inputs (i.e., 3) with 3 possible values each, we have to build $3^3$ = 9 rules for the fuzzy system (see Table 2). An increase of the number of classes would then have led to a larger number of rules and then to an increase of the complexity. In such a case, for example, a hierarchical architecture could have been developed that would have simplified the rule base building (See for example [esta1] for a hierarchical fuzzy controller of an anaerobic digestion process).

***Table 2 :*** *The Rule Base of the fuzzy based supervisory system*

| $V_1$ | $V_2$ | $V_3$ | $\Delta Q_1$ | $\Delta Q_2$ | $\Delta Q_3$ |
|---|---|---|---|---|---|
| Low | - | - | Low | - | - |
| Normal | - | - | Normal | - | - |
| High | - | - | High | - | - |
| - | Low | Low | | Low | Low |
| - | Low | Normal | - | Normal | High |
| - | Low | High | - | Normal | High |
| - | Normal | Low | - | Normal | Low |
| - | Normal | Normal | - | Normal | Normal |
| - | Normal | High | - | Normal | High |
| - | High | Low | - | Normal | Low |
| - | High | Normal | - | Normal | Low |
| - | High | High | - | High | High |

Finally, the fuzzy information contained in the conclusive consequence of the rules is aggregated into a number (i.e., defuzzified) to determine the numerical corrections for the flow rates. This step is achieved using the "gravity center" method.

# 5 Simulation Results

For simplicity, and regarding the structure of the controller 1, we tested in simulation a standard stationary LQ controller. The only problem of the synthesis procedure is to optimally compute the tuning matrices $Q$ and $R$ in the criterion. Here, since the system is very simple, we just proceeded by trial and error in order to limit the variations of $Q_2$ as much as possible. The PI controller has also been tuned using a trial and error approach (proportional term : 0.0025, integral term : 0.0015)

Concerning the disturbances, we disposed of 1440 hours of measurements on the real process. After analysis of these data, it appears that the mean value of the input flow rate $Q_{in}$ is about 90 m$^3$/h while the mean value of the input TOC $C_{in}$ is about 3000 mg/l. Concerning $Q_{tr}$ and $C_{tr}$, they are assumed to be constant : $Q_{tr}$ = 1 m$^3$/h and $C_{tr}$ = 35000 mg/l. In the future, the mean load is expected to be increased by 34 %.

In the following, the proposed control algorithm is tested with a 34 % increase in the concentration while keeping the input flow rate as in the measurements. The operating point corresponding to the mean value of the available data with a 34 % increase of the input TOC concentration (i.e., $\overline{C}_{in}$ = 3860 g/m$^3$) but with a 34 % increase of the input TOC concentration (i.e., $\overline{Q}_{in}$ = 90 m$^3$/h is computed given that $\overline{Q}_{tr} = 1$ m$^3$/h and $\overline{C}_{tr}$ = 35000 g/m$^3$.

The operating point (computed from $\dot{x} = 0$ in (1)) is thus defined by $\overline{V}_1 = 400$ m$^3$, $\overline{V}_2 = 800$ m$^3$, $\overline{V}_3 = 800$ m$^3$, $\overline{Q}_1 = 1$ m$^3$/h, $\overline{Q}_2$ =90 m$^3$/h, $\overline{Q}_3$ =90 m$^3$/h, $\overline{C}_1$ =35000 g/m$^3$,

$\overline{C}_2$ =3860g/m$^3$, $\overline{C}_3 = 3860$ g/m$^3$. The simulation results are provided in Figures 5.

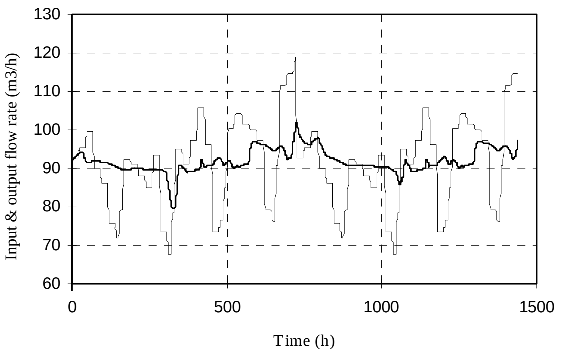



***Figure 5a :*** *Input (thin line) and output (bold line) flow rates*

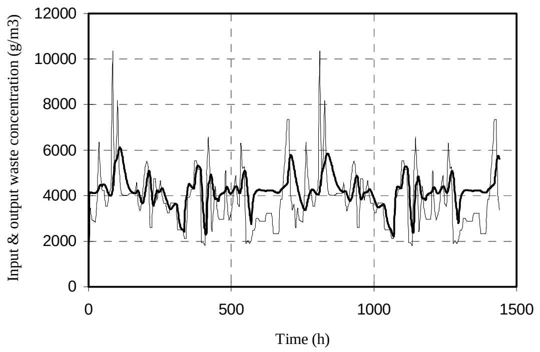



***Figure 5b :*** *Input (thin line) and output (bold line) TOC concentrations*

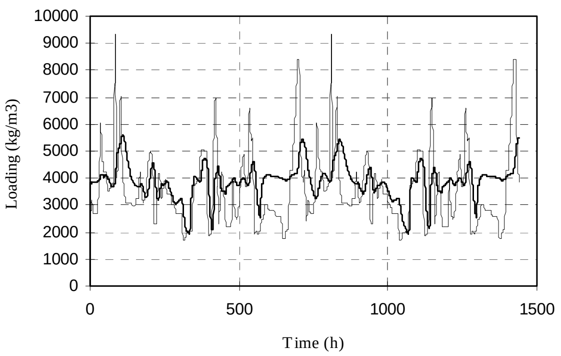



***Figure 5c :*** *Input (thin line) and output (bold line) loading*

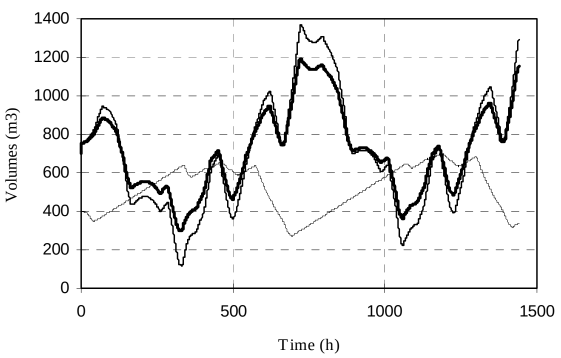



***Figure 5d :*** *Actuators ($V_1$ to $V_3$ from thinner to thicker lines)*

From these simulations, we can obtain the following statistical characteristics :

***Table 3 :*** *Statistical evaluation of the control strategy*

| | **Variances** | | |
|---|---|---|---|
| | *Flow rate* | *Waste Concentration* | *Loading* |
| *Influent* | 121.8 | 2.8 $10^6$ | 3.2 $10^6$ |
| *Effluent* | 17.3 | 1 $10^5$ | 9.5 $10^5$ |

Notice that these statistical results have to be relativated from a control engineering perspective. Indeed, they only have a real pertinence when involved within a classical regulation problem evaluation. However, this is not exactly the case here since the setpoint is adjusted depending on the input disturbances. As a consequence, the setpoint is time-varying and the variance looses a little bit its physical meaning. Note, however, that from process engineering point of view reduction of the variance is paramount and that the equalization performance is best analyzed using these statistical numbers.

The following conclusions can be drawn from these results :

- Our control objectives are quite well fulfilled. Indeed, $Q_{\text{out}}$ is almost constant and the output waste concentration is very well attenuated compared to the input.
- At the same time, we are able to manage the overall time period without any saturation in the volumes.

To simulate the effect of a 34% increase in load, also the other extreme case (i.e., a 34% increase in the flow rate while the concentration was maintained as in the plant data) was simulated. The results of this were comparable to the ones presented but are not shown here.

# 6 Conclusions & Perspectives

This paper presented an advanced control strategy based on the association of a fuzzy logic supervisor with 2 local controllers for the control of an equalization system. The obtained results were in very good agreement with our objectives and they demonstrated the ability of a combined LQ controller/setpoint determination fuzzy logic based system to manage effectively an equalization system.

# 7 Acknowledgments

This research was financially supported by the "Flemish Institute for the Promotion of Scientific-Technological Research in Industry (IWT)", Belgium.

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