# Lessons learnt from the application of advanced controllers in the Mekolalde WWTP: good simulation practices in control

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## INTRODUCTION

Located at the region of Gipuzkoa (northern Spain), the *Mekolalde* Wastewater Treatment Plant (WWTP) was designed and constructed in 2005 to serve a total population of about 50000 inhabitant-equivalent. With capacity to process each day up to 10000 $m^3$ of pre-treated wastewater, a conventional activated sludge configuration was adopted to deal with nitrogen removal requirements. Since its start-up in June 2008 until April 2011 the only operative controllers in the secondary treatment have been, as in many other plants, those connected with low-level operations such as regulating (1) the internal recycling flow-rate, (2) the surplus sludge flow-rate, and (3) the concentration of dissolved oxygen in the aerated basins. The plant was equipped with advanced on-line instrumentation for suspended solids (MLSS), nitrates ($NO_3$-N) and ammonia ($NH_4$-N); however, their use was confined to merely assist the decisions by plant operators. **Figure 1** illustrates the plant-layout of the secondary treatment, with sensors and actuators also included.

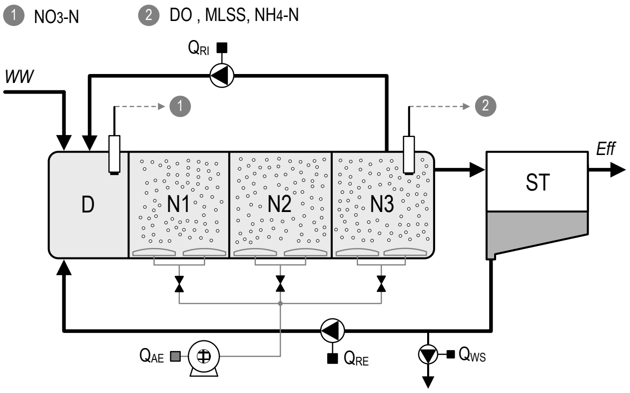

**Figure 1**. The *Mekolalde* WWTP: plant-layout of the secondary treatment

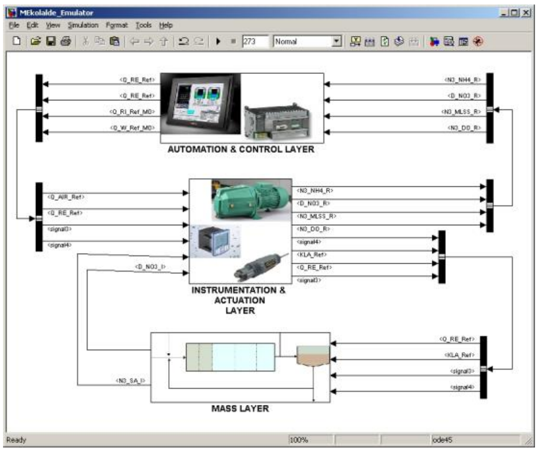

**Figure 2**. Software emulator for the *Mekolalde* WWTP

In 2010 and under the acronym ADD-CONTROL, a two-year European research project was launched with the ambition of producing new WWTP-domain specific simulation software (henceforth, *Add-control* software) totally oriented to ensure a rapid and reliable development of advanced control products (Maiza et *al*., 2011). As part of the work-plan, the *Mekolalde WWTP* was the case-study selected to test and verify the performance of this new software. Unlike other previous works that covered mathematical modelling and programming issues connected with *Add-control* software (Brokmann et *al*., 2011; Amerling et al., 2012), this paper rather deals with its practical value which is exemplified through its contribution to the realization of an advanced control product for the *Mekolalde* WWTP.

## CONTROLLER DESIGN: SIMULATED BEGINNINGS…

The software *Add-control* and, specifically, its comprehensive library of models for treatment units, real sensors, real actuators, controllers, etc. were used to easily obtain an emulator of the plant-

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layout in **Figure 1**. As a distinctive feature in *Add-control*, the emulator followed a three-layer implementation where each layer was respectively devoted to mimic tanks and reactors (wrapped in the so-called mass bottom-layer), sensors and actuators (instrumentation intermediate-layer), and controller devices (control top-layer). **Figure 2** shows a *Matlab/Simulink*®-based implementation of the emulator where each block corresponds to each of the above three layers.

Once the emulator for *Mekolalde* was completed, historical information on the performance of the plant in 2009 was collected to proceed with its calibration. The latter involved not only assigning appropriate values to the the coefficients of the biochemical model but, equally important, to the parameters of the models associated with real sensors and actuators. Moreover, special interest was addressed at predicting the consumption of energy by (1) the air blowers and (2) the internal recirculation pumps. Being its potential to save energy the most persuasive credit in favour of advanced control, the design of control products using specifications of energy reduction at the onset of the simulation study becomes *de facto* imperative. Nonetheless, unlike other simulation studies in which fine predictions are highly recommended, here calibration tried to reach trade-offs between model accuracy and time required to complete the process. In compliance with modern control design, the calibration conducted in this work sought to specify, rather than fixed values for the model coefficients, the uncertainty space in which model predictions were reasonably acceptable. It is noticed however that only nominal performance specifications were imposed to design the advanced controller. The robust performance of the designed controller was assessed by running simulations over the specified uncertainty space. **Table 1** summarizes the uncertainty space that was finally obtained after calibrating the model for a 9-month period of plant operation. **Figure 3** illustrates the quality of predictions through comparison of real values for effluent $NH_4$-N and $NO_3$-N with simulation results.

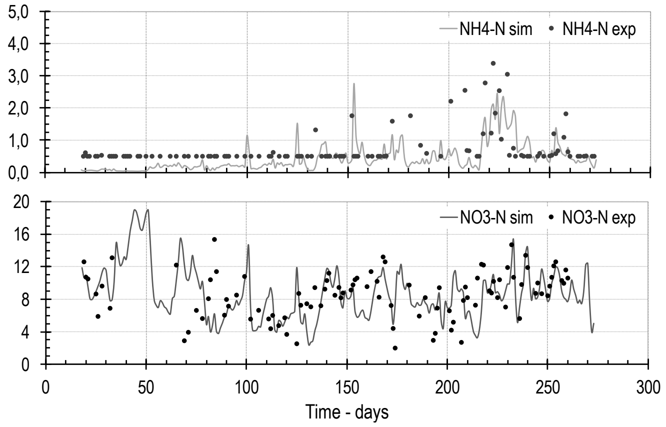

**Figure 3**. Plant model predictions with the emulation software

| Parameter | Unit | Min | Max |
|---|---|---|---|
| $\eta_h$ | -- | 0.6 | 0.8 |
| $K_{OH}$ | mg $O_2$/L | 0.28 | 0.4 |
| $K_{NO}$ | mg $NO_3$-N/L | 0.2 | 0.5 |
| $K_{OA}$ | mg $O_2$/L | 0.3 | 0.6 |
| $K_{NH}$ | mg $NH_4$-N/L | 0.82 | 1.00 |
| $\mu_{aut}$ | $d^{-1}$ | 0.76 | 0.97 |

*Note: Variables are not totally uncorrelated. In fact, for the determination of the uncertainty space, clustering and PCA techniques were applied (details have been omitted here)*

**Table 1.** Uncertainty ranges for model coefficients after calibration

Contained in the control layer, an advanced control solution made up of three non-interacting PID-based controllers was integrated into the emulator. While this control scheme (**Figure 4**) can be easily recognised amongst the vast literature dedicated to automatic control of activated sludge systems (Olsson et *al.*, 2005), it was the manner to attack the design of each PID that introduced a subtle difference with similar works in the topic. Specifically, the parameters of the $NH_4$-N controller were tuned only after the non-linear characteristic of blowers, the dynamic response of the DO sensor and the "discrete" nature of the $NH_4$-N signals had been added to the problem. In doing so, it was possible to design a controller that combined proper disturbance rejection properties with minimum use of the control effort and, therefore, of the energy for aeration. Similarly for the second controller, the $NO_3$-N controller, design specifications gave priority to minimising the control effort, in this case the internal recirculation flow-rate which, in addition, was constrained to values in the range of 150-500 m$^3$/h.

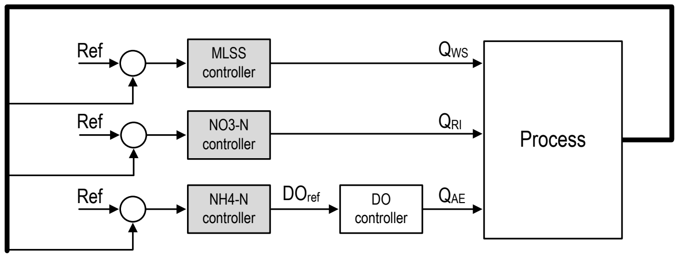

**Figure 4**. Controller scheme

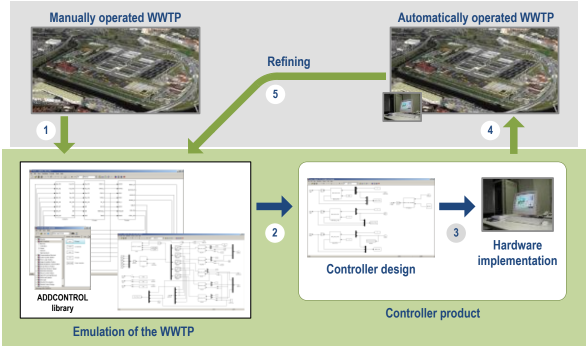

**Figure 5**. Control design procedure

Though the third controller was originally specified to maintain MLSS concentrations close to a constant reference, simulations revealed that this goal demanded designs with relatively high gains. Surplus sludge pumps (the control action of the MLSS controller) account for a small part of the treatment costs. It meant that energy savings were not relevant here and, hence, that the control effort was not dictated by energy considerations. The argument for limiting in this case the control effort was the very well known effect that the surplus sludge flow-rate has not only on the secondary treatment (it determines the sludge retention time) but also on the sludge treatment stream (sludge load). It was seen that high-gain designs achieved good rejection of disturbances in the secondary treatment but at the expense of introducing large and undesired disturbances in the sludge treatment. The latter required a redefinition of the original control specifications; in particular, the specification for disturbance attenuation in the secondary treatment had to be relaxed. Thus, the new design tried to reach a reasonable trade-off between acceptable disturbance rejection in the secondary treatment and minimum impact on the sludge treatment. It is worth mentioning that, in chronological order, the redesign of the MLSS controller was conducted after feedback about the real performance of the original design was collected from the plant. Actually, the above was a confirmation that the design of advanced controllers for WWTP involves an iterative process that begins with simulations, continues with full-scale validation and, finally, requires further simulations to refine the original control solution (**Figure 5**).

| | | **Convent. Op.** | **Controlled Op.** |
|---|---|---|---|
| NH4-N | mg/L | 0.55 (0.11) | 0.84 (0.14) |
| NO3-N | mg/L | 8.93 (0.26) | **5.56** (0.28) |
| TIN | mg/L | 9.48 (0.30) | 6.40 (0.39) |
| Energy costs | kW | 45.3 (0.2) | 41.5 (0.4) |

*Note: In parenthesis, standard deviation values*

**Table 2**. Simulation study: performance results of the advanced controllers

| | | **Jul** | | **Aug** | | **Sept** | | **Oct** | | **Nov** | | **Dec** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ***'10*** | ***'11*** | ***'10*** | ***'11*** | ***'10*** | ***'11*** | ***'10*** | ***'11*** | ***'10*** | ***'11*** | ***'10*** | ***'11*** |
| **Qinf** | m$^3$/h | 116 | 145 | 108 | 99 | 130 | 168 | 140 | 137 | 207 | 218 | 178 | 262 |
| **Temp** | ºC | 21 | 19 | 21 | N/A | 20.7 | N/A | 18.4 | 18.7 | 15 | 16.9 | 12.2 | 14.5 |
| **MLSS** | mg/L | 3602 | 3333 | 3828 | 3211 | 3839 | 3553 | 3993 | 3176 | 3370 | 2968 | 3283 | 3062 |
| **$Q_{RI}$** | m$^3$/h | 418 | 204 | 371 | 202 | 419 | 221 | 441 | 207 | 481 | 200 | 388 | 191 |
| **$Q_{AE}$** | Nm$^3$/h | 537 | 461 | 475 | 327 | 554 | 559 | 621 | 576 | 544 | 642 | 632 | 654 |
| **DO** | mg/L | 1.7 | 0.5 | 2.4 | 2 | 1.7 | 0.5 | 2.0 | 0.6 | 5.2 | 0.8 | 1.9 | 0.8 |
| **TIN eff** | mg/L | 3.1 | 4.1 | 10.3 | 4.1 | 4.9 | 3.7 | 7.2 | 4.5 | 14.2 | 4.7 | 9.2 | 5.8 |

**Table 3**. Plant performance: comparative results of manual operation (*'10: 2010*) versus controlled operation (*'11: 2011*)

The same procedure was followed to design each individual PID controller. Steady-state simulations were performed first and the value of the proportional gain adjusted to get steady-state error values close to the accuracy range of the sensors involved. Then, the integral time was tuned in order to provide smooth adaptation of the control action to medium/long-term disturbances (weekly and seasonal variations). Finally, the derivative term was tuned to keep deviations of the controlled signal caused by hourly disturbances within acceptable levels. After this, the performance of the above controllers was analyzed running *random* simulations over samples taken from the model uncertainty space. The results of this study are summarised in **Table 2** which also includes simulation results for a conventional operation of the plant. As usual, performance results were quantified in terms of water quality (Total Inorganic Nitrogen – TIN = $NH_4$-N + $NO_3$-N) and operating costs (energy). In short, simulations proved to be useful not only to design and tune each controller but also to give a first estimate of the expected improvements: by about 32% and 8% for water quality and energy savings, respectively.

## … REAL ENDINGS: FULL-SCALE VALIDATION

In May 2011 once the simulation study had been concluded, the three controllers were implemented and put into operation at the plant. Since then plant operation has permanently exhibited an out-performance in the same order of magnitude as that predicted with the emulation software. Results in **Table 3** compare the average performance of the plant between the months of July and December in two consecutive years, 2010 (manual operation) and 2011 (controlled operation). Some figures have been highlighted in grey boxes to signify superior performance (either in effluent quality or energy consumption). From the above figures, it is clearly attributable to the action of the advanced controllers a substantial improvement in the quality of the effluent. In particular, while in 2010 the effluent TIN experienced continuous variations with values ranging from 3 to 14 mg N/L, during 2011, this process variable was consistently kept in average values below 6 mg N/L. A concurrent reduction of the dissolved oxygen in the aerated basins (DO) and of the internal recycling flow-rate ($Q_{RI}$) was in part the cause of these positive results. Specifically, while the average DO lowered up to values below 1 mg/L, $Q_{RI}$ was reduced by about 50% when compared with the values of 2010. A rough estimate of aeration savings was obtained by contrasting plant performances in October 2010 and 2011. These two months showed similar values for the influent flow-rate ($Q_{INF}$) and temperature (Temp), and therefore a reasonable basis for comparison. In this regard, the air flow-rates values were reduced by 7% due to the ammonia controller. This improvement was, however, far below simulated expectations (20%). Assuming reliability of measurements, two major arguments for this under performance are: (1) that the influent nitrogen load in October 2011 would have been higher than that in October 2010, (2) that the effluent ammonia was higher in October 2011 (2.05 mg N/L versus 0.3 mg N/L in October 2010) and, consequently, the required oxygen lower. Finally, it was not possible to obtain direct values for energy because the plant did not have sensors of power consumption for the internal recycling pump and for the blower. Nonetheless considering that the controllers lowered the operating flow-rates of these two actuators, it can be objectively asserted that energy consumption also experienced proportional reductions.

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