Add Control: plant virtualization for control solutions in WWTP

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Abstract
This paper summarises part of the research work carried out in the Add Control project, which proposes an extension of the WWTP models and modelling architectures used in traditional WWTP simulation tools addressing next to the classical mass transformations (transport, physico-chemical phenomena, biological reactions), all the instrumentation, actuation and automation & control components (sensors, actuators, controllers), considering their real behaviour (signal delays, noise, failures and power consumption of actuators). Its ultimate objective is to allow a rapid transition from the simulation of the control strategy to its implementation at full-scale plants. Thus, this paper presents the application of the Add Control simulation platform for the design and implementation of new control strategies at the WWTP of Mekolalde.

Keywords
Automatic control; component based modelling; simulation; wastewater treatment plants.

Introduction

Tougher effluent quality standards, increasing wastewater loads, and energy consumption and operation costs reduction requirements are nowadays forcing wastewater treatment plants (WWTP) to work under more and more stringent conditions. Many automatic control strategies have shown their usefulness at simulation scale, or even pilot plant scale for improving WWTP performance without structural changes in the plant (Zarrad *et al.*, 2004; Olsson *et al.*, 2005; Yong *et al.*, 2006a; Yong *et al.*, 2006b; Holenda *et al.*, 2007; Stare *et al.*, 2007). However, they are experiencing limited full-scale plant applicability (Ayesa *et al.*, 2006) due to the still low reliability of the data provided by on-line sensors and analyzers and the ideal behaviour of sensors and actuators commonly assumed by existing WWTP-specific simulation platforms: wastewater systems-specific modelling & simulation tools (e.g., WEST®/Tornado) provide quite limited and ideal behaviour based controller models, whereas general purpose modelling & simulation tools (e.g., MATLAB®/Simulink®) lack wastewater treatment-specific processes model libraries. Therefore, neither WWTP-specific nor general purpose simulation packages are suitable for the design and implementation of wastewater system automatic controllers.

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The Add Control project addresses this problem and proposes an extension of the WWTP models and modelling architectures used in traditional WWTP simulation platforms considering next to the classical mass transformations (transport, physico-chemical phenomena, and biological reactions) all the instrumentation, actuation and automation & control components (Maiza *et al.*, 2011). Regarding instrumentation and actuation, their real (not ideal) behaviour is modelled, including actuators power consumption. Hence, all aspects considerably influencing the real controllers' performance and strategy are accounted for.

Project Information

Objective

The objective of the Add Control project is to design, develop and validate a modelling and simulation software (SW) tool which will ultimately allow a rapid transition from the simulation of control strategies to their implementation at full-scale plants. Frequently the real behaviour of sensor and actuators is not taken into consideration when designing controllers, either because no appropriate SW tools are available or its influence on controllers performance is considered negligible. However most of the times this is considerable. Thus, the Add Control project aims at providing a tool for virtualizing an entire WWTP, which means modelling all components involved in the operation of the plant, that is, from treatment processes to instrumentation, actuation and control components.

Consortium

Add Control is a 24-month 'Research for SMEs' FP7-EU project that started in June 2009 and with ten partners from four EU countries: six SMEs (Mondragón Sistemas de Información, Soc. Coop., Spain, Project Coordinator; MOSTforWATER, Belgium; NASKEO Environnement, France; AQUA-CONTACT Praha v.o.s; Czech Republic; Société Coopérative Agricole de Distillation d'Ornaisons (SCAD), France; Aguas de Gipuzkoa S.A.; Spain); two research institutions (Centro de Estudios e Investigaciones Técnicas (CEIT), Spain; Institut National de la Recherche Agronomique (INRA), France) and; one university (Ghent University, Belgium). Further information can be found at www.addcontrol-fp7.eu.

Methods

This paper focuses on the application of the Add Control platform for the design and implementation of automatic controllers at the full-scale, real plant of Mekolalde. Before analysing the obtained results, some details of the used Add Control modelling and simulation platform and the implemented automatic controllers are given.

The Add Control simulation platform

The Add Control platform proposes a multilayer modelling architecture for interfacing all components of a plant. Being the main application of this software tool the design and development of automatic controllers, a classical automation & control hierarchical structure is followed.

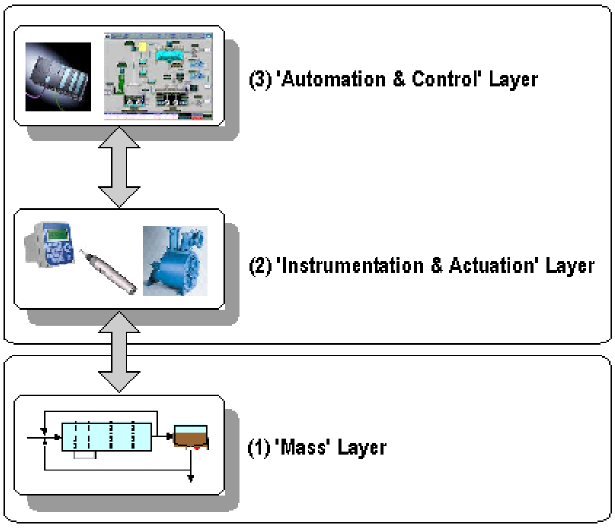

Figure 1. Schematic representation of Add Control's multilayer architecture.

The multi-layer modelling architecture separates the mathematical models of the mass-flows derived from water treatment processes (tanks, reactors, settlers, hydraulic connections, hydraulic flows, etc.) from the virtualization of the data-flows associated with instrumentation, actuation and control devices. Consequently, three model layers are defined: (1) the treatment process or 'mass' layer describing the biochemical, physico-chemical, equilibrium, liquid-gas transfer, hydraulic and other processes that take place in the different reactors of the plant based on the Plant Wide Modelling specification of Grau *et al.*, 2007; (2) the 'instrumentation & actuation' ('I&A') layer, describing sensors' and actuators' real behaviour based on the work of Alex *et al.* 2009a, Alex *et al.* 2009b and Rosen *et al.* 2008, including signal delays, noise and failures and power consumption; (3) the 'automation & control' ('A&C') layer, describing automatic control devices (ON/OFF controllers, PID controllers, Fuzzy controllers, etc.) and signal processing algorithms (sampling, filtering, A/D & D/A conversions, etc.). This architecture allows readily integrating the different mathematical models and replicating the classical control architecture of real plants.

Automatic controllers for the WWTP of Mekolalde

The objective of implementing automatic controllers for a full-scale WWTP is to explore the appropriateness of the Add Control solution as WWTP modelling and simulation platform for the design and implementation of controllers. For this purpose, Project Partner CAG kindly provided their WWTP of Mekolalde and all the requested data to Project Partners CEIT and MSI, who were responsible of the design and industrial implementation of the automatic controllers respectively.

The WWTP of Mekolalde, located in the town of Bergara, was designed to treat wastewater coming from the towns of Bergara, Elgeta and Antzuola (Spain) with a total capacity of 40000 equivalent inhabitants. It has three water lines where at this moment one is active; shortly, the other two will be activated. In this project automatic controllers for the secondary treatment (water line) of the active line of the plant which corresponds to a conventional pre-denitrifying activated sludge process made up of four tanks arranged in series were designed and implemented. The first tank operates under non aerated conditions, necessary to perform the denitrification of nitrates. A blower injects air into the other three reactors for supplying the oxygen required to keep the effluent ammonia concentrations below upper limits.

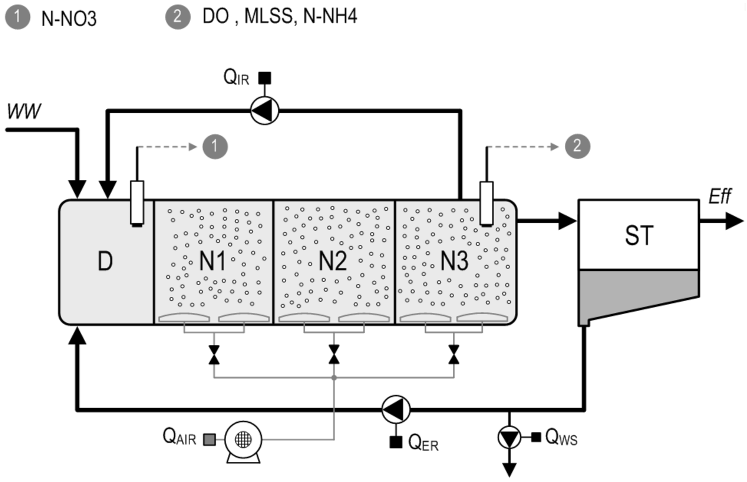

Figure 2. Configuration of the secondary treatment of the WWTP of Mekolalde.

In agreement with the literature (Ayesa *et al.*, 2006), a decentralised control schema based on three non-interacting feedback controllers has been designed and implemented, each SISO loop being devoted to control (1) the concentration of suspended solids in the mixed liquor (MLSS); (2) the ammonia concentration in the last aerobic reactor; and (3), the nitrates in the first anoxic tank respectively.

Results

The results herein described refer to the use of the Add Control modelling and simulation platform for the design and implementation of the above MLSS, ammonia, and nitrates controllers at the full-scale secondary treatment of the Mekolalde WWTP. Before addressing the implementation of the controller in real plant, a simulation study aimed at analysing the performance of the control solution designed by the Add Control platform in terms of energy costs and water quality was carried out, for which the sensor models and pump and blower cost functions defined in Add Control, 2011 were incorporated.

Simulation study

Tables 1 and 2 show the average performance of the Mekolalde WWTP for a 9-month simulation period of the plant operated on two different control strategies: (i) a conventional open-loop strategy (OL); (ii) a closed-loop (CL) strategy where the above controllers (MLSS + ammonia + nitrates) are activated.

Table 1. Comparative cost simulation results of two control strategies at the Mekolalde WWTP

	Q_{AIR} Cost kWh	**Q_{IR} Cost** kWh	**Total Costs** kWh	Savings* (%)
OL	265712	33282	298994	(reference point)
CL	255470	21980	277450	7.2

**Average values relative to the OL strategy*

Table 2. Comparative quality simulation results of two control strategies at the Mekolalde WWTP

	Effluent NH4-N mg N/L	**Effluent NO3-N** mg N/L	**MLSS** mg/L
OL	0.64 (1.4)*	9.41 (3.2)	3172 (420)
CL	0.94 (1.5)	7.79 (2.8)	3004 (92)

** Average values (standard deviation in parenthesis)*

where Q_{IR} and Q_{AIR} stand for 'internal recirculation flow rate' and 'total air flow-rate'.

The CL control strategy leads to a total saving of 7.2% with respect to OL. This saving is mainly attributed to the performance of the ammonia controller. The effluent ammonia in the OL strategy takes average values near 0.64 mg N/L. Being the ammonia requirement at the effluent 1 mg N/L, these strategy evidences an over-aeration and, consequently, extra costs. Conversely, the ammonia controller was able to perform well by adjusting at every instant the amount of air needed to keep the effluent ammonia at levels near the required upper limit (0.94 mg N/L): as a result, not negligible reductions in aeration costs are obtained. An extra saving comes from the fact that with the CL strategy a unique pump working in the range of 150-250 m^3/h is used for internal recirculation, whereas with the OL strategy two parallel pumps working in the range of 300-500 m^3/h were used.

While energy savings is one of the important benefits of using the proposed new controllers, the benefits in water quality can be observed by looking at the results of the nitrates at the effluent. The activation of the nitrates controller could reduce this process variable by about 2 mg N/L (from 9.41 in OL to 7.79 mg N/L in CL).

Full-scale implementation of the controllers

The simulation studies demonstrated the improvements derived from the new control solution designed by the Add Control platform. Subsequently a real implementation of the controllers was addressed. The performance of the WWTP before and after the implementation of these controllers was compared, at periods where the influent water was as similar as possible regarding influent flow-rate, TKN, TSS and temperature.

The NH4-N and NO3-N controllers designed with the Add Control platform were activated at the Mekolalde plant in April 2011. Accordingly, the period selected for the experimental validation covered the following time periods:

- April, May, June (2010): it corresponds to one year before the implementation of the NH4-N, NO3-N and MLSS controllers. The plant was operating in open loop, with no automatic controllers. As shown in Table 3, the influent water exhibits similar characteristics for the same time of years 2010 and 2011.
- January, February, March (2011): this period corresponds to the months immediately before the activation of the new controllers, which is helpful to observe changes in plant performance attributable to these controllers.
- April, May, June (2011): as mentioned above, it was in April 2011 when the new controllers begin its operation at the plant. Since then, the plant has been working in closed loop as indicated in the table below.

A summary with average values corresponding to these periods is shown in Table 3. In February and March 2011 there was a breakdown of the SCADA system and no sensor values are available for that period, so some average values corresponding to the months previous to implementing the new control solution are omitted.

Table 3. Experimental influent water, manipulated variables and output average values.

Influent	**OL**		**CL**	**Operating variables**	**OL**		**CL**	**Process variables**	**OL**		**CL**
	2010	**2011**	**2011**		**2011**	**2011**	**2011**		**2010**	**2011**	**2011**
Flow-rate (m^3/h)	139	150	148	DO N1	1.7	N/A	1.9	**Eff. NH4**	1.27	1.18	0.61
TSS (mg/L)	92	95	101	DO N3	2.1	N/A	1.1	**Eff. NO3**	8.61	9.01	4.0
TKN (mg/L)	32	29	33	Q_{IR}	438	N/A	249	**NO3 D**	8.1	N/A	4.6
Temp. (ºC)	16	16	16	Q_{WS}	1.9	N/A	7.2	**MLSS**	3200	2200	3600
				Q_{AIR}	604	N/A	559				

where Q_{WS} stands for 'wastage flow-rate'.

As shown in Table 3, the influent water keeps similar in terms of flow-rate, TSS, TKN and temperature. This makes the experimental validation of the different control designs possible. The implementation of the controllers designed by the Add Control platform improves the operation of the plant according to different criteria:

- Effluent quality: with NH4-N concentration remaining at suitable levels (0.61 mg/L), a significant improvement in nitrates is observed, where a reduction of about 5 mg/L in the effluent and the stabilisation of the process are achieved.

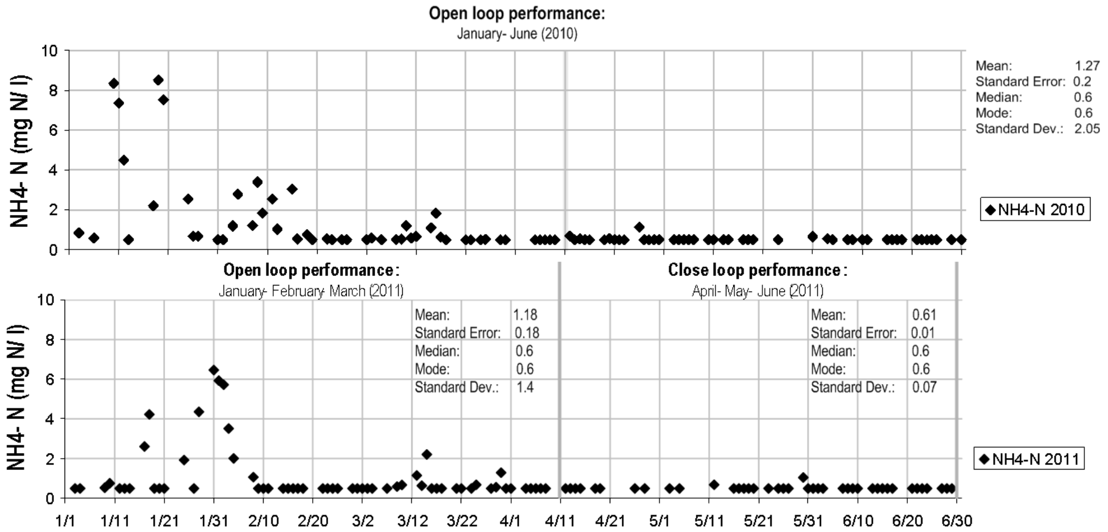

Figure 3. NH4- N concentration in the effluent in 2010 and 2011 between January and June.

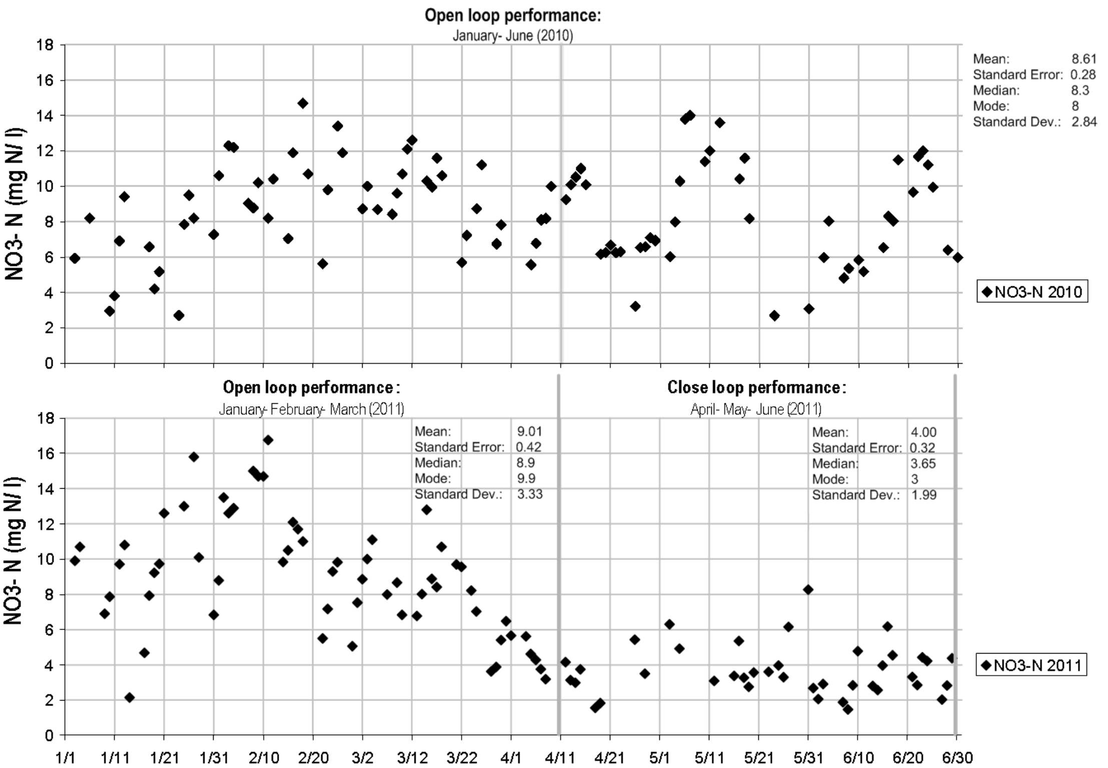

Figure 4. NO3- N concentration in the effluent in 2010 and 2011 between January and June.

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- Power consumption: taking into account that Q_{IR} and Q_{AIR} are considerably reduced (see Table 3) a decrease in energy consumption is estimated. This estimation could not be corroborated with power consumption measurements because at that time no power meters were installed in the plant. This could be shortly done as an installation of such meters is planned.

Conclusions

Conclusions of the work carried out focus on the results obtained by the implementation of the control strategies designed by the Add Control platform at the Mekolalde WWTP. In this respect, we conclude that:

- The simulation studies confirm the good software architecture choice made for the Add Control modelling and simulation platform. The simulations were run by combining the two modelling and simulation SW tools considered by this project: WEST®/Tornado (mikebydhi.com) and MATLAB®/Simulink® (www.mathworks.com); the plant model was implemented in the WEST®/Tornado platform, whereas the sensor and actuator models and the control algorithms were implemented in the MATLAB®/Simulink® platform. This allowed taking advantage of the strengths of both platforms, which are clearly WWTP modelling and automatic control modelling oriented, respectively. This was possible thanks to the multilayer architecture chosen for the Add Control modelling and simulation software platform.
- The experimental results collected during the full-scale implementation of the proposed control strategies corroborate the simulation studies showing that the new control strategies improve Mekolalde's operation performance in terms of water quality and energy consumption. This demonstrates the utility of the Add Control modelling and simulation platform for the design and testing of automatic controllers for WWTPs, which was project's main objective.
- Finally, it is noted that with the plant model available, the design, testing and implementation of the controllers took only 3 months time. This proves the contribution of Add Control to a rapid industrialization of control strategies for WWTPs, which was another of the major objectives of the project.

Summarising, the implementation of the control strategies proposed for the Mekolalde WWTP clearly shows the potential benefits of applying automatic control strategies to WWTPs in terms of water quality and operational costs, as well as the step forward that the Add Control platform can make towards the industrialisation of automatic control strategies for WWTPs, which can surely promote the adoption of advanced control solutions in WWTPs among Water Authorities and the Industry.

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