A multi-layer modelling software framework supporting the design of automatic control solutions in WWTPs

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A MULTI-LAYER MODELLING SOFTWARE FRAMEWORK SUPPORTING THE DESIGN OF AUTOMATIC CONTROL SOLUTIONS IN WWTPs

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Abstract
This paper addresses the mathematical modelling of wastewater treatment plants (WWTPs) extending the traditional WWTP models by considering not only the actual treatment processes but also the associated measurement, actuation and control equipment. Thus, a three-layer, component-based modelling architecture replicating a complete WWTP is presented: (1) the “mass” layer, i.e. WWTP’s unit processes; (2) the “instrumentation & actuation” layer, i.e. sensors and actuators; and (3) the “automation & control” layer, i.e., control devices. Important aspects for assessing controllers’ performance such as signal noise, signal delay, faults, sampling frequency or energy consumption have been also considered in order to mimic the real conditions at which controllers usually operate. Based on this, a first implementation integrating two well known simulation platforms (Matlab/Simulink and WEST/Tornado) has been carried out.

Keywords
Wastewater treatment plants; component based modelling; simulation; control; sensors; actuators.

INTRODUCTION
Nowadays, mathematical modelling and simulation have become essential tools for supporting not only the design and operation of wastewater treatment plants (WWTPs) but also the analysis and synthesis of control algorithms. The original Benchmark Simulation Model no. 1 (BSM1) protocol and its sequels, the Long-Term BSM1 (BSM1_LT) and the BSM2, are three important simulation benchmarks aimed at providing researchers with standard methodologies for the objective comparison of control strategies (Copp *et al.*, 2002). Since their publication, multiple automatic control approaches have been tested and verified by using these protocols: (1) conventional PID controllers (Yong *et al.*, 2006a); fuzzy controllers (Yong *et al.*, 2006b); (2) model-based predictive controllers (Zarrad et al, 2004; Holenda *et al.*, 2007); and (3) feedback/feedforward controllers (Stare *et al.*, 2007). However, few practical implementations of advanced controllers in full-scale WWTPs have accompanied the extensive work undertaken in the simulation domain (Ayesa *et al.*, 2006). One reason for this is the fact that the design of good controllers requires working on more practical aspects than just the design of the control algorithms, i.e. the behaviour of sensors and actuators (Rosen *et al.*, 2008), communication systems, databases and other technical aspects. Another reason is that existing WWTP-specific simulation frameworks have traditionally been intended for design and operation studies rather than for control law definition purposes. In practice, these software tools fail to allow a rapid transition from the simulation of the control strategy to its implementation in full-scale plants.

This work proposes an extension of the traditional WWTP models and modelling architectures used in current WWTP-specific simulation tools, focusing on the needs for automatic control. The principle is to virtualize (model) the entire plant and simulate all the components influencing the final control solution: from mass transformations (transport, physico-chemical phenomena, and biological reactions) to instrumentation, actuation and automation systems. Important aspects for assessing controllers’ performance such as signal noise, signal delay, faults, sampling frequency or energy consumption have been also considered.

METHODS

Modelling architecture

Virtualizing the entire WWTP, i.e. modelling all the components involved in the operation of the plant implies integrating several different types of models: (1) Ordinary Differential Equation (ODE) + Algebraic Equation (AE) systems used to describe the dynamics of Unit Processes (UPs); (2) fitting models used to predict the dynamic response of sensors and actuators; (3) probabilistic models used to reproduce noise, faults and similar random events; (4) event-driven models related to control actions (sampling, if-then-else rules, etc.); and, (5) algebraic models used to estimate operating costs (associated with water pumps, blowers, mixers, etc.). For that, a modelling architecture supporting such an integration of models and replicating the architectures of existing full-scale plants is proposed (see Figure 1).

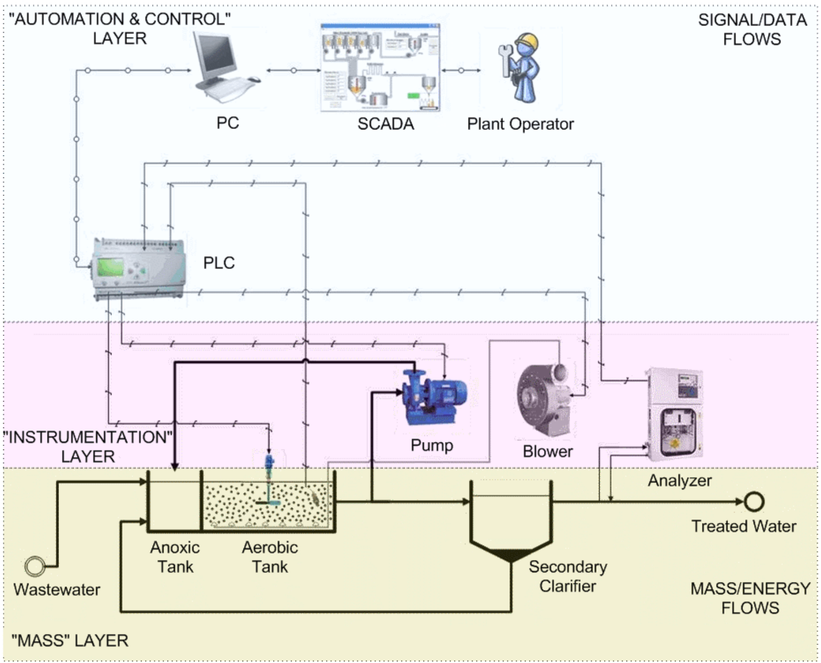


Figure 1. Schematic representation of the three distinct layers to be distinguished in a generic WWTP.

Thus, a multi-layer architecture separating the mathematical models of the mass-flows derived from the water treatment itself (tanks, reactors, settlers, hydraulic connections, hydraulic flows, etc.) from the virtualization of the data-flows associated with instrumentation, actuation and control devices (sensors, actuators, controllers) is presented. Specifically, three different model layers have been defined: (1) the “mass” layer, for predicting all the UPs involved in the wastewater treatment (i.e., buffer tanks, reactors, settlers, etc.); (2) the “instrumentation & actuation” layer, where effects on real sensors and actuators such as delays, noise, faults, etc. are simulated; and (3) the “automation & control” layer, aimed at the virtualization of control devices. It is noted that the actual power consumption of pumps and aeration systems of layer (2) “instrumentation & actuation” is modelled, making it possible to design and test controllers aiming at optimizing energy consumption, whereas communication and data exchange between layers, where sampling frequency plays an important role, are also implemented as usually play an important role in controllers’ performance.

The “mass” layer

As mentioned above, the “mass” layer relates to the physical processes of a WWTP. This layer is represented and modelled in terms of Unit Processes (UP), where each UP represents a physical element of the plant. The UPs are modelled according to the Plant Wide Modelling (PWM) specification (Grau *et al.*, 2007), based on the following two main features:

- A common state-vector is shared by all UPs.
- Conservation of mass and charge is considered in all transformations.

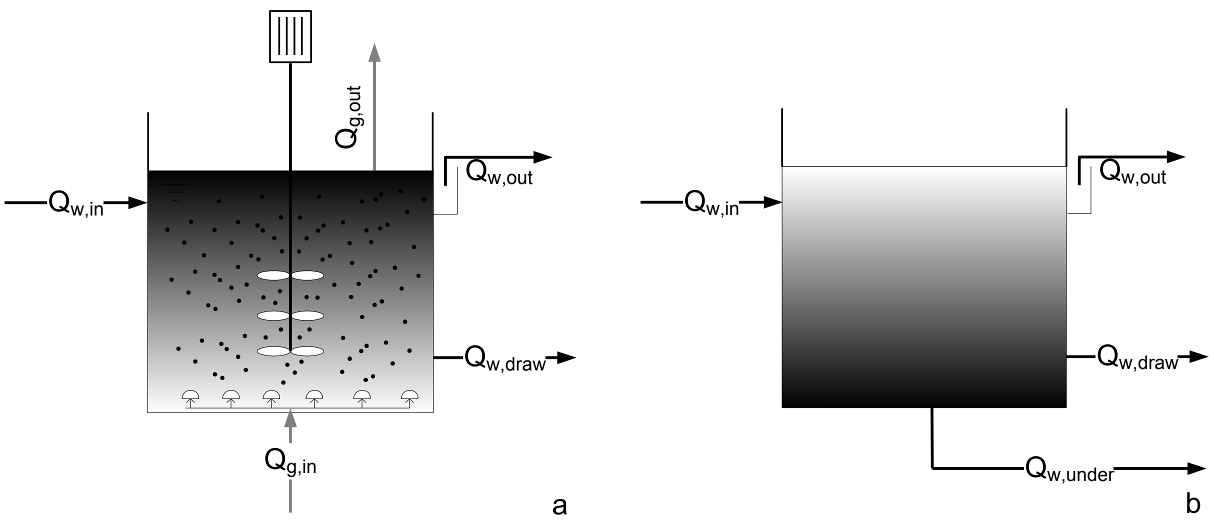
MSL (Model Specification Language) is the language chosen for modelling the UPs. Taking this into account, two PWM categories have been implemented:

Category	**Description**
CN_AnD	Carbon, Nitrogen and Anaerobic Digestion. This category gathers all components and transformations, which dynamically describe aerobic, anoxic and anaerobic COD biodegradation and N removal.
C2NP_AnD	C2NP_AnD: Carbon, Nitrogen, Phosphorous and Anaerobic digestion. This category gathers all components and transformations, which dynamically describe aerobic, anoxic and anaerobic COD biodegradation, biological P removal, N removal in two steps ($NO_3^- \rightarrow NO_2^- \rightarrow N_2$) and anaerobic ammonia oxidation (the Anammox process).

Regarding the UPs of the "mass" layer, the main UPs implemented by this work are next listed:

UP	**Description**
Buffer Tank (Completely Stirred Tank - CST)	-No biological reactions or mass transport considered. -Variable volume. -2 output flows: weir-type and pump-type.
Completely Stirred Open Tank Reactor (O-CSTR)	-Open tank, variable volume. -2 output flows: weir-type and pump-type.
Completely Stirred Closed Tank Reactor (C-CSTR)	-Closed tank, variable volume. -2 output flows: weir-type and pump-type.
Intermittently Stirred Open Tank Reactor (O-ISTR)	-Variable volume. -Two operation modes: +O-CSTR +Settling tank -3 output flows: weir-type, filtration-type, concentrate-type.
Settling Tank	Point Settler/Multi-Layer Settling Tank

where the description of the internal transformations of those tanks considering biological reactions will depend on the PWM category selected. Figure 2 shows exemplarily the graphical layout of the O-ISTR tank reactor.



a) The Open Stirred Tank Reactor layout. *b) The settler layout.*

Figure 2. O- ISTR layout when operating as (a) O-CSTR, and (b) Settler.

The "instrumentation & actuation" layer

The "instrumentation & actuation" layer deals with the mathematical modelling of sensors and actuators with real behaviour. For sensors, a generic sensor model has been built, no matter pH-probes, DO-sensors, flow rate sensors, temperature probes…are to be modelled. The idea is not to take an actual sample from a process unit such as an activated sludge tank, but to distort a perfect signal into a more realistic signal.

A virtual sensor gets its input (i.e. the ideal signal) from the "mass" layer and it outputs a mimicked real signal taking into account: 1) sensor dynamics (response time, delay and temporal resolution (sample-and-hold)), 2) signal noise and 3) sensor faults. The concept of the virtual sensor model is illustrated in Figure 3. Basically, it takes a signal input from the "mass" layer and produces a sensor signal and a sensor fault signal, which are communicated to the "automation & control" layer.

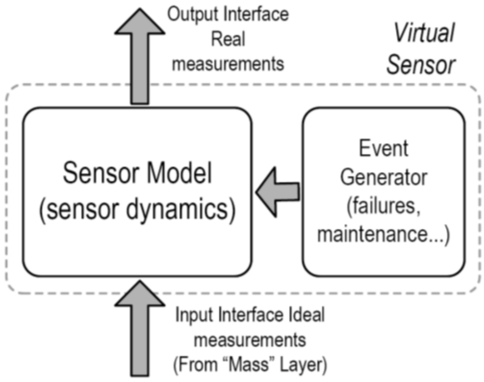


Figure 3. Illustration of the virtual sensor concept.

The implementation of the above generic virtual sensor, some of the associated sub-models and the fault model are partly based on the work of Alex *et al.* (2009a), Alex *et al.* (2009b) and Rosen *et al.* (2008).

Concerning actuators, the modelling of pumps and aeration blowers has been addressed, since those are the most important energy consumers in wastewater treatment plants. An extensive literature review revealed that much knowledge is available on the theoretical functioning of pumps and blowers from a design point of view, but that no dynamic energy consumption models are readily available for implementation. Even though some commercial software packages for calculating and optimizing features for energy consumption of (mostly) pumps already exist, often these are static instead of dynamic. This research work proposes an approach to create dynamic models for the calculation of pumping and (bubble) aeration power, based on steady-state models and considering an ideal behaviour, and with the possibility to test different pump and blower types and different control mechanisms often used in practice.

Regarding pumps, centrifugal pumps and positive displacement pumps have been addressed. For these, generic models based on generic pump curves, generic system curves and generic approaches to efficiency calculation have been developed. The general approach deals with delivering the required flow rate from a single pump. However, this would in most cases not be the situation in a real plant where the total flow rate between unit operations is the result of using two or more pumps in parallel. Thus, power consumption calculation for pump groups of different layouts (individual discharge pipes, one common discharge pipe) has also been implemented. The Markov chain concept followed by the fault modelling strategy used for sensors (Rosen *et al.*, 2008) has also been applied to actuators by adapting the associated states and transition probabilities, both for the single pump model and the pump group model.

Regarding blowers, centrifugal blowers and positive displacement blowers have been addressed. Energy consumption for blowers, similar to that of pumps, is a function of air flow rate, efficiencies and discharge pressure. Thus, generic models based on generic blower curves, generic system curves and generic approaches to efficiency calculation have also been developed here. However, significant differences and complexities are introduced to aeration blower applications due to the compressibility of air. Characteristics such as air density, relative humidity, altitude and temperature influence the required airflow to the system and, therefore, also the energy requirement of the blower. These aspects, together with the selected process control strategy, are the key issues that have been considered when evaluating the energy consumption of aeration systems.

All sensor and actuator models have been implemented in both Modelica and Matlab/Simulink.

The "automation & control" layer

The "automation & control" layer deals with modelling approaches for controllers and signal processing. Controller models range from simple ON/OFF controllers and common PID controllers to advanced controllers, such as Fuzzy Logic Controllers and model based or adaptive controllers. The described modelling approaches for signal processing cover signal converters, signal analysis, digital filters, fault detection, data input and output as well as pseudo real-time simulation and OPC communication. Regarding fault detection, it is noted that a fault detection strategy based on receiving and processing fault signals sent from sensors and actuators and therefore, on the integration with the "instrumentation & actuation" layer has been implemented, where the fault signal sent by the sensors and actuators depends on the fault state of sensors/actuators.

The models have been implemented in both Modelica and Matlab/Simulink.

Software architecture

Typically, the actual wastewater treatment processes and the instrumentation, actuation and control equipment are modelled using domain specific software tools. WEST/Tornado (mikebydhi.com) and Matlab/Simulink (www.mathworks.com) are two well known and widely used modelling and simulation platforms. This work considers two implementation architectures: (a) a one platform-based implementation and; (b) a two platforms-based hybrid implementation. The (1) "mass" layer is built within the WEST/Tornado platform, whereas the (2) "instrumentation & actuation" layer and the (3) "automation & control" layer are built in both WEST/Tornado and Matlab/Simulink platforms. Having the entire plant modelled in one platform makes the interfacing between different models easier, whereas using a hybrid solution allows exploiting the power of every specialized software platform at the expense of making the interfacing between different models more complicated.

A conceptual diagram of the above software architecture is given in Figure 4. In this example, the subsystem functionality of Matlab/Simulink has been employed to embed the "instrumentation & actuation" and "automation & control" layers separately. A specific Matlab/Simulink block has been used to communicate these two Matlab/Simulink-based layers and the WEST/Tornado-based "mass" layer. Since both Matlab/Simulink and WEST/Tornado have their own numerical solvers to simulate their models, a synchronization mechanism has been required to ensure a unique simulation time in both platforms. Typically, models in the "mass" layer have to be simulated using stiff solvers; in contrast, fixed-step solvers seem to be appropriate for simulating the two other layers. This feature and the fact that the "mass" layer has been embedded into a specific Matlab/Simulink block leads to a hierarchical architecture where the Matlab/Simulink solver is on top of the WEST/Tornado solver.

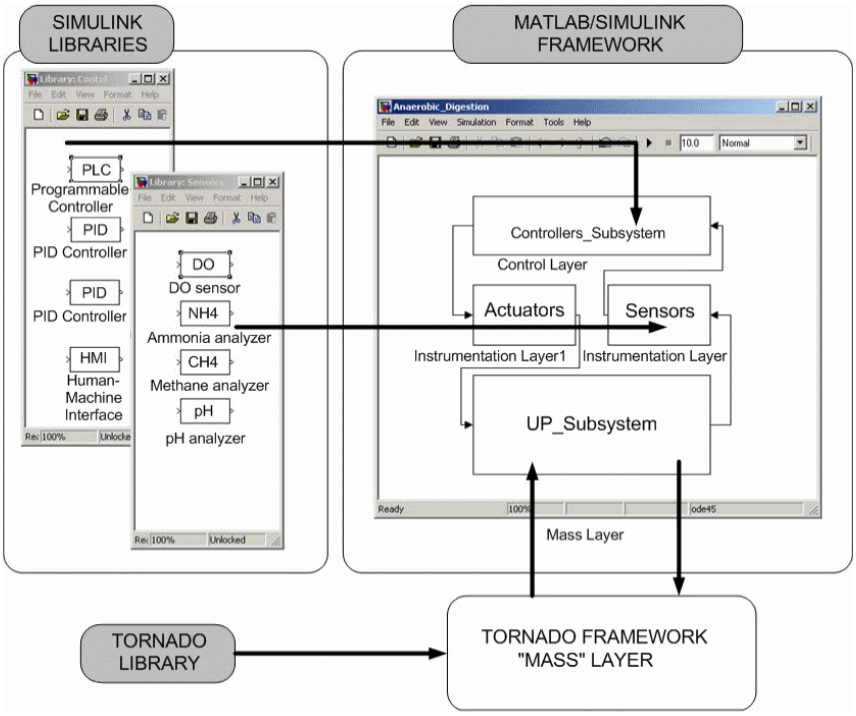
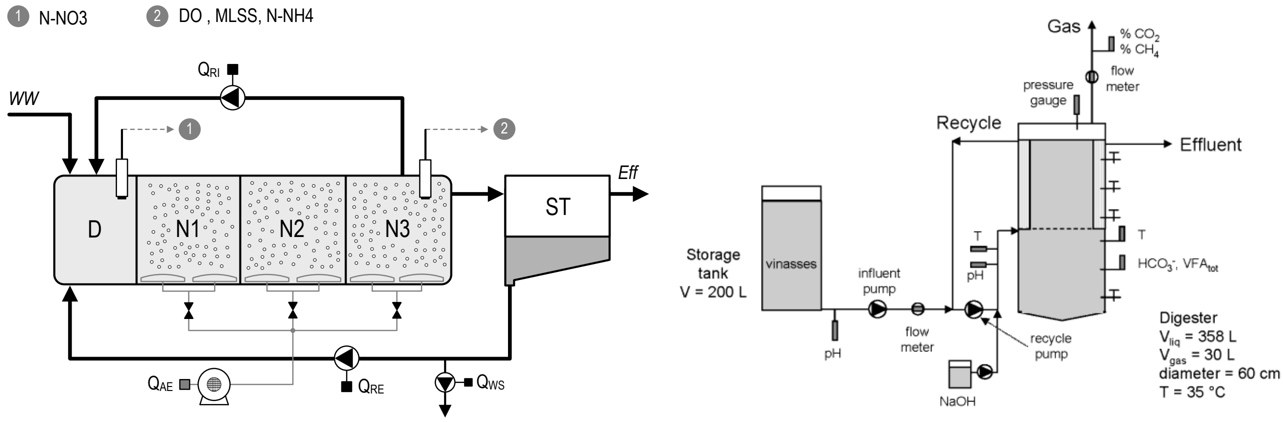


Figure 4. Software implementation of the proposed simulation software framework.

RESULTS AND DISCUSSION

Currently, the simulation framework herein proposed is at the validation stage. Two different case studies have been implemented by means of the proposed simulation framework:

(a) Full scale secondary treatment (water line) of the *Mekolalde* WWTP (Bergara, Spain).
(b) Pilot scale anaerobic digester located at INRA and fed by the industrial distillery wastewater of the distillery in Ornaisons, France (SCAD).



(a) **(b)**

Figure 5. Implementation case studies: (a) urban WWTP; (b) industrial anaerobic digester.

Regarding the secondary treatment (water line) of the *Mekolalde* WWTP, it corresponds to a conventional pre-denitrifying activated sludge process made up of four tanks arranged in series. 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. An illustrative screenshot of the *Mekolalde* simulator implemented under the proposed simulation platform is shown in Figure 6. In accordance with the architecture proposed by this work, the "mass" layer appears on the bottom of the West Experiment GUI, the "instrumentation & actuation" layer in the middle and, finally, the "automation & control" layer on top (low-level as well as advanced controllers).

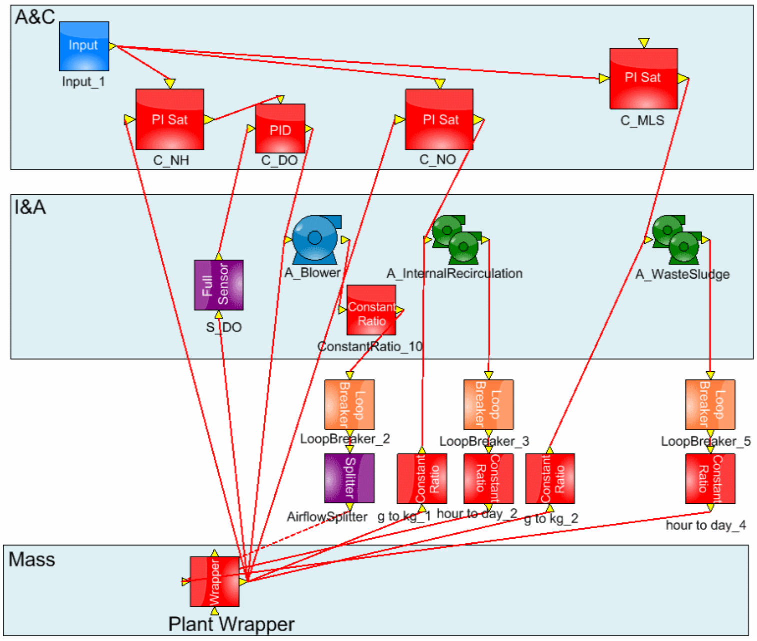


Figure 6 WEST/Tornado implementation of the *Mekolalde* WWTP.

With the *Mekolalde* simulator operative, its appropriateness for testing and validating automatic controllers is explored by implementing a decentralised control schema of three non-interacting feedback controllers: (1) suspended solids in the mixed liquor (MLSS); (2) ammonia in the last aerobic reactor; and (3), nitrates in the first anoxic tank. Figure 7 shows simulation results of the DO controller for summer season (upper plots) and winter season (lower plots). The DO reference trajectory, which combines short-term (daily) and long-term (seasonal) changes in the wastewater, is shown for two, two-day periods on the left hand plots, whereas corresponding tracking responses of the DO controller are shown of the middle and right hand plots.

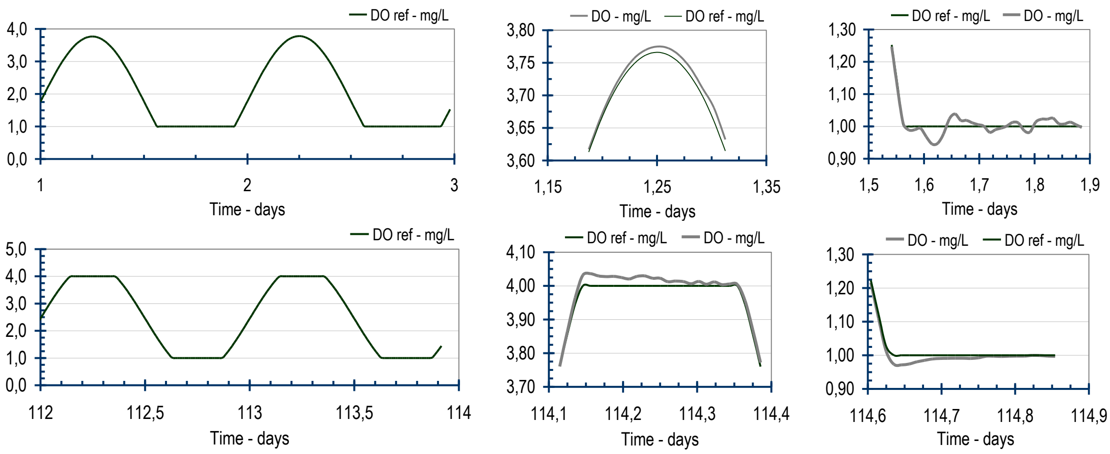


Figure 7 Performance results of the DO controller: tracking response.

Regarding the pilot scale anaerobic digester, four different control strategies have been designed and tested by simulation: two PI controllers, taken from “automation & control” layer and two model-based controllers, for the total VFA control and methane gas flow rate control. Both conventional PI controllers and model-based controllers are able to keep the defined set-points despite variations in the influent COD concentration to the digester. Aiming to mimic realistic conditions, different signal noise, signal delay and sampling frequency levels have been successfully tested, which is representative of the potential of the modelling architecture and simulation platform herein presented.

CONCLUSIONS

Current WWTP-specific simulation tools are unable to deal successfully with the inherent complexity involved in the design of automatic controllers. Subsequent steps in WWTP modelling must address not only mathematical formulations for mass transformations but also virtual representations for sensors, actuators and automation systems. In this work, a multi-layer modelling architecture considering not only the actual treatment processes but also the associated instrumentation, actuation and control equipment and their real behaviour is presented. On the one hand, separating the models into three different layers ("mass" layer, "instrumentation & actuation" layer and "automation & control" layer) allows modellers working separately and with different software platforms (if desired) on their respective models without interfering with the rest. On the other hand, having the possibility to work with complete models including the real behaviour of instrumentation, actuation and control equipment allows the design and development of more reliable and robust control strategies. In this respect, one full scale and one pilot scale case study have been modelled by the proposed simulation platform. Several control strategies for different signal noise, signal delay and sampling frequency levels have in all cases been successfully implemented and tested, which shows the potential of the platform at the simulation level. The controllers of the full scale case study have already been implemented on the real plant, being currently at the validations stage.

ACKNOWLEDGMENTS

The authors would like thank the financial support received from the EU FP7-SME-2008-1 programme (project ADD CONTROL 232302) as well all project partners (http://www.addcontrol-fp7.eu/). They would also like to thank the financial support received from the Spanish Ministry of Science and Innovation (project NOVEDAR CONSOLIDER CDS2007-00055). Alain Castro (CEIT) is thanked for his technical support in the R&D tasks.

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