EOLI ICA4-CT-2002-10012
Efficient Operation of Urban Wastewater Treatment Plant

REPORT ON FULL-SCALE PERFORMANCE OF THE ADAPTIVE OPTIMAL CONTROL LAW

Deliverable 5.2 (draft version)

Deliverable Type: Report
Number: D5.2

Contractual Date of Delivery: T_0*+30*
Actual Date of Delivery: 09.05.2005

Tasks WP5-Control design&application: WP5.3-Control law validation, WP5.4-Proc.improvement eval.
Responsible: Jaime A. Moreno (UNAM)
Involved partners: UU, LBE-INRA and UNAM

By Jaime A. Moreno and Manuel J. Betancur
Insitute of Engineering (iiNGEN)
Universidad Nacional Autónoma de México (UNAM)
Ciudad Universitaria, 04510, Coyoacan, Mexico D.F.
Emails: JMorenoP@iingen.unam.mx, MBetancurB@iingen.unam.mx

Abstract: This report describes the validation and the improvement assessment of the control laws designed for the WWTP models EM1 and EM2. Special attention is given to experimental results and their relation to the potential impact of the improvements in economic-related variables as Treatment time, Daily applicable load, Energy consumption, Air consumption and Tanks size.

Keywords: Activated sludge WWTP, Sequencing Batch Reactor (SBR), Optimal control

Table of Contents

1. Introduction

In this project, three types of wastewater are considered. The first one coming from a dairy industry, contaminated with organic carbon components as well as nitrogen, the second typical for an area including chemical industry, containing toxic or recalcitrant compounds, the third one a domestic wastewater which occasionally contains toxic or organic overloads. To model the problem it was agreed to use two models: the first one (denoted as EM1: EOLI Model 1) is dedicated to the carbon removal process, and the other one (denoted EM2) is dedicated to remove carbon and nitrogen (involving nitrification/denitrification). The EM1 deals with the wastewater treated by UNAM and IBTech; while the EM2 is related to the WWTP for the following partners: UU, LBE and POLIMI (+ENEA as subcontractor).

Previous deliverable D5.1 reports the Time Optimal Control laws designed for each of the EM. Now this deliverable (D5.2) reports the experimental validation and the assessment of the process's performance increase. Chapter 2 is devoted to EM1 and chapter 3 to EM2.

2. Time Optimal Control for EM1-type processes

2.1. *Methodology*

The EM1 process and its Event Driven Time Optimal Control (EDTOC) are described in deliverable D5.1. The experiments used to analyze process improvements and validation when using such EDTOC for the EM1 are described in WP1 reports. The experiments were done using a 7L lab-scale SBR (UNAM-01 in Fig. 1) following the standard conditions agreed in EOLI Mexico meeting (May 8th 2003). This means that the SBR was acclimated to such a standard conditions and operated continuously (iteratively) in Fixed Time Control (FTC) mode before specific EDTOC experiments were done, i.e. every time an EDTOC experiment was done the reactor was assumed to be in the standard conditions.

Figure 1. UNAM-01 Lab-scale (left) and UNAM-02 Field-scale (right) SBRs

After an individual EDTOC batch experiment was finished the SBR was put again to work in standard FTC mode. The FTC batch previous to the EDTOC experiment, and the one following it, are called the "Before" and "After" kinetics, respectively. These are used to evaluate the impact and the SBR's performance changes produced by the EDTOC batch.

The amount of successfully performed experiments constitutes itself a practical validation for the EDTOC. At least three dozens of standard EDTOC kinetics were performed by WP1. Not a single time the EDTOC behaved badly, moreover it behaved as theoretically expected.

Additionally to the Standard condition EDTOC experiments, a series of SHOCK experiments was done by WP1. There the influent's toxicant concentration $S_{C,in}$ was raised, as if an unknown perturbation, to some high peak value. Such value was measured for calculation purposes but was not fed to the EDTOC algorithm, that is, it was unknown to the controller. In order to compare the performance increase and the ability to reject such a perturbation, some benchmark was needed. Unfortunately the competing FTC is not able to cope with such Shock peak loads because it lets the SBR to get strongly inhibited, or even disabled, for input concentrations in excess of 3 times the standard one (Buitrón *et al*., 2005), so the alternative was to compare the total time needed, by each strategy, to degrade the same (known) amount of known toxicant mass. This means that the perturbation is no longer an unknown perturbation for the FTC but a known parameter, so the operator dilutes the toxicant appropriately, i.e. before feeding the SBR, in order to meet the FTC standard conditions. Of course various successive **standard** FTC batches would be needed to degrade the same amount of toxicant that the EDTOC may degrade in a single **long** batch (see Fig 2).

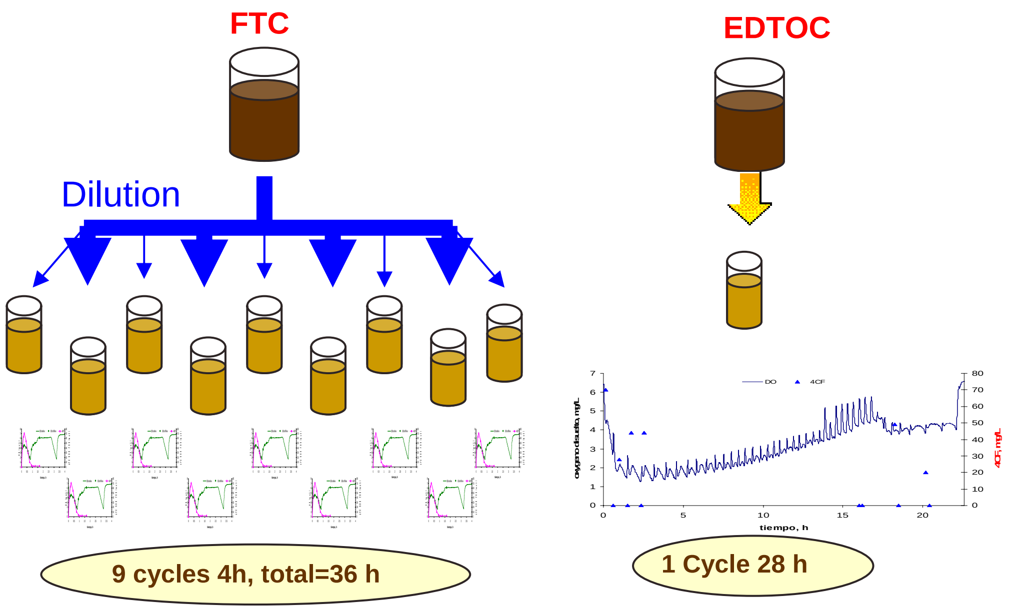


Figure 2. Dilution needed in order to compare EDTOC Vs.FTC degrading the same amount (12g) of 4CP

Long term EDTOC experiments, that is to run the SBR under EDTOC strategy continuously (iteratively), to assess biomass impact (activity, settling, ..), are in progress by WP1.

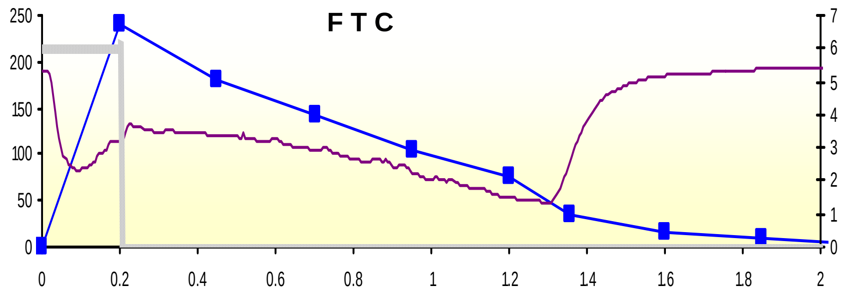
A second, field-scale SBR (UNAM-02 in Fig. 1) is under construction, now almost finished. Once IBTech delivers it to UNAM then WP1 plans to perform experiments to scale the SBR-UNAM-01 lab-scale results to field-scale ones.

2.2. *Results and Discussion*

The EDTOC strategy was validated both in simulations (using EM1 delivered by WP2 using WP1 data) and experimentally (using experiments performed by WP1). No stability problems were ever encountered when standard conditions for the experiment were kept.

WP1 results show an important reduction in treating time (almost -50%), meaning that, for a given daily load rate, it is possible to design smaller, more economical, SBRs or, equivalently, that more toxicant mass can be treated per time unit in a given size SBR. It also means that less energy in stirring and air pumping is needed. Additionally good robustness to unknown influent's perturbations, i.e. toxicant concentration shocks (high peak unknown values), was verified (in excess of twenty times the standard or, equivalently, +20000%).

Figure 3 show the typical kinetics, for a single batch, using the standard 350mg4CP/L influent's toxicant concentration, under the two different control strategies.



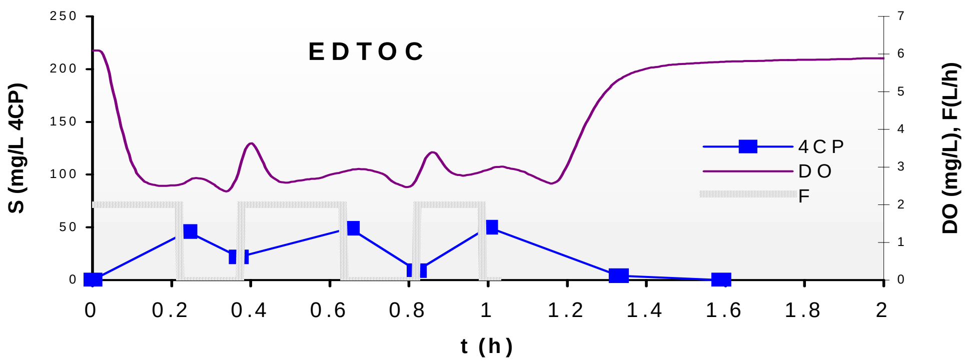


Figure 3. Typical Standard kinetics for degrading 4L of 350mg4CP/L: Only the fill&react phases are shown. a) FTC: Fixed Time Control; b) EDTOC: Event Driven Time Optimal Control

2.2.1 **Reaction time**

Fig. 4 compares the total treating time needed to degrade 4L of influent to the given 4CP concentration, where 350 mg4CP/L is considered as the standard one. For the FTC pre-dilution was needed in order to obtain the most effective treating time possible. Without pre-dilution the FTC can not treat concentrations in excess of three times the standard one (treating time goes to infinity), while the EDTOC was able to treat twenty times the standard concentration without problems. Time saving is about (almost) 50%.

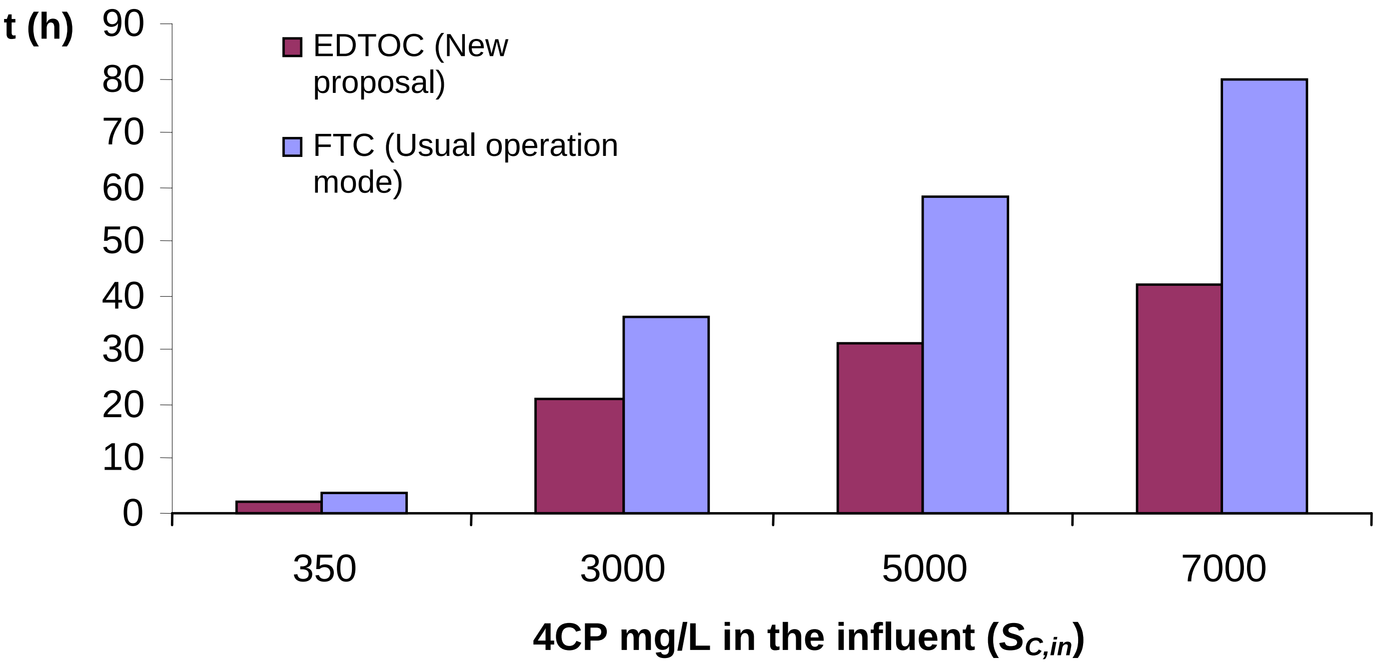


Figure 4. Total treating time Comparison for standard (350 mg4CP/L) and Shock conditions

2.2.2 **Applied load**

As a consequence of the time near optimality attained by the EDTOC an increment in the SBR's applicable load seems to be possible. Assuming long term studies produce no restrictions to operate the SBR in EDTOC mode continuously the Table 1 gives an idea of the potential increment for a given size SBR. This means that facilities already built, and currently running in FTC mode, may be upgraded with the addition of a couple of sensors (Dissolved Oxygen and Volume level) and an EDTOC controller. The potential savings, not requiring new additional WWTP facilities, for an increasing load demand are self explicatory.

Table 1. Increment in daily applicable load, comparing EDTOC Vs.FTC

<table>
<tr><th rowspan="2">$S_{C,in}$
4CP, mg/L</th><th colspan="2">Load,
Kg COD/m^{3}d</th><th rowspan="2">Increment (%)</th></tr>
<tr><th>FTC</th><th>EDTOC</th></tr>
<tr><td>350</td><td rowspan="4">2.52</td><td>. ? .</td><td>. Ivan ? .</td></tr>
<tr><td>3000</td><td>4.11</td><td>63</td></tr>
<tr><td>5000</td><td>4.80</td><td>90</td></tr>
<tr><td>7000</td><td>4.77</td><td>89</td></tr>
</table>

2.2.3 **Air consumption savings**

As a consequence of the reaction time reduction attained by the EDTOC, savings in air consumption in excess of 25% are possible. Table 2 shows the potential savings.

Table 2.Savings in Air consumption, comparing EDTOC Vs.FTC

$S_{C,in}$ 4CP, mg/L	Air Volume ,m^3		Air Savings (%)
	FTC	EDTOC	
350	0.29	0.18	38
3000	2.63	1.98	25
5000	4.39	2.70	39
7000	5.85	3.87	34

2.2.4 **Stirring Energy Savings**

As a consequence of the reaction time reduction attained by the EDTOC, not only savings in air consumption are possible, but also a reduction in the energy necessary to stir the tank. Table 3 shows the potential savings, i.e. exactly the same as savings in air.

Table 3.Savings in Stirring, comparing EDTOC Vs.FTC

$S_{C,in}$ 4CP, mg/L	Energy Savings (%)
350	38
3000	25
5000	39
7000	34

2.2.5 **Shock load effects and perturbation rejection**

The standard toxicant influent’s concentration was set as 350 mg4CP/L. For the FTC pre-dilution was needed in order to obtain the most effective treating time possible. Without pre-dilution the FTC can not treat concentrations in excess of three times the standard one as shows Table 4a. On the other hand the EDTOC was able to treat twenty times the standard concentration without problems (Table 4b).

Table 4a. Shock load response, using FTC, and impact in the posterior behavior of the SBR

Strategy	*4CP mg/L*	*q mg4CP/gVSS/h*	*q after experiment*	*Reference*
FTC	*350*	*53.2±15.7*	*no variation*	*this study*
	700	*34.4*	*37.5*	*Buitrón* et al., *2005**
	1050	*4.6*	*17.9*	
	1400	*0.9*	*total activity loss*	

Table 4b. Shock load response, using EDTOC, and impact in the posterior behavior of the SBR

Strategy	*4CP mg/L*	*q mg4CP/gVSS/h*	*q after experiment*	*Reference*
EDTOC	*350*	*105±17.9*	*no variation*	*this study*
	3000	*41.3±5.9*		
	5000	*49.1±0.7*		
	7000	*54.5±1.9*		

2.2.6 **Summary of Advantages and Disadvantages**

The FTC strategy does have the advantage of not requiring neither sensors nor computing equipment. A simple timer and a low-high volume-level detector will do. However its disadvantages are numerous:

- An expert should balance the risks to decide the time settings for the different phases of the SBR, as these settings are used to operate the reactor in open-loop mode for the standard conditions, i.e. without being sure that the control objectives are satisfied for every single batch, especially if the standard conditions are not exactly met.
- Even if standard conditions are satisfied the treating time is not optimal, i.e. it is bigger than the minimum time practically attainable.
- When higher than standard, inhibitory, concentrations are fed to the SBR the treating time increases more rapidly than linearly and, in fact, it tends to infinity when the biomass gets strongly inhibited. As a consequence there is no guarantee that the reaction, i.e. the most important phase of the WW treatment, is finished in the assigned time. This means there is the risk of delivering water, supposedly treated but, still containing toxicants beyond the acceptable level.
- Equalization tanks are needed in order to smooth out the eventual high peak concentration perturbations of toxicant that may arrive, from time to time, causing a Shock condition to the SBR.
- If a lower than the standard toxicant concentrations is fed then the wasted time is even bigger than in standard conditions, meaning also there is a waste in air consumption and in stirring energy. This also means that the SBR is sub-utilized because the reaction time is less than the fixed one given by the standard conditions, and with no sensors there is no way to know this is happening. A non desirable side effect is starvation. This means that the biomass will be more time deprived from food. Short term effects may not be important, but in the long run this may lead to deacclimation of the biomass, meaning that the SBR will no longer be ready to withstand a standard batch and perform as expected for such a standard condition.

On the other hand, the proposed EDTOC strategy needs instruments and a minimum computing capability. However, nowadays, the sensor technologies needed, i.e. Dissolved Oxygen and Volume level measurements, are mature, well proven, and have reached a cost/performance optimal level. Computing capability is no longer a problem either. The advantages of having such sensors integrated with the EDTOC are:

- There is no need for an expert to decide reaction times. The EDTOC control may know precisely when the reaction phase is practically finished even if other than the standard conditions are present.
- The treating time will be close to the minimum attainable time for every single batch in the standard conditions.
- When higher than standard, inhibitory, concentrations are fed to the SBR the treating time increases almost linearly and, in fact, the biomass never gets strongly inhibited. The EDTOC will take the necessary time, and only the necessary time, to guarantee that the reaction, i.e. the most important phase of the WW treatment, is finished. This means there is no risk of delivering water still containing toxicants beyond the acceptable level.
- Equalization tanks are not strictly needed, or their size may be greatly reduced, as peak inlet concentrations are fed to the reactor in such a way that no Shock is caused to the biomass.
- If a lower than the standard toxicant concentrations is fed then the treating time adjust accordingly, meaning there is no starvation nor waste in air consumption and in stirring energy.
- The EDTOC is robust to kinetic model parameters uncertainties. These parameters take no part in the solution, i.e. they are not needed by the controller. Even more, the EDTOC is robust against kinetic model structure uncertainties, i.e. the Specific biomass growth rate does not have to be close to the Haldane one. From Monod to any other model that does have a single unique maximum will do.
- The EDTOC is robust to yield model parameters uncertainties. These parameters take no part in the solution, i.e. they are not needed by the controller.

3. EM2 type processes

3.1. *Methodology*

The …

3.2. *Results and Discussion*

The….

Conclusions

The Event Driven Time Optimal Control (EDTOC) strategy developed solves the optimization criteria chosen for the EM1 problem and needs only sensors of well proven mature technologies. Moreover it is robust against model structure uncertainties and against uncertainties in most of the model parameters, specially the most uncertain ones. Treating time reduction of almost 50% was achieved compared to the Fixed Time Control mode, for various input toxicant concentrations, including Shock conditions as large as 20 times the standard one. As a consequence there is potential to increase Applicable Load, to reduce energy consumption and to avoid the need for big equalization tanks.

List of abbreviations

4CP	4-Chloro-Phenol
ASM	Activated Sludge Model
CESAME	Centre for Systems Engineering and Applied Mechanics
D1.x – D9.x	Deliverables
DO	Dissolved Oxygen Concentration
DSS	Decision Support System
EC	European Commission
EDTOC	Event Driven Time Optimal Control (New way to operate a SBR)
EM1, 2	EOLI Model 1, 2
EOLI	Efficient Operation of Urban Wastewater Treatment Plant
FDI	Fault Detection and Isolation
FTC	Fixed Timing Control (Traditional way to operate a typical SBR)
GRADIENT	Groupe de Recherches et d'Animations pour le Développement, l'Innovation et l'Enseignement en Technologie
INCO	International Scientific Cooperation Projects
INRA	Institut National de la Recherche Agronomique
LBE	Laboratoire de Biotechnologie de l'Environnement
OMUR	Oxygen Mass Uptake Rate
POLIMI	Politecnico di Milano
SBR	Sequencing Batch Reactor
SPES	Società di Progettazione Elettronica e Software
UCL	Université Catholique de Louvain
UNAM	Universidad Nacional Autónoma de México
UTC	Université Technologique de Compiègne
UU	Universidad de la República Oriental des Uruguay
WP	Work Package
WWTP	Wastewater Treatment Process

References

Buitrón G., Schoeb M.-E., Moreno-Andrade I. and Moreno J.A. (2005). Evaluation of two control strategies for a sequencing batch reactor degrading high concentration peaks of 4-chlorophenol. *Wat. Reserch*, **39**, 1015–1024.