



CONTROL LAWS BASED ON SOFTWARE SENSORS FOR OPTIMISING THE PERFORMANCE OF SBRs

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Abstract: This report describes the proposed control solutions for the problem of increasing the performance of WWTPs. For the Carbon removal case (Eoli Model 1, EM1) an Event Driven Time Optimal Control (EDTOC) is proposed. It exhibits characteristics that are desirable in a practical solution: requires little knowledge of the mathematical model and parameters of the plant, uses only sensors of proven technology, rejects the dangerous inlet toxicant concentration perturbations and reduces significantly the treating time and, consequently, the energy consumption. For the EM2 case ...

Keywords: Activated sludge WWTP, Sequencing Batch Reactor (SBR), Optimal Robust Control, Software Sensor

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1. Introduction

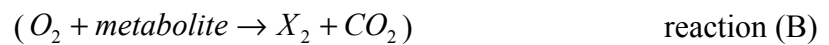
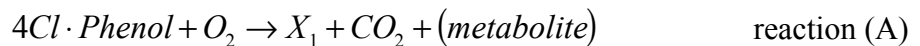
In this project, three types of wastewater are considered. The first one coming from a dairy industry, contaminated with organic carbon components as well as nitrogen, the second typical for an area including chemical industry, containing toxic or recalcitrant compounds, the third one a domestic wastewater which occasionally contains toxic or organic overloads. They are grouped in two model classes: one with only Carbon as the substrate to be removed (denoted EM1: EOLI Model 1), and another with Nitrogen, where nitrification and denitrification are needed (denoted EM2).

The control laws proposed in this WP are therefore linked to the specific application in accordance with its model. Chapter two presents the Control Law devoted to EM1 that deals with the wastewater treated by UNAM and IBTech; while chapter three is dedicated to EM2, related to the WWTP for the following partners: UU, LBE and POLIMI (+ENEA as subcontractor).

2. Control Law for EM1 process (wastewater at UNAM and IBTech)

2.1. EM1 dynamical model

The main process is related to the first reaction describing the degradation of the treated substrate via aerobic digestion. The originally proposed model was:



with X_1 and X_2 the corresponding biomasses for both reactions, respectively.

Experimental results showed that the metabolite is only produced if there is strong inhibition; otherwise there is only a weak quantity of metabolite. Moreover, it is not directly measurable. For this reason, and considering that no strong inhibition should occur if optimal control laws are applied, it was decided to avoid useless problem complexification and to simplify the model considering only the one main reaction (A), which indeed represents the most relevant and important behaviour, for control purposes, of the EM1 type WWTP.

The main idea for controlling the reaction phase is to use a fed-batch approach, manipulating the inlet flow rate F_{in} in the SBR, to optimise (i.e. to reduce) the treatment time. So a process model considering the fill and react phases (settling, decanting and idling phases are not addressed here) was needed. It was developed in WP2 as EM1. Let us denote S_C , S_O , and X respectively, the concentration of the substrate to be treated (i.e. 4-Chlorophenol) (*also denoted simply as S in some related publications*), the concentration of the dissolved oxygen (DO) in the water (*also denoted simply as O*) and the concentration of the biomass for the first reaction.



Using the simplified version of reaction (A), a simple mass balance leads us to obtain the following EM1 equations for the Standard Operation conditions of the SBR (fill and react phases only, acclimated, not strongly inhibited, no Oxygen limitation, bounded inflow):

$$\frac{dX}{dt} = \left(\mu - \frac{F_{in}}{V} \right) X \quad (1)$$

$$\frac{dS_C}{dt} = -k_1 \mu X + \frac{F_{in}}{V} (S_{C,in} - S_C) \quad (2)$$

$$\frac{dV}{dt} = F_{in} \quad (3)$$

$$\frac{dS_O}{dt} = -(k_2 \mu + b) X + \frac{F_{in}}{V} (S_{O,in} - S_O) + K_L a (S_{O,sat} - S_O) \quad (4)$$

where k_1 , k_2 , b , $K_L a$, $S_{C,in}$, $S_{O,in}$, $S_{O,sat}$ and V are the yield coefficient for substrate degradation (also denoted as $1/Y_{x/s}$ or simply $1/Y$), the oxygen yield coefficient (also denoted as $1/Y_{x/o}$), the specific endogenous respiration rate of the biomass in the water (also denoted as r), the oxygen mass transfer coefficient, the influent substrate concentration (also denoted as S_{in} or simply S_i), the influent DO concentration (also denoted as O_{in} or simply O_i), the saturation DO concentration in the liquid medium (also denoted as O_{sat} or simply O_s) and the wastewater volume being treated in the SBR tank, respectively.

As the substrate (i.e. 4-Chlorophenol) inhibits the biomass growth, the Haldane model can be applied to approximately describe the specific growth rate of the biomass, μ , such as:

$$\mu = \frac{\mu_{\max} S_C}{K_S + S_C + \frac{S_C^2}{K_I}} \quad (5)$$

where $\mu_{\max}$, K_S and K_I are the maximum specific biomass growth rate (also denoted as μ_0), the Michaelis-Menten affinity constant and the inhibition constant for a Haldane kinetics model of the specific biomass growth rate, respectively.

Remark 1- Inhibitory model structure:

The Haldane model is just a reference. Any inhibitory model with a similar structure, i.e. exhibiting a single unique maximum μ^* at $S_C = S_C^*$ and tending to zero as S_C tends to either infinity or zero, as in Fig.1, should also be accounted for. Note that if S_C^* is allowed to go to infinity the model structure changes and inhibition is no longer present. The same is true if $S = S_C^*$ is not reachable.

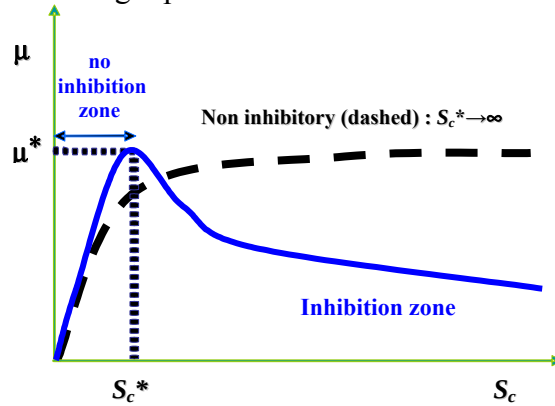


Figure 1. Two different specific biomass growth rate models: The continuous line represents $\mu(S_C)$ for an inhibitory substrate (it grows monotonically until reaching a unique maximum μ^* @ $S_C = S_C^*$ and then decreases, also monotonically). The dashed line depicts the non inhibitory case.



2.2. EM1 control challenge

The problem formulation states that, for technical and economical reasons, neither toxicant nor biomass concentrations are measurable on-line. Additionally, parameter $S_{C,in}$ is highly uncertain and even time-varying. It is therefore to be considered unknown and unmeasurable, so it becomes the main perturbation for the carbon removal process. A nominal $S_{C,in}$ value is assumed for designing the SBR and for acclimation of the biomass, but such a value is only a statistical reference and should not be considered for individual batch operations. If an arbitrary open-loop uncontrolled F_{in} was to be used (i.e. batch mode) then high values for such a parameter may inhibit the SBR and, moreover, shock peak values, i.e. unexpected and unknown extremely high toxicant substrate concentrations in the inflow, may even disable it permanently. The experimental work done for developing EM1 also shows that model parameters as k_1 , k_2 , b , $S_{O,in}$, μ_{max} , K_S and K_I are uncertain too, while $K_I a$, $S_{O,sat}$ are easy to identify with certitude.

The challenge for designing a control that increases the SBR performance is then to use only the available measurements (Dissolved Oxygen, S_O , and Volume level, V) to achieve minimum treating time, while rejecting the main unmeasurable perturbation $S_{C,in}$, relying only in the more certain parameters ($K_I a$, $S_{O,sat}$) or, at least, being robust against uncertainties of all other parameters that might be needed for control purposes. The control must also perform in such a way that the EM1 standard operation conditions are preserved, that is that no strong inhibition do happen ever and that no deacclimation (i.e. because strong starvation) occurs. Bounds in inflow rate and in reaction time must also be considered. This means that no infinite (nor negative) inlet flow rate values are allowed and that convergence time (if any) for software-sensors and for controllers should be neglectable compared to the total reaction time of a single batch.

Remark 2- Bounds:

There are natural conditions for the problem that impose restrictions to EM1 in equations (1-5). All variables and parameters should be strictly positive and bounded, as should also be the total treating time for any single batch, i.e. the time horizon for the solution is finite.

Remark 3- Actuator and Sensors:

Although handling dilution $D=F_{in}/V$ as a control variable may be theoretically easier, for practical reasons (constant flow rate pumps are cheaper and more robust than variable ones) we choose to manipulate directly the inflow rate, i.e. bounds for real actuators must be considered in the problem formulation explicitly, i.e. $0=F_{min} \leq F_{in} \leq F_{max}$. Moreover, as real sensors are prone to get saturated and to exhibit delays and/or high frequency non modeled behaviors, the standard operating condition of the SBR must be designed in such a way as to avoid these problems, i.e. the choice of F_{max} should consider both sensor related delays, which makes it desirable to use a low value, and maximum allowable total filling time.

Assumption 1- Perturbation:

Influent substrate concentration may vary largely and even, in very rare cases, be almost inexistent (no toxicant in the feed). However to simplify the problem, without sacrificing generality, a natural condition is assumed: the influent's toxicant concentration is greater than the singular one ($S_{C,in} > S_C^*$), furthermore it must always be greater than the one inside the SBR to the point that, if the influent pump is turned on to its maximum value, then the toxic concentration inside the tank will always increase, i.e. $F_{in}=F_{max} \rightarrow dS_C/dt > 0$

2.3. Event Driven Time Optimal Control (EDTOC)

A Time Optimal Control (TOC) for the SBR guarantees that the problems posed in previous section 2.2 are addressed. But a direct approach to implement such a TOC may require knowing, with certitude, the value of most of the model parameters and also the measurement of the unmeasurable variables. The original plan for solving the challenge included the use of the measurable variables, fed to a Software-Sensor, in order to estimate the value of the unmeasurable variables and/or parameters needed for controlling the plant, specifically substrate concentrations (in the influent and inside the tank). While working on such an idea a different, but related, approach was discovered. In fact, it was learned that for controlling the reaction in an optimal way it is not really necessary to know, at all, the substrate concentrations but, instead, it suffices to know the relation of the value of the reaction rate to its maximum reachable value. Exploiting such an idea did lead to the development of the Event Driven Time Optimal Control (EDTOC) which is a practical, realisable, Bang-Bang approximation of the TOC.

The EDTOC will be explained in the next subsections: first a description of the optimal law will be made, then an approximation to that law by means of a Bang-Bang (on/off) control will be given and, finally, a way to drive such a Bang-Bang approach by using only the available measurements will conclude the explanation.

2.3.1 Time Optimal Control (TOC)

The optimal feeding profile for a minimum time fed-batch operation of the SBR is well known for EM1 type processes (Moreno, 1999). The advantage of applying such an optimal profile is that most of the main problems associated with the standard Fixed Time Control (FTC) batch-mode operation of the SBR could be solved, i.e. the substrate concentration inside the SBR is kept near the maximum possible value that does not cause inhibition, S_C^* , thus preventing inhibition. Moreover, the instant in which the reaction ends could be perfectly known, thus allowing to avoid both starvation and premature decantation of the SBR. The difficult thing to do is to practically implement a control law that behaves in such an optimal theoretical way.

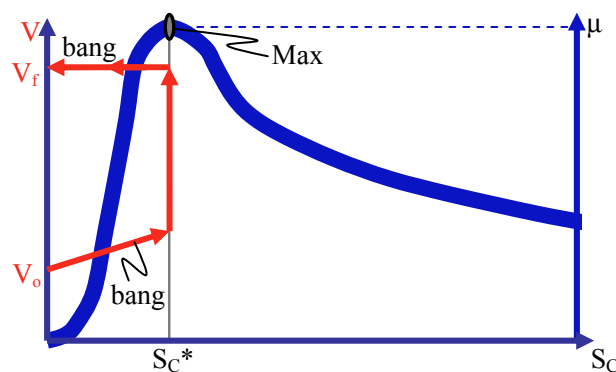


Figure 2. Optimal trajectory, projected into the $S_C V$ plane, composed of 3 arcs (arrows). Note that the singular arc is vertical, meaning the SBR is filled without altering the internal toxicant concentration S_C . The secondary axis shows, superimposed, $\mu(S_C)$

The TOC trajectory path consists of three arcs as shown in Fig. 2. The feeding profile to obtain it consists, respectively, of three segments. The first one starts when the filling phase starts at $V=V_0$ and is a Bang-Bang one, meaning the actuator is set to one of its limit values in

order to allow the system's trajectory to go, as fast as possible, to a point where $S_C = S_C^*$. Typically the initial substrate concentration lies in the left region of S_C^* so the actuator gets set to its maximum value F_{max} . Once $S_C = S_C^*$ the second, singular, segment begins. The inflow is changed to a singular one (F_{sng} at Eq.6; Moreno, 1999) that maintains $S_C = S_C^*$ at all times just until the reactor gets full i.e. $V = V_f$. The last step is also a Bang-Bang one, to turn off the inlet flow, i.e. $F_{in} = 0$, and wait until the toxicant inside the reactor gets below some acceptable $S_{C,f}$ maximum finishing limit. After that the final settling and drawing phases in the SBR sequence may be initiated.

$$F_{sng} = \frac{k_1 \mu^* V X}{S_{C,in} - S_C^*} \quad (6)$$

2.3.2 EDTOC: a Bang-Bang realization to approximate the Time Optimal Control

If S_C could be measured and μ could be completely known then a simple way to implement an approximation to the TOC would be to use feed-back in a Bang-Bang law, as depicted in Figures 3 and 4. Two switching limits are needed (Fig.3), one low (S_l) to turn on the inlet pump, as long as the tank is not yet full, when $S_C < S_l$ and other high (S_h) to turn it off. As this solution depends on logical events to drive the Bang-Bang switching it will be called Event Driven Time Optimal Control (EDTOC)

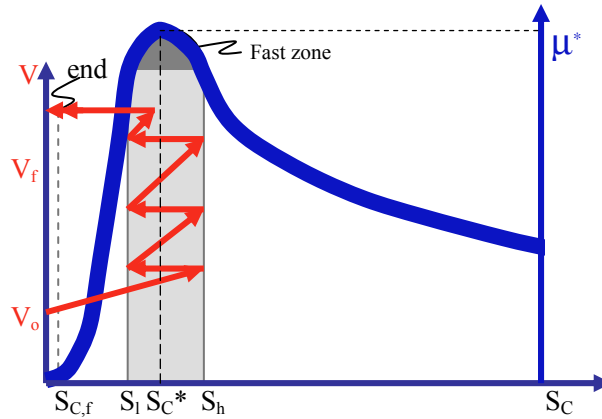


Figure 3. Bang-Bang trajectory for the EDTOC, projected into the $S_C V$ plane. The secondary axis superimposes μ in order to relate it to the switching limits (S_l , S_h) for S_C . The initial and final Volume level of the SBR tank in any single batch are denoted as V_0 and V_f respectively.

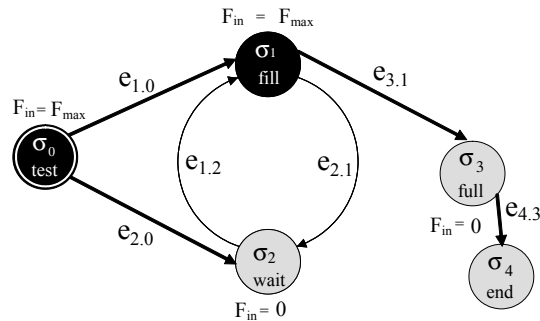


Figure 4. Finite states automata representation of the Bang-Bang approximation to the EDTOC. The initial state σ_0 performs a test to assess the initial condition of the process in terms of toxicant substrate. An occurrence of an event $e_{k,j}$ (see Table 1) drives the system from a given state σ_j to a new one σ_k . Note: if the current state is other than σ_j then any event $e_{k,j}$ has no effect in the system status.

Table 1. Events driving the Bang-Bang approximation to TOC

Tag	Event	Meaning
$e_{1,0}$	$S_C \leq S_C^*$	Not Inhibited
$e_{2,0}$	$S_C > S_C^*$	Inhibited
$e_{2,1}$	$S_C \geq S_h$	MustWait (stop filling)
$e_{1,2}$	$S_C \leq S_l$	MustFill (fill at maximum flow rate)
$e_{3,0}; e_{3,1}$	$V \geq V_{max}$	TankFull
$e_{4,3}$	$S_C \leq S_{C,f}$	EndReaction

Note that the initial and final arcs of the TOC solution are perfectly followed by such an EDTOC approximation when the standard conditions are fulfilled. If that is not the case and the initial conditions depart from the standard one in such a way that $S_{C,0}$ happens to be greater than S_C^* (i.e. the systems starts inhibited) then the test state σ_0 will put the system in the right path by jumping to σ_2 instead of σ_1 (see Fig.4). The singular arc (vertical arrow in Fig.2) is approximated by using a sequence of Bang-Bang arcs, i.e. the zig-zaging arrows in Figure 3 produced by the alternative cycling of σ_1 and σ_2 in Figure 4. Note also that this approximation may be done as fine as desired by choosing $S_{l,h} \rightarrow S_C^*$, i.e. the EDTOC solution is suboptimal but may be done as close to the optimal as desired. Furthermore it is robust against influent concentration perturbations ($S_{C,in}$ value is not involved in the solution).

The problem is that, not having a way to measure S_C , the events in Table 1, needed to drive the Bang-Bang switching of the influent pump, are not available. Next subsection will show how to detect such events, indirectly, without measuring S_C and without exactly knowing the exact formula for μ .

2.3.3 Events Software-Sensor for the EDTOC

Next the explanation about how to use a function γ of μ (Fig. 5) to estimate the events needed to operate the Bang-Bang solution previously explained will follow. A physical meaning and the way to compute such a γ function will be given in the next subsection so, for now, let us assume γ is measurable (see Fig. 6) and focus on the Software-Sensor workings.

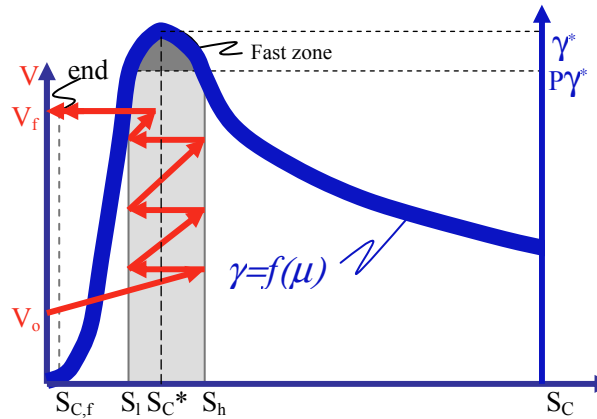


Figure 5. Bang-Bang trajectory for the EDTOC projected into the $S_C V$ plane. The secondary axis superimposes γ ; a function of μ that keeps its shape even if some features remain unknown. $0 < P < 1$ is a tuning parameter; the closer it gets to “1” the closer to the optimal is the solution.

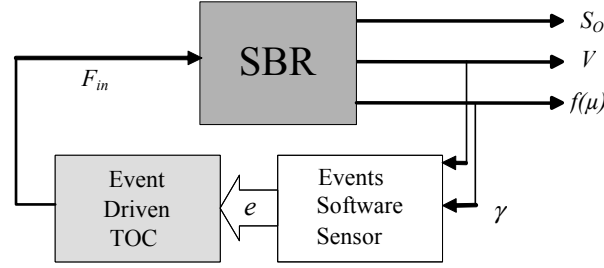


Figure 6. Event Driven Time Optimal Control scheme, assuming a measurable γ does exists.

There are various ways to estimate the events described in Table 2 for the control architecture given in Figure 6. The classical one would be to use a regular observer to estimate S_C and, independently, get to know S_l and S_h . After that a simple comparison allows to generate the events that depend on them. In such a solution the observer uses the measurable variables to estimate a continuous analog variable (i.e. substrate concentration S_C , as in Vargas *et al.*, 2000) which is later used to compute a logical one (i.e. the event e itself). By contrast the new solution we propose estimates directly the logical event e , without caring for the actual real value of S_C and/or S_l , S_h . Avoiding the intermediate step of estimating S_C makes the solution easier to implement, more robust and independent of most of the, otherwise needed, model parameters.

It will be assumed that $f(\mu)$, in Figures 5 and 6, is a strictly monotonic increasing and continuous function of μ , as for example Equation 7, for a , b , c unknown constants, a , $c > 0$. The maximum $\gamma^* = \max_{S_C \geq 0} f(\mu(S_C)) = f(\mu^*)$ is then well defined. It should be noted that it is not necessary to know the exact shape of μ or $f(\mu)$. If Assumption 1 is satisfied, and because the monotone increasing (decreasing) behavior of $S_C(t)$ when it goes from S_l to S_h (from S_h to S_l , respectively), it is clear that $\gamma(t)$ increases from $\gamma_l = f(\mu(S_l))$ ($\gamma_h = f(\mu(S_h))$) until maximum γ^* and then decreases until γ_h (γ_l respectively). If γ^* is assumed constant but unknown, this leads to the scheme in Figure 6. There, the Events Software-Sensor (ESS) estimates a maximum of $f(\mu)$ in real time, as $\gamma_k^*(t) = \max(f(\mu(S_C(\tau))))$ for $\tau \in (t_k, t)$, where t_k is the instant when the last k^{th} state change in the EDTOC took place.

$$\gamma = f(\mu) = (a\mu + b)c \quad (7)$$

Comparing the actual values of γ and γ_k^* allows to determine if $S_C = S_l$ or $S_C = S_h$ have been reached, even if S_C , S_l and S_h do remain unknown. In particular, consider $S_l < S^*$ and $S_h > S^*$ such that $f(\mu(S_l)) = f(\mu(S_h)) = P\gamma^*$, where $0 < P < 1$ is a near-optimality control parameter. Making P close to one renders S_l , S_h close to S^* . Figure 5 shows the relation between S_l , S_h , γ^* and P for the case $\gamma = f(\mu) = (a\mu + b)c$. The ESS also determines easily if $S_C > S^*$ or not, i.e. if the system is in the inhibition zone (see Table 2).

Table 2. Estimation of the Events for driving the Bang-Bang approximation to TOC

Tag	Event trigger	Estimates	Meaning
$e_{1.0}$	$d\gamma/dt > 0$	$S_C \leq S_C^*$	Not Inhibited
$e_{2.0}$	$d\gamma/dt < 0$	$S_C > S_C^*$	Inhibited
$e_{2.1}$	$\gamma \leq P\gamma_k^*$	$S_C \geq S_h$	MustWait (stop filling)
$e_{1.2}$	$\gamma \leq P\gamma_k^*$	$S_C \leq S_l$	MustFill (fill at maximum flow rate)
$e_{3.0}; e_{3.1}$	$V \geq V_{max}$	(measured)	TankFull
$e_{4.3}$	$\gamma < \gamma_f$	$S_C \leq S_{C,f}$	EndReaction

Table 2 shows the events estimated by the ESS. Using such events the EDTOC shuts down or powers up the influent pump F_{in} as appropriate. The finite state EDTOC is exactly the same as depicted earlier in Figure 4. The initial state at $k=0$ for $t=t_0=0$ is always σ_0 . If inhibited, the system will jump instantaneously to state σ_2 . After the initial bang-bang arc, the cycling between σ_1 and σ_2 will approximate the singular arc. Once the tank is filled, σ_3 will complete the last bang-bang arc. The reaction finishes when σ_4 is reached. After this the rest of the batch sequence (settling, draw...) may be completed and, afterwards, a whole new batch cycle may be started.

2.3.4 Practical Events Software-Sensor (ESS)

In the previous subsection a γ variable, used to estimate the events driving the EDTOC, was assumed to be measurable, but that is not the case. In this subsection a γ candidate is analyzed: the total Oxygen Mass consumed by the total biomass per Time unit. It is estimable (i.e. computable using signals coming from sensors of proven mature technology as Dissolved Oxygen concentration and Volume level) and it does have a clear physically meaning.

In usual terms γ [MT^{-1}] is chosen to be equivalent to *Volume* [L^3] times the *Oxygen Uptake Rate* (OUR) [$MT^{-1}L^{-3}$]. Note that because of the stoichiometric relation between them, for a given Biomass value, maximizing such Oxygen Mass Uptake Rate (OMUR) is equivalent to maximizing the Substrate degradation rate, which is just another way to look at the optimality objective for the problem at hand. And that is what the EDTOC does, to maximize γ . In this subsection it will be shown how the ESS itself may real-time compute such a $\gamma=OMUR$, using only the available variables F_{in} , S_O and V , to generate the events needed for control, as depicted in Figure 7.

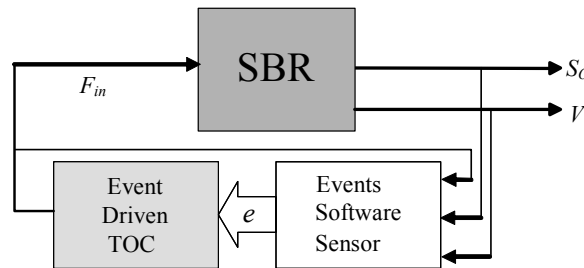


Figure 7. Event Driven Time Optimal Control scheme for the given available variables

The Dissolved Oxygen Concentration in the liquid medium of the SBR changes depending on the difference between the Oxygen Transfer Rate (OTR), the Biomass Oxygen Uptake Rate (OUR) and the dilution effect as shown in Eq. 8 (Bastain and Dochain, 1990)

$$\frac{dS_O}{dt} = OTR - OUR - \frac{F_{in}S_O}{V} \quad (8)$$

Comparing Equations 4 and 8 it is easy to see that the OUR depends on both the oxygen consumption due to the exogenous respiration and the one owed to the metabolic activity of the Biomass, as expressed in Equation 9. If both sides are multiplied by V Eq.10 is obtained, where $B=XV$ is the total biomass mass and γ is the Oxygen Mass Uptake Rate (OMUR).

$$OUR = (k_2\mu + b)X \quad (9)$$

$$OMUR = V * OUR = (k_2\mu + b)B \quad (10)$$

Note the similarity between Equations 7 and 10. If just B was constant then OMUR in Equation 10 could be used as the γ in Equation 7, for the ESS in the EDTOC. And that is almost just the case for the EM1 toxicant removal process. Experiments performed by WP1 show that the total biomass ($B=XV$) increase during a single standard batch reaction for EM1 is less than 2%. i.e. from a practical point of view it is almost constant. Moreover, if fed-batch EDTOC is used instead of FTC (pure batch mode) then various fill-wait sub-cycles will be performed during a single reaction, and the increase of B during each individual sub-cycle is even less. For example if 4 sub-cycles are performed during a single batch then the change of B during each one of them (on or off) semi-cycles is around 0.25% (Remember that the total biomass growth follows a stoichiometric relation, so it depends on the total mass of substrate treated and not on the time spent to do it). A full analysis for the case when B cannot be assumed to be almost constant is given in Betancur *et al.* (2005).

Now, to compute such a γ note that from Equations 4 and 7, and considering the usual case in which the influent is deprived from oxygen ($S_{O,in}=0$), Eq.11 follows, which depends only on available variables and parameters, i.e. it is real-time computable.

$$\gamma = OMUR = F_{in}S_O + K_1a(S_{O,sat} - S_O)V - V \frac{dS_O}{dt} \quad (11)$$

As long as close to the standard conditions are preserved for EM1 the EDTOC could be applied directly to the real SBR as explained above. However, if effects such as non-modeled sensor dynamics become important then EDTOC performance may get degraded. That could be the case if F_{max} is badly chosen (too high) or if $S_{C,in}$ is extremely high (extreme shock loads), or if tuning parameter P is chosen too close to 1 (heavy actuator switching rate), as in all of these cases the time needed for the system to go from $S_C=S_l$ to $S_C=S_h$ would be too short for the Dissolved Oxygen Sensor to follow the real S_O dynamics, and hence the OMUR will be computed badly. Practical aspects as considering the time delay introduced by sensors, and the option of using variable flow rate pumps to adapt the inflow in order to increase practical robustness against very high shock loads, are considered in Betancur *et al.* (2004)

3. Control Law for EM2 type process

3.1. EM2 dynamical model

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Conclusions

The proposed Event Driven Time Optimal Control (EDTOC) solves all of the problems stated for EM1 type processes. It demands little knowledge of the mathematical model and parameters of the plant, is easy and economic to implement, and allows to increase significantly the performance of the WWTP.

For the EM2 ...

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