# OPTIMIZATION METHODOLOGY FOR HIGH COD NUTRIENT-LIMITED WASTEWATERS TREATMENT USING BAS PROCESS

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## ABSTRACT

Optimization of biofilm activated sludge (BAS) process via mathematical modelling is an entangle activity since economic, environmental objective and technical decision must be considered. This paper presents a methodology to optimize the operational conditions of BAS process in four steps by combining dynamic simulation techniques with non-linear optimization methods and with operative decision making criteria. Two set of variables are separately prioritized in the methodology: essential variables related to physical operation to enforce established process performance, and refinement variables related to biological processes that can generate risks of bulking, pin-point floc and rising sludge. The proposed optimization strategy is applied for the treatment of high COD wastewater under nutrient limitation using an integrated mathematical model for COD removal that include predation, hydrolysis and a simplified approach to the limiting solids

flux theory in the secondary clarifier in order to facilitate the convergence of the optimization solver. The methodology is implemented in a full scale wastewater treatment plant for a cellulose and viscose fibre mill obtaining: i) improvement of the effluent quality index (Kg pollution/m$^3$) up to 62% and, ii) decrease the operating cost index (€/m$^3$) of the process up to 30% respect the regular working operational conditions of the plant. The proposed procedure can be also applied to other biological treatments treating high COD nutrient-limited industrial wastewater such as from textile and winery production among others.

## 1. Introduction

Emission limits for industrial effluent are constantly being tightened up. Activated sludge (AS) process is a common system for biological treatment of industry effluents; however, more sustainable solutions require other technologies such as biofilm activated sludge process (BAS). BAS is composed of moving bed biofilm reactor (MBBR) and activated sludge reactor (AS) that are used as bacterial and predator stage respectively (Sointio et al. 2006, Revilla et al. 2016a). The overall result in BAS processes increases COD removal performance respect to other conventional treatment and, at the same time, lay out lower sludge production**.** An additional and determining benefit is the improvement sludge settleability in the final stage of secondary settling (Rankin et al. 2007) that allows that the activated sludge reactor to be operated at increased biomass concentration while simultaneously total suspended solids (TSS) concentration in the effluent can be reduced (van Haandel and van der Lubbe 2015). Moreover, this biologic double stage process can avoid the risk of bulking when it is operated under nutrients limitation (Rankin et al. 2007)**.** Predation is the powerful mechanism of the BAS process that allows achieving their main characteristic as the low sludge yield.

Modelling of biofilm stages and activated sludge provided a better understanding of the intrinsic connections between soluble and particulate compounds, biomass properties and process performance in terms of COD, BOD and TSS (Fan et al. 2017). Commercial simulation platforms, including GPS-X and BioWin can be used to describe the one dimensional (1-D) multi-species biofilm structure and biological behaviour of the treatment process (Li et al. 2016); however, none of these platforms include the description of the predator microorganism which plays a predominant role in a BAS process under certain conditions such as nutrient limited conditions (Revilla et al. 2016a).

The authors published recently the mathematical model of BAS process including hydrolysis and predation and uses wastewaters coming from viscose and cellulose production industrial process to validate the model. In Revilla et al. 2016a the whole BAS process was simulated and the evaluation of the role and contribution of predator microorganisms towards COD removal, nutrient requirements and sludge production is displayed.

More strict regulations are being imposed regularly in terms of COD, BOD and TSS removal that enforce wastewater treatment technologies to progress (Guerrero et al. 2011; Kamali and Khodaparast 2015). Optimization of an existing facility in terms of cost, operational improvements and removal efficiency is the most effective method of achieving the stricter compliance and the most effective method to overtake common trade-off between treatment results and operational costs. However, expectation of having to satisfy simultaneously a variety of objectives (environmental, economic and technical) increases the complexity of the problem and becomes a very difficult task that should be solved blending experience engineers and specific mathematical tools (Descoins et al. 2012; Hakanen et al. 2013). In this context, practical experience of the operator in the prioritization of conflicting objectives or in the application of rules of thumb, needs to be considered in the mathematical model since certain units at wastewater treatment plant (WWTP) may be exceptionally difficult or risky to operate.

Multiple objective optimization (MOO) has been widely applied in operation and design of municipal WWTP for different applications using interactive approaches between several optimization and decision making tools (Dai et al. 2016; Garrido-Baserba et al. 2016; Hakanen at al. 2011; Rivas et al. 2008; Sweetapple et al. 2014). However, a systematic methodology of multiple objective optimization of a full-scale BAS process has not been addressed, to the best of our knowledge.

Generally, urban wastewater has high presence of nutrients that facilities the biological process; however, some type of wastewater such as viscose and cellulose industry wastewater are poor in nutrients that must be added externally with the consequent increase in the operating costs of biological treatments (Rankin et al. 2007).

In this paper, an optimization methodology for BAS processes treating highly COD wastewater under limited nutrient is presented. Simultaneous optimization of effluent quality and operating cost under prioritized technical specifications is the main goal of this procedure. Applicability of the proposed methodology for biological treatment processes using biofilm is illustrated using two industrial-scale case studies from viscose and cellulose wastewaters.

## 2. Identification of the problem

### 2.1. Problem statement

The problem of optimizing the operational conditions of the BAS plant can be stated as follows: given is a BAS plant with known design parameters and given is an influent stream with known flow rate that contain certain pollutants with known concentrations; the goal of this problem is to identify the operational conditions of the plant at minimal operational cost and minimal pollutant discharge in the effluent stream taking into account technical specifications.

To solve this problem a conceptual optimization methodology approach, based on four sequential stages showed in Figure 1, is proposed in this work. As explained previously, BAS process included two biological sequential steps: MBBR reactor and AS reactor. In MBBR reactor nutrient dosing is the unique variable that can be manipulated. Furthermore, the mathematical model of the MBBR reactor presented previously by the authors (Revilla et al. 2016b) is a multi-substrate biofilm and bulk liquid model and the mathematical model of the AS is continuous stirred-tank reactor. These two biological sequential steps described (MBBR and AS) are the base of the four sequential stages of the optimization methodology.

Starting from the regular operation conditions of an industrial plant, the first stage of the optimization methodology is the “Synthesis of Alternatives”; nutrient different dosage is the essential variable of the process (performance and cost) being used to generate different process alternatives. All the alternatives are simulated for MBBR reactor in the second stage “Simulation” using a previous MBBR mathematical method; besides, the results of “Simulation” allows obtaining the initial point of the variables of the AS process. The third step is the “Activated Sludge Multicriteria Optimization” that allows to obtain optimal solutions of the process variables under economic and environmental evaluation criteria. This procedure ("Simulation of MBBR" and later "Activated Sludge Multicriteria Optimization") requires much less computation computational effort than using an optimization software under dynamic and spatial conditions.

The last stage is the "Decision Making Process" where a set of refinement operation bound let to obtain the optimal conditions under additional evaluation criterion. The proposed methodology is iterative until the optimal solution is reached.

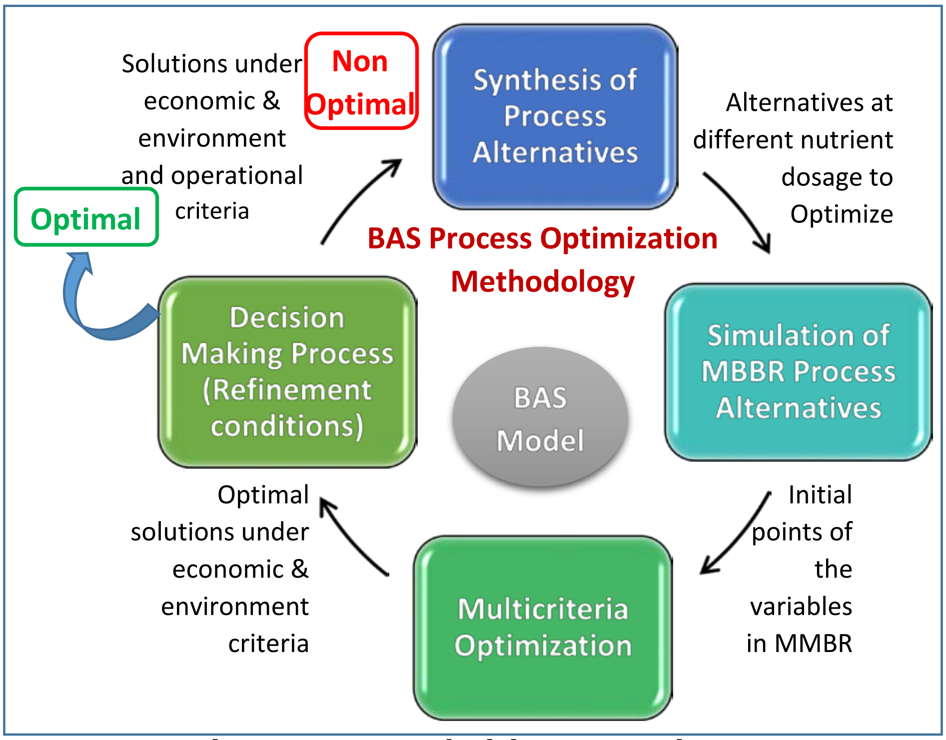


Figure 1.- Conceptual optimization methodology approach.

## 2.2. BAS mathematical model

A complete description for the mathematical models of four units involved in the BAS process (MBBR, AS, secondary clarifiers and splitter) including the biological reactions, stoichiometric and kinetic coefficients appears in previous papers presented by the authors (Revilla et al. 2016a, b). In the present paper a significant modification has been done in the mathematical model of secondary clarifier in order to evaluate the clarification and thickening functions; a "simplified approach" proposed by von Sperling (2007) to the limiting solids flux theory has been included in the model. Limiting solids flux concept is widely used in the bibliography trough the "non-differentiable minimum function" (Amanatidou et al. 2015a, b) which requires iterative methods to solve it numerically and can raise convergence issues when uses optimization algorithms (Hreiz et al. 2015a). The use of the simplified approach facilitates the convergence of the optimization algorithms.

The simplified approach proposed by von Sperling (2007) takes into account four variables i) hydraulic loading rate (HLR) which corresponds to the quotient between the influent flow rate ($Q_i$) and the surface area of the secondary settler (A) (equation 1), ii) solids loading rate (SLR) which corresponds to the quotient between applied solids load and the surface area of the secondary settler (equation 2), iii) sludge settling velocity (v) (equation 3) and, iv) limiting solids flux (GL) (equation 4):

$$\text{HLR } (\text{m}^3/\text{m}^2 \text{ hour}) = Q_i/A \quad (1)$$

$$\text{SLR } (\text{Kg TSS}/\text{m}^2 \text{ hour}) = (Q_i + Q_R) \times TSS_{AS}/A \quad (2)$$

$$\text{v } (\text{m}^3/\text{m}^2 \text{ hour}) = (\text{vo}) \times e^{-K \times TSS_{AS}} \quad (3)$$

$$\text{GL } (\text{Kg TSS}/\text{m}^2 \text{ hour}) = m\,(Q_R/A)^n \quad (4)$$

where $Q_R$ is the sludge recycle flow rate; $TSS_{AS}$ are the total suspended solid concentrations in AS reactor; vo, K, m and n are specific correlation parameters.

In this work, “fair settleability”, with sludge volume index (SVI) between 100-200 mL/g, vo (8.6 m/hour), K (0.50 $m^3$/Kg), m (0.72) and n (8.41) is considered.

Finally, two new conditions are included in the previous BAS mathematical model developed by the authors in order to ensure the clarification and thickening function.

- Clarification function: hydraulic loading rate (HLR) $<$ sludge settling velocity (v)
- Thickening function: solid loading rates (SLR) $<$ limiting solid flux (GL)

Blue section of the Figure 2 shows the essential attributes of the BAS process model including the appropriated operational variables and its constraints and bounds for the secondary settler tank and for the AS reactor apply in the present work. These suitable operational variables are included due to operational consistencies (Espírito Santo et al. 2013) even though other authors can point out lightly different values (Henze 2008; Hreiz et al. 2015a; van Haandel and van der Lubbe 2015).

## 3. Optimization methodology

The complexity for simultaneous reduction of operational costs, reduction of the amount of pollutants discharged into sewer together with reduction of sludge generated, and the requirement of a technically well-operated full-scale wastewater plant have motivated this paper. Furthermore, this optimization process involves some other challenges such as, i) high number of (non-linear) equations and variables, and ii) dynamic and spatial distribution of the components into the length of the biofilm of the MBBR rectors.

The optimization methodology to fulfil the proposed objectives is divided into four consecutive steps detailed in the following sections. This approach simplifies the convergence of the mathematical models and the determination of the initial points of the variables. A detailed flowchart of the proposed optimization methodology and the relation with the mathematical model is shown in Figure 2.

This methodology can be used for wastewater under nutrient limitations coming from different industrial sector such as pulp and paper, petrochemical, pharmaceutical or food (Bakos et al. 2016; Freedman et al. 2005; Gray 2004; Hussain et al. 2015)

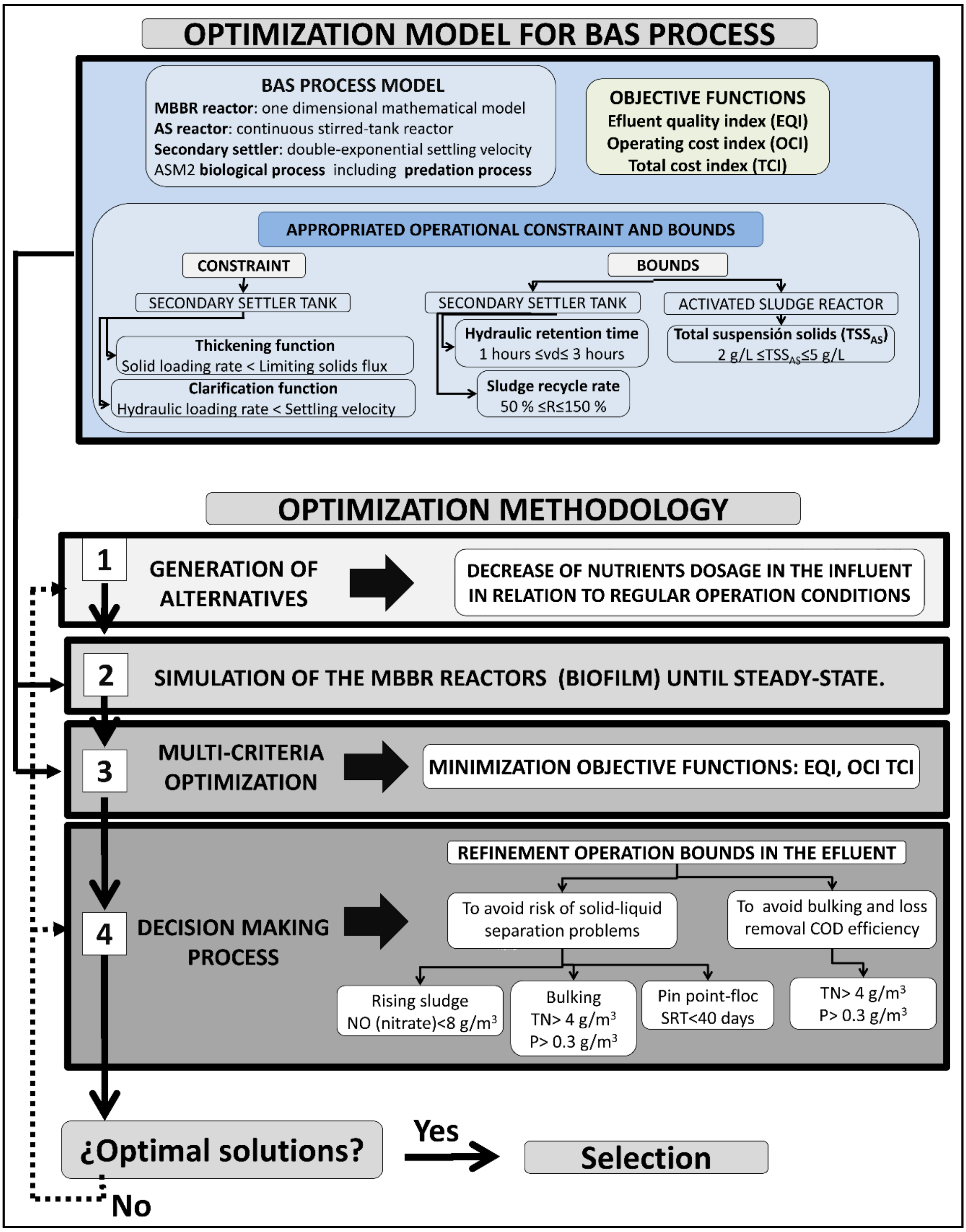


Figure 2. Flowchart of the optimization methodology.

### 3.1. Generation of alternatives

Nutrients must be dosed into the influent to ensure the proper growth of the microorganisms because the BAS process under-study treats high COD wastewater under limited nutrient condition. The optimization methodology starts generating alternatives by selecting one independent variable as additional constraint (Hreiz et al. 2015b). The selected variable in this work is the nutrient dosage in the influent; this variable affects the behaviour of MBBR reactors and the overall performance and cost of the BAS process. Different intervals of the nutrient dosage are considered to generate several alternatives depending on the precision degree required for the optimization process.

### 3.2. Simulation of the MBBR reactors (biofilm) until steady-state.

The mathematical model of the MBBR reactor previously developed by the authors (Revilla et al. 2016b) allows the determination of the concentration of the components in the reactor with time and the spatial distribution along the length of the biofilm. The AS model used by the authors for the AS step is simpler than MBBR model since it is modeled as a continuous stirred-tank (Revilla et al, 2016a).

The optimization methodology separates the BAS process into two stages: simulation of the MBBR reactor and optimization of the rest of BAS process. The simulation stage fulfils two aspects: i) solve a complex multi-species and multi-substrate biofilm and bulk liquid MBBR model and ii) facilitates the determination of the initial points of the variables for optimization process.

In the previous as well as in the present work, general chemical engineering process software (Aspen Custom Modeler) is used to simulate the behaviour of MBBR reactors since this software facilitates the creation of rigorous dynamic and spatial model. In this second stage of the optimization, this MBBR model is used to simulate the behaviour of the components for each alternative in the biofilm and in the reactor until steady-state. Once the steady-state is reached, the MBBR results of each alternative are sent to third stage of the methodology: optimization of the conditions of the BAS process.

## 3.3. Multicriteria optimization

Once MBBR behaviour is simulated until steady-state, the rest of the process is optimized for each alternative using three different index as objective functions: total cost index, effluent quality index or/and operating cost index as objective functions. The optimization of the BAS process is done by the software General Algebraic Modeling System (GAMS) using CONOPT as NLP algorithm (El Shorbagy et al. 2013).

### *3.3.1. Objective functions*

Three indexes are used as objective functions to be minimized in the present work: effluent quality index (EQI) that measure the presence of pollutant in the effluent, and operating cost index (OCI), that evaluates operation expenses in the plant. An additional index, the total cost index (TCI) linking effluent quality and operating cost indexes, is considered as objective function by weighting method (Flores-Alsina et al. 2008).

*Effluent quality index (EQI)*

The effluent quality index (EQI) (Copp 2002; Foscoliano et al. 2016) quantifies into a single term, the effluent pollution load into a receiving water body (kg pollution/day) (Vanrolleghem and Gillot 2002). The discharged of different pollutants into the effluent is considered as a weighted sum of six evaluation criteria: total Kjeldahl nitrogen (TKN), COD, BOD, TSS, nitrate (NO) and total phosphorous (P). Equation 5 shows the weighted sum of each evaluation criteria where $Q_e$ is the effluent flow rate.

$$\mathrm{EQI}\ \left(\mathrm{Kg}\,\frac{\mathrm{pollution}}{\mathrm{day}}\right) = \left[20 \times \mathrm{TKN}\left(\frac{\mathrm{g}}{\mathrm{m}^3}\right) + 1 \times \mathrm{COD}\left(\frac{\mathrm{g}}{\mathrm{m}^3}\right) + 2 \times \mathrm{BOD}\left(\frac{\mathrm{g}}{\mathrm{m}^3}\right) + 2 \times \mathrm{TSS}\left(\frac{\mathrm{g}}{\mathrm{m}^3}\right) + 20 \times \mathrm{NO}\left(\frac{\mathrm{g}}{\mathrm{m}^3}\right) + 100 \times \mathrm{P}\left(\frac{\mathrm{g}}{\mathrm{m}^3}\right)\right] \times \mathrm{Q_e}\left(\frac{\mathrm{m}^3}{\mathrm{day}}\right) \times 10^{-3} \tag{5}$$

*Operating cost index (OCI)*

The operating cost index (OCI) that is used as the economic objective function, is an approximate measure of the plant's operational cost, involves the main operating costs, such as power consumption by aerators, sludge production, pumping energy and nutrient cost. The operating cost index (OCI) (equation 6) is calculated as the weighted sum of aeration energy associated to the oxygen consumption for the carbonaceous demand (CD), aeration energy associated to the oxygen consumption for the nitrogenous demand (ND), mixing energy (ME), pumping energy (PE), sludge production (SP) and nutrient cost (NC), using the weighting factors as Chen et al. 2015 and Zhou et al. 2015.

$$\mathrm{OCI}\ (€/\mathrm{year}) = 25 \times (\mathrm{CD} + \mathrm{ND} + \mathrm{ME} + \mathrm{PE}) + 75 \times \mathrm{SP} + \mathrm{NC} \qquad (6)$$

*Total cost index (TCI)*

Total cost index (TCI) is defined in equation 7 as the sum of the effluent quality index and operating cost index optimized (Vanrolleghem and Gillot 2002; Kim et al. 2015).

$$\mathrm{TCI}\ (€/\mathrm{year}) = 50 \times \mathrm{EQI}\ (\mathrm{Kg\ pollution/day}) + \mathrm{OCI}\ (€/\mathrm{year}) \qquad (7)$$

Along the paper the values of EQI, OCI and TCI were calculated per $m^3$ of wastewater treated (Guerrero et al. 2011) in order to maintain the confidentiality of the industrial effluent characterization.

## 3.4. Decision making process

The proposed optimization strategy produces one optimal solution for each alternative and for each selected objective function. The variables included in the step 1 are related to operational conditions that are essential to obtain a minimum AS performance process. The last part of the methodology considers refinement conditions by including some variables related to the biological processes to avoid risks of inefficiencies in the downstream liquid-solid separation processes; these variables can be used as decision making process. Even though most of the optimization models do not include priority levels such as essential operational variables and refinement operation variables, the incorporation of this type of prioritization allows extending the use of the methodology under circumstances where refinement variables or bounds can be skipped. The AS and clarifying units of the BAS process can run even without fulfilling the bounds of some of these refinement conditions but, generally, fulfilling them improve the behaviour of the BAS process.

The last unit of the BAS process is the separation of sludge from wastewater in the secondary settler since most of the sludge is returned to AS tank while a minor part is taken out to be wasted. The separation of the sludge depends on the microorganism growing in large aggregate called flocs; however, the microorganisms do not always grow in the adequate form leading to sludge separation problems.

Avoiding the risk of separation solid-liquid problems in the secondary settler and loss of COD removal efficiency in the overall BAS process were selected as refinement o decision making requirements (Comas et al. 2008; Flores-Alsina et al. 2009). In the present work, these aspects have been tackled by considering some variables in the unit models and by adapting the upper or lower limits of these variables to the wastewater and process under study, as pointed out in the fourth step of Figure 2.

If after the decision making process none optimal conditions have been obtained it is necessary to come back to step 1 (generation of alternatives) to extend the number of alternatives or to come back to step 4 to extend the bounds of the decision-making variables.

## 4. Industrial installation

Veolia have installed more than 90 BAS plants worldwide to treat wastewater from pulp industry. In this work, the full-scale BAS process for biological COD removal consist of: an equalization tank (1,600 $m^3$), two MBBR reactors in-series (5,331 $m^3$), an AS reactor (47,000 $m^3$), two parallel secondary settler tanks (volume 4,143 $m^3$ and 1,017 $m^2$ unit surface area) and one splitter to recirculate part of the sludge and to disposal the remaining part (Figure 3). The equalization tank is also used to dose nitrogen as urea (40% w/w) and phosphorous as phosphoric acid (72%). The MBBR reactors were filled with carriers type BiofilmChip P of Veolia´s AnoxKaldnes™ to 10% of volume. The aeration system in MBBR reactors uses a blower of a unit air flow 31,600 $Nm^3/h$ for each MBBR reactor and perforated tubes in the bottom of reactor to produce medium bubbles (3 mm of diameter) with a high mixing capacity and medium oxygen transfer efficiency (16 %). The aeration system of AS reactor uses one blowers of a unit air flow 31,600 $Nm^3/h$ and diffusers of membrane to produce fine bubbles (1 mm of diameter) with a high mixing capacity and high oxygen transfer efficiency (45.5 %). Due to the high oxygen transfer efficiency in the AS reactor, the airflow supplied by the blower associated to the oxygen consumption for the carbonaceous (CD) and nitrogenous demand (ND) is lower than in the MBBR reactors resulting in a lower energy consumption (von Sperling 2007).

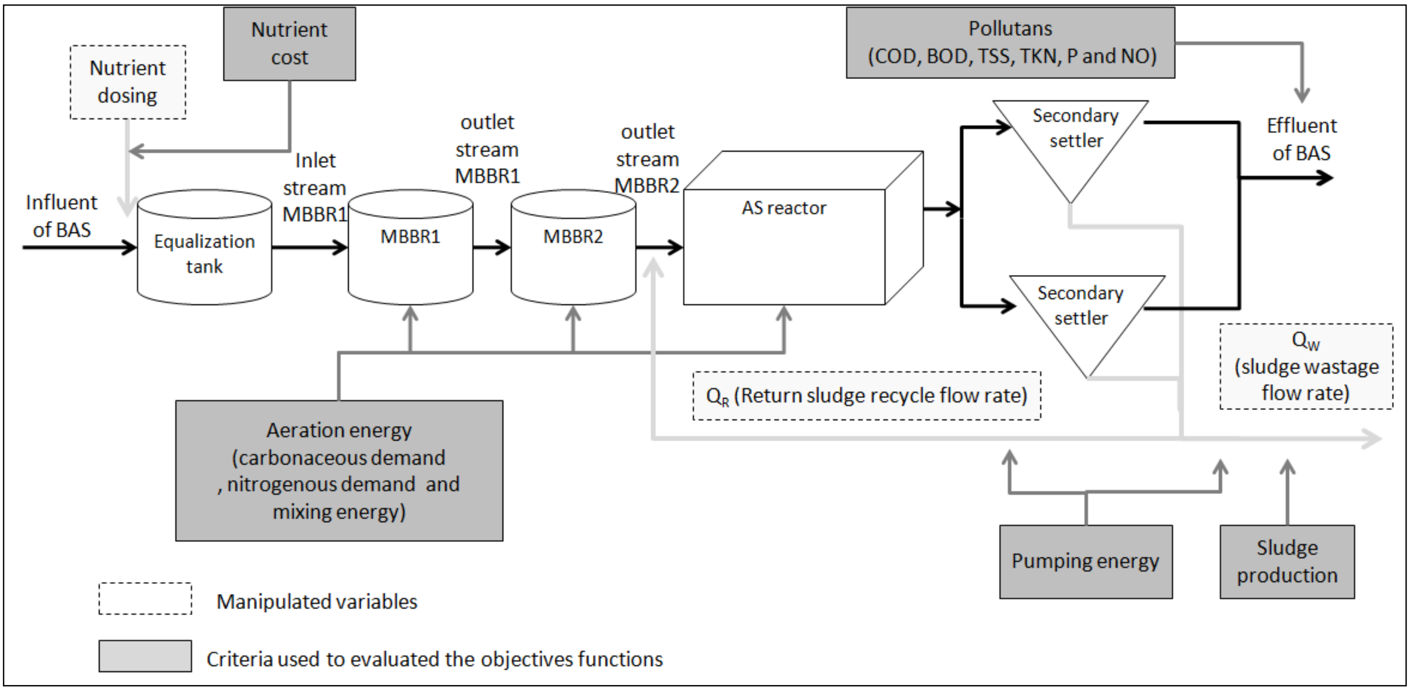


Figure 3. Flow sheet of the full-scale BAS process with detail of the manipulated variables and criteria used to evaluate the objective functions.

The full-scale real BAS plant works under two different conditions (case-study A and B) due to different industrial production requirements of the pulp integrated plant. The case-study A treats wastewater from viscose and cellulose industry and the case-study B treats wastewater from cellulose industry. The regular operational conditions of the studied industrial BAS process (Table 1) are based on the industrial heuristic knowledge.

The low values of nutrient dosage used in this work in comparison with the "thumb rule" (100 COD:5 N:1 P) are explained by the large amounts of nutrients that are regenerated in the AS reactor (Comeau et al. 2003) since the biomass is consumed by predator microorganisms.

Table 1 additionally lists a summary of the main outlet stream characteristics obtained working at these regular operational conditions that reach a high COD removal percentage of 76% and 85% for case studies A and B respectively. Besides, the values of the objective indexes obtained working at regular operational conditions appear at the end of Table 1.

Table 1.Characteristics of *regular working conditions* for the two case-studies of the BAS process together with the variables and indexes obtained for these conditions.

| **Parameters of the treatment plant at regular operation conditions** | | **Case-study A** | **Case-study B** |
|---|---|---|---|
| **Influent conditions** | Wastewater origin | Viscose & Cellulose | Cellulose |
| | $Q_i$ ($m^3$/day) | 1.0 q* | 0.59 q* |
| **Manipulated variables** | vd (hours) | 3.12 | 6.07 |
| | $COD_f$:N:P | 100:2.14:0.28 | 100:1.13:0.24 |
| | R (%) | 110 | 80 |
| | SRT (Days) | 19 | 30 |
| | $Q_W$ ($m^3$/day) | 1,082 | 636 |
| **Key variables** | COD removal percentage | 76 | 85 |
| | Sludge yield (Tn TSS/Tn COD removed) | 0.207 | 0.155 |
| | Efficiency (Tn COD removed/day) | 35.4 | 28.3 |
| **Objective indexes** | TCI (Total cost index) (€/$m^3$) | 0.431 | 0.401 |
| | EQI (Effluent quality index (Kg pollution/$m^3$) | 1.790 | 0.861 |
| | OCI (Operating cost index) (€/$m^3$) | 0.186 | 0.245 |

*Reference value: q for $Q_i$.

It is important to remark that hydraulic retention time in the secondary settler (vd) for a well-driven BAS plant should be between 1-3 hours (van Haandel and van der Lubbe 2015); however, vd is 6.07 hours in case-study B, therefore, in the present paper for optimization purpose, only one secondary settler tank is considered in the case-study B since the usage of two secondary settlers would give infeasible solutions.

## 5. Results and discussion

### 5.1. Generation of alternatives

Nutrient needs to be dosed in the influent of viscose and cellulose wastewater since this type of wastewater do not contain them. Correct balance of nutrient dosage is crucial considering that: i) *nutrient overdosing* can produce effluents with high nitrogen and phosphorus discharges into the sewer (Malmqvist et al. 2007) or unwanted nitrifying bacteria, which consume oxygen and generates additional liquid-solid separation problem due to denitrification in secondary settler tanks (Henze 2008), ii) *severe deficiency of nutrient* results in a loss of COD removal efficiency and bulking (van Haandel and van der Lubbe 2015; Welander et al. 2002) and, iii) *nutrient dosage* also influences the *sludge production* and reduction on dosage can result in growth limitation in the MBBR reactors and a consequent reduction of the waste sludge production (Welander et al. 2002).

Nutrient dosage is incorporated in the mathematical model in order to generate a wide number of alternatives. The dosage used in the regular operation condition is considered the starting point for the generation of alternatives (100:2.14:0.28 for case study A and 100:1.13:0.24 for case-study B); and the alternatives are generated by decreasing nitrogen and phosphorous dosage by 5% until the efficiency of the process (Tn de COD removed by day) decreases more than 2.0% in relation to the regular operation conditions. In this way, in case-study A, 17 different alternatives of nutrient dosage are generated until nutrient dosage value of 100:0.34:0.06 and in case study B, 15 different alternatives are generated until nutrient dosage value of 100:0.34:0.07. Alternatives generated are enough for this study but higher number of alternatives can be easily considered if necessary when the characteristics of the processes are particularly sensitive.

### 5.2. Simulation of the MBBR reactors until steady-state

The MBBR reactors of the treatment plant under-study are simulated using Aspen Custom Modeler software to describe the dynamic and longitudinal behaviour of the reactors. The generated alternatives with different nutrient dosage are simulated during 30 days until steady-state is reached. Once steady-state is attained, the simulated results obtained at the outlet stream of the second MBBR reactor are sent to optimization software to obtain the optimal conditions of the remaining BAS process under-study.

### 5.3. Multicriteria optimization

The BAS process is optimized for each alternative minimizing total cost index, which include operation cost and wastewater quality criteria. As one optimal solution is obtained for each alternative, 15 and 17 optimal solutions are obtained for case-study A and B respectively. In general, it is observed that the decrease of nutrient dosage has a big impact on objective index. The TCI lowest score alternative occurs for the lowest nutrient dosage: 100:0.34:0.06 and 100:0.34:0.07 for case-study A and B respectively (TCI=0.208 €/$m^3$, TCI=0.244 €/$m^3$).

Table 2 shows the optimal values of selected variables for the lowest score alternative using TCI as objective function; the key characteristic of BAS process is the low sludge yield (Tn TSS/ Tn $COD_f$ removed) without compromising treatment efficiency, and therefore the sludge yield and efficiency appears as key variables. First of all, it is observed that the comparison between the key variables in Table 1 (regular operational conditions) and Table 2 (optimal values using TCI as objective function) shows that the optimal conditions decrease the sludge yield to the half respect to the regular operational conditions (from 0.207 to 0.108 Tn TSS/Tn COD removed) and a little decrease of the efficiency is also observed (from 35.4 to 34.5 Tn COD removed /day) for case-study A. For case study B, similar decreases are observed for the best alternative: sludge yield from 0.155 to 0.082 and efficiency decrease from 28.3 to 27.9Tn COD removed /day.

Table 2. Optimal values of the operation conditions for the best alternative minimizing total cost index (TCI) *before* and *after* the decision making process.

| Variables and Index / Optimal solutions | Optimal values ***before*** decision making process | | Optimal values ***after*** decision making process | |
|---|---|---|---|---|
| | Case study A | Case study B | Case study A | Case study B |
| ***Manipulated Variables*** | | | | |
| $COD_f$:N:P | 100:0.34:0.06 | 100:0.34:0.07 | 100:0.54:0.07 | 100:0.45:0.10 |
| $Q_W$ ($m^3$/day) | 461 | 313 | 1.218 | 655 |
| R (%) | 109 | 82 | 109 | 82 |
| ***Objective Indexes*** | | | | |
| TCI (€/$m^3$) | 0.208 | 0.244 | 0.223 | 0.270 |
| EQI (Kg pollution/$m^3$) | 0.684 | 0.541 | 0.680 | 0.593 |
| OCI (€/$m^3$) | 0.114 | 0.170 | 0.130 | 0.189 |
| ***Key variables*** | | | | |
| Sludge yield (Tn TSS/Tn COD removed) | 0.108 | 0.082 | 0.155 | 0.108 |
| Efficiency (Tn COD removed/day) | 34.5 | 27.9 | 35.4 | 28.3 |
| ***Technical decision making variables*** | | | | |
| SRT (days) | 39 | **51** | 17 | 28 |
| NO (g/$m^3$) | 5.4 | 1.8 | 7 | 3.8 |
| TN (g/$m^3$) | 5.9 | **1.9** | 6.5 | 4 |
| P (g/$m^3$) | **0.1** | **0.2** | 0.3 | 0.6 |

**Value:** Values that not fulfil the refine operation bounds.

Figure 4 shows in a box plot fashion the summary of effluent quality and operating cost indexes for all studied alternatives when total cost index is minimized. The lowest values of EQI and OCI correspond with the lowest nutrient dosage. Figure 4 also compares the optimal results with the results of the regular operational conditions. It is observed that for nearly all of the alternatives the operating cost and the effluent quality index values are lower than the regular operational conditions in both case studies.

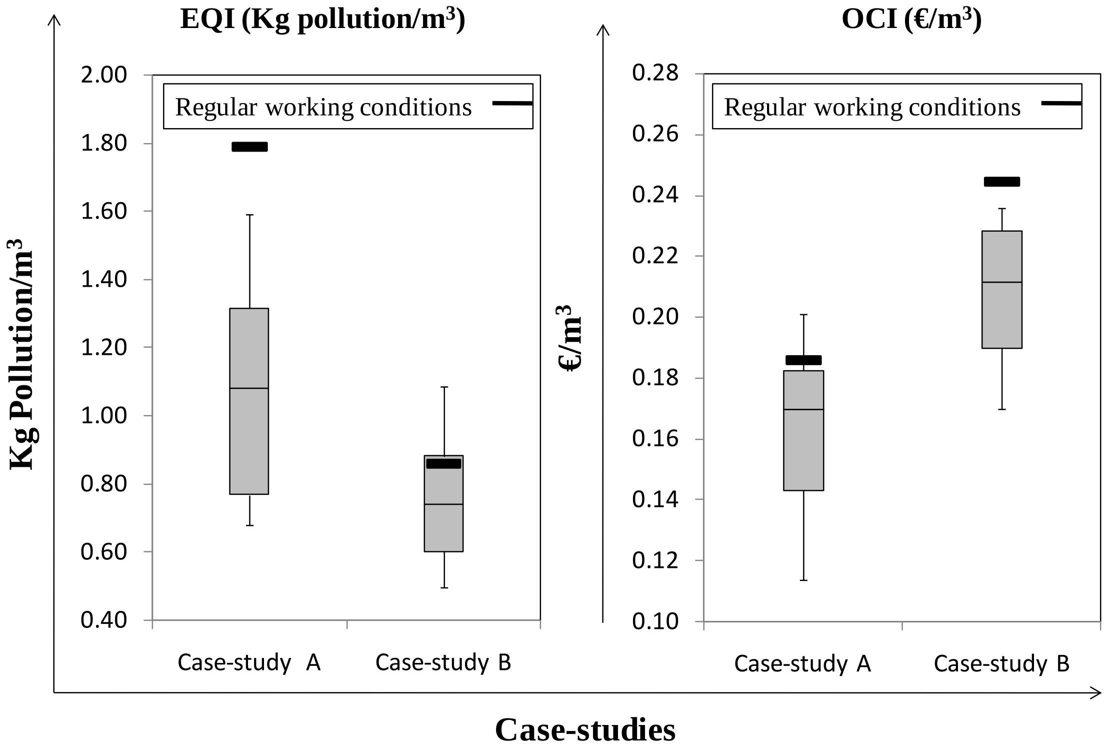


Figure 4. Box plots for the distribution of EQI and OCI indexes in case-study A (17 alternatives) and case-study B (15 alternatives) when TCI is minimized, and the comparison with the results at the regular working conditions.

Figure 5 show the contribution of each particular criterion on the effluent quality (EQI) and operating cost (OCI) indexes for the lowest and the highest values of nutrient dosage when TCI in minimized. In general, the lower the nutrient dosage in the influent, the lower $Q_W$ is purged and higher SRT is obtained and consequently: i) less nitrogen and phosphorous are discharged in the effluent and less nitrogen is available in the AS reactor resulting in a decrease of nitrification rate and, therefore, less nitrogen is oxidized to nitrate (NO) by autotrophic microorganisms and, ii) more TSS is discharged in effluent resulting in increase of COD and BOD. For these reasons, when the nutrient dosage is the lowest, COD contributes up to 63% and 66 % of the pollution discharge in case-study A and B respectively and NO contributes 7-16%. When the nutrient dosage is the highest, the COD contributes 25-30%, NO contributes 30-35% and P contributes 31-33%. In relation to OCI there is a lower influence of the nutrient concentration; in both case-study, it is remarkable that when the nutrient dosage is the lowest, CD is reduced 2-14% due to airflow supplied in AS reactor is lower than in MBBR reactor.

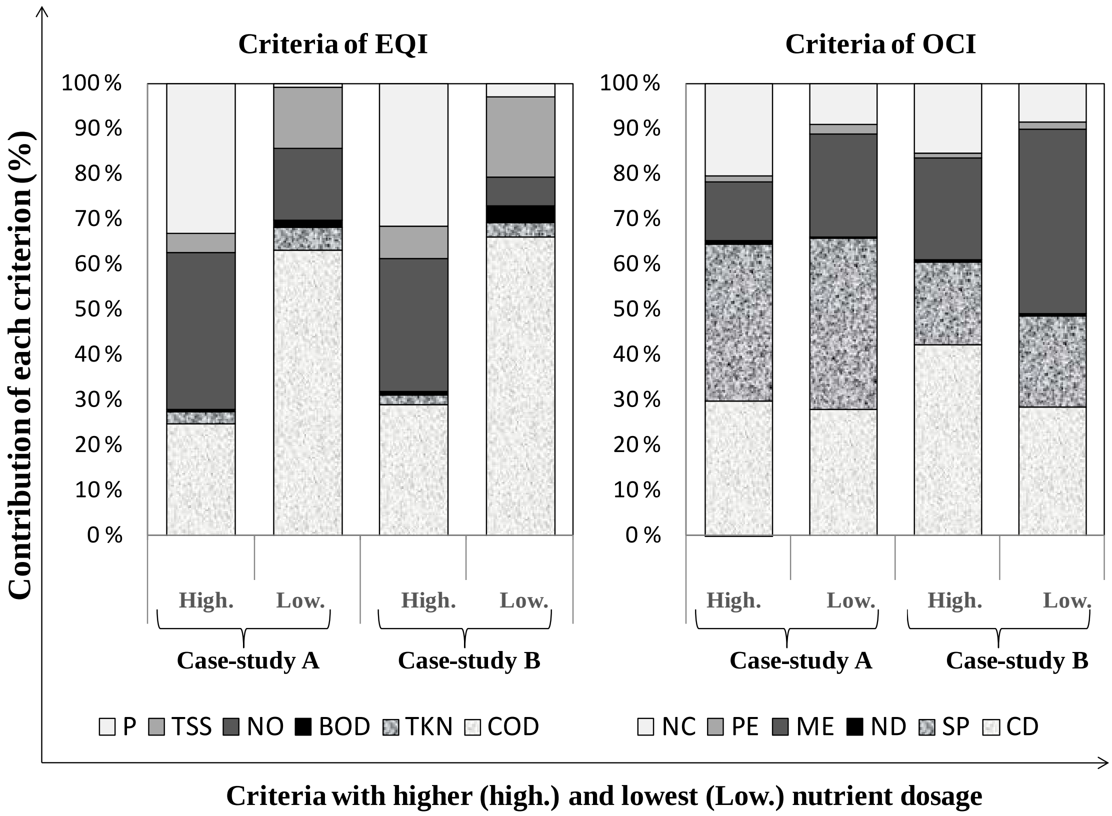


Figure 5. Contribution of each criterion on the effluent quality (EQI) and operating cost (OCI) indexes in each case-study for the highest (High.) and the lowest (Low.) values of nutrient dosage when TCI in minimized.

### 5.4. Decision-making process.

Decision making process is the last step of the methodology and includes the determination of some discrimination variables and their limits. The operational constrains and bounds included in the step 1 of the methodology are essential for the adequate running of an activated sludge process; however, there are other variables whose limits are recommendable but that nonetheless under diverse circumstances do not need to be considered. At present there are more than 600 municipal or industrial Veolia MBBR treatment plants in operation or under construction in more than 50 countries (van Haandel and van der Lubbe 2015); some of these installations are used as pre-treatment of activated sludge since MBBR is an upgrade to existing AS systems with little disturbance but high efficiency. The diverse circumstances that can take places in each installation support the idea of classifying the variables into essential and refinement.

The consideration of the refinement conditions in the decision making process of the optimization methodology will help, a) to facilitate the trade-off among effluent quality index, operating cost index and technical arrangement (Hakanen et al. 2013) and, b) to obtain BAS process adapted to different operation circumstances, for example: low pH wastewater, oversize installations, wastewater with different origin, low Food/Microorganisms (F/M) ratio for AS process and excess of greases and oils among others.

In the activated sludge process, the operational problems with biological origin are among the most serious and most difficult matter to solve in wastewater treatment plants. Even though the optimal conditions shown in Table 2 fulfil the appropriated operational conditions for BAS process of Figure 2, in the refinement conditions three biological aspects are pointed related with the growth of microorganism: i) “bulking” since too low nutrient dosage can bring excessive growth of filamentous bacteria (van Haandel and van der Lubbe 2015; Welander et al. 2002) that leads to solid-liquid separation problems (Flores-Alsina et al. 2009), ii) “pin-point floc” due to the formation of the old and overoxidised sludge produce by endogenous metabolism (Comas et al. 2003) and iii) rising sludge due to denitrification in the secondary settler where nitrates are converted to nitrogen gas (Flores-Alsina et al. 2010). The refinement operation bounds included in the decision making variables are divided into two categories:

*Bulking and decrease of COD removal efficiency*

Until now, the nutrient dosage has been considered *in the influent*; however, very low concentrations of the TN and P *in the effluent* can mean too severe decrease of nutrient dosage resulting in sludge settleability (bulking) or even in a loss of COD removal efficiency (van Haandel and van der Lubbe 2015). For this reason, in this work has taken into account lower limits in the *effluent* for the concentration of TN of 4 g/m$^3$ and 0.3 g/m$^3$ for P as proposed by Welander et al. 2002.

It is observed at Table 2 (Bold figures) that the optimal solutions before decision making process do not fulfil some of the P or/and TN values in the *effluent* and therefore the undesirable bulking can occur.

*Risk of solid-liquid separation problems due to "pin-point-floc" and rising sludge*

In addition to the TN and P bounds described above, two new technical requirements are now adding (Figure 2): i) concentration of nitrate (NO) and, ii) SRT in the AS reactor of the BAS process. Nitrate concentration in the secondary settler higher than 8 g/m$^3$ (Henze et al. 1993) is not recommended since the bottom layer of the secondary settler (where nitrogen bubble formation through biological denitrification) can break into small flocs and part of the sludge would flow out into the effluent; furthermore, an increase of COD, BOD, TKN and P in the effluent would occurs (Flores-Alsina et al. 2010).

High values of SRT produce an old and overoxidised sludge with large amount of inert matter called "pin-point floc" (Comas et al. 2003). 40 days is selected in this work as upper limit of SRT because the hydraulic retention time (HRT) in AS reactor is greater than 30 hours and it is considered an extended aeration tank which optimal SRT value lower or equal to 40 days (Tchobanoglous et al. 2003).

Above described operational bounds of the effluent are included in step 4 of the optimization methodology shown in Figure 2. Figure 6 shows the pareto graph between the sludge yield and TCI index values for all alternatives before (red symbols) and after the decision making process (green symbols) as well as the regular operational conditions (black and brown symbols). It is observed that in both case-studies the minimum values of TCI and sludge yield agree but only few alternatives (green symbols) fulfil the refinement bounds.

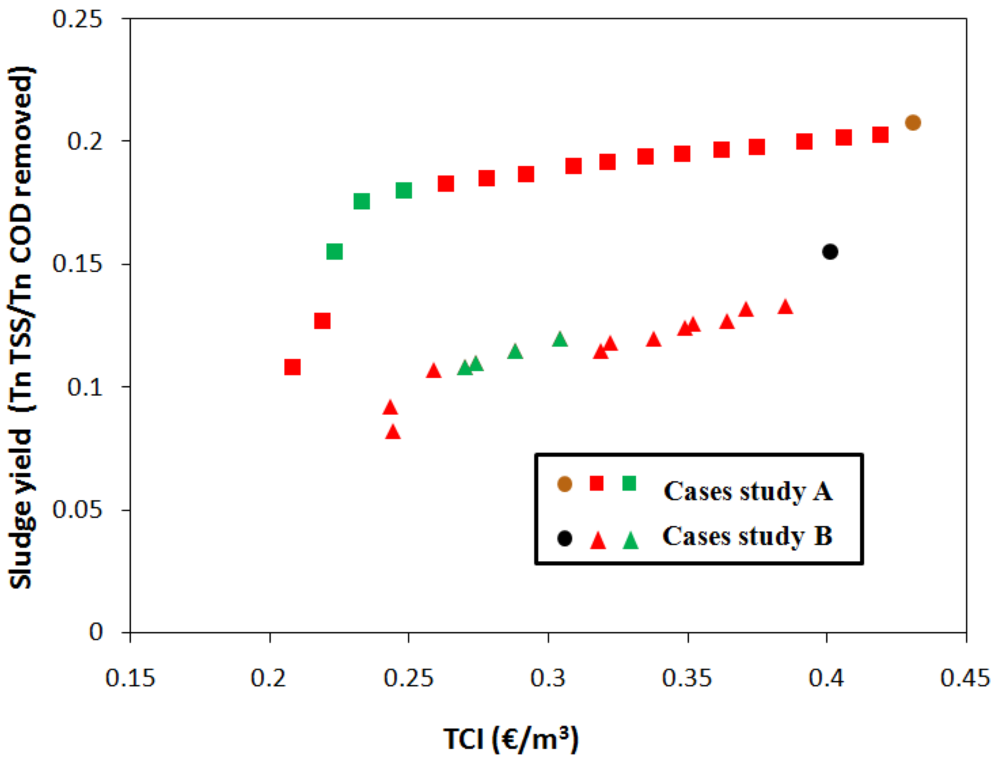


Figure 6. Pareto graph between sludge yield and TCI index values before decision making process in Case Study A (■) and B (▲) and after the decision making process in Case Study A (■) and B (▲). The regular operational conditions are represented in Case Study A (●) and Case Study B (●).

Figure 7 shows the 3 (case-study A) and 4 (case-study B) alternatives that fulfil the values of refinement operation bounds simultaneously and compares the results of these alternatives respect to the regular operational conditions. It is observed in Figure 7 reductions of TCI up to 45% and 25% for case-study A and B respectively in comparison with the regular operational conditions, mainly due to the high reductions of EQI (up to 60% in A and up to 31% in B).

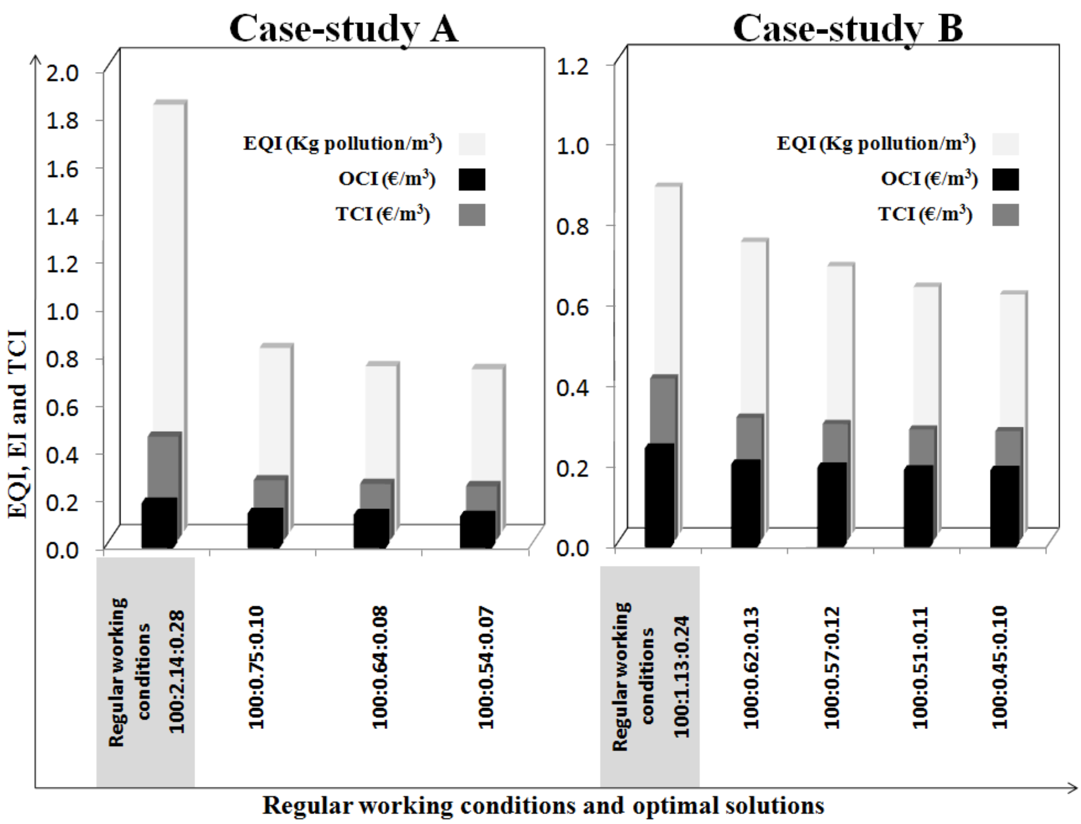


Figure 7. Optimal values of the feasible alternatives for the effluent quality index (EQI), operating cost index (OCI) and total cost (TCI) index after of the decision making and the comparison with the regular operational conditions.

Finally, the right column in Table 2 shows the optimal values of variables for the best alternative for case-study A and B after decision making selection. It is observed that the nutrient dosage and sludge yield are higher than before to decision making process.

Besides, the sludge yields in Table 2 are inside the range of others studies as such as Malmqvist et al. 2007 and Rankin et al. 2007.

The application of the proposed methodology allows a reduction of the operating cost of treatment (€/$m^3$) up to 30% whereas the efficiency (Tn COD removed per day) do not decrease respect to the regular operational conditions used in the full-scale wastewater plant. Furthermore, the quality of the wastewater is also much better since the EQI (Kg pollution/$m^3$) is reduced up to 62%.

In Figure 8, the different contributions of each evaluation criterion for the best alternative are shown. The major contribution to effluent quality index (EQI) is the COD (21 % in case-study A and 17 % in case-study B), since the contribution of NO and P are reduced in comparison to regular operational conditions due to low nutrient dosage. Respect to the major contribution to operation cost index (OCI) after decision making is the energy consumption for carbonaceous demand (CD) (21% in case-study A and 28 % in case-study B) due to the BAS process in this work was designed to the high removal of COD in aerobic conditions (Revilla et al. 2016a); moreover, a large decrease in the nutrient cost (NC) is observed compared to regular operational conditions.

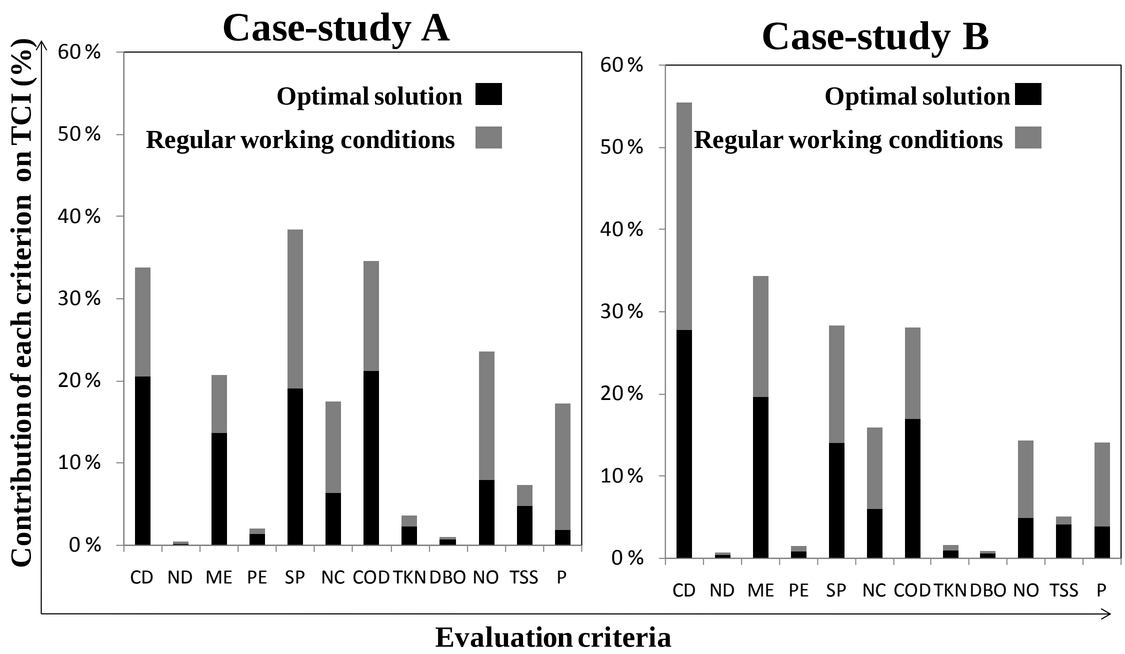


Figure 8. Contribution of evaluation criteria on the total cost index (TCI) of the optimal solution compared to the regular operational conditions.

## 5. Conclusions

This paper presents a methodology that allows obtaining the optimal operational conditions for an industrial BAS plant treating highly COD wastewater under limited nutrient conditions. The methodology formulates BAS process as a mathematical optimization problem combining economic and environmental criteria as objective function and overtakes some challenges such as high number of (non-linear) equations and variables and the dynamic and spatial distribution behaviour of components into the biofilm. The optimization methodology is divided into four consecutive steps: i) generation of alternatives, ii) simulation of the MBBR reactors (biofilm) until steady-state, iii) multicriteria optimization and iv) decision making process. The optimization methodology establishes priority levels of several technical specifications (essential and refinement variables) related with the activated sludge tank and secondary clarifiers.

The application of this methodology at two industrial-scale case studies from viscose and cellulose wastewaters allows a reduction of quantity of pollutants per $m^3$ wastewater treated up to 60% and a reduction of the operating costs (€/$m^3$) up to 30% in comparison with the regular operational conditions used in the industrial BAS wastewater plant.

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