Multi-criteria Optimization of a Bioreactor-separator System used for Biological Treatment of Wastewater

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The objective of this work was to optimize the operating parameters of a system used for biological wastewater treatment. The system consists of two reactors (one anoxic and one aerobic), a separator, a recirculation line and a purge line. In order to satisfy the effluent requirements for environmental discharge (e.g. the EU Directive 91/271/ECC) and to minimize the energy cost in terms of aeration and pumping of the recycled and wasted sludge, the airflow and the recirculation and purge ratios, were optimized. The results obtained with the optimized values of the operating parameters showed that the system performance was improved while still in good agreement with the EU Directive.

Keywords: biological wastewater treatment, Pareto optimization, energy savings, activated sludge, dynamic modeling

The biological treatment with activated sludge, one of the most used techniques for wastewater treatment, involves a mixed community of microorganisms, of which the bacteria play a vital role in the conversion of the pollutants. The structure and functions of this community are influenced by the nature of the wastewater treated, by the concentrations of the pollutants [1-3], and by the operating conditions such as aeration intensity, solid (SRT) and hydraulic (HRT) retention times, temperature, pH [4-9], and the recirculation and purge ratios [10].

Heterotrophic organisms are responsible for the degradation of organic substrate under both aerobic and anoxic conditions, through nitrification and denitrification. Two different groups of aerobic microorganisms carry out nitrification. The ammonia-oxidizing bacteria (AOB) oxidize ammonia to nitrite (NO₂⁻), and the nitrite is then oxidized to nitrate (NO₃⁻) by the nitrite-oxidizing bacteria (NOB). Hence, the activity and abundance of microbial populations, especially of nitrifying organisms, in wastewater processing is important in the design and operation of treatment systems. Having very low growth rates and high sensitivity to environmental disturbances and inhibitors, these microorganisms have their concentration easily decreased and, thus, can adversely influence the system’s performance. The dissolved oxygen (DO) concentration is one of the main parameters in an activated sludge process, since the activity and composition of the nitrifying bacteria can be changed by the dissolved oxygen level. Therefore, at low DO levels the nitrification process is inhibited, leading to a decrease in pollutant removal [11], while too high DO concentrations lead to increased energy consumption and maybe lower the quality of the effluent.

The biomass recycling is also a vital part of any treatment strategy because of its role in maintaining the bacteria concentration at a high level inside the bioreactor. The recirculation of the biomass also shortens the acclimation period of microorganisms when the environmental conditions change; the slow growth microorganisms are less affected, which reflects in maintaining the system’s performance [12-14]. Simultaneously, a purge line is usually used to remove a fraction of the cells from the system with the purpose of avoiding the indefinite accumulation of the dead cells inside the bioreactor. While the employment of a recirculation and a purge lines offers the aforementioned advantages, the pumping energy related to these flows increases the operating costs.

Consequently, the air, the recycling and the purge flow rates should be high enough to ensure an elevated value of the active cells inside the bioreactor (equivalent to an effluent suitable to be discharged into environment), but low enough to avoid the consumption of a large amount of pumping energy, which makes their selection an optimization problem.

In the present study, an optimization was performed with the purpose of finding the set of operating parameters that maximizes the conversion and productivity, and minimizes the energy consumption, and, at the same time, keeps the substrate at the output below an imposed value, despite the large variations of the inflow rate and of the substrate concentration of the incoming wastewater. The effluent quality was tested in accordance with the 91/271/EEC Directive concerning urban wastewater treatment, which fixes the maximum pollutant concentration allowed in the effluent of a small size wastewater treatment plant.

The physical abstraction and the mathematical model

The system whose efficiency is optimized contains two reactors, a settler, a recirculation sludge lineage and purge (fig. 1). The first reactor, with a working volume of 2000 m³, is operated under anoxic conditions, while the second one, with a working volume of 4000 m³, is operated under aerobic conditions. The secondary settler is assumed ideal and no biochemical reactions take place inside it. The activated sludge along with the mixed liquor is recycled from the bottom of the settler into the anoxic bioreactor. While the recycling line offers the aforementioned advantages, the pumping energy related to these flows increases the operating costs.

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The input data used in this study are reported in the benchmark study (http://www.benchmarkwwtp.org) [15]. The samples were taken every 15 minutes for a period of two weeks, for three operating time windows: “dry weather”, “stormy weather”, and “rainy weather”. The
The system's influent flow rate varied randomly, and so did the pollutant concentrations. These variations induce large disturbances of wastewater treatment system processes, affecting the performance of the system. The aim of the optimization of this system is to search for the particular operating parameters (the command variables) that ensure the Chemical Oxygen Demand (COD) and the Total Kjeldahl Nitrogen (TKN) below their corresponding discharge limits for the large variations in the flowrates and substrate concentrations of the incoming wastewater.

The model used in this work is based on the Activated Sludge Model No. 3 with two steps for nitrification and denitrification (ASM3-2N) [15]. The main processes considered by the model are the removal of organic compounds by heterotrophic bacteria and the nitrification, which involves the transformation of ammonia into nitrite by ammonia-oxidizing bacteria (AOB) and after transformation of nitrite into nitrate by nitrate-oxidizing bacteria (NOB). These processes require the presence of enough dissolved oxygen and take place in the aerobic bioreactor. The anoxic reactor is the host of both denitrification, which is the transformation of nitrate and nitrite into gaseous nitrogen, and oxidation of organic compounds with nitrate as electron acceptor, which also requires the absence of oxygen. Three are the main assumptions of the model:

- both reactors are perfectly mixed;
- the separation of the liquid and solid phases is perfect (no particulate compounds are discharged into the effluent);
- no biological process develops in the settler.

The state variables of the system are divided into two categories: the concentrations of the soluble components (these are the components assumed to be transported by water), denoted by S, and the concentrations of the particulate components (associated with the activated sludge concentrated in the settling tank), denoted by X. According to the ASM general philosophy, the unstructured COD is split into the required partitions [16]. In Table 1 the initial values of the state variables are presented.

The mathematical model consists of overall and partial mass balances for all components of the wastewater around each reactor, together with the appropriate expressions for the kinetics of different biological processes associated with the degradation of the pollutants [17].

Assuming perfect mixing, the generic partial mass balance for the first tank in series, the anoxic bioreactor, reads [10, 17]:

\[
\frac{d\bar{x}_{\text{anox}}}{dt} = \frac{Q_{\text{in}} \cdot \bar{x}_{\text{in}} + Q_{\text{rs}} \cdot \bar{x}_{\text{rs}} - Q_{\text{anox}} + Q_{\text{anox}} \cdot \bar{x}_{\text{anox}}}{V_{\text{anox}}} + \bar{v}_{\text{anox}}
\]

where:
- the vectors \(\bar{x}_{\text{in}}, \bar{x}_{\text{rs}}, \bar{x}_{\text{anox}}\) denote the concentrations of a generic substrate (i.e., soluble or insoluble) in the influent, \(Q_{\text{in}}\), in the recycled sludge, \(Q_{\text{rs}}\), and in the outlet, \(Q_{\text{anox}} + Q_{\text{rs}}\), of the anoxic reactor, respectively, \(\text{g/m}^3\);
- \(\bar{v}_{\text{anox}}\) is the vector formed by the reaction rates of each component, \(\text{g/(m}^3 . \text{s)}\);
- \(v_i = \sum_j c_{ji} \cdot \rho_j\), where \(c_{ji}\) is the stoichiometric coefficient of \(p_j\) component in the \(i^{th}\) reaction, according to the stoichiometric matrix of the model ASM3-2N, while \(\rho_j\) is the kinetic rate of the \(j^{th}\) reaction, \(\text{g/(m}^3 . \text{s)}\);
- \(V_{\text{anox}}\) is the volume of the anoxic bioreactor, \(\text{m}^3\).

<table>
<thead>
<tr>
<th>State variables</th>
<th>M.U.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 SO(_2)</td>
<td>Dissolved Oxygen</td>
</tr>
<tr>
<td>2 SS</td>
<td>Readily biodegradable substrates</td>
</tr>
<tr>
<td>3 SN(_2)g</td>
<td>Dinitrogen released by denitrification</td>
</tr>
<tr>
<td>4 SNH(_4)</td>
<td>Ammonium</td>
</tr>
<tr>
<td>5 SNO(_2)</td>
<td>Nitrite nitrogen</td>
</tr>
<tr>
<td>6 SNO(_3)</td>
<td>Nitrate nitrogen</td>
</tr>
<tr>
<td>7 SI</td>
<td>Soluble inert organics</td>
</tr>
<tr>
<td>8 SALK</td>
<td>Alkalinity</td>
</tr>
<tr>
<td>9 XI</td>
<td>Inert particulate organics</td>
</tr>
<tr>
<td>10 XS</td>
<td>Slowly biodegradable substrates</td>
</tr>
<tr>
<td>11 XH</td>
<td>Heterotrophic biomass</td>
</tr>
<tr>
<td>12 XSTO</td>
<td>Organics stored by heterotrophs</td>
</tr>
<tr>
<td>13 Xns</td>
<td>Nitrite-oxidizing autotrophs</td>
</tr>
<tr>
<td>14 Xnb</td>
<td>Ammonia-oxidizing autotrophs</td>
</tr>
</tbody>
</table>

Table 1
NOTATIONS USED FOR THE STATE VARIABLES DESCRIBING THE BEHAVIOUR OF THE WHOLE SYSTEM

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Fig. 1. The sketch of the system:
1) mixer; 2) anoxic bioreactor;
3) aerobic bioreactor; 4) settler
The generic partial mass balance for the aerobic bioreactor reads [10, 17]:
\[
\frac{d\vec{x}}{dt} = \left(\vec{Q}_m + \vec{Q}_{rs}\right) \cdot (\vec{x}_{\text{amw}} - \vec{x}) + \vec{v}_{\text{aero}}
\]
(2)
where:
- \(\vec{x}_{\text{amw}}\) - the vectors denote the concentration of a generic substrate (i.e. soluble or insoluble) in the inlet, \(\vec{Q}_m + \vec{Q}_{rs}\), and in the outlet, \(\vec{Q}_m + \vec{Q}_{rs}\), of the aerobic bioreactor, respectively, g/m³;
- \(\vec{v}_{\text{aero}}\) is the vector formed by the reaction rates of each component, g/(m³ · s);
- \(c_{ij}\) is the stoichiometric coefficient of \(i^{\text{th}}\) component in \(j^{\text{th}}\) reaction, according to the stoichiometric matrix of the model ASM3-2N, while \(p_j\) is the kinetic rate of \(j^{\text{th}}\) reaction, g/(m³ · s);
- \(Vaero\) is the volume of the aerobic bioreactor, m³.

In the aerobic tank, the mass balance for oxygen has an additional term that describes the oxygen mass transfer from the air diffuser to the mixed liquor, equal to the product between the volumetric mass transfer coefficient and the drag force responsible for the transfer [10, 17]:
\[
\frac{dS_o}{dt} = K_{La} \cdot (S_o^\text{sat} - S_o) - \frac{1}{\alpha} \cdot \frac{Q}{\alpha} \cdot \frac{1}{T} \quad (3)
\]
where,
- \(K_{La}\) - the oxygen volumetric mass transfer coefficient, d⁻¹;
- \(S_o^\text{sat}\) - the saturation concentration of oxygen in the liquid phase, g/m³;
- \(S_o\) - the oxygen concentration in the liquid, g/m³.

The recirculation and purge flows are limited by two upper threshold values. These are calculated based on the average influent flow during the dry weather period [18]:
\[
F_i = \frac{1}{\alpha} \sum_{i=1}^{n} \frac{1}{\alpha} \quad (4)
\]

Criteria used to assess the performance of the treatment system

In order to analyze and optimize the efficiency of the studied wastewater treatment system, three operational parameters strongly influencing the active biomass concentration have been investigated, namely the recirculation and the purge ratios, together with the air flow rate. The recirculation ratio, \(\alpha\), varied between 0.1 and 0.5, the purge ratio, \(\beta\), varied between 0.001 and 0.005, as recommended in [10], and the air flow rate varied between 1880 and 5640 m³/h, limits resulted from the benchmark data.

The Pareto approach used to optimize this system implies a dual-objective function.

The first metric used to assess the performance of the system took into account the conversions of COD and TKN, computed using their concentrations in the inlet (TKNᵢ, CODᵢ) and in the effluent (TKNᵢᵢᵢ, CODᵢᵢᵢ) of the system:
\[
\text{Conv}_{\text{TKN}} = \frac{\text{TKN}_i - \text{TKN}_i^{\text{effluent}}}{\text{TKN}_i} \quad (5)
\]
\[
\text{Conv}_{\text{COD}} = \frac{\text{COD}_i - \text{COD}_i^{\text{effluent}}}{\text{COD}_i} \quad (6)
\]

The concentrations of the two substrates in the inlet and in the effluent were computed according to the following expressions, using the ASM-3-2N notations:
\[
\text{TKN}_i = \text{INSS}_i + \text{INSI}_i + \text{INXS}_i + \text{INXI}_i \quad (7)
\]
\[
\text{COD}_i = \text{SS}_i + \text{SI}_i + \text{XS}_i + \text{XI}_i \quad (8)
\]
\[
\text{TKN}_{\text{effluent}} = \text{INSS}_{\text{effluent}} + \text{INSI}_{\text{effluent}} + \text{INXS}_{\text{effluent}} + \text{INXI}_{\text{effluent}} \quad (9)
\]
\[
\text{COD}_{\text{effluent}} = \text{SS}_{\text{effluent}} + \text{SI}_{\text{effluent}} + \text{XS}_{\text{effluent}} + \text{XI}_{\text{effluent}} \quad (10)
\]

where, INSS, INSI, INXS, INXI are the fractions of nitrogen in carbonic substrates (SS, SI, XS, XI), and hSS, hSI, hXS, hXI are the fraction of SS, SI, XS, and XI in the COD.

The conversions that the two substrates must reach, according to the imposed discharge limits, are:
\[
\text{Conv}_{\text{TKN,dev}} = \frac{\text{TKN}_i - \text{TKN}_{\text{dev}}}{\text{TKN}_i} \quad (11)
\]
\[
\text{Conv}_{\text{COD,dev}} = \frac{\text{COD}_i - \text{COD}_{\text{dev}}}{\text{COD}_i} \quad (12)
\]

where \(\text{COD}_{\text{dev}}\) and \(\text{TKN}_{\text{dev}}\) are the discharge limit values: \(\text{TKN}_{\text{dev}} = 15\text{ g/m³}, \text{COD}_{\text{dev}} = 125\text{ g/m³}\).

In order to make sure the treatment process observes the restrictions for both substrates, the maximum of the two conversions was computed:
\[
\text{Conv}_{\text{dev}} = \max \{\text{Conv}_{\text{TKN,dev}}, \text{Conv}_{\text{COD,dev}}\} \quad (13)
\]

When at least one of the final conversions gets lower than this value, the computation of this objective function stops and the optimizer proposes another point. If both conversions satisfies the aforementioned rule, the computations continues and the first objective function gets evaluated:
\[
F_i = \frac{1}{\alpha} \sum_{i=1}^{n} \frac{1}{\alpha} \quad (4)
\]

The second objective function is related to the operating costs. The main component of the total operating cost of a wastewater plants is represented by the aeration energy. However, the energy consumed during the pumping of recycled and wasted sludge also contributes to increasing the operating cost and all these parameters (i.e. the oxygen flow rate, the recirculation and purge ratios) are of great importance when trying to make the process more cost effective.

The aeration energy (AE) is a function of the volumetric mass transfer coefficient, \(K_{La}\), and the operating period, \(T\) [18,19]:
\[
AE = 24 \cdot \frac{1}{T} \cdot 0.4032 \cdot K_{La} \cdot 7.8408 \cdot \dot{Q} \cdot \text{kWh/d} \quad (15)
\]

The mass transfer coefficient, expressed in h⁻¹ in eq. (15), was computed using the empirical equation established by Shah [20,21]:
\[
K_{La} = 0.467 \cdot U_g^{0.8} \quad (16)
\]
where \(U_g\) is superficial gas velocity, m/s.

Similarly, the pumping energy (PE) is a function of all the flows involved and the same operating period, \(T\) [18,19]:
\[
PE = 0.04 \cdot \frac{1}{T} \sum \dot{Q} \cdot \text{kWh/d} \quad (17)
\]

where:
Q_a – the air flow, m³/d;
Q_σ – the sludge recycle flow, m³/d;
Q_w – the wasted sludge flow, m³/d;

The second objective function \( F_2 \) is the sum of these two energies:

\[
F_2 = AE + PE
\]  (18)

Finally, the third objective function used is the system productivity, defined as the amount of substrate metabolized in the system by microorganisms in the hydraulic retention time (HRT) and expressed as the ratio between the amount of pollutants and product between the biomass and the HRT.

The following steps are required to compute the productivity:

- the hydraulic retention time of the system:
  \[
  HRT = \frac{V_{am} + V_{wn}}{Q_σ}
  \]  (19)

- the mass of substrate in the inlet flow:
  \[
  m_s = SS_a + SNH_4 + SI_a + X_{Hanox} + X_{Hanero} \cdot V_{am}
  \]  (20)

- the activated sludge mass at the beginning of the treatment process:

\[
\text{cells}_{mocul} = XH_{am} + Xns_{am} + Xnb_{am} \\
\cdot V_{am} + XH_{amo} + Xns_{am} + Xnb_{amo} \cdot V_{amo}
\]  (21)

- the mass of substrate in the effluent, at any moment, \( t \):
  \[
  m_{out} \cdot t = Q_σ \cdot (1 - \beta) \cdot SS \cdot t + SNH_4 \cdot t + SI \cdot t
  \]  (22)

- the activated sludge mass in the system at any moment, \( t \):

\[
\text{cells} \cdot t = \left[ XH_{am} + Xns_{am} + Xnb_{am} \cdot t \right] \cdot V_{am} + \\
\left[ XH_{amo} + Xns_{amo} + Xnb_{amo} \cdot t \right] \cdot V_{amo}
\]  (23)

where:

\( X_{Hanox}, X_{Hanero} \) are the concentrations of heterotrophic bacteria in the anoxic and aerobic bioreactors;

\( X_{nsanox}, X_{nsaero} \) are the concentrations of autotrophic bacteria (Nitrosomonas) in the anoxic and aerobic bioreactors;

\( X_{nbanox}, X_{nbaero} \) are the concentrations of autotrophic bacteria (Nitrobacters) in the anoxic and aerobic bioreactors;

\( X_{nsanox}, X_{nsaero} \) are the concentrations of autotrophic bacteria (Nitrosomonas) in the anoxic and aerobic bioreactors;

\( X_{nbanox}, X_{nbaero} \) are the concentrations of autotrophic bacteria (Nitrobacters) in the anoxic and aerobic bioreactors;

The productivity of the system, at any moment \( t \), is:

\[
\text{prod} \cdot t = \frac{m_{out} \cdot m_{mocul}}{\text{cells} \cdot t \cdot HRT}
\]  (24)

and the third objective function that can be used to optimize the system's performance is:

\[
F_3 = 1 - \text{prod} \cdot t \cdot \frac{m_{mocul}}{\text{cells} \cdot HRT}
\]  (25)

Using these objective functions, three different dual-objective problems were defined, namely: 1) the first and the second objective functions (eq. (14) and (18)), 2) the first and the third objective functions (eq. (14) and (25)), and 3) the second and the third objective functions (eq. (18) and (25)).

All effluent concentrations involved in the objective functions are computed after the system reached steady state and all optimizations were carried out for the dry weather conditions. The dynamic simulations were performed with the steady-state parameters and using the inlet data for all weather conditions (dry, rainy, stormy).

The Pareto optimizations were carried out using the genetic algorithm as encoded in Matlab™.

**Results and discussions**

Since the genetic algorithms belong to the stochastic optimization methods, different runs with different numbers of individuals (30, 70, 100) and generations (15, 30, 50) have been performed; the results obtained were almost identical. In what follows, the results obtained with 50 generations and 100 individuals are presented.

Figure 2 shows the results obtained for the three aforementioned combinations of the objective functions: \( A - F_1, F_2 \) and \( F_3 \), \( B - F_1 \) and \( F_3 \), \( C - F_2 \) and \( F_3 \).

Figure 2.A presents the Pareto front obtained when using the conversion and the energy consumption as objective functions. As expected, the energy consumption increases
as the conversion increases, strengthening the conclusion that for high conversions the operating costs should be also high. However, very small changes in conversion can be observed when the energy is increased over 2500 kWh/d. This point corresponds to the following values for the operating parameters:

\[
\alpha = 0.4; \quad \beta = 0.001; \quad Q_a = 2873 \text{ m}^3/\text{d}
\]

Since all points are of equal optimality in the Pareto sense, the point for which both conversion, and energy consumption are minimal (0.7428; 1653 kWh/d) is the right choice:

\[
\alpha = 0.1195; \quad \beta = 0.0022; \quad Q_a = 1952.7 \text{ m}^3/\text{d}
\]

Figure 2.B presents the Pareto front obtained as a result of using the conversion and the productivity as objective functions. The lower productivities which correspond to the higher conversions could be related to the increase of the cells concentration, faster than the consumption of the substrates. This is possible due to the recirculation, which increases the concentration of the cells. As the smallest conversion is high enough so that the effluent to be in the discharge limits, the chosen point from the Pareto front corresponds to the following values of the dual-objective function: conversion = 0.1195; productivity = 0.524. The parameters that give this optimal solution are:

\[
\alpha = 0.1156; \quad \beta = 0.0049; \quad Q_a = 4127.11 \text{ m}^3/\text{d}
\]

Table 2 strengthens this observation, and shows that the lowest pollutant levels for COD were obtained in the first case of dual-objective optimization and for TKN in the second case; the highest values resulted with the parameters corresponding to the last optimization case (energy consumption and productivity), for all weather conditions (dry, rainy, stormy). The higher air flow obtained in the second case (4127.11 m³/d), influenced the bacterial growth, which further affected the pollutant removal (especially TKN removal).
Table 3
THE VALUES OF COD AND TKN CONCENTRATIONS IN EFFLUENT FOR ALL OBJECTIVES IN ALL WEATHER CONDITIONS

<table>
<thead>
<tr>
<th>Optimization strategy</th>
<th>α</th>
<th>β</th>
<th>Q_0, m³/d</th>
<th>TKN in effluent, g/m³</th>
<th>COD in effluent, g/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRY</td>
<td></td>
<td></td>
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<tr>
<td>F₁+F₂</td>
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<td>0.0022</td>
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<td>3.49</td>
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<td>0.0043</td>
<td>1883.94</td>
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<td>47.78</td>
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<td>0.0022</td>
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<tr>
<td>F₁+F₃</td>
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<td>0.0043</td>
<td>1883.94</td>
<td>4.49</td>
<td>47.80</td>
</tr>
</tbody>
</table>

Fig. 4. COD temporal profile for the three weather conditions with the parameters obtained after the F₁+F₂ optimization:
A – DRY; B – RAIN; C – STORM

Fig. 5. Comparison of TKN variation in effluent, when the system was operated under dynamic conditions, in DRY weather:
…… optimal values of the parameters; ___ non-optimal values of the parameters
A – F₁, F₂; B – F₁+F₃; C – F₂+F₃
an aeration flow rate of 5000 m$^3$/d. The aeration flow rate of the optimized system was only 1883.94 m$^3$/d. This means that the aerobic biological processes are carried out at a minimum level, with the major consequence of smaller growth rates and activities of the aerobic bacteria (mainly autotrophs) and, consequently, higher TKN concentrations. Although it may seem the non-optimized operation gives better results owing to the lower TKN concentrations, the necessary air flow, which is approximately 2.6 times lower than the non-optimized flow, and the fact the TKN is still under the discharge limits, make the optimized system to be more economically attractive.

**Conclusions**

In order to assess and improve the efficiency of a wastewater treatment system, three operational parameters (aerobic flow rate, recirculation and purge ratios) have been investigated. The performance was evaluated in terms of the effluent quality, treatment efficiency and operating costs through the three metrics defined: the conversion ($F_c$), the energy consumption ($F_e$) and the productivity ($F_p$). These metrics were then grouped into three bi-objective problems and a Pareto front was obtained for each of them, for the dry, rainy and stormy weather.

Several simulations were carried out under dynamic inlet conditions (variable flow and concentrations) for each weather conditions. For each type of weather, the lowest COD effluent values were achieved with the first dual-objective optimization strategy (conversion and energy consumption), for TKN the lowest values were in the second case, while the highest values were obtained with the last dual-objective optimization strategy (energy consumption and productivity). However, the latter remains the best combination of objectives, as the effluent is dischargeable and the air flow has the lowest value of all.

**Notations**

- System with one separator
  - $\alpha$ – recirculation ratio
  - $\beta$ – purge ratio
  - $Q_r$ – recirculation flow
  - $Q_f$ – feeding flow
  - $Q_p$ – purge flow
  - $k_l a$ – Oxygen mass transfer coefficient, h$^{-1}$
  - COD – Chemical Oxygen Demand, g O$_2$/m$^3$
  - ASM – Activated Sludge Model
  - HRT – Hydraulic Retention Time
  - SRT – Solids Retention Time

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