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Abstract: This paper presents a systematic procedure for multiobjective optimization of control strategies in environmental systems. The optimization of control strategies in environmental systems is a complex activity due to the large number of objectives that must be considered simultaneously e.g. economic, environmental, technical, legal. The accomplishment of those objectives generates significant synergies, but in many cases they are subject of clear trade-offs. This procedure is approached as a multicriteria decision analysis (MCDA) and involves the quantification and normalization of a set of evaluation criteria and a weighted sum. A sensitivity analysis is also included in order to show the variation of the selected option when the relative importance of the control objectives is changed. The usefulness of the proposed procedure is demonstrated by optimizing PI control loops for aeration and internal recirculation in the IWA/COST benchmark plant.

Keywords: wastewater, multiobjective optimization; control strategies; modelling, environmental systems.

1. INTRODUCTION

The optimization of control strategies in environmental systems is a complex task due to the large number of objectives that must be considered (e.g. economic, environmental, technical, legal). The accomplishment of those objectives generates significant synergies, but in many cases they are subject of clear trade-offs.

For this reason systematic procedures are necessary to solve multiobjective problems due to their complex nature (Ingildsen *et al.*, 2002), the need for complex assessments and the analysis of the multidimensional results (Flores *et al.*, 2005).

In this paper a novel multiobjective optimization procedure of control strategies in environmental systems is presented. This procedure is approached as a MCDA (see, for example, Vincke, 1992; Belton and Stewart, 2002) and allows the inclusion of different control objectives with several sensitivity analyses highlighting their influence in the final decision. The paper is illustrated with a case study where the control strategy of a wastewater treatment plant is optimized according to a defined control objective and process performance.

2. MULTIOBJECTIVE OPTIMIZATION PROCEDURE

This section details the proposed multiobjective optimization procedure. This procedure comprises three steps which are described hereafter.

In the first step, the control strategies are represented as options that are mutually exclusive [$A=\{A_1,\ldots,A_m\}$]. Different criteria [$X=\{X_1,\ldots,X_n\}$] are used to measure the degree of satisfaction of the defined control objectives [$OBJ=\{OBJ_1,\ldots,OBJ_p\}$] and several weighting factors are assigned to determine the relative importance of these objectives [$w= \{w_1,\ldots,w_p\}$]. Weights are normalized (to add up to 1) and distributed across the evaluation criteria. The quantification of a control strategy A_j with respect to criteria X_i is indicated as $x_{j,i}$. Thus each option can be represented as a n-dimensional score profile [$A_j= (x_{j,1},\ldots,x_{j,n})$].

In step 2, value functions, [v_i (X_i)], map the score profiles of each control strategy with a value normalized from 1 to 0. Values of 1 and 0 are associated to the best (x_i^*) and the worst (x_{i*}) situation respectively, whilst a mathematical function is used to evaluate the intermediate effects (Beinat 1997). The collection of the best [$x^* = (x_1^*,\ldots,x_n^*)$] and the worst [$x_* = (x_{1*},\ldots,x_{n*})$] scores for all criteria determine the best [$v(x^*) = (v_1(x_1^*),\ldots,v_n(x_n^*)) = 1$] and the worst profiles [$v(x_*) = (v_1(x_{1*}),\ldots,v_n(x_{n*})) = 0$].

In step 3, a weighted sum (see eq 1) is used to obtain a unique value for each option $s(A_j)$. The weighted sum is calculated for each control strategy by adding the product of each normalized criterion [$v_i(x_{j,i})$] times its corresponding weight [w_i].

$$s(A_j) = \sum_{i=1}^{n} v_i(x_{j,i}) \cdot w_i \tag{1}$$

The option with highest score is the control strategy with the best accomplishment of the control objectives and, therefore, the one recommended for implementation.

3 CASE STUDY

The IWA/COST simulation benchmark wastewater treatment plant (Copp, 2003) is the environmental system to study. The plant has a modified Ludzack-Ettinger configuration with five reactors in series (tanks 1 & 2 are anoxic with a total volume of 2000 m^3, while tanks 3, 4 & 5 are aerobic with a total volume of 4000 m^3) linked with an internal recirculation from the 3rd aerobic tank to the 1st anoxic tank, a 10-layer secondary settling tank (with a total volume of 6000 m^3) and two PI control loops. The first loop (DO) controls the dissolved oxygen in the 3rd aerobic tank through the manipulation of the aeration flow, and the second loop (NO) controls the nitrate in the 2nd anoxic tank by manipulating the internal recycle flowrate. The optimization of both controllers exemplifies the usefulness of the proposed procedure. Each block of the procedure, together with numerical details, is discussed in the following sections

3.1 Step1. Definition and quantification of the control objectives and criteria

The different states of the controllers result in 72 possible options [$A=\{A_1,\ldots,A_{72}\}$]. The NO and DO setpoints have a range of 0.5 to 4.5 $gN \cdot m^{-3}$ and 0 to 3.5 $gO_2 \cdot m^{-3}$ and are evaluated using four control objectives [$OBJ=\{OBJ_1,\ldots,OBJ_4\}$]. For this case study we assume equal importance for all the control objectives, and thus $w_p = 0.25$ (p = 1 to 4). Table 1 describes the control objectives and the evaluation criteria used to measure their degree of satisfaction.

Table 1. Control objectives, evaluation criteria and criteria scales

OBJ_1: minimize environmental impact ($w_1 = 0.25$)			
X_1	Impact on water		%
OBJ_2: minimize economical costs ($w_2 = 0.25$)			
X_2	Operation costs		€·year^{-1}
OBJ_3: maximize technical reliability ($w_3 = 0.25$)			
X_3	Robustness		-
X_4	Flexibility		-
X_5	Control performance	$X_{5,1}$ = DO controller	$(gO_2 \cdot m^{-3})^2 \cdot day$
		$X_{5,2}$ = NO controller	$(gN \cdot m^{-3})^2 \cdot day$
X_6	Risk of separation problems	$X_{6,1}$ = Foaming	%
		$X_{6,2}$ = Bulking	%
		$X_{6,1}$ = Rising	%
OBJ_4: comply with the limits set by the European Directive 91/271/EEC ($w_4 = 0.25$)			
X_7	Time in violation (TIV) for TSS		%
X_8	Time in violation (TIV) for COD		%
X_9	Time in violation (TIV) for BOD_5		%
X_{10}	Time in violation (TIV) for TN		%

A single criterion is proposed to measure the satisfaction of OBJ_1 (X_1). This criterion is defined as the percentage reduction of the wastewater contaminant load entering the plant (eq 2). X_1 relates the effluent (EQ) to the influent (IQ) quality index (see Copp 2003 for details).

$$X_1 = \frac{IQ - EQ}{IQ} \tag{2}$$

The operation cost index (Vanrollghem and Gillot, 2002) is used to measure the degree of satisfaction of OBJ_2 as stated by eq 3

$$X_2 = \alpha_{EQ} \cdot EQ + \alpha_{AE} \cdot AE + \alpha_{PE} \cdot PE + \alpha_{sldg} \cdot P_{sldg} \tag{3}$$

EQ is the effluent quality index; AE and PE represent the aeration and pumping energy rates ($kW \cdot h \cdot day^{-1}$) respectively. P_{sldg} is the sludge production rate ($kg \cdot day^{-1}$). The α_j coefficients are the operating costs weighting factors and represent yearly operating costs. The equations to calculate AE, PE and P_{sldg} can be found in Copp 2003.

Robustness (X_3) and flexibility (X_4) are defined as the degree to which the process can handle short and long term disturbances affecting its dynamics.

Several short term (Z=3: rain, storm, and ammonium shock events) and long term (Z=3: step increases in the influent flow, organic matter and nitrogen concentration) perturbations are used. In this case study the robustness and flexibility is computed for criterion X_2, (Vanrolleghem and Gillot, 2002) because it combines effluent and operational variables and it is quantified as the inverse of the normalized sum of the squared sensitivities (see eq 4 and 5). $\Delta\theta$ is the overall range of variation expected for a certain parameter (Rousseau *et al.*, 2001).

$$S_i = \frac{\partial X_2}{\partial \theta_i} \frac{\Delta \theta_i}{X_2} \tag{4}$$

$$X_3 = X_4 = \frac{1}{\sqrt{\frac{1}{z}\sum_{i=1}^{z} S_i^2}} \tag{5}$$

The ISE (Stephanopoulos, 1984) measures the performance of both controllers ($X_{5.1}$ and X_{5-2}) and it is shown in eq6. $Z_{OBSERVED}$ is the controlled variable (the nitrate and the oxygen concentration in the 2nd anoxic and the 3rd aerobic tank, respectively) and is the desired setpoint $Z_{SETPOINT}$. This deviation is computed during the evaluation time (t_F-t_0).

$$X_{5,1} = X_{5,2} = \int_{t_0}^{t_F} (Z_{SETPOINT} - Z_{OBSERVED})^2 dt \tag{6}$$

The quantification of risk to separation problems (X_6) is quantified using knowledge-based flow diagrams. A review of the existing knowledge regarding these problems (Comas *et al.*, 2006), combined with the authors' expertise, enabled the construction of three decision trees: one for sludge one for foaming ($X_{6,1}$) and filamentous bulking ($X_{6,2}$) and another for rising sludge ($X_{6,3}$). These decision trees were codified as a set of IF-THEN rules, incorporating fuzzy logic (Bellmann and Zadeh, 1970). Therefore, the limitation of using rules with crisp confines, which are based on bivalent Boolean logic, is avoided.

The effluent quality violation criteria (X_7, X_8, X_9, and X_{10}) are used to measure the accomplishment of OBJ_4 and reflect the percentage of time that the effluent concentration of the pollutant exceeds the effluent quality limits (91/271/EEC) during the evaluation period (1 week). The limits for these calculations are: TSS (Total Suspended Solids)= 35 $g \cdot m^{-3}$(X_7), COD (Chemical Oxygen Demand) = 125 $g \cdot m^{-3}$ (X_8), BOD (Biochemical Oxygen Demand)= 25 $g \cdot m^{-3}$(X_9) and TN (Total Nitrogen) = 15 $g \cdot m^{-3}$ (X_{10}).

All the criteria are calculated by dynamic simulation. The simulations are performed with the MatLab-Simulink© environment. The International Water Association model number 1 (ASM1) was chosen as a biological process model (Henze, 2002). The model includes 13 components (state variables) describes the biochemical carbon removal with simultaneous nitrification and denitrification by 8 processes. Through material balances over a CSTR, a set of ordinary differential equations are derived. The double exponential settling velocity of Takács *et al.* (1991) based on the solid flux concept, was selected as a fair representation of the settling process with a ten layer pattern. All the dynamic simulations follow a steady state simulation to ensure a consistent initial point and avoid the influence of starting conditions in the dynamic modelling. Only the data generated during the last seven days are used to quantify the criteria.

Once all the simulations are carried out, more than a dozen of three dimensional surfaces are created. Figure 1 shows a selection of the surfaces for the criteria X_1 (a), X_2 (b), X_4, (c), $X_{5,2}$ (d), $X_{6,3}$ (e) and X_{10} (f).

Figure 1a shows how the maximum satisfaction of OBJ_1 (minimum impact on water) is found when the DO and NO setpoints are 0.5 $gO_2 \cdot m^{-3}$ and 3.5 $gN \cdot m^{-3}$, respectively. This is mainly due to the improvement of the denitrification process achieved reducing the quantity of oxygen and increasing the quantity of nitrate in the anoxic zone arriving from the aerobic reactor via the internal recycle.

The operation costs are minimized when the DO and the NO setpoint are 0.5 $gO_2 \cdot m^{-3}$ and 1 $gN \cdot m^{-3}$, respectively, as depicted in Figure 1b. If the OD setpoint is higher, the aeration costs ($\alpha_{AE} \cdot AE$) has to increase, thus requiring a major contribution of air. Moreover, as mentioned before, the higher oxygen in the anoxic zones transported via internal recycle, the more damages the plant denitrification capacity. This issue causes an irremediable increase of effluent fines ($\alpha_{EQ} \cdot EQ$). Otherwise, if the NO setpoint is high, the quantity of nitrate to recycle from the aerobic reactor increases and more pumping energy (PE) are needed, although the impact on water and the effluent fines ($\alpha_{EQ} \cdot EQ$) is reduced.

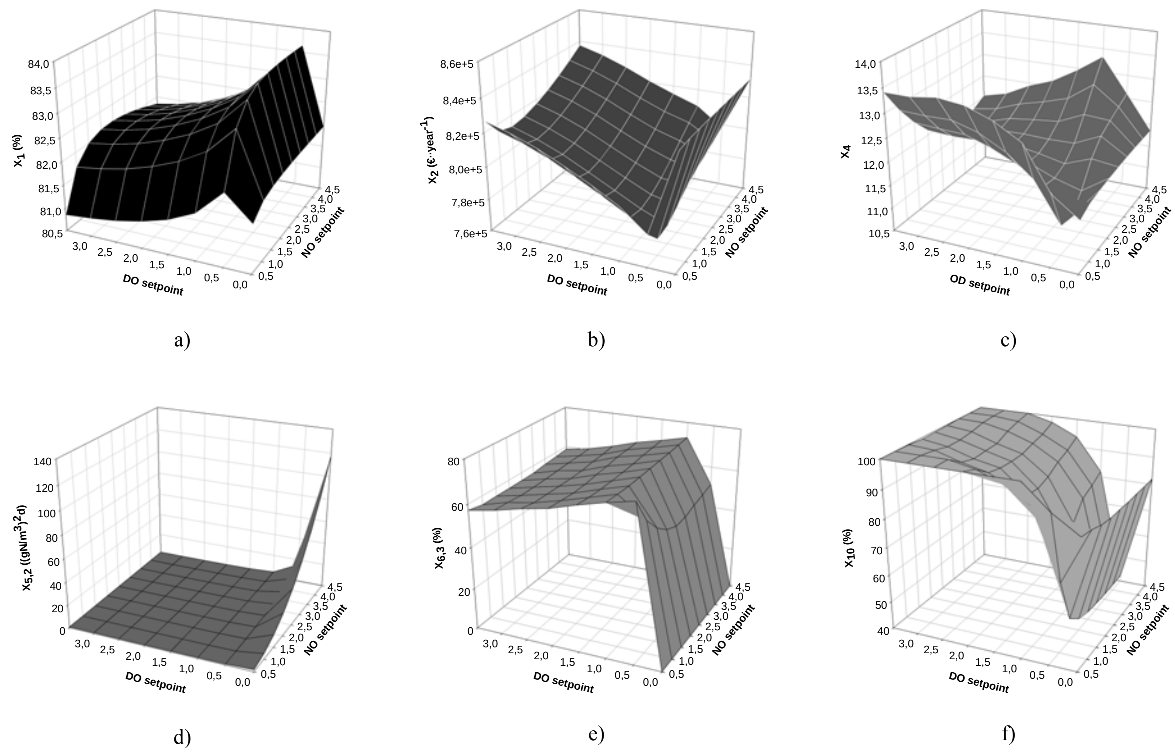

Figure 1. Representation of the: a) impact on water (X_1), b) operation costs (X_2), c) flexibility (X_4), d) nitrate control performance ($X_{5,2}$) e) rising risk ($X_{6,3}$) and f)Time in Violation (TIV) for TN (X_{10}).

The plant adaptation to long term variations is represented in Figure 1c. The less sensitivity of criterion X_2 (*i.e.,* the highest values in the flexibility index) is due, on the one hand, when the DO and NO setpoints are high and low respectively, and on the other hand, when the DO and NO setpoints are low (not zero) and high respectively. High airflow rates and low recycle flow rates improve the handling of the first long term perturbation (step increase of influent flow rate). If the oxygen levels in the third aerobic reactor the population of autotrophic bacteria will increase and it is avoid its complete wash out. Nevertheless, when the perturbation is a step increase of organic load, the most suitable strategy consist of decreasing the air flowrate and increase the internal recycle flow rate, in order to remove all the organic soluble substrate via denitrification.

With respect to the NO controller performance (Figure 1d), the controller performs better if the nitrate setpoint is low. It is caused by the recycle flow rate of nitrates from the aerobic zone is not sufficient to keep the desired setpoint in the second anoxic reactor. Furthermore, it is important to point out that the higher DO concentration in the aerobic zone, the lower volume of mixed liquor that has to be pumped via internal recycle, due to increase the nitrification efficiency.

In Figure 1e the increase of rising risk between the DO setpoints of 3.5 and 1 $gO_2{\cdot}m^{-3}$ is shown. This is mainly due to the higher the DO setpoint the higher the removal of the influent organic biodegradable substrate in the aerobic or anoxic zone, avoiding its arrival to the secondary settler. Nevertheless it is important to point out that if the DO setpoint is lower than 1, there is a dramatically decrease of the rising risk because the quantity of nitrate produced in the aerobic zone is reduced.

The last Figure (Figure 1f) highlights the degree of satisfaction of the European Directive for TN. As the Figure shows exists less penalty when the DO is low (DO= 0.5 $gO_2{\cdot}m^{-3}$) and high recycle flow (NO=3.5$gN{\cdot}m^{-3}$), because this combination of parameters achieve the better trade-off between the denitrification process and the overall nitrogen removal.

The results for the remaining criteria are not shown for space reasons but the main results are next summarized. The plant adaptation to short term perturbations (X_3) increases as the DO setpoint increases. In general the DO controller performs well (criterion $X_{5,1}$) except when the setpoint are high because it is difficult to reach the desired values for the controller. The lower DO, the higher increase in $X_{6,2}$ (bulking risk) due to the oxygen deficit. For this case study $X_{6,1}$, X_7, X_8 and

X_9 have the same value, and therefore they are not useful to discriminate the competing control schemes.

To sum up, Figure 1 depicts that there is existent synergies in the accomplishment of some objectives e.g. OBJ_1 and OBJ_4 but others are subjected to clear trade offs e.g. OBJ_2 and OBJ_1 or OBJ_3 and OBJ_4.

3.2 Step 2. Criteria normalization.

Once the criteria defined are quantified for all the proposed alternative options, the extreme profiles (based on expert judgement) are defined: $[(x)^* = ($ $x_1^* = 100$, $x_2^* = 7{\cdot}10^5$, $x_3^* = 25$, $x_4^* = 25$, $x_{5,1}^* = 0$, $x_{5,2}^* = 0$, $x_{6,1}^* = 0$, $x_{6,2}^* = 0$, $x_{6,3}^* = 0$, $x_7^* = 0$, $x_8^* = 0$, $x_9^* = 0$, $x_{10}^* = 0)]$ and $[(x)_* = ($ $x_{1*} = 0$, $x_{2*} = 1{\cdot}10^6$, $x_{3*} = 0$, $x_{4*} = 0$, $x_{5,1*} = 1$, $x_{5,2*} = 1$, $x_{6,1*} = 100$, $x_{6,2*} = 100$, $x_{6,3*} = 100$, $x_{7*} = 100$, $x_{8*} = 100$, $x_9^* = 100$, $x_{10*} = 100]$. Then, a linear model between these extreme values is adjusted to calculate the intermediate effects (*e.g.* the criterion X_1 has the following value function $v_1(X_1) = 0.01{\cdot}X_1$).

3.3 Step 3. Weighted Sum

Finally a multi objective 3-D surface is obtained adding the normalized criteria by its corresponding weight (Figure 2).

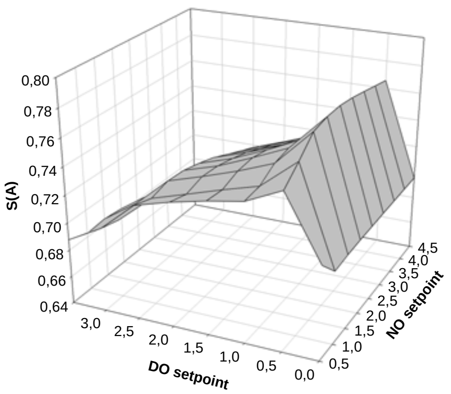

Figure 2. Representation of the multicriteria surface ($w_i = 0.25$, i = 1 to 4).

Analysing the results of Figure 2 we conclude that the combination of setpoints that achieves the best level of satisfaction of the control objectives, when all have equally important, is 0.5 $gO_2{\cdot}m^{-3}$ and 2.5 $gN{\cdot}m^{-3}$, for DO and NO controllers, respectively. The low DO setpoint is mainly due to a better denitrification performance, lower operation costs and lower rising risk, in spite of the detriment in terms of plant adaptation to short and long term perturbations (robustness and flexibility) and the nitrate control performance. On the other hand the excessive pumping rate and the bad control performance suggest a medium NO septpoint in spite of having the best overall nitrogen removal when it is higher

4. SENSITIVITY ANALYSIS.

Finally a weight sensitivity analysis is performed. The objective of this analysis is to show how the selected combination of setpoints can vary when the relative importance of the control objectives is modified. Figure 3 shows the variations in the DO and NO setpoints when different combinations of weights are assigned in the defined control objectives.

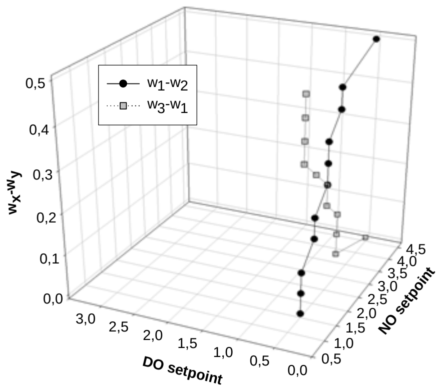

Figure 3. Representation of the setpoint variation when the importance of the control objectives is changed

From the results reported in Figure 3 it can be noticed that high values in $w_1 - w_2$ (minimize impact on water is prioritized) clearly favours large pumping recycle rates because the denitrification is improved as is shown in Figure 1a. However, as w_2 (minimize economical costs) gains in value, this pumping rate is reduced because supposes higher operation costs (see Figure 1b).

Otherwise, if the OBJ_3 (maximize technical reliability) is prioritized at the expense of environmental impact (high values in w_3-w_1), lower nitrate setpoints are recommended. In this way, a good control performance is ensured (Figure 1d). Nevertheless if environmental impact is prioritized the NO setpoint will be 4.5 $gN{\cdot}m^{-3}$.

5. CONCLUSIONS

This paper addresses the problem of multiobjective optimization of control strategies in environmental systems, by presenting a novel procedure. The usefulness of the proposed procedure is demonstrated thought optimization of the PI control loops for aeration and internal recirculation, respectively, of the IWA COST simulation benchmark plant.

For this procedure, approached as a multicriteria decision analysis, several control objectives are defined assigning their importance by means of weights. A set of evaluation criteria is proposed quantified and discussed in order to know the degree of satisfaction of the defined control objectives.

Since all criteria are quantified in different units, a set of value functions to facilitate the comparison is proposed according to the extreme value profiles.

Finally, a weighted sum is used as an evaluation method to know the optimal control strategy among all the competing alternatives, according to the defined control objectives, their importance and the overall process performance.

A side result of this case study is that performing a sensitivity analysis is recommended to highlight the influence of the control objectives in the final decision. Moreover, this analysis shows how the selected strategy vary when the importance of control objectives are modified.

6. ACKNOWLEDGEMENTS

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