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Multi-criteria selection of optimum WWTP control setpoints based on microbiology-related failures, effluent quality and operating costs

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ABSTRACT

This work aims at optimising the performance of WWTP with simultaneous biological C, N and P removal by improving its automatic control system. The success of control strategies is highly dependent on the selected operational setpoints of the controlled variables. These setpoints should be optimised to achieve the best effluent quality with the lower operating costs and, at the same time, ensuring an operation with low probability to develop biomass settling problems. Two different objective functions were used to optimise the setpoints of the tested control strategies: a cost function based on the operational costs by converting the effluent quality into monetary units and a multi-criteria function based on the effluent quality, the operational costs and settling problems of microbiological origin. Three different control strategies were evaluated: (i) open loop; (ii) optimised fixed setpoints for the ammonium and nitrate control loops and (iii) daily optimised setpoints. The multi-criteria optimisation resulted in a set of optimal setpoints with a Pareto distribution. This multi-criteria function was developed so that any of the criteria (effluent quality operating costs or microbiological risks) was conditional to another and thus, optimal scenarios with a high risk of failure due to microbiological issues could be rejected. Moreover, it was concluded that the optimisation process could be enhanced by using both objective functions in a complementary way. While the multi-criteria function enabled a more extensive evaluation of the different alternatives, once the weights are selected the operational costs function optimisation could be used to define an optimum set of setpoints to adapt the system to influent variations.

1. Introduction

Wastewater treatment plants (WWTP) based on activated sludge systems are considered as one of the most economical and environmentally sustainable alternatives for municipal wastewater treatment. In addition to organic matter degradation, the European Water Framework Directive (2000/60/CE) fixed nitrogen and phosphorus removal as additional objectives for municipal WWTP in order to prevent eutrophication of sensitive water bodies. To this aim, different plant configurations such as A^2/O, UCT or Bardenpho have extensively been applied for achieving simultaneous C, N and P removal. WWTP operation aims at meeting the required discharge limits against minimal costs. Thus, stringent legislation for WWTP is currently a top driving force for the optimisation of these treatment technologies, including novel operational modes or upgrading them with new control structures. Although several solutions have been reported so far, a number of plants still operate without being optimised.

The feasibility of different configurations and control strategies for WWTP is nowadays often evaluated with mathematical models. In the past, reliable kinetic models (activated sludge models, ASM) were developed as a powerful tool for model-based optimisation of the WWTP operation or for designing and tuning its control systems. For example, IWA ASM2d [1] is a complex model that provides the kinetics, the stoichiometry and the mass balances needed

Abbreviations: A&N-DVS, ammonium and nitrate daily variable setpoints; A&N-FS, ammonium and nitrate fixed setpoints; AE, aeration energy; ASM, activated sludge models; DO, dissolved oxygen; EBPR, enhanced biological phosphorus removal; EQ, effluent quality; k_La, global oxygen transfer coefficient; MCF, Multi-criteria function; MR, microbiological risks; OC, operational costs; OCF, operating costs function; OL, open loop; PE, pumping energy; PI, Proportional-integral; Q_{REXT}, external recirculation; Q_{RINT}, internal recirculation; Q_W, purge flow; TN, total nitrogen; TSS, total suspended solids; WWTP, wastewater treatment plants.

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for describing biological C/N/P removal processes from wastewater. With respect to control, the utilisation of automatic control systems has improved the performance of numerous WWTP. Although several control strategies have been proposed for the enhancement of C and N removal [2–5], the improvement of P-removal by control implementation deserves more interest. Moreover, little attention has been paid to enhance the performance of WWTP controllers, for example by tuning of the controller parameters [6] or optimising the setpoint for better WWTP performance purposes [7,8]. The evaluation of the improvement of the WWTP when a control system is implemented is not a straightforward issue because several performance indexes must be taken into account: operational costs (OC), effluent quality (EQ) or risk of developing settling problems of microbial origin (microbiological risks, MR). Most control strategies reported so far are only based on the OC and the EQ indexes. Vanrolleghem and Gillot [9] proposed the evaluation of the plant performance with a single cost function based on the OC by converting the EQ into monetary units. Nevertheless, the control optimisation based on integrated cost functions could lead to undesirable optimal operating conditions due to an incorrect weighing of both OC and EQ indexes. Guerrero et al. [8] proved that the weight selection for the EQ costs is a key factor to avoid subordinating the quality of the effluent to the cost of plant operation. Multi-criteria tools [5,10] could be a useful alternative to overcome these problems since they allow optimising a system taking into account different criteria, which can be separately analysed.

Even with a proper EQ and OC weighing, the optimal scenario could result in operating problems of microbiological origin when implemented in a real WWTP, mostly related to the final settling step (bulking, foaming or rising sludge) [11]. A modelling effort to include these microbiology-related problems using knowledge-based flow diagrams has been recently reported [12,13]. These diagrams were developed from textbook knowledge and operating expertise on organic matter and N removal, while P removal was not the focus yet. Thus, the inclusion of enhanced biological phosphorus removal (EBPR) process in the analysis of possible solid separation problems is necessary since it involves an anaerobic phase that may affect, for example, the presence of filamentous bacteria. This integrated assessment could be a useful tool for redesigning plants with EBPR or for developing new control strategies.

In this framework, this work is a simulation-based study that aims at designing optimum control strategies for a WWTP with simultaneous biological C, N and P removal. For this purpose, an activated sludge pilot plant with several control loops was simulated using ASM2d. The success of these control strategies fully relies on a proper construction of the objective function that will be used for optimisation purposes. Two different objective function are compared: (i) an operating costs function (OCF) calculated by adding EQ converted into monetary units to OC (the most commonly reported in the literature) and (ii) a new multi-criteria function based on three performance indexes: EQ, OC and MR related to solid separation problems. This is the first work which links possible microbiology-related failures to the inclusion of EBPR (i.e. previously, MR criterion has only been applied to systems with C and N removal) when developing optimum control strategies for a WWTP.

2. Materials and methods

2.1. Plant description

The simulated plant (Fig. 1) was a continuous anaerobic/anoxic/aerobic (A^2/O) system for simultaneous C, N and P removal consisting of three CSTRs and one settler (modelled using the 10-layer model of Takács et al. [14]). The hydraulic model mimicked the configuration of a real pilot plant (146 L), where the best control strategy found in this work would be further evaluated. The first reactor (R1, 28 L) was anaerobic for favouring P removal. The second reactor (R2, 28 L) was anoxic and denitrification took place using the nitrate supplied by the internal recirculation (Q_{RINT}). The last reactor (R3, 90 L) was aerobic and complete organic matter and P removal occurred together with nitrification. The settler (50 L) produced an effluent stream and a biomass enriched stream, most of which was returned to the system by the external recirculation (Q_{REXT}) while the rest was purged (Q_W). Air flow rates were set by the k_La (global oxygen transfer coefficient) value in the aerobic reactor. The flow rate and the composition of the influent varied in time according to the Dry-2 influent proposed by the IWA Task Group on Benchmarking [15], with 0.25 m^3 day^{-1} as the average flow-rate value. The simulated plant included four local control loops:

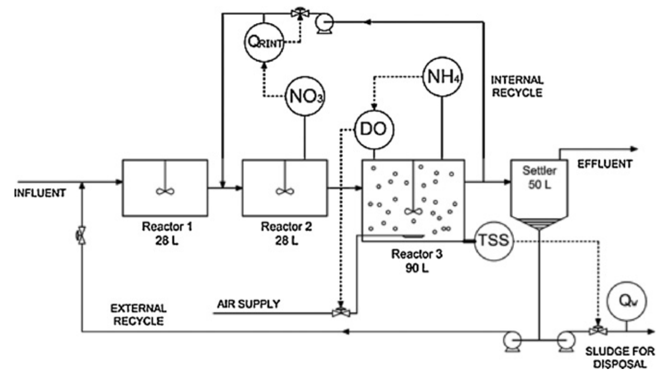

Fig. 1. Schematic representation of the plant with an A^2/O configuration and the implemented control loops. Dashed lines represent the manipulated variables of the control loops.

1. Dissolved Oxygen (DO) in R3 was controlled with a feedback PI-controller using the oxygen transfer coefficient (k_La) as the manipulated variable.
2. Effluent ammonium was controlled using a cascade control structure with a PI-controller as primary controller with the DO setpoint in R3 as the manipulated variable. The thresholds of DO and ammonium setpoints were 0–4 mg DO L^{-1} and 0–10 mg N-NH_4^+ L^{-1}, respectively.
3. Nitrate in R2 was controlled with a feedback PI-controller with setpoint limits between 0 and 3 mg N-NO_3^- L^{-1} and using Q_{RINT} as the manipulated variable.
4. Total suspended solids (TSS) in R3 were controlled with a feedback PI-controller by acting on Q_W. TSS were considered as inventory variable (i.e. variables that must be controlled for a proper plant management) and were kept constant (2500 mg TSS L^{-1}) to avoid the effect of a possible change in TSS concentration on the treatment capacity or the sludge age and for a better comparison of the removal efficiency related only with the tested control strategies [16,17]. Q_W was limited from 0.002 to 0.02 times the influent flow rate, providing an SRT range from 3.5 to 7.17 days.

2.2. Control strategies description

The different control strategies tested are summarised next:

- *Open Loop (OL)*: The system was simulated under open-loop conditions (i.e. all the control strategies were disabled, except for TSS control loop in R3). The aeration was kept constant in R3 with a k_La of 240 day^{-1} to avoid oxygen limitations. Q_{RINT} and

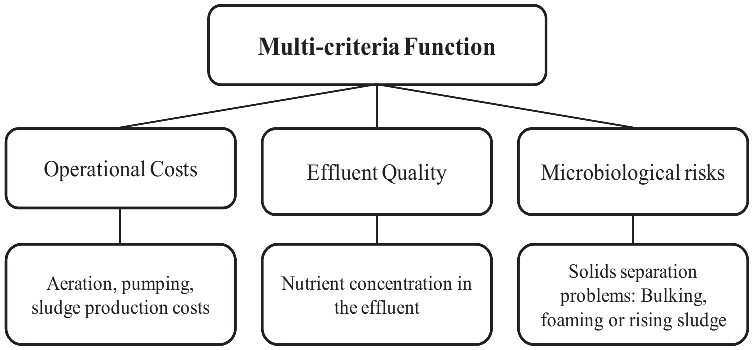

Fig. 2. Three dimensional multi-criteria function.

Q_{REXT} were about three times ($0.763\,m^3\,day^{-1}$) and one time ($0.250\,m^3\,day^{-1}$) the average influent flow-rate, respectively. These values were selected based on the work of Gernaey and Jorgensen [15], who reported reasonable P-removal with this configuration.

- *Ammonium and nitrate fixed setpoints (A&N-FS)*: This strategy consisted of using fixed ammonium and nitrate setpoints during the simulated period. These setpoints were optimised using the methodology reported in Section 2.4.
- *Ammonium and nitrate daily variable setpoints (A&N-DVS)*: The setpoints of ammonium and nitrate were daily redefined by mathematical optimisation in order to adjust the plant operation to the daily influent flow pattern of the plant.

2.3. Plant performance function development

Two different functions were used for optimising the setpoints of the control strategies. On the one hand, the operating costs function, OCF (Eq. (1)) described the cost of the secondary treatment of a WWTP by including the EQ converted into monetary units [9].

$$\mathrm{OCF}\ [€\,\mathrm{m}^{-3}] = \gamma_E(\mathrm{AE}+\mathrm{PE}) + \gamma_{SP}\mathrm{SP} + \mathrm{EF} \quad (1)$$

Aeration energy (AE) and pumping energy (PE) were calculated using empirical equations based on k_La and recycle flows as in Stare et al. [7]. The evaluation of the aeration energy using k_La, an easily accessible simulation variable, is difficult to be applied in real aeration systems. In future works, AE should be correlated to energy consumption in real systems using the rotational speed of the blowers or the surface aerators speed. SP corresponds to the sludge production and EF represents effluent fines. EF were calculated comparing the effluent ammonium, total nitrogen (TN) and phosphate with the discharge limits [8,9]. γ_E ($0.1\,€\,kWh^{-1}$) represents the cost of 1 kWh and γ_{SP} ($0.5\,€\,kg^{-1}$) stands for the cost of the treatment of produced sludge [7].

On the other hand, Fig. 2 shows the multi-criteria function (MCF) used, which analyses the performance of the process by means of a three-dimensional function. In this case, OC were calculated similarly to Copp [18] but considering cost per cubic meter of wastewater treated in order to avoid specific plant characteristics and facilitate the comparison between different plants. EQ was evaluated in terms of pollutant concentration in the effluent [15] because the conversion of EQ into monetary units is not required by the MCF. A third criterion (microbiological risks, MR), which considers risk of microbiology-related solids separation problems, was also applied for the first time in a simulated plant which included biological P removal. The possible occurrence of such solids separation problems was assessed according to the different knowledge-based decision trees proposed by Comas et al. [12]. The authors reported a risk assessment model for settling problems of microbiological origin (filamentous bulking, foaming and rising sludge) as a function of operating conditions and influent composition. The outcome of this model is a risk to develop such problems between 0 and 1, considering a threshold of 0.8 as a high risk. Considering MR criterion in the optimisation process allowed for obtaining more realistic optimal scenarios, in contrast to OCF, because proper EQ and OC together with low MR occurrence could be find. Hence, the operational point optimised considering the three criteria should guarantee a good effluent quality (low EQ), reduced operating costs (low OC) and low risk to observe settling problems (low MR).

2.4. Simulation and optimisation

The model used was an extension of IWA ASM2d [1] that included nitrite as additional state variable. Hence, nitrification and denitrification were modelled as two-step processes with nitrite as intermediate to describe accurately the anoxic COD consumption. The dynamic model and the microbiological risks calculation were implemented in MATLAB® and integrated using *ode15s*, a variable order method recommended for stiff systems.

The setpoint optimisation aimed to find the maximum performance that a specific control structure could achieve. A perfect knowledge of the influent characteristics was considered for performing the optimisation (i.e. using the Dry-2 influent proposed by the IWA Task Group on Benchmarking). Different optimisation methods were used for each proposed function: (i) OCF: the optimal setpoints (i.e. ammonium in R3 and nitrate in R2) that result in the minimum OCF were found using the Pattern search method implemented in MATLAB® under constrained conditions as reported in Guerrero et al. [8]; (ii) MCF: Monte Carlo simulation principles were followed and thus, 1500 sets of setpoints in the proposed search space were randomly generated and evaluated. Each control strategy was simulated during 28 days under Dry-2 conditions and the setpoint optimisation was conducted using the results of the last 7 days of simulation. The starting point for each simulation was the steady-state reached after a simulation of 100 days with Dry-2 influent under open-loop conditions.

3. Results and discussion

3.1. Operating costs function

Fig. 3 summarises the results for the different control strategies described above when the OCF was minimised. EQ and MR indexes were also quantified for comparison purposes, although they were not used for the minimisation. The optimised control strategies resulted in a more efficient operation than the open-loop operation. A decrease of 40% in the OCF was obtained mainly due to the improvement in EQ (the pollutant effluent content was reduced by up to 28% when comparing to open-loop operation, see

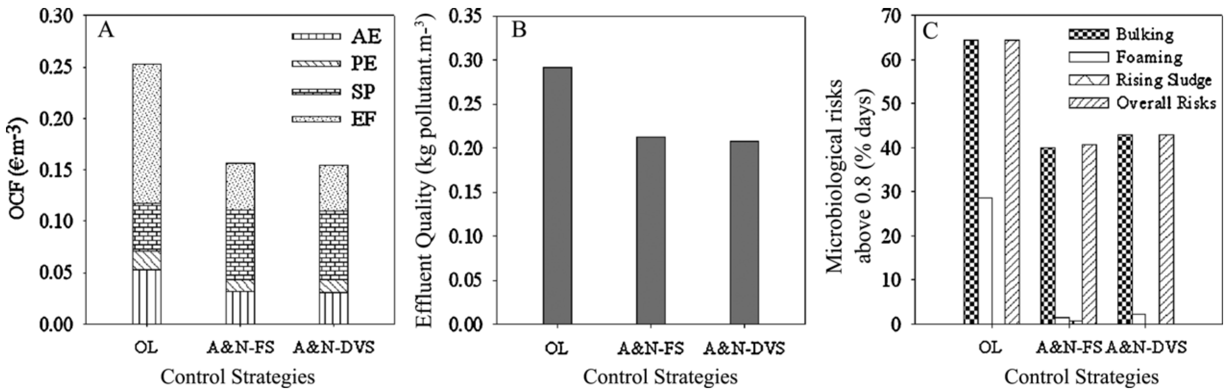

Fig. 3. Main results obtained by OCF optimisation with the three different control strategies: total operating costs (A), effluent quality (B) and percentage of simulated time that microbiological risks probability was above 0.8 (C).

Fig. 3B). P-removal efficiency was also improved from 8.5% obtained in the open-loop operation to 84%, despite there was not any specific control-loop implemented for P-removal. In fact, this improvement was the effect of the reduced nitrate load recycled to the anaerobic reactor, as a consequence of the optimised setpoints of nitrate in R2 and ammonium in R3.

The utilisation of fixed and daily variable optimised setpoints provided similar results (Fig. 3), although the A&N-DVS adjusted the plant operation to the daily wastewater pollutant content. A&N-DVS resulted in two groups of setpoints for ammonium, one for weekdays and the other for weekends (Fig. 4). The setpoints were directly related to wastewater load, as lower optimum setpoints for ammonium were obtained for weekend days. The observed changes in the setpoint for nitrate were marginal: a maximum difference of 0.07 mg N-NO_3^- L^{-1} was detected. This small range is below the usual margin of accuracy of an on-line sensor for nitrate and, hence, a fixed setpoint around 0.1 mg N-NO_3^- L^{-1} as the obtained in A&N-FS strategy can be recommended for this WWTP configuration. These results were in agreement with previous work [8] in which a detailed study of the improvement of the OCF by setpoint optimisation can be found. Moreover, the percentage of time with high MR occurrence (i.e. above a threshold of 0.8) was also reduced by up to 25% when comparing the optimised control strategies to the open-loop operation, even though this criterion was not included in the optimisation process. As Fig. 3 shows, the possibility to develop bulking formed the main contribution in the determination of MR.

Unfortunately, optimising the setpoints when all the criteria are converted into monetary units as in OCF could lead to high EQ compensated with minimal OC (e.g. low aeration could limit nitrification process). The weight selection for the economical penalties when the effluent components were above the discharge limits is a key factor to avoid such undesired results [8]. To overcome these problems, a multi-criteria function was developed, in which the different criteria were not conditional to each other (Fig. 2). Thereby, the OC and the EQ were analysed separately and the additional performance criterion MR was considered. Hence, theoretical optimal scenarios (i.e. low EQ or OC) but with an unrealistic application in full-scale WWTP due to high risk of MR occurrence could be rejected.

3.2. Multi-criteria function

MCF was evaluated for 1500 randomly generated sets of setpoints for A&N-FS control strategy. The results obtained for the three criteria were represented in pairs (Fig. 5), resulting in the formation of Pareto fronts except for the MR-OC pair. In the Pareto front, any point is better than other on both criteria at the same time or, in other words, any point could be improved in one criterion without worsening the other. Hence, improving the EQ by reducing the amount of pollutants in the effluent resulted in an OC increase. This was caused by the increase of the aeration required for nitrification and the increase of the internal recycle flow rate required to denitrify the produced nitrate. These facts resulted in an increase of energy consumption (around 90%) and thus, in the OC. Setpoints leading to high concentration of pollutants in the effluent resulted in lower MR because more readily biodegradable organic substrates (S_F) would enter to the aerated reactor increasing biomass growth. Consequently, the purge flow rate would be increased to maintain the TSS setpoint resulting in a decrease of SRT, which lowers the risk for occurrence of bulking or foaming [12]. Regarding the MR-OC pair (Fig. 5), the points tested could not be approximated by a Pareto front. However, a point with the lowest OC (0.10 € m^{-3}) and a minimal occurrence of MR (40%) was found. Moreover, a limit of minimal occurrence of MR (around 40%) for any OC and a maximum of 67% was obtained, due to the influent and operational conditions used in these simulations.

Fig. 5 shows that the operating point found by OCF optimisation (originating from the utilisation of different weights to convert EQ and OC into monetary units) was well located in the Pareto front of OC and EQ. This result demonstrates that the OCF optimisation was a specific case of the Pareto front for EQ vs. OC. Moreover, as MR was not included in the OCF, this optimised operating point does not appear in the Pareto front of EQ-MR or in MR-OC as expected.

Fig. 6 represents the three criteria evaluated with the MCF in a single graph for the A&N-FS control strategy. As can be observed, the optimal points could be approximated by a Pareto surface, whose location in this surface would be conditional by the weights selection. Therefore, the regional discharge limit penalties or electricity cost would play the major role in the setpoint selection to obtain a particular operational scenario. As can be observed in Fig. 6, the optimum point obtained with the OCF was practically part of the Pareto surface, being a nice example of such optimal operational scenarios that are defined by the weight selection.

Table 1 shows the results obtained for two different points situated at the edges of the Pareto surface where the value of one of the criteria was minimal. The operating point that resulted in the lowest OC conducted the system to aeration energy savings (i.e. reduction of aeration costs) but limited the nitrification process. Moreover, the internal recycle, which was involved in the nitrate control loop, was extremely reduced in order to decrease the pumping costs (around a 90% compared to the edge of the Pareto surface with the minimal EQ). These actions resulted in an increase in effluent pollutants and thus, in a worsening of EQ. When the minimal value of EQ was obtained, the removal capacity of the plant was highly enhanced resulting in an effluent with low pollutant content.

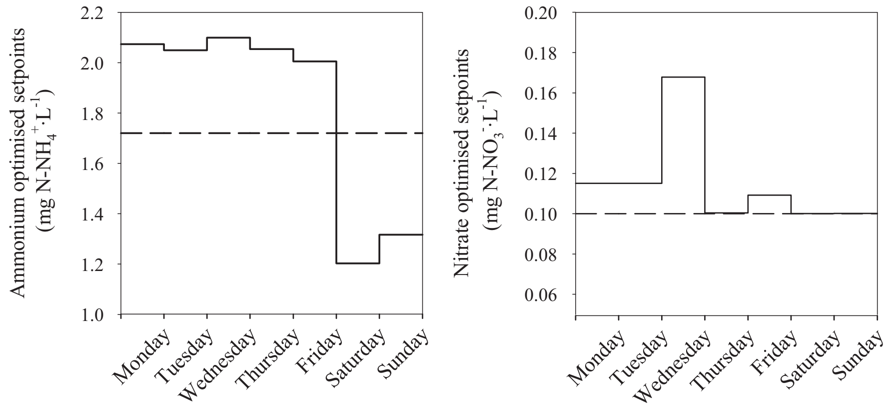

Fig. 4. Best setpoints obtained by OCF optimisation for ammonium and nitrate control loops. A&N-FS and A&N-DVS are represented with dashed and solid lines, respectively.

Table 1
Results obtained for two extremes operating points within the Pareto surface.

	Operational costs (€ m^{-3})	Effluent quality (kg pollutant m^{-3})	Microbiological risks above 0.8 (% days)
Operational costs minimization	0.099	0.254	40.00
Effluent quality minimization	0.137	0.188	42.14

However, the aeration invested to improve the nitrification process and the energy applied in the internal recycle (necessary for the denitrification process) increased the OC. With respect to the MR, both scenarios resulted in a similar plant performance. In both cases, the low SRT obtained resulted in a lower risk for occurrence of bulking problems, the major microbiology-related problem. In fact, the rest of the MR parameters were related to the influent conditions, which were the same for all the operational scenarios and thus, no important variations were observed.

The A&N-DVS strategy is characterised by variable daily set points to adapt the plant operation to the time variation conditions of the influent. A daily profile of setpoints was generated from the 1500 random set of setpoints tested in the A&N-FS (i.e. the average value of the daily profile was the setpoint tested in the A&N-FS). Moreover, the optimal setpoints found with the OCF evidenced substantial differences between weekend and weekdays (Fig. 4). For this reason, the setpoints for the weekend period were randomly reduced in order to adapt the system to the above-mentioned flow pattern behaviour.

Fig. 7 shows the results of MCF when implementing the A&N-DVS control strategy. This strategy did not result in a significant improvement of any criterion and a much more complex optimisation process was required since 14 setpoints were optimised (2 setpoints for each of the 7 days). Figs. 6 and 7 are also in agreement with the results obtained with the OCF, where the fixed and daily setpoints provided similar operational performance. In a preliminary optimisation test, an unconstrained random generation of the setpoints for A&N-DVS control strategy was performed resulting in a non-practical plant operation since a highly variable and inconsistent profile of setpoints was obtained. This fact showed the importance of using optimisation methods without random point generation as for example the pattern search method (used in the OCF optimisation, section 3.1). Hence, the complementarity of both optimisation methods should be considered. Once a consistent set of weights is chosen (i.e. according to the legislation), the OCF-strategy could be used to obtain an optimum setpoint profile that could adapt the plant operation to the influent variations with lower calculation efforts. On the other hand, the utilisation of MCF led to a more thorough evaluation where none of the criteria was conditional to the other. Moreover, a Pareto surface could be drawn using MCF approach including microbiological problems related to the solids separation encountered in the daily operation of the plant. The included MR index ensures that the optimum control strategy obtained has low risk of developing settling problems of microbiological origin. If the OCF approach had to be used, the translation of MR into monetary units would be required. In

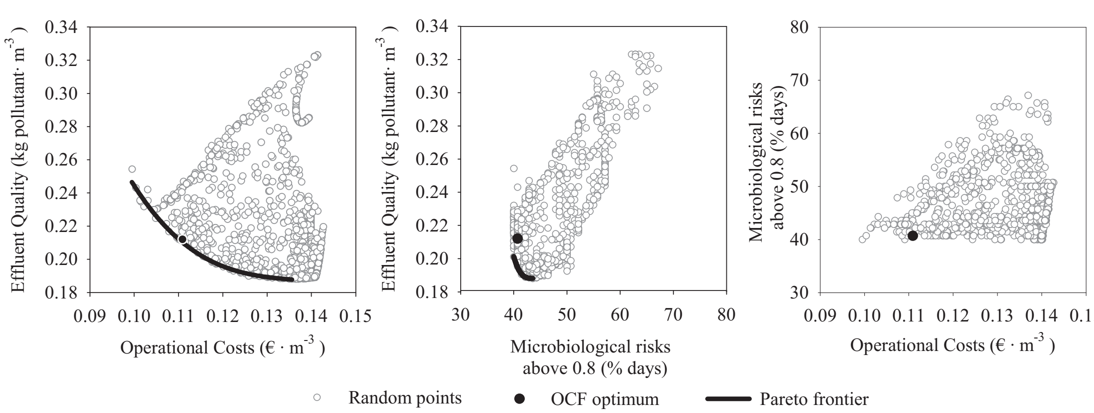

Fig. 5. Results of the 1500 random set of setpoints analysed for A&N-FS control strategy using the MCF.

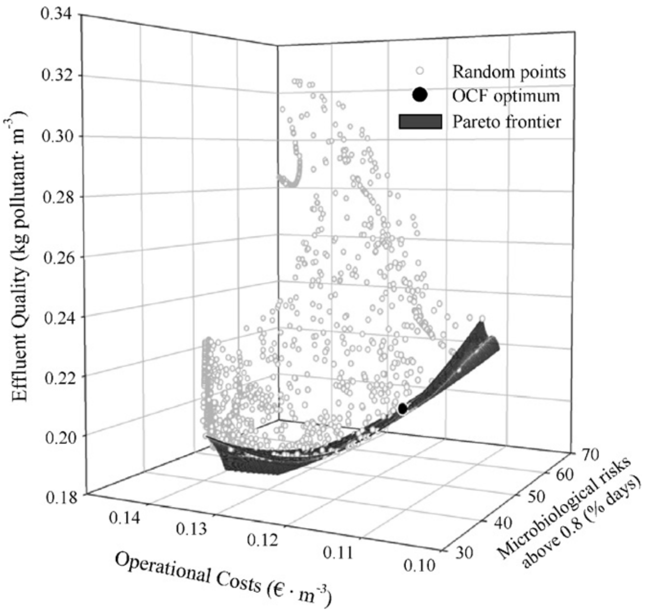

Fig. 6. Three-dimensional representation of the A&N-FS control strategy behaviour in terms of operational costs, effluent quality and microbiological risks for 1500 random set of setpoints.

this sense, some authors [13] have already reported model-based studies where the settling process was modified according to the occurrence of such solid separation problems. The change in settleability would have an impact on the effluent TSS concentration, which is used to calculate EQ, and would finally provide a measurable effect of MR on EQ.

3.3. Practical implications

Some limitations could appear for the implementation of the proposed approach in a full-scale WWTP with a highly variable influent (mainly for A&N-DVS implementation), since perfect knowledge of the influent is required for finding the optimum setpoints. In this case, the utilisation of feed-forward control is recommended in order to adapt the plant operation to the highly variable influent, although additional sensors gathering information of the influent would be required [4]. However, here is proved that if a usual influent profile is available, an optimum set of setpoints for the control structure proposed could be found and an important improvement in the operation could be obtained without the need of using feed-forward control. Hence, more simple controllers could be used (i.e. PI-controller) in comparison to other controllers that present more complex structures and may lead to technical difficulties. Moreover, the adaptation of the MCF modelling approach presented in this work to a full-scale WWTP would be useful to study different optimal scenarios considering the three criteria presented. Once this step is finished, the optimal scenario could be selected according to the requirements for that WWTP (i.e. regional discharge limits or energy costs) in order to prioritise some criteria against the rest (e.g. the effluent quality against the operational costs or settling problems). The OCF approach is more useful when the weights of EQ and MR are already selected, since it simplifies the optimisation process for finding the best setpoints for the local controllers.

For a full-scale WWTP it is also important to consider the reliability and accuracy of the measurements used in the control loops. Measurements of nutrients as ammonium and nitrate in activated sludge systems can be noisy or with low precision and, for example, the daily tuning of setpoints may be not feasible because the different theoretical setpoints are all around the same value considering the measurement error. In any case, the results presented demonstrate that an optimised fixed setpoint (as the points on the Pareto surface of Fig. 6) would provide a reasonable performance better than using control loops without optimised setpoints (other points of Fig. 6 out of the Pareto surface). The improvement would be much better when the performance is compared to open-loop operation or optimised open-loop conditions [19], because these non-controlled approaches are not able to react properly to important changes of the influent characteristics.

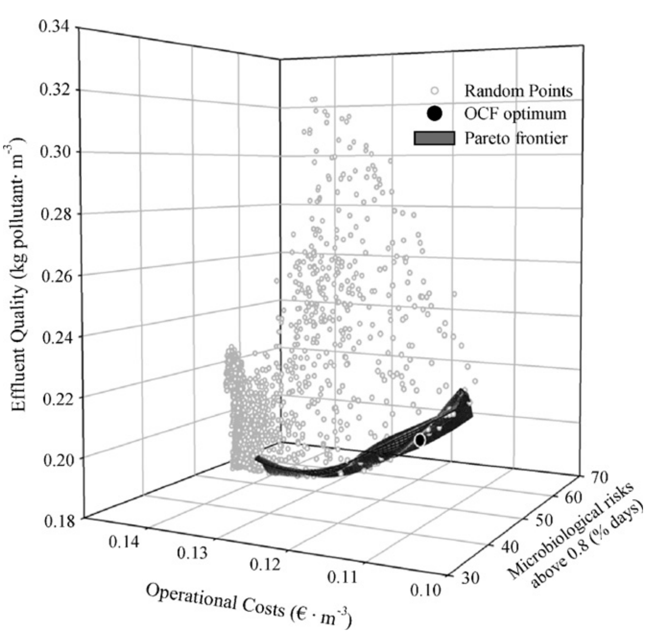

Fig. 7. Three-dimensional representation of the A&N-DVS control strategy behaviour in terms of operational costs, effluent quality and microbiological risks for 1500 random daily set of setpoints.

4. Conclusions

The major achievement of this work was the utilisation for the first time of the risk for occurrence of microbiology-related failures, as part of the multi-criteria function, in order to optimise the setpoints of different control strategies implemented in a WWTP that included biological P removal. The operational costs and the effluent quality were also integrated in such function in order to optimise the WWTP operational efficiency.

The multi-criteria optimisation resulted in a set of optimal operation setpoints that could be approximated by a Pareto surface. The optimised setpoint within this surface could be selected by the requirements that are established for each WWTP in terms of the three criteria. These requirements could be translated into monetary weights as was done with OCF. Hence, the OCF optimisation resulted in an optimised scenario that was located on this surface.

Finally, it was observed that the optimisation process could be enhanced by using both objective functions in a complementary way. The multi-criteria function enabled a more extensive evaluation of different alternatives where none of the criterion is conditional to the other. Once the weights are selected according to the WWTP requirements, the OCF optimisation could be used to adapt the plant operation to the influent variations.

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