Application of mathematical tools to improve the design and operation of activated sludge plants. Case study: the new WWTP of Galindo-Bilbao

Part II: Operational strategies and automatic controllers

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Abstract This paper presents a new sensitivity analysis methodology for Activated Sludge WWTPs. It is based on both (a) the calculation of the range of “manipulated input variables” that satisfy the restrictions imposed on the “output variables” and (b) on the computation of isolines of the output variables inside the feasible operating space. This analysis allows a more precise description of the operating constraints, facilitates the understanding of the steady-state behaviour of the process and detects possible areas where the process is very sensitive to small disturbances. The feasible operating space for two Activated Sludge WWTP processes for C N removal (RDN, DRDN), using SRT and DO level as “input variables” as well as effluent quality and exploitation costs as the main “output variables” is studied. The proposed methodology facilitates the selection of the appropriate operational strategy and the design of automatic controllers. Some examples of the application of this methodology for the design of automatic controllers in a real WWTP are briefly presented.

Keywords Activated Sludge; control; nitrogen removal; operating point; operating space; sensitivity

Introduction
In process systems terminology, the operating space of a process is defined in terms of the manipulated input variables and the feasible operating space by the range of their values that satisfy a set of operating constraints. In this way, in a typical WWTP, constraints may be process related variables (oxygen level in aerated reactors), equipment related variables (maximum pumping rates) or safety related variables (effluent requirements) (Olsson and Newell, 1999).

Operational strategies could be defined by some optimisation criteria imposed on the output variables, but maintaining the manipulated input variables within the feasible operating space. In this sense, mathematical optimisation algorithms are very useful for the automatic selection of the “best operational point” inside the feasible operating space (Ayesa et al., 1998). However, a precise description of the variability of the output variables in the proximity of the optimum point can be crucial in order to detect possible sensitive areas where the process is very vulnerable to small changes under operational conditions. For this reason, calculation and graphical representation of the results (by means of isolines of the output variables) improve significantly the understanding of both the process behaviour in the vicinity of the current operating point and the influence that the input variables have on the plant operation. Thus, it facilitates the design of operational strategies. A more detailed analysis of the feasible operating space should take into account the different time-scale of the process by developing the “Incidence matrix” of the system (Jeppsson, 1996).

In this manner, once the boundaries of the feasible operating space and the isolines of the output variables are defined, the appropriate operational strategy can be easily designed.
Commonly analysed output variables are related to plant operational costs and to effluent quality. Therefore, a global operational strategy should maintain operating the plant and reduce exploitation costs complying with the restrictions of the output variables in spite of disturbances (Ayesa et al., 1995).

**Analysis of feasible operating space for the Galindo-Bilbao WWTP**

Once the process and dimensions of the new WWTP of Galindo-Bilbao (Spain) were defined, the next task was the development of basic rules for the efficient management of the plant. This paper emphasises the importance that sensitivity analysis has for both the selection of operational strategies and for the design of automatic controllers for WWTPs. The sensitivity analysis is based on the calculation of the steady-state performance of the plant for each combination of input variables, operating with different temperatures and influent loads. The mathematical algorithms are presented in a complementary paper (Rivas et al., 2001, this issue) and the biodegradation model is based on IAWPRC AS Model No.1 (Henze et al., 1987).

The WWTP of Galindo-Bilbao can be operated either as a RDN or as DRDN process (Figures 2 and 3). The main manipulated variables for both processes are the Dissolved Oxygen (DO) concentration in the aerated reactors, the Solids Retention Time (SRT) in the biological reactors, the sludge recycle flow rate, the internal recycle flow rate and the fractionating of the influent flow (only in DRDN process). However, the analysis of the feasible operating space was simplified by considering only the DO concentration and the SRT as the main input variables since these variables have greater effect on the plant performance. The sludge recycle flow rate was maintained at a constant value in all simulations.
(50% of influent flow rate). The internal recycle flow rate and the influent fractionating were automatically optimised in every steady-state calculation by minimising the total effluent nitrogen as the objective criteria. Hence, the evaluation of the feasible operating space was focused on the sensitivity analysis of the output variables to different combinations of SRT and DO values. In this particular case, the feasible operating space was reduced to only a two-dimensional feasible operating area.

The calculated output variables for each steady-state operational point were the effluent ammonia and nitrates concentration, the Mixed Liquor Suspended Solids (MLSS) concentration in the last biological reactor, the air consumption (in terms of $K_L a$) and the sludge production. The boundaries of the feasible operating space were computed for temperature values higher than and equal to 13°C subject to the following restrictions:

- Effluent ammonia + nitrates concentration $\leq 13.0$ mg N/l
- Effluent ammonia concentration $\leq 2.0$ mg N–NH$_4$/l
- Last biological reactor MLSS concentration $\leq 3500$ mg MLSS/l
- $0.8$ mg DO/l $\leq$ DO concentration in the aerobic reactors $\leq 2.0$ mg DO/l

The restriction on ammonia + nitrates concentration is imposed by local authorities and concerns effluent quality. Moreover, an additional restriction in effluent ammonia concentration was included to assure nitrification stability, because the minimum effluent total nitrogen (TN) concentration would otherwise be associated with severe effluent ammonia concentration. The maximum value of MLSS concentration was included to bound solids flux to the secondary settler. The minimum DO concentration prevents both anaerobic zones and deterioration of the sludge settling properties. The maximum DO concentration was considered to be an appropriate limit to attain reasonable aeration efficiency.

All simulation results have been summarised in two-dimensional plots representing isolines (generated with MATLAB (1999)) of the output variables within the boundaries of the feasible operating area. Figure 4 shows the boundaries of the feasible operating area for the RDN process computed at three different temperatures (13, 17 and 22°C). Figures 5 to 7 show the isolines for the output variables inside the feasible operating area evaluated at 22°C. Figure 5 represents effluent ammonia and nitrate concentrations and Figure 6 represents effluent ammonia+nitrates (TN) concentration and MLSS concentration in the last biological reactor. Finally, Figure 7 shows the isolines of the consumed $K_L a$ and the sludge production (in % relative to their maximum values inside the feasible operating area). Sludge production has been considered to be an operational cost. Similarly, Figures 8 to 11 describe former variables for the DRDN process.

Considerations about the feasible operating area
The analysis of the boundaries and isolines of the feasible operating area illustrates the process behaviour at different temperatures, as well as the steady-state effects of the manipulation of the DO level and SRT. Figures 4 and 8 show, respectively, the feasible operating area for the RDN and the DRDN processes at different temperatures. The upper boundary of the two-dimensional feasible operating area computed at each temperature is determined by the MLSS concentration restriction. The lower boundary is determined by the maximum ammonia concentration allowed in the effluent. The left- and rightmost boundaries have been arbitrarily set at reasonable limits for the DO concentration (0.8 – 2.0 mg DO/l). The size of the feasible operating area increases as temperature goes up. The maximum feasible SRT increases slightly with temperature due to the rise of endogenous respiration, and the minimum feasible SRT, together with the minimum feasible OD level, decrease when temperature rises due to higher rates of biological nitrogen elimination.
It should be emphasised the significant increase in operational flexibility as temperature rises. Consequently, the plant is temporarily oversized at high temperature. All combinations of DO and SRT values inside the feasible operating area are valid operating points for the plant. Therefore the WWTP operator has the possibility of modifying the operating point defined for critical conditions and shift the process to different operating points where the management costs or effluent quality can be improved.

Figures 4 and 8 clearly show that the feasible operating area for the DRDN process is significantly larger than the one given by the RDN process. In the former process, the maximum SRT value is slightly reduced due to a small reduction in the solids gradient between reactors and the minimum SRT is broadly reduced due to the higher nitrification rate of the Regeneration reactor. The final effect is an increase in the size of the feasible operating area and consequently in the flexibility of the plant.

Considerations about the isolines for the output variables
Figures 5 and 9 show the isolines corresponding to the effluent ammonia and nitrates concentrations for the RDN and DRDN processes computed at 22°C. Clearly, ammonia concentration decreases as DO concentration or SRT increases. As an example, an effluent ammonia concentration of 1.5mg N–NH₄/l can be achieved either with an oxygen level of 1.0 mg DO/l and a SRT value of 20.85 days, or with an oxygen level of 1.7 mg DO/l and a SRT value of 13 days. It should be noted that the process becomes more sensitive to disturbances when operated close to the lower left-most boundary of the feasible operating area.

Figures 6 and 10 show the isolines for the effluent ammonia+nitrates concentration and the MLSS concentration in the last biological reactor. It can be appreciated that the total amount of nitrogen does not constrain the feasible operating area. The effluent total amount of nitrogen slightly decreases as SRT increases and DO level decreases. The analysis of the isolines shows the existence of an optimum DO level that minimises the effluent nitrogen concentration for a given SRT. This optimum value rises as SRT decreases. The interest of operating the plant with lower DO concentration when it is oversized has been previously discussed in Larrea et al. (2001). The horizontal isolines of the MLSS concentration indicate that this variable is only influenced by the selected sludge age.

Figures 7 and 11 show the effect that the DO level and the SRT have on the operational cost of both the RDN and DRDN processes, respectively. Sludge production is determined by the selected SRT, and $K_1a$ coefficient increases as either DO or SRT increases. Variability of oxygen consumption for exogenous respiration can be neglected and the observed changes are mainly due to modifications in either endogenous respiration or oxygen transfer efficiency. It can be observed that the air consumption and the sludge production vary significantly within the feasible operating area at 22°C depending on the selected feasible operating point. The analysis of the isolines shows that the maximum steady-state reduction of the operational costs at this temperature is about 25% for air consumption ($K_1a$) and 12% for sludge production in the RDN process and 25% and 20% respectively for the DRDN process. Both maximum reductions can not be obtained simultaneously, but the selection of high SRT and low DO level should be a good choice to reduce the operational costs.

The internal recycle flow and the fractionating of the influent flow were automatically optimised for each steady-state calculation. The optimum internal recycle flow rate varies significantly according to the study case. However, all simulations show that the optimum concentration of nitrates in the anoxic reactor is always between 0.5 and 1.5 mg N–NO₃/l. This range guarantees the presence of nitrates required for denitrification, reduces pumping costs and avoids possible inhibition of the denitrification process due to an excess of recycled dissolved oxygen. The influent flow fractionating for the DRDN process shows a very
Figure 4 Feasible operating zone for the RDN process working at different temperatures

Figure 5 Isolines of effluent ammonia and nitrates concentrations for the RDN process at 22°C

Figure 6 Isolines of effluent total nitrogen and MLSS concentrations for the RDN process at 22°C

Figure 7 Isolines of $K_L a$ and sludge production for the RDN process at 22°C

Figure 8 Feasible operating zone for the DRDN process working at different temperatures

Figure 9 Isolines of effluent ammonia and nitrates concentrations for the DRDN process at 22°C

Figure 10 Isolines of effluent total nitrogen and MLSS concentrations for the DRDN process at 22°C

Figure 11 Isolines of $K_L a$ and sludge production for the DRDN process at 22°C

Figure 12 Operating points inside the WWTP feasible operating zone
low influence on the final results because of the small size of the regeneration volume. A fixed fractionating of 25%-75% has shown good results for every operating point inside the feasible operating area.

Once the feasible operating area and the isolines of the output variable have been defined for a given plant (specific process, biological model, influent load and temperature), the suitable operating point depends on the particular priorities of each WWTP manager. For example, point A in Figure 12 is the safest operating point in terms of nitrification stability and effluent requirements but the solids load to the settler is near to its maximum. Although sludge production is minimised because of the high SRT, air consumption attains its maximum value. On the contrary, both points B and C are sensitive points in terms of nitrification, but safe in terms of solids flux to the settler. Point B has higher air consumption and sludge production than point C. Finally, point D is not very sensitive in terms of nitrification and has low sludge production and air consumption. Thus, the selection of an operating point with maximum SRT and minimum DO should be a good choice for over-sized plants (or underloaded during a specific period) if the operator wants to reduce the sludge production and the air consumption. However, it is important to notice that the performance of the plant near the boundaries of the feasible operating space must be carefully controlled in order to guarantee safe behaviour of the process against possible input disturbances. In this particular case, the restrictions of maximum MLSS concentration in the reactors and maximum ammonia concentration in the effluent should be fulfilled if maximum SRT and minimum DO (point D) were selected as the plant operating point. Considering the usual disturbances of the plant (basically influent load and temperature), the manipulated variables should be continuously adapted to the changes (in size or shape) of the feasible operating area. The design and application of automatic controllers is then strongly recommended.

Design of automatic controllers
The analysis of the steady-state influence that manipulated variables have in the effluent quality and in the main operational costs allows the selection of a suitable operating strategy. However, in the practical implementations of operational strategies require the automatic control of the manipulated variables. In Galindo-Bilbao’s WWTP, the selected operational strategy consists in operating the plant near the point D (Figure 12), in order to reduce the operational costs, and setting the nitrates concentration in the anoxic reactor.

![Diagram](https://iwaponline.com/wst/article-pdf/43/7/167/429822/167.pdf)

**Figure 13** MLSS, ammonia and nitrates controllers
within the optimum range (between 0.5 and 1.5 mg N–NO₃/l). The influent fractionating is maintained at a fixed value of 25%. The safe and efficient operation of the plant near the left-top corner of the SRT/DO feasible operating area requires the implementation of the three uncoupled controllers presented schematically in Figure 13.

The two first controllers guarantee the restrictions concerning maximum MLSS and effluent ammonia. The MLSS controller (Figure 13(a)) reads the instantaneous Suspended Solids concentration, calculates a 24-hour mobile-average measurement and automatically manipulates the Sludge Waste Flow to maintain a MLSS reference of 3500 mg/l in the last biological reactor. The ammonia controller (Figure 13(b)) manipulates the DO level to maintain a 24-hour mobile-average ammonia concentration in the effluent at 2.0 mg N–NH₄/l. The third additional controller (Figure 13(c)) automatically governs the internal recycle flow rate to maintain a continuous concentration of nitrates in the anoxic reactor near to a set-point of 1.0 mg N–NO₃/l. A complete description of different possibilities for this type of controllers can be found in Suescun et al. (2001) and Galarza et al. (2001).

The verification of the behaviour of these controllers was made by simulation, using the mathematical models for the RDN and DRDN processes but using real influent load and temperature data registered in the actual full-scale Galindo-Bilbao’s WWTP during eight months. Some results of this verification are presented in the figures below. In this way, Figures 14 and 15 show the behaviour of the controlled ammonia and MLSS and Figures 16 and 17 show the Sludge Waste Flow rate and DO level automatically selected by the first two controllers. DO range has been fixed in the range 1.0–2.5 mgDO/l for this particular simulation study case.

The application of the controllers increases from 96% to 99% the number of days that satisfy the effluent requirements, and simultaneously reduces the air consumption by a 16% and the sludge production by 9%. Therefore, the proposed controllers stabilise the WWTP near the desired objectives, maintain the process inside the feasible operating space when possible and minimise sludge production and air consumption. At the moment of writing this paper the controllers are tested in a pilot plant with real sewage. Some preliminary experimental results have been already presented in Galarza et al. (2000).
Conclusions
Mathematical optimisation algorithms have already demonstrated their usefulness in the automatic selection of the ‘best value’ for the manipulated variables within the feasible operating space of a process, depending on the selected objective criteria. This paper emphasises the importance that sensitivity analysis has for both the selection of operational strategies and for the design of automatic controllers for WWTPs. The proposed sensitivity analysis is based on the calculation and graphical representation of boundaries and isolines of the feasible operating space computed at each temperature. Two advanced WWTP processes for CN removal (RDN and DRDN) have been analysed with this methodology.

The proposed methodology allows a more precise description of the output variables near the optimum point, detecting possible sensitive areas where the process is very vulnerable to small disturbances. The isolines of the most significant output variables, related to effluent quality criteria or operation costs, simplify the understanding of the process behaviour near the current operating point and facilitate the selection of the most appropriate operational strategy and the design of automatic controllers inside the feasible operating space. Some examples of the application of this methodology have also been briefly presented.

Acknowledgements
The authors want to express their gratitude to the Basque Government, CADAGUA S.A., MSI S. Coop. and Consorcio de Aguas del Gran Bilbao for their technical collaboration and financial support of the research project “Design and development of advanced control strategies for the new WWTP of Galindo-Bilbao”.

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