Investigation of tuning of a fuzzy-logic controller for biological wastewater treatment systems

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Summary of key findings

Fuzzy-logic control (FLC) is a tool which has been shown to keep wastewater treatment at high performance. This is because it is not affected by the non-linearity of the biological processes. However, there is no systematic approach for its design. In this contribution, a study investigating one of the main design features of a FLC, namely the membership functions (MFs) of the controlled variables (CVs), is performed. In particular, the control strategy by Boiocchi *et al.* (2014) applied for a single-stage partial nitritation/Anammox reactor was used as basis and the MFs of one of the CVs were perturbed. From this study, it emerged that the design of MF of a CV decides its set point and that the slope of the MFs of a CV determines the speed of the control response to disturbances.

Background and relevance

Wastewater treatment plants (WWTPs) are required to meet effluent quality limits on total nitrogen, total phosphorus and chemical oxygen demand before discharging to receiving water sinks. To fulfil these requirements, a relatively-high process performance needs to be ensured despite severe influent disturbances. This can be achieved by means of properly-designed controllers. In WWTP control, Proportional Integral Derivative (PID) control is one of the most frequently used tools. However, the performance of these controllers relies on the approximation that the controlled processes are linear. Hence it may happen that PID controllers are not the best tools to enable achieving high WWT process performance, as these processes are always non-linear. On the contrary, the performance of Fuzzy Logic Controllers (FLCs) is independent from the linear nature of the process system itself. FLCs are designed on the basis of the knowledge acquired during operational experiences with the process system to be controlled. Their design allows the integration of quantitative mechanistic knowledge with qualitative knowledge, which could improve the overall controller performance. On the other hand, the FLCs typically have a large number of design parameters, which are usually defined ad hoc on the basis of process engineering insights. This makes them very flexible and adaptable to changes in function of specific requirements. However, unlike the PID where a large body of work about optimal design and tuning rules is already established, a straightforward systematic methodology describing the proper way to choose the design of a FLC in function of the desired control performance does not exist yet. Although the choice of some parameters is more intuitive and experience-based than mechanistic, it is important to note that wrong design decisions can lead to instances of low sensitivity or instability of the control system itself. For this reason, in order to improve the awareness of FLC designers regarding the impact of their decisions on the control response to disturbances, a study based on a control system applied to a Complete Autotrophic Nitrogen Removal (CANR) reactor is here carried out. CANR is a novel process designed for the side-stream partial nitritation/Anammox treatment of the reject water produced from the dewatering unit of anaerobically-digested sludge. This process consists of an overall autotrophic conversion of ammonium into nitrogen gas. This treatment unit is increasingly integrated within existing WWTPs in order to achieve high nitrogen removal along with convenient operating costs. However, in order to take real advantage from this integration, it is important to operate the CANR reactor efficiently (i.e. high nitrogen removal). Starting with a control strategy already developed by Boiocchi *et al.* (2014), an investigation regarding the membership functions (MFs) of controlled variables (CVs) on the control system response time to influent disturbances is carried out in this study. The results of this study will provide the FLC designers with relevant instructions regarding the decisions that need to be taken when designing the MFs of the CVs in order to achieve the desired control system response.

Materials and methods

As disclosed in the introduction, the objective of this work is to know the impact of the design of the MFs of the FLC input variables on the controller performance. The control strategy developed by Boiocchi *et al.* (2014) is used as basis for this study. In particular, the MFs of the ammonium removal efficiency (R_{eff}), one of the key input variables, are perturbed and different control strategies are generated thereby. These control strategies are then applied to a single-stage continuous reactor for CANR system modelled according to Vangsgaard *et al.* (2012) into a simulation environment (MATLAB/Simulink). Dynamic responses to a 15%-step increase in the concentration of influent total ammonia nitrogen by the different controllers generated are then compared. The total simulation time is 1500 days and the step increase is applied at day 500. From the comparison of the different responses, the effect of the perturbed parameter will be consequently addressed. In this section, first a description of the generic work of a fuzzy-logic inference system is given. Afterwards, the mathematical model describing the biological system and the control structure used as basis for the investigation are briefly illustrated for the sake of completeness. Finally, the approach adopted for the aforementioned investigation is explained.

Perturbations of the membership functions of R_{eff} performed

The two perturbations performed on the MFs of R_{eff} are the following: (1) increase the right-hand side slope of the MF for fuzzy subset "medium" (Figure 1.1a) and (2) increase the crisp value to which a degree of membership to the fuzzy subset "medium" equal to zero corresponds (Figure 1.1b). As outputs from these perturbations, three control strategies are generated: (1) control strategy A (*CSA*), the original one by Boiocchi *et al.* (2014), (2) control strategy B (*CSB*), resulting from the perturbation depicted in Figure 1.1a, and (3) control strategy C (*CSC*), resulting from the perturbation displayed in Figure 1.1b.

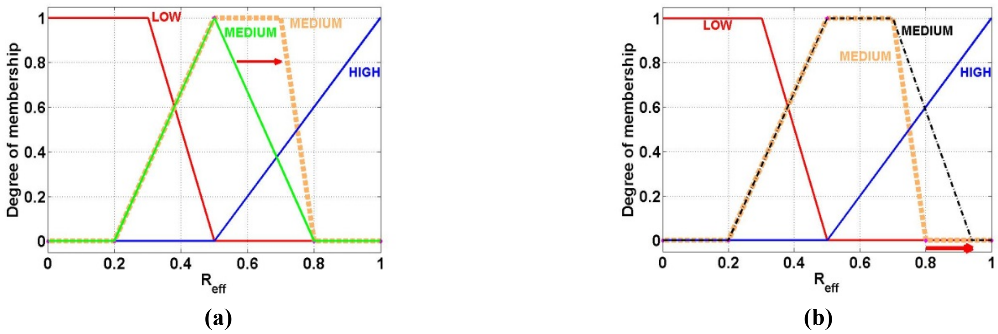
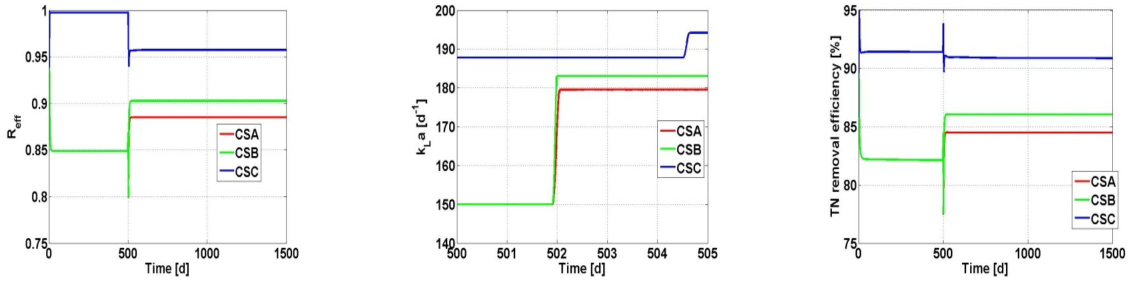


Figure 1.1: (a) Increase of the MF slope for fuzzy subset "medium" of R_{eff}, and (b) increase of the crisp value to which 0 degree of membership to fuzzy subset "medium" corresponds.

Results and discussion

Figure 1.2 summarizes the main results obtained by simulating the three control strategies developed as mentioned in Section "materials and methods" tested on the biological system by Vangsgaard et al. (2012).

By comparing R_{eff} dynamics resulting from application of control strategy *CSA* and *CSB* in Figure 1.2b, it can be deduced that when the slope of the MF of fuzzy subset "medium" for R_{eff} is increased, the controller response is faster. As a matter of fact, during its decrease due to the step increase, R_{eff} assumes a higher degree of membership to be "medium" when the slope is steeper. Consequently, a higher degree of membership for the FLC output (i.e. $\Delta k_L a$) will be inferred by the Inference Engine. Hence, a higher crisp output is applied to the biological system. From Figure 1.2a, even by looking at the period before the step increase, a much higher value of R_{eff} is obtained when the 0-degree-of-membership point of the MF for the fuzzy subset "medium" is moved to a higher crisp value. As a matter of fact, by doing this, R_{eff} is detected to be "medium" at higher crisp values and the controller will react in order to keep the variable at values higher than this.



(a) (b) (c)

Figure 1.2: Dynamic simulation results for Scenario 1: (a) ammonium removal efficiency (R_{eff}), (b) k_La, and (c) total nitrogen removal efficiency.

Conclusions

An investigation about the effect of the main fuzzy-logic control parameters on the control response has been carried out in this study. By perturbing the membership function of the ammonium removal efficiency, the following considerations can be concluded:

- The design of the MFs of FLC controlled variables decides their set points,
- Increasing the slope of the MFs for those fuzzy subsets where a change in the manipulated variable is required will speed up the response of the controller to input disturbances.

References

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