# Smart, Data-Driven Aeration in Water Resource Recovery Facilities for Balancing Wastewater Treatment and Energy Consumption

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# Smart, Data-Driven Aeration in Water Resource Recovery Facilities for Balancing Wastewater Treatment and Energy Consumption

## Introduction

Existing electricity networks need to adapt to the increasing amount of renewables to maintain a safe and stable supply. This will require massive developments in smart energy systems. Hence applications such as building heat, vehicle charging and industrial cooling have received attention in their ability to "smartly" consume/save energy in selected periods without significant loss of utility for the users. In this transformation, urban water systems can also provide an important contribution.

Water Resource Recovery Facilities (WRRF) in the US demand approximately 0.8% of the total US electricity consumption (Pabi et al. 2013) and a similar picture is drawn in many other countries. More specifically, WRRFs use 40-75% of their total electricity for biological nutrient removal (i.e. aeration of wastewater). Currently, WRRFs are typically operated by using fixed rules for control which do not account for variations in electricity prices (Figure 1 a-d). However, in this perspective we argue that a new flexible control framework can be used to prioritize electricity consumption in selected periods, i.e. moving consumption as a function of electricity prices (Figure 1 e-h).

The solution that is proposed builds on a Model Predictive Control (MPC) algorithm (Stentoft et al. 2019) which uses online data from the plant to dynamically model the nutrient concentrations in the biological treatment tank as a function of time and aeration. The MPC uses a simplified stochastic model (Stentoft et al. 2018) based on stochastic differential equations inspired by the well-established IWA Activated Sludge Model 1 (Henze et al. 2000). Results from literature suggest that this flexible approach can potentially be applied in WRRFs worldwide and thereby it creates a potential for integrating WRRFs into future smart electricity grids.

## Methodology

Modern WRRFs consist of several treatment steps that are each designed to target different fractions of "waste" in the water. One important step is the biological removal of nutrients which targets organic carbon, nitrogen and phosphorus through controlled bio-chemical processes. In this step, oxygen concentration is an essential control parameter to ensure the desired quality of the WRRF effluent, and different types of blowers are used to maintain the desired oxygen level in the tanks. Also, online sensors placed directly in the tanks measuring ammonium, nitrate, phosphorus and organic carbon provide a continuous overview of the wastewater quality, enabling real-time optimization of the treatment.

The biological processes in WRRFs are well described by state-of-the-art mathematical models. By combining these deterministic models with data from online sensors, "grey-box models" can be determined. With these, it is possible to predict the incoming wastewater composition and treatment processes performance (Stentoft et al. 2018). This means, that the processes of the biological nutrient removal can be predicted as a function of aeration control sequences and hence, it is possible to identify the best aeration control sequence that fulfills outlet requirements.

The existing control instrumentations (actuators, sensors, weirs) can be used by MPC algorithms aiming at optimizing both outlet concentrations and electricity prices. The MPC can operate the plant based on two different electricity markets: the spot-price (where hourly energy prices are known 24 hrs in advance) and the demand-response market (where large consumers should be mobilized/disconnected from the grid to compensate for fluctuations and deviations from the expected pattern). Additionally, the smart aeration control (Figure 1) can be combined with integrated MPC, where available storage volume in the sewer network is used to store wastewater during high price periods (Figure 2) to further establish flexibility.

## Results and Future Perspectives

The proposed MPC approach was tested with data from five different Danish WRRFs. **Fejl! Henvisningskilde ikke fundet.** shows an, where it is possible to investigate how the MPC modifies the aeration process according to the electricity price (**Fejl! Henvisningskilde ikke fundet.**a). This results in a variation in the concentrations of different compounds, with the MPC balancing among NH4 and NO3 concentrations (**Fejl! Henvisningskilde ikke fundet.**b) without compromising outlet quality, which remains below the discharge limits (**Fejl! Henvisningskilde ikke fundet.**c). It was found in (Stentoft et al. 2019) that this control could save 20.9% on electricity costs and effluent taxes as compared to a rule-based control. Both this MPC and the integrated control strategy shown in Figure 2 have been tested full scale, and shows early but promising results.

The suggested control uses the excess average capacity as a buffer. Hence it is important for the wider applicability that such an excess capacity exists. It is found from the extensive dataset for European WRRFs collected by Longo et al. (2018) that 82% of the 168 analysed plants had load factors smaller than 1, indicating that the actual load is smaller than the designed capacity. A similar picture is seen in China, where Zhang et al. (2016) found out of 656 investigated plants, 83% had load factors lower than 1 and 52% of the analysed plants had load factors below 0.8.

Furthermore the design of WRRFs tends to overestimate the load per PE. This is because *Applicable flow variation*, *adaptability* and *reliability* are important factors in the design of secondary treatment processes, and hence safety factors are often added to the design. In some examples, it is found, that the aerobic volume could be reduced by 35% compared to the widely applied design guidelines without compromising design effluent requirements (Corominas et al. 2010), thus indicating that existing WRRFs could potentially have larger actual capacities than their design suggests. This mismatch between load and capacity in the biological treatment step is not the only driver for exploiting flexibility in urban wastewater systems. Flexibility can also be exploited by using upstream volumes in basins or pipes to store wastewater as shown in Figure 2. This will probably further extend the applicable cases, as most catchments have some storage. However, this will require specialized integrated control algorithms as demonstrated in Kolding WRRF (Bjerg et al. 2015).

## Conclusion

In this abstract, a framework for prioritizing electricity consumption for aeration in municipal water resource recovery facilities in low price periods is presented. The framework manages to use more aeration when electricity is cheap compared to when it is expensive without compromising the effluent requirements. Given the existing imbalance between design and actual pollutant load at many WRRFs, the proposed approach may potentially be widely applied to optimize energy consumption and to link WRRFs to Smart Grid systems. The potential for implementing this control on many plants arguably exists, as many plants have load factors that suggest a spare capacity.

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## References

Bjerg E. B., Grum M., Courdant V. A. T., Halvgaard R. F., Vezzaro L., Mikkelsen P. S., 2015, Coupling of weather forecasts and smart grid-control of wastewater inlet to Kolding WWTP (Denmark), Proceedings of the 10th international urban drainage modeling conference, 47-59

Corominas L., Flores-Alsina X., Muschalla D., Neumann M.B., Vanrolleghem P.A. 2010, Verification of WWTP design guidelines with activated sludge process models. Proc Water Environ Fed; 2010(18):137–46.

Henze, M., Gujer, W., Mino, T. & van Loosdrecht, M. C. M. 2000 Activated Sludge Models: ASM1, ASM2, ASM2d and ASM3. Scientific and Technical Report no 9. IWA Publishing, London, UK

Longo S., Hospido A., Lema J.M., Mauricio-Iglesias M., 2018, A systematic methodology for the robust quantification of energy efficiency at wastewater treatment plants featuring Data Envelopment Analysis, Water Res., 141 317-328

Pabi, S., Armanath, A., Goldstein, R., and Reekie, L. (eds.) (2013). Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Electric Power Research Institute (EPRI).

Stentoft P. A., Munk-Nielsen T., Vezzaro L., Madsen H., Mikkelsen P. S., Møller J. K. 2018. Towards model predictive control: Online predictions of ammonium and nitrate removal by using a stochastic ASM. Water Sc. Technol., 79(1), 51-62

Stentoft P. A., Guericke D., Munk-Nielsen T., Mikkelsen P. S., Madsen H., Vezzaro L., Møller J. K. 2019. Model Predictive Control of Stochastic Wastewater Treatment Process for Smart Power, Cost-Effective Aeration. Dycops 2019, Dynamics and Control of Process Systems including Biosystems 23-26 April, Florianopolis, Brazil

Zhang Q.H., Yang W.N., Ngo H.H., Guo W.S., Jin P.K., Dzakpasu M., Yang S.J., Wang Q., Wang X.C., Ao D., 2016, Current status of urban wastewater treatment plants in China, Environment International, 92-93 (2016) 11-22

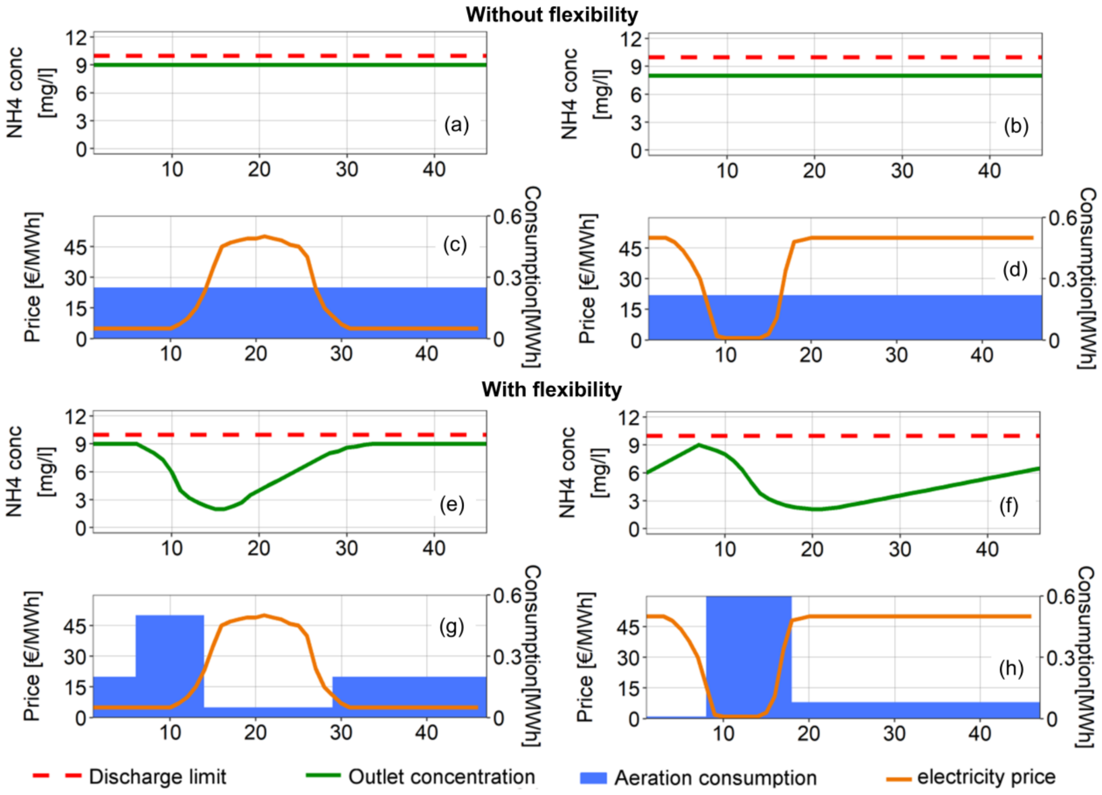

**Figure 1** Two conceptual examples of WRRF operation without flexibility (a-d) and two with flexibility (e-h) in energy consumption. Outlet concentrations (a,b,e,f); electricity prices and consumption due to aeration (c,d,g,h). The electricity prices are identical in the height (i.e. in c, g and d, h) but expected effluent concentrations are different due to different controls. However, the discharge limits are always satisfied.

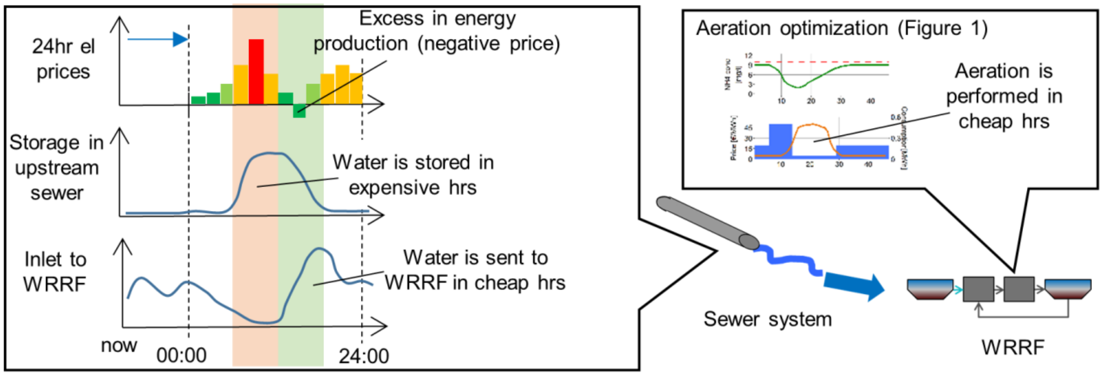

**Figure 2.** Schematic representation of the different integrated control approaches that can be handled by the proposed MPC strategy.

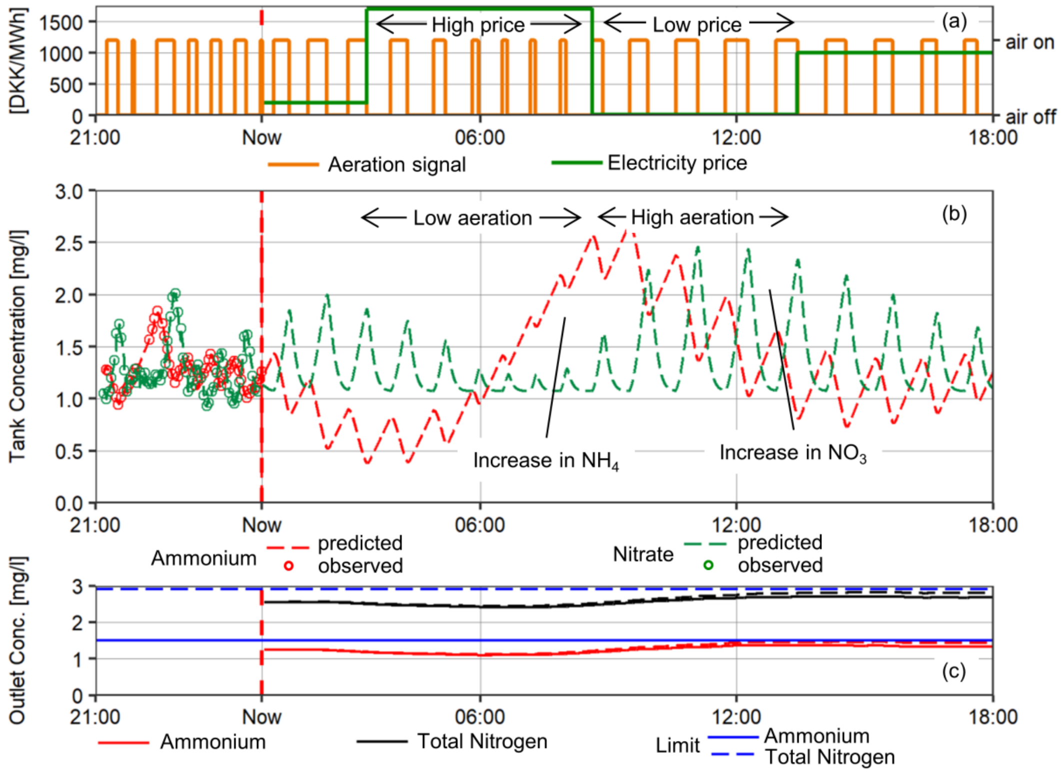

**Figure 3.** Example of the results of the proposed MPC approach with data from a small Danish WRRF. (a) Electricity prices and aeration signal; (b) measured and predicted ammonia concentrations in the biological treatment tank: (c) Ammonium and total N concentrations in the plant outlet.