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Stochastic Model Predictive Control of Phosphorus Concentration for Smart Power, Cost-Effective Municipal Wastewater Treatment

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Abstract: This study is a proof-of-concept of a stochastic Model Predictive Control (MPC) strategy for effluent phosphorus concentration in municipal wastewater treatment. Firstly, a simple data-driven model providing adequate predictions of phosphorus was created and demonstrated. Secondly, the model was used to find the optimal aeration control upholding legal requirements within a fixed amount of computation time. The optimal control is here considered the cheapest control in terms of electricity costs with variable electricity prices and effluent taxes on phosphorus. Results showed significant reductions (~ 45 %) in operational costs compared with a rule-based control.

Keywords: Stochastic MPC; Aeration control; Wastewater treatment; Activated Sludge Process.

Introduction

Wastewater treatment is a vital process in modern societies and uses a significant amount of resources for the sufficient treatment of incoming water. It is estimated that up to 4 % of the total electricity produced is used to power Wastewater Treatment Plants (WWTPs) (Longo *et al.* 2016), whereof up to 70 % is used to power aeration equipment in the biological treatment step (Longo *et al.* 2016). Currently, methods for controlling aeration equipment are primarily focused on keeping the contents of nutrients at constant low levels (e.g. Nielsen and Onnerth, 1995), which may be suboptimal in terms of costs and exploitation of green energy. Furthermore, a stochastic Model Predictive Control (MPC) strategy for nitrogen has been developed (Stentoft et al., 2019), however, this does not include phosphorus, and consequently an important nutrient is missing in the optimisation. Hence, this study suggests (i) a stochastic and adaptive model for accurate predictions of effluent phosphorus and (ii) a stochastic MPC strategy used with forecasts of electricity prices, to plan aeration accordingly. Ultimately, it will be demonstrated how the strategy allows phosphorus concentrations to vary, while constraints ensure that effluent phosphorus is always kept within required limits.

Material and Methods

This study employs a stochastic grey box modelling approach to construct a model for use in stochastic MPC. The data used for constructing the model originates from the Nørre Snede WWTP in central Jutland, and includes online sensor measurements of phosphorus concentrations, the oxygen setpoint used for aeration, and measurements of the inflow rate. The plant is controlled with alternating operation of the Activated Sludge Process (ASP) (Kayser, 2008) as described by Nielsen and Onnerth (1995). These measurements were taken over a 2 month time span from September to November of 2016. Furthermore, hourly electricity prices from Nord Pool A/S during this time period were used (Nord Pool A/S, 2019).

The model was built using data analysis tools, i.e. hypothesis tests, residual analysis etc., as well as by drawing inspiration from physical, deterministic models, such as the ASM 2 developed by Gujer *et al.* (1995) and similar stochastic models for ammonium and nitrate suggested by Stentoft *et al.* (2018). A forward selection strategy was employed in the modelling process to gradually expand on the initial model, chosen to be a one-dimensional Ornstein-Uhlenbeck process (Thygesen, 2016). This type of model was chosen as it is easy to identify the rate and mean parameters of the process, and this structure was preserved throughout the modelling process.

To utilise some of the features of the ASM 2, such as Monod kinetics, some assumptions were made during the modelling procedure. For example, it was assumed that the growth in microorganisms is sufficiently slow to be considered constant within the computation time limit. The phosphorus concentration is exclusively described by oxygen content and inflow in this study.

The proposed model consists of three states described by coupled Stochastic Differential Equations (SDEs). To fit this model to the data, the Extended Kalman Filter (EKF) is used, which provides predictions for each state, and the parameter values are estimated by approximate Maximum Likelihood (Jazwinski, 1970). This is accomplished through the “CTSM-R” package for R (CTSM-R Development team 2018). We propose a model relating the oxygen control input to phosphorus concentration using a hidden state representing oxygen saturation. The primary focus during development was on relating oxygen supply (the controlled variable) with phosphorus concentration, by using the oxygen setpoint for constructing the artificial oxygen state. Therefore, the impact of other treatment methods than the biological, such as chemical precipitation, is not investigated and incorporated into the model in this study, but provides a basis for further studies.

Predictions for future phosphorus concentrations are based on the model, and optimal control of aeration is planned from these predictions. This poses a constrained optimisation problem, with constraints given by aeration equipment and legislation related to phosphorus content in the effluent. Aeration during the ASP is then optimised based on the following factors: the outflow rate, the electricity price, and the phosphorus emission tax. This optimisation problem is solved by using a Genetic Algorithm (GA) available in the “rgenoud” package in R (Mebane *et al*, 2011).

The stochastic MPC was tested in a simulation study, by simulating new measurements corresponding to the adaptively optimised aeration control.

Results and Discussion

Using standard notation for SDEs (Øksendal, 2007), the model developed for the study is given by

$$dS_{PO_4,t} = \left(\theta_1\left(\mu_{1,t} - S_{PO_4,t}\right) - \frac{\theta_2 S_{PO_4,t}}{\theta_2 k_1 + S_{PO_4,t}} S_{O_2,t}\right) dt + \sigma_1 dW_{1,t}$$

$$dS_{O_2,t} = \left(\theta_3\left(kO_t\left(1 - S_{O_2,t}\right) - \frac{\theta_2 S_{PO_4,t}}{\theta_2 k_1 + S_{PO_4,t}} S_{O_2,t}\right)\right) dt + \sigma_2 dW_{2,t}$$

$$d\mu_{1,t} = \sigma_3 dW_{3,t}$$

Here $S_{PO_4,t}$ describes the concentration of phosphorus during wastewater treatment, and $S_{O_2,t}$ describes the oxygen saturation of the water, ranging from 0 to 1 effectively. All $W_{i,t}$ are standard Brownian Motions.

$\mu_{1,t}$ is a random walk representing the inflow concentration of phosphorus. This form was chosen as the deterministic diurnal pattern of inflow did not have an apparent effect on the phosphorus content at the WWTP in question. Introducing some random variation in the inflow proved fruitful, leading to this particular model. Naturally, inflow is expected to have an effect in WWTPs in general, and further studies should determine how to incorporate inflow appropriately in the model.

To demonstrate the performance of the model, a plot of out-of-sample predictions can be seen in figure 1. It is seen that the model is able to capture the general variation in the data, only underestimating the phosphorus concentration during peaks slightly. As such the system of SDEs is able to describe variation in phosphorus during wastewater treatment, under normal conditions, by using a relatively simple model. Predictions from the model will thus form a basis for reliably planning aeration control with reasonable precision, up to a day ahead.

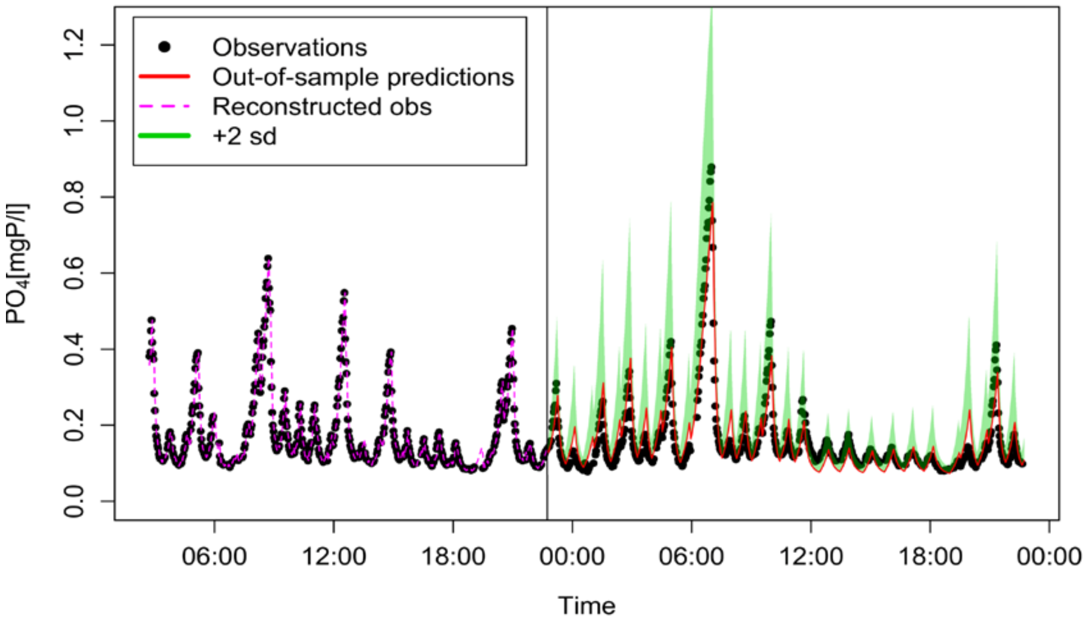

Figure 1: Out-of-sample predictions up to one day ahead by using the described model. The black vertical line indicates the transition from training set to out of sample measurements.

To ensure that the proposed model is generally applicable, the performance was verified using data from Kolding WWTP. This WWTP is much larger in size, load, and inflow rate, than the WWTP in Nørre Snede, thus facing different challenges. Furthermore, in the data from Kolding WWTP, phosphorus content exhibited a stronger dependence on the volumetric inflow to the aeration tank than was seen in the original data. Using the data from Kolding WWTP, the model was still able to accurately predict the variations in the data (Dahl and Sørensen, 2019).

Based on the predictions, an aeration control signal for the following day can be constructed by using the GA on the constrained optimisation problem posed by aeration. This optimisation problem can be summarized by the following equations, with $\hat{X}_t$ describing the phosphorus concentration in the wastewater, $U_{1,t}$ as the aeration control signal, and $U_{2,t}$ as the (volumetric) outflow.

$$\min_{U_{1,t}} C_1(U_{1,t+M}) + C_2(\hat{X}_{t+M}, U_{2,t+M})$$
$$s.t. \quad U_{1,t+M} \in I$$
$$\sum_{i=1}^{M} \hat{x}_{t+i} < p$$

where $U_{t+M} = [u_{t+1}, u_{t+2}, \ldots, u_{t+M}]$and $\hat{X}_{t+M} = [\hat{x}_{t+1|t}, \hat{x}_{t+2|t}, \ldots, \hat{x}_{t+M|t}]$. Here M is the prediction horizon, in this study chosen to correspond to 24 hours of data points. $C_1()$ and $C_2()$ are cost functions associated with electricity consumption and phosphorus emission respectively. The constraints for proper equipment handling are defined by I, and p is the legal limit on the daily average phosphorus emission.

In the implementation of this constrained problem, the legal limit is incorporated in the form of a (very large) penalty term in the objective function. Alternatively, the penalty term could be altered to represent the costs associated with the chemical precipitation required to reduce phosphate content to a satisfactory level.

To present the performance of the stochastic MPC, several tests were designed to provide a realistic perspective into the performance for situations with little time between updates to aeration control. The tests consisted of a day of continually refitting the model to incoming data, planning aeration control by solving the constrained optimisation problem, and simulating data from the model. This should all be accomplished within 10 minutes of computation time, as data is assumed to arrive at this frequency. The cost associated with phosphorus emission was set to 165 DKK/kg PO_4 (the emission tax in Denmark), and forecasts of outflow were based on a diurnal (sinusoidal) pattern. Furthermore, two different electricity price scenarios were used during testing. Firstly, the actual electricity prices at the time of data recording were used, taken from the Nord Pool A/S database. Secondly, an artificial price scenario was generated to assess the performance of the MPC during extreme price variations. Both of these scenarios were also tested against an equivalent fixed price scenario, where the electricity price was set to the mean price from the given scenario.

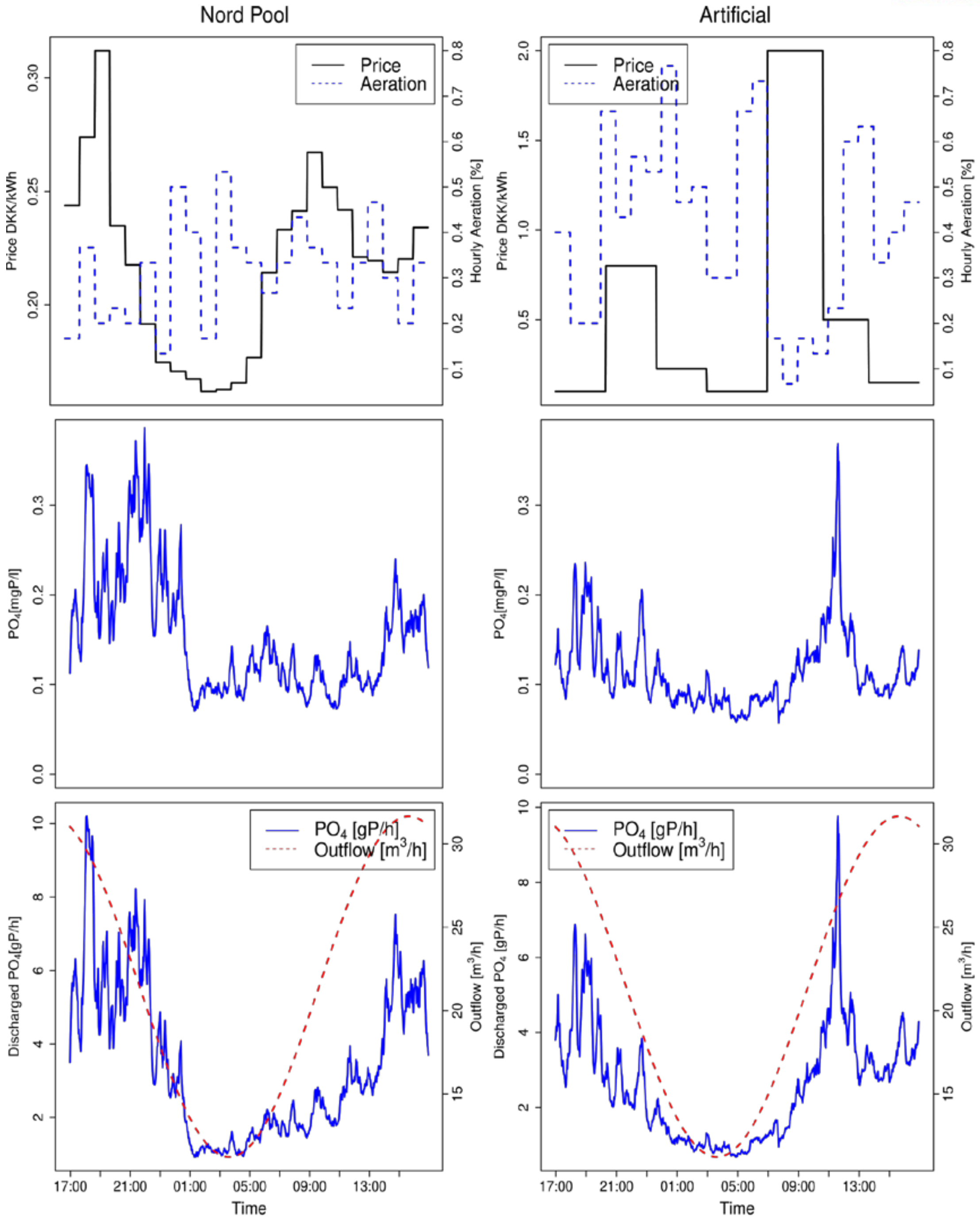

Figure 2: Resulting plots from 1 day of testing the stochastic MPC strategy using the Nord Pool spot prices (left column) and the artificial prices (right column). Hourly aeration percentage is defined as the percentage of time spent aerating, measured every hour. Measurements of phosphorous were simulated using an Euler scheme with $\Delta t = \frac{1}{1000}$ (Iacus, 2008).

The outflow in the WWTP is identical for both tests on the stochastic MPC; hence the price of electricity is the only varying factor when comparing the two. The difference in price range between the two scenarios has some interesting implications for the stochastic MPC strategy. Most notably, it means that emitting phosphorous is comparably cheaper when using the artificial price scenario rather than the real (Nord Pool) prices. It is also noted that the Nord Pool prices follow a very similar diurnal pattern to the outflow, as demand for electricity increases when the general population is awake.

Examining the aeration percentages, it is seen that the variance is much higher for the artificial prices, as a direct result of the generally larger variation in price. For the Nord Pool prices, very little aeration is performed during the first 6 hours of testing, during which the electricity prices peak. Aeration is performed much more frequently in the period with low prices, but is only decreased slightly in the period of mid-high prices. This behaviour is a result of a period of high outflow, where costs can be reduced further by reducing phosphorus concentration through aeration. The reduced emission can be seen as well, and the peak in phosphorus emission/concentration is much less distinct than what is expected from the outflow curve. Generally, the discharged phosphorus graph has a very similar behaviour to the electricity price scenario, and only deviates slightly in the aforementioned time span.

In the artificial price scenario, aeration seems to be more dependent on the electricity price. The hourly aeration percentage remains quite high during periods of low electricity price, even when the outflow is low, as it is affordable. During the peak in electricity price aeration is kept at a minimum, and as a result, phosphorus concentration increases rapidly.

These tests, along with the corresponding fixed price tests can be seen in table 1.

Table 1: Table of measures for the tests on variable pricing and corresponding fixed price tests. The tests were performed on a computer with an i7-3770 CPU and 8 GB DDR3 RAM.

Pricing	**Cost (DKK)**	**Aeration time (min)**	**Phosphorus emitted (g/day)**	**Average comp. time (s)**	**Max comp. time (s)**
Artificial	125.25	596	62.79	363.4	1027
Fixed Mean	157.89	492	118.9	324.2	525.0
Nord Pool A/S	62.05	452	82.42	308.3	529.3
Fixed Mean	74.63	464	150.1	269.6	391.0

The cost of using variable compared to fixed pricing, is significantly lower in both scenarios. For the artificial pricing signal, the reduction in cost is approximately 20 %, and using real-life variable prices yielded a reduction of around 16 %. The total aeration time using the artificial variable pricing is much higher than the fixed price test, which in addition to the significantly lower phosphorus emission, shows how powerful the MPC strategy can be with variable prices. While not as pronounced, similar results are seen in for the price scenario from Nord Pool A/S. Here, similar aeration times with significantly lower phosphorus emission illustrates the MPC's ability to adapt to changing the outflow rate as well.

Regarding computation times, it was seen that the 10 minute time frame was exceeded, but only in 6 out of the 144 iterations of the MPC, and only for the artificial variable pricing. Furthermore, it should be noted that tests were performed on older consumer-grade hardware, and much faster computation times are expected from industrial hardware. Thus, overall the results show that variable pricing performs favourably compared to fixed pricing, and results in lower operational costs, albeit slightly longer computation times.

Comparisons between the MPC and the current control performed using a Rule Based Control scheme (RBC) (Nielsen & Onnerth, 1995) is also performed, by upscaling the variable prices to include tariff costs, as seen in Table 2.

Table 2: Table showing comparison of cost, aeration time, and phosphorus emission for the variable priced MPC and the current fixed price controls.

Control	Cost (DKK)	Aeration time (min)	Phosphorus emitted (g/day)
MPC	117.64	452	82.42
RBC	216.13	502	92.92

This comparison is not entirely fair, given that the measurements used for the MPC are simulated from the model itself. Furthermore, the RBC is based on other nutrients besides phosphorus. Nonetheless, the results clearly show that combining the MPC approach with variable pricing on electricity has the potential to greatly reduce the operational costs for a WWTP. The similar aeration time and phosphorus emitted, achieved at a substantially lower cost, also shows the strength of the MPC approach. Being able to keep phosphorus emissions low during periods of high inflow and utilising the, at times, lower electricity prices, can reduce operational costs significantly.

Conclusions

The study finds that even by using relatively simple stochastic models for describing the concentration of phosphorus during wastewater treatment, sufficiently accurate predictions on phosphorus can be made. By combining the model with an adaptive approach for fitting and optimising, it is possible to plan aeration up to a day ahead by using these predictions, while upholding requirements on phosphorus content in the effluent. As such, the study proves the concept of using a stochastic MPC approach for regulating phosphorus during treatment. Furthermore, it is shown that the MPC allows for easy planning of aeration by variable electricity prices, and that substantial reductions in operational costs can be made. Throughout the study, reductions of up to 20 % could be achieved when using variable pricing compared to fixed prices, and using the MPC approach yielded reductions of 45 % compared to RBC methods. Hence we see this as a step towards cost-optimal aeration control that utilises smart power flexibility in the processes.

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