Receding-horizon control of full-scale wastewater treatment plants as water resource recovery facilities with energetic constraints

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Introduction

Context:
The arising paradigm of perceiving wastewater as a sustainable source of water, raw materials, and energy, pressures for solutions to operating wastewater treatment plants as water resource recovery facilities [1, 2].

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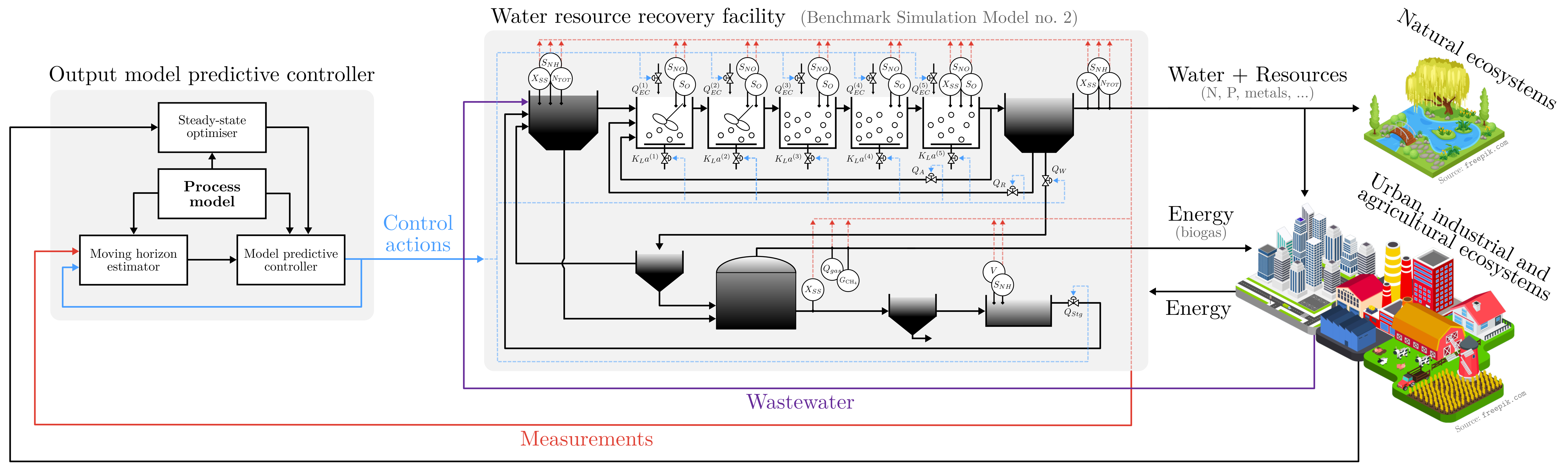
Dynamic demands for recovered resources require flexible policies to operate the plant, while ensuring a balanced water-energy nexus.

Model predictive controllers that adjust the effluent quality to match external demands, while recovering energetic costs from disposed sludge.



Process model (BSM2, [3])

We consider the "expanded" state-space representations

Continuous-time state-space		Discrete-time state-space (ZOH)
$\dot{x}(t) = f(x(t), u(t), w(t)\|\theta_x)$	$\Rightarrow$	$x_{k+1} = x_k + \int_{t_k}^{t_{k+1}} f(x(t), u_k, w_k)dt$
$y(t) = g(x(t)\|\theta_y)$		$y_k = g(x_k)$

by concatenating the state-, input-, and output-vector of each plant unit

$$x = (\underbrace{x^P}_{\text{Clarifier}}, \underbrace{x^{A(1)}, \dots, x^{A(5)}}_{\text{Bio-reactors}}, \underbrace{x^{S(1)}, \dots, x^{S(10)}}_{\text{Secondary settler}}, \underbrace{x^D}_{\text{Digester}}, \underbrace{x^{Stg}}_{\text{Storage}}) \in \mathbb{R}^{225}$$

$$u = (Q_A, Q_R, Q_W, Q_{Stg}, u^{A(1)}, \dots, u^{A(5)}) \in \mathbb{R}^{14}$$

$$y = (y^P, y^{A(1)}, \dots, y^{A(5)}, y^{S(10)}, y^D, y^{Stg}) \in \mathbb{R}^{22}$$

$$w = (Q_{IN}, x^{A(IN)}) \in \mathbb{R}^{15}$$

Output model predictive control [4, 5]

MPC: The control actions deployed to the plant are obtained as numerical solutions to finite-horizon optimal control problems of the form

$$\begin{aligned} \text{min.} \quad & \sum_{n=k}^{k+N_c-1} \left(\|x_n - x_n^{\text{ref}}\|^2_{Q_n^c} + \|u_n - u_n^{\text{ref}}\|^2_{R_n^c} \right) + \|x_{k+N} - x_{k+N}^{\text{ref}}\|^2_{Q^c_{k+N_c}} \\ \text{s.t.} \quad & x_{n+1} = z^{(n)}_{\Delta t_c} + A^{(n)}_{\Delta t_c} x_n + B^{(n)}_{\Delta t_c} u_n + G^{(n)}_{\Delta t_c} \hat{w}_k, \quad x_k = \hat{x}_k \\ & x_n \in \mathcal{X}_n, \quad u_n \in \mathcal{U}_n, \quad (x_n, u_n) \in \mathcal{Z}_{xu,n} \end{aligned}$$

MHE: Current state and disturbance estimates are obtained as numerical solutions to finite-horizon optimal estimation problems of the form

$$\begin{aligned} \text{min.} \quad & \|\hat{x}_{k-N_e+1} - \bar{x}_{k-N_e+1}\|^2_{Q^{-1}_{x_0}} \\ & + \sum_{n=k-N_e+1}^{k} \left(\|\hat{y}_n - y_n^{\text{data}}\|^2_{Q_v^{-1}} + \|\hat{w}_n - \bar{w}_n\|^2_{R_w^{-1}} \right) \\ \text{s.t.} \quad & \hat{x}_{n+1} = z^{(n)}_{\Delta t_e} + A^{(n)}_{\Delta t_e} \hat{x}_n + B^{(n)}_{\Delta t_e} u_n + G^{(n)}_{\Delta t_e} \hat{w}_n, \\ & \hat{x}_n \in \widehat{\mathcal{X}}_n, \quad \hat{w}_n \in \widehat{\mathcal{W}}_n \end{aligned}$$

SS-OPT: We design a hierarchical layout in which the plant is stabilized around operating points obtained as solutions to optimisations of the form

$$\begin{aligned} \text{min.} \quad & \|Hg(x_n^{\text{ref}}) - \tilde{y}_n^{\text{ref}}\|^2_{W_y} + \|u_n^{\text{ref}} - \tilde{u}_n^{\text{ref}}\|^2_{W_u} \\ \text{s.t.} \quad & 0 = f(x_n^{\text{ref}}, u_n^{\text{ref}}, \hat{w}_k^{\text{ref}} \| \theta_x) \\ & x_n^{\text{ref}} \in \mathcal{X}_n^{\text{ref}}, \quad u_n^{\text{ref}} \in \mathcal{U}_n^{\text{ref}} \end{aligned}$$

Case-study: Tracking of effluent nitrogen

- **Task:** Tracking references on effluent total nitrogen ($N_{TOT}^{S(10)}$) restricted to non-positive operational cost index ($\text{OCI}_{\text{kWh}} \leq 0$)
- **Results:** Desired profiles are achieved within ± 1.87 g m^{-3} on average with 1211.2 kWh d^{-1} of energy surplus on average

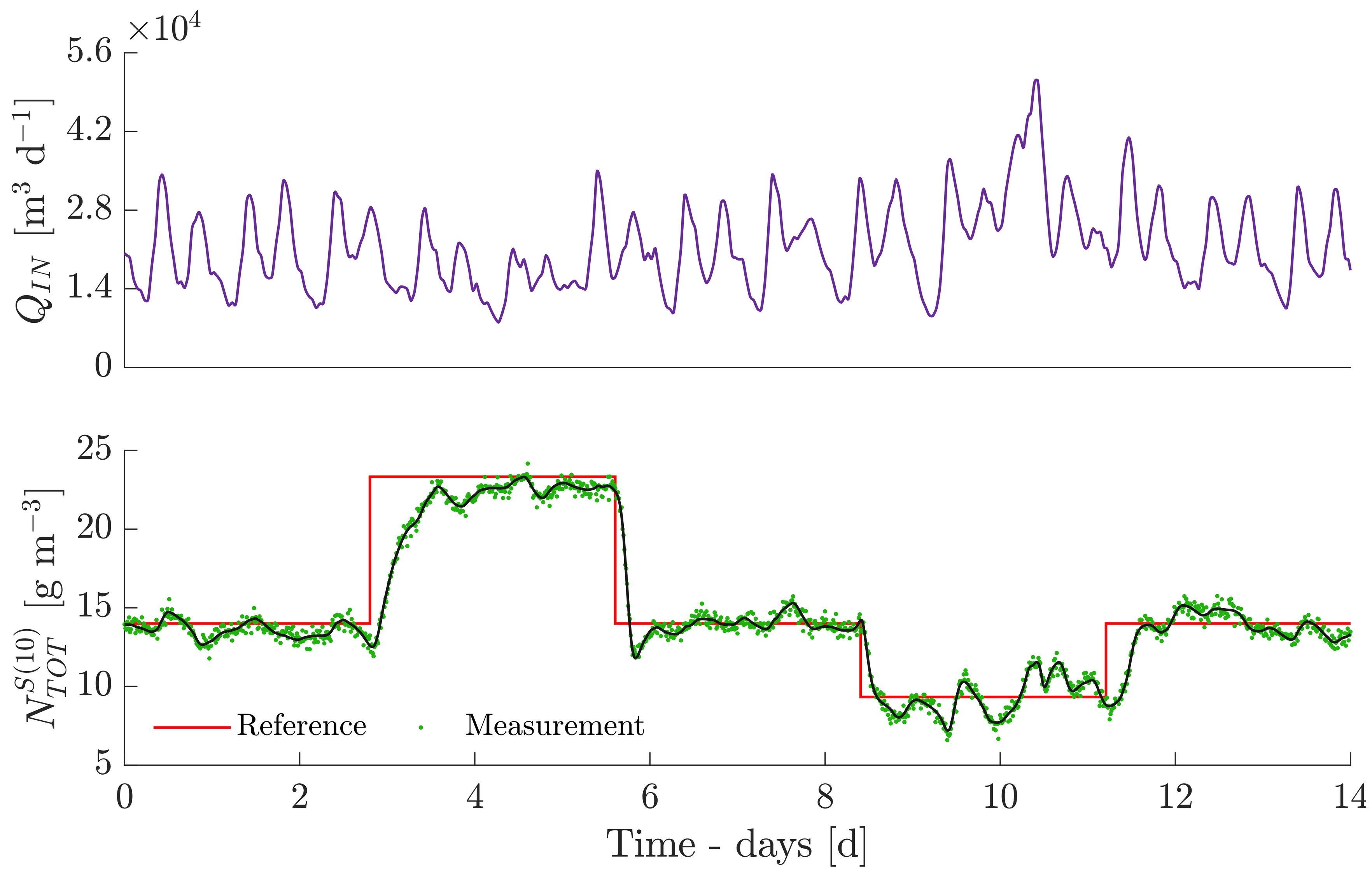


Figure 1: Output-MPC: Tracking of effluent total nitrogen, $N_{TOT}^{S(10)}$. The reference signal describes three objectives: Conventional treatment of nitrogen ($t \in [0, 2.8) \cup [5.6, 8.4) \cup [11.2, 14)$ d), producing nitrogen-rich reuse water for agriculture ($t \in [2.8, 5.6)$ d), and satisfying stricter regulations ($t \in [8.4, 11.2)$ d).

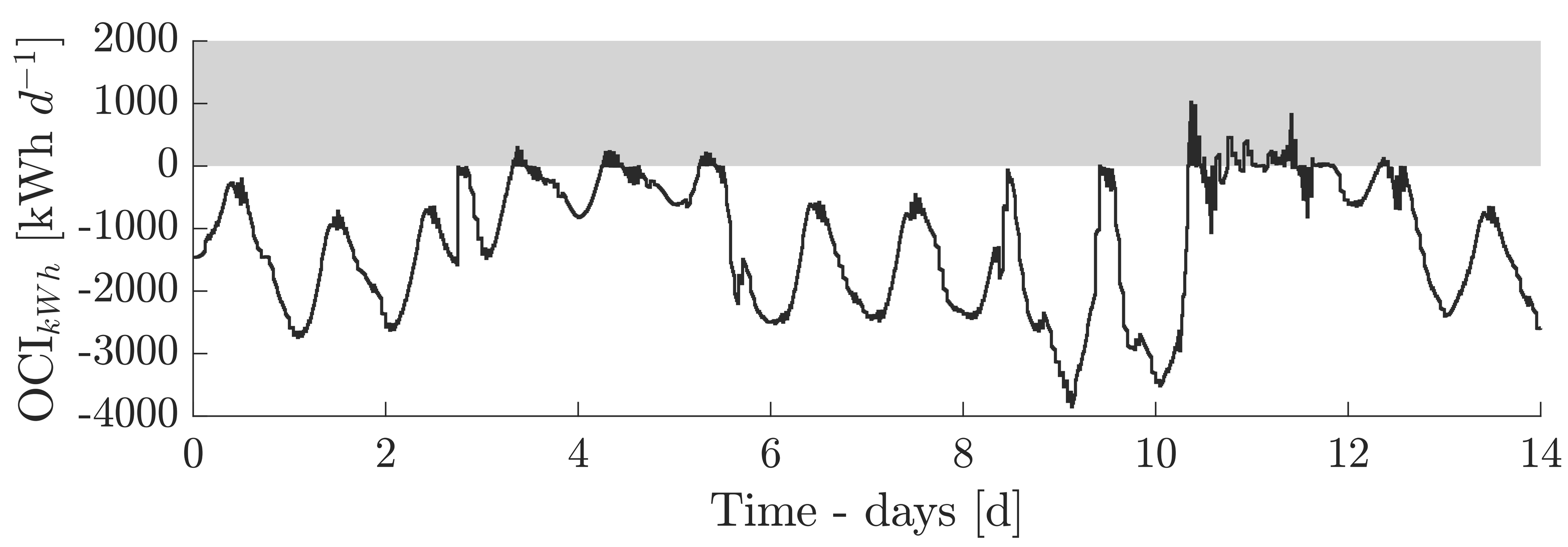


Figure 2: Output-MPC: Operational cost index, $\text{OCI}_{\text{kWh}} = \text{AE} + \text{PE} + \text{ME} - 6\text{MP} + \max(0, \text{HE} - 7\text{MP})$, given aeration (AE), pumping (PE), mixing (ME) and heating (HE) energies, and methane production (MP).

References

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