Experimental validation and comparison of time-optimal and industrial strategy for membrane separation process

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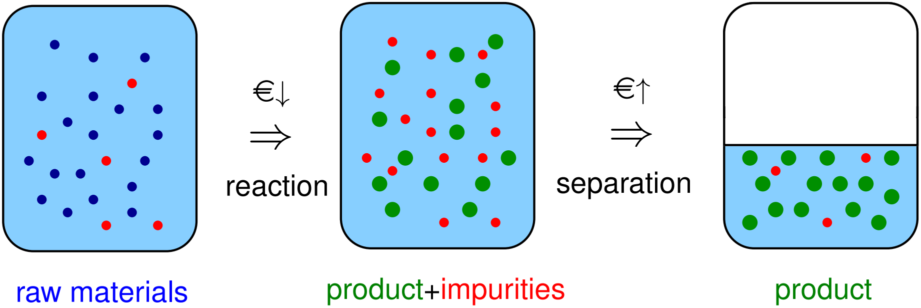
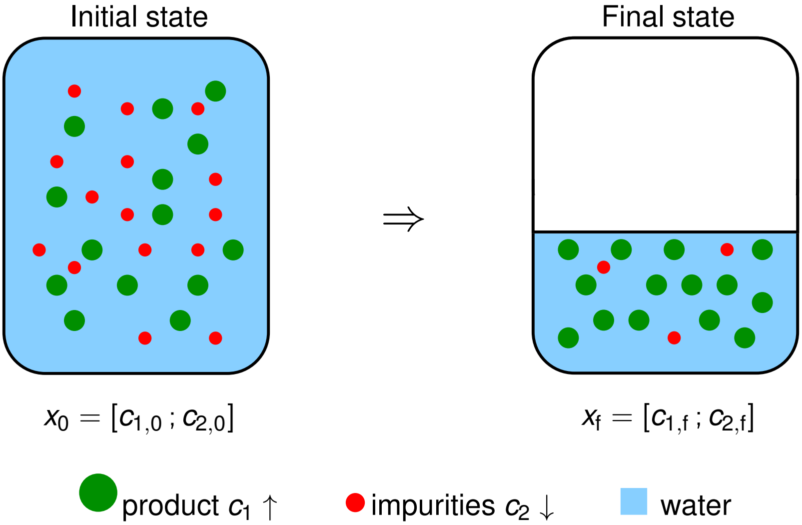
Profit €

- production in (bio)chemical industry → profit

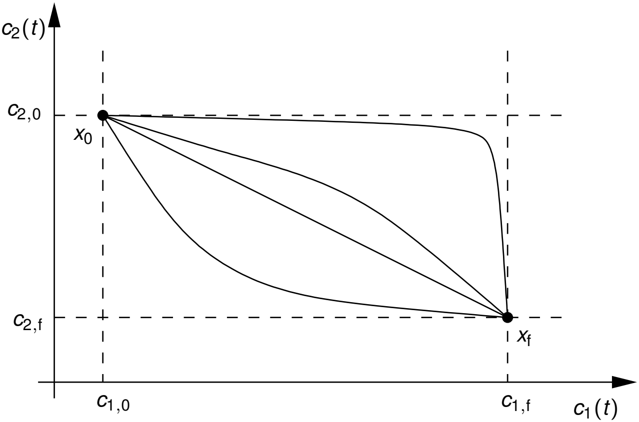


- control must - guarantee the product quality (purity)
  - optimize the profit (production cost)

BATCH PROCESS GOAL



Batch process goal



$$x_0 \to x_f \quad \Leftrightarrow \quad \begin{cases} \text{product } c_1 \uparrow \\ \text{impurities } c_2 \downarrow \end{cases}$$

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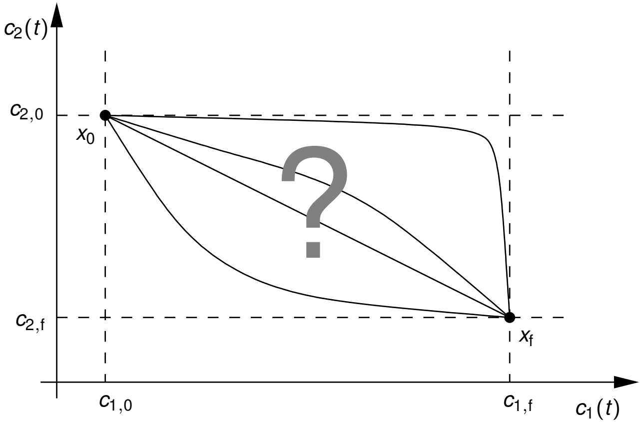

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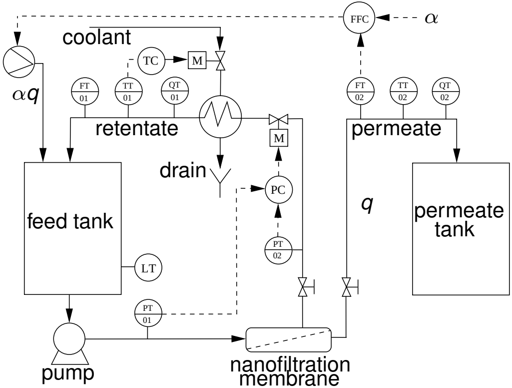
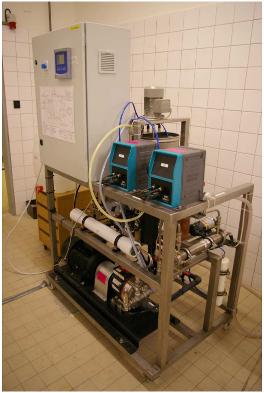
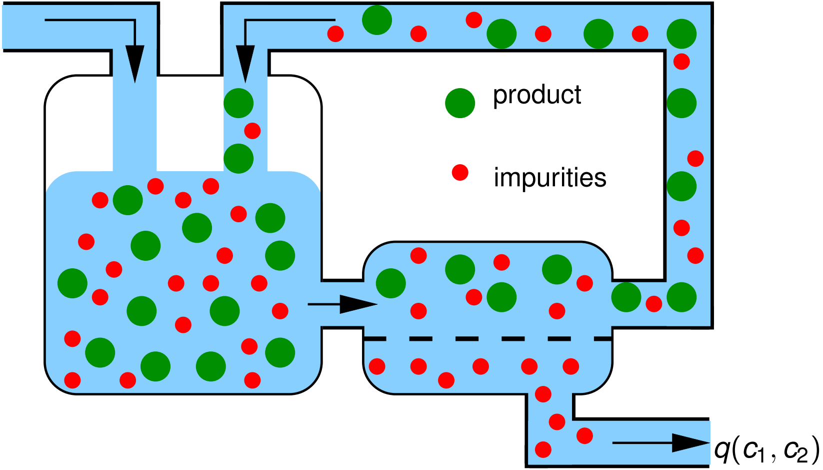
Process description





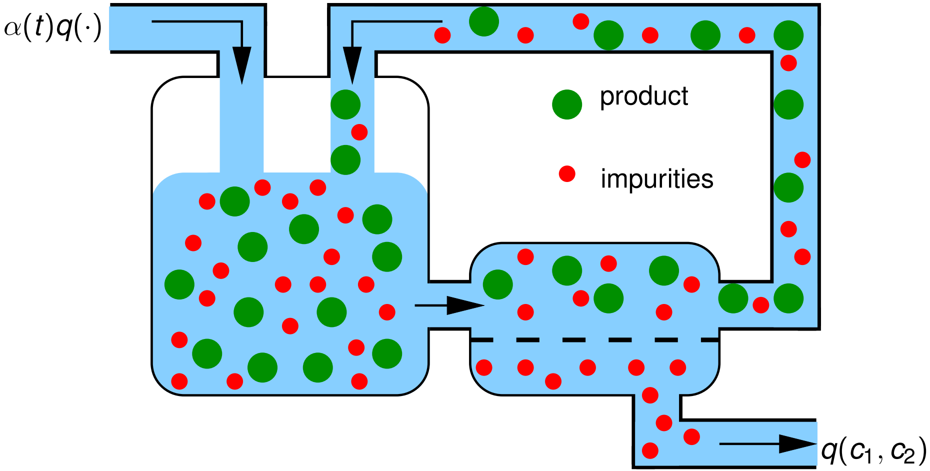
– transmembrane pressure: controlled at fixed value (wear-and-tear)

– temperature: controlled at fixed value (product degradation)



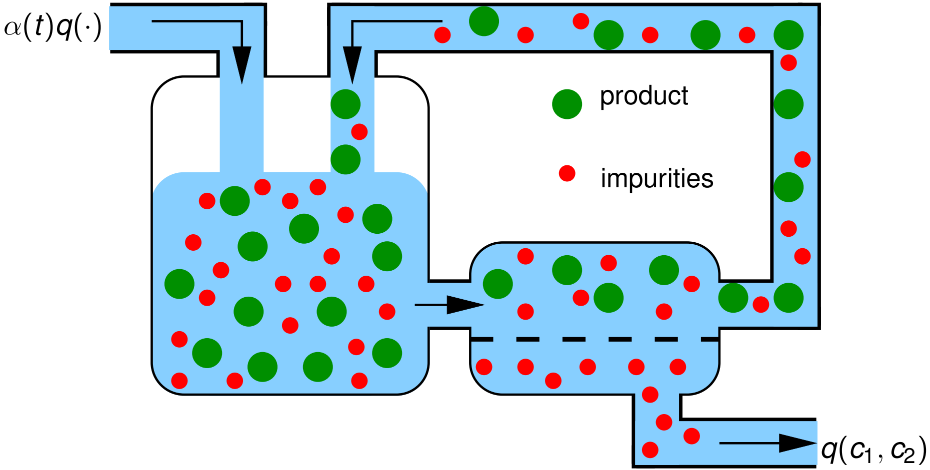
– membrane model: permeate flow $q(c_1, c_2)$

Process description

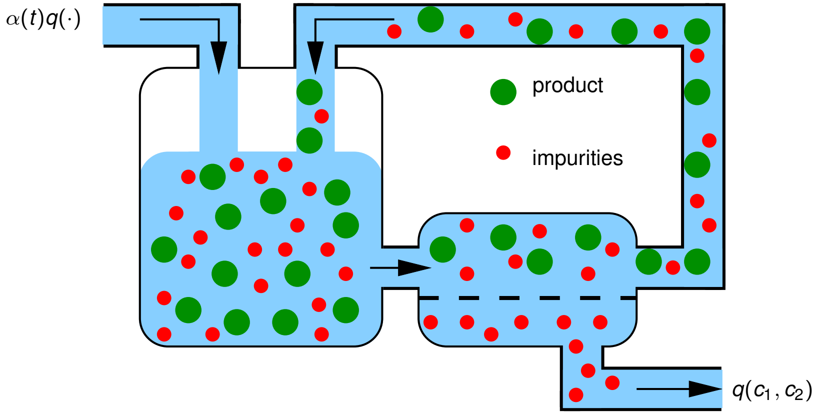


– concentrations dynamically adjusted by the water inflow $\alpha(t)q(\cdot)$

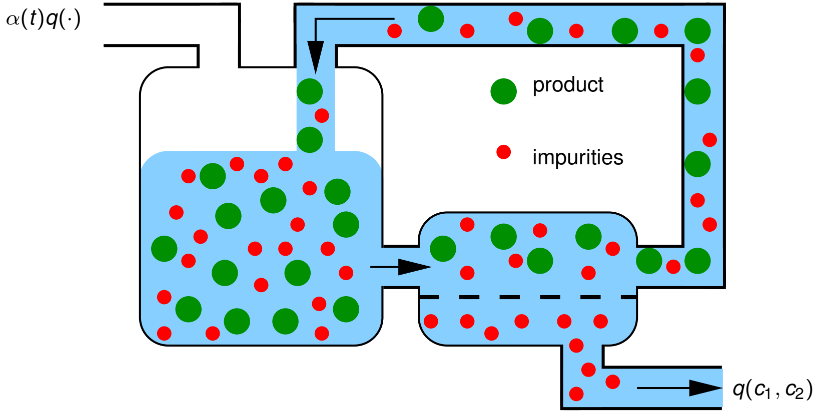
Optimization goal



– find $\alpha(t)$ to minimize final (batch) time

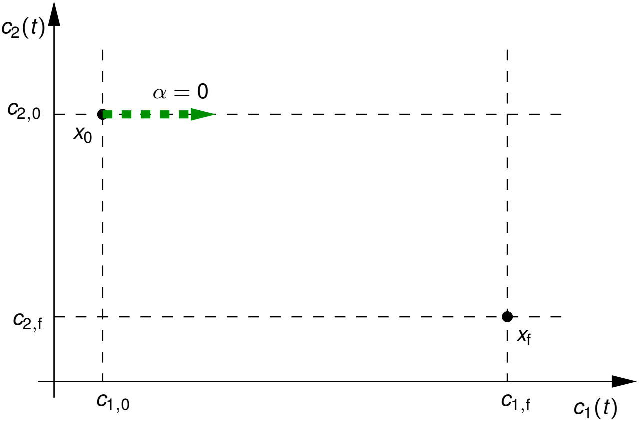


– manipulated variable: $\alpha(t) \in [0, \infty)$



– concentration mode: $\alpha(t) = 0$ $c_1 \uparrow$ $c_2 \approx$ const.

Operation modes



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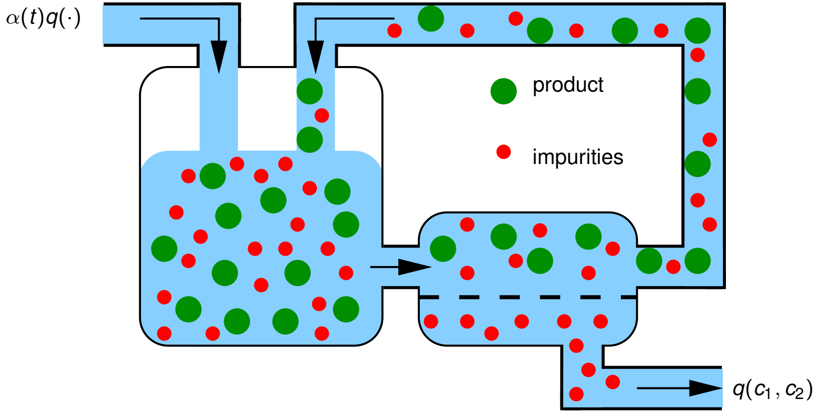
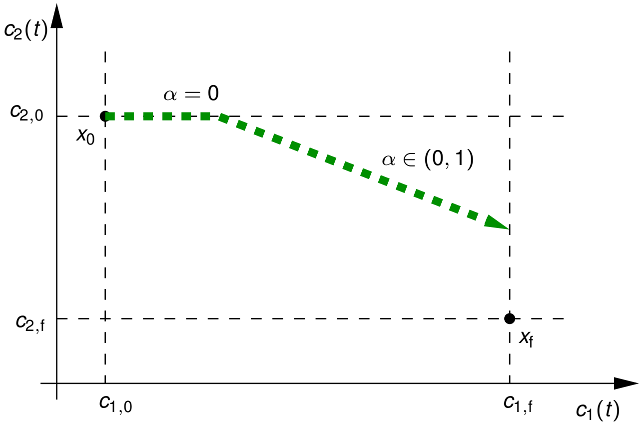


– variable volume diafiltration: $\alpha(t) \in (0, 1)$ $c_1 \uparrow$ $c_2 \downarrow$



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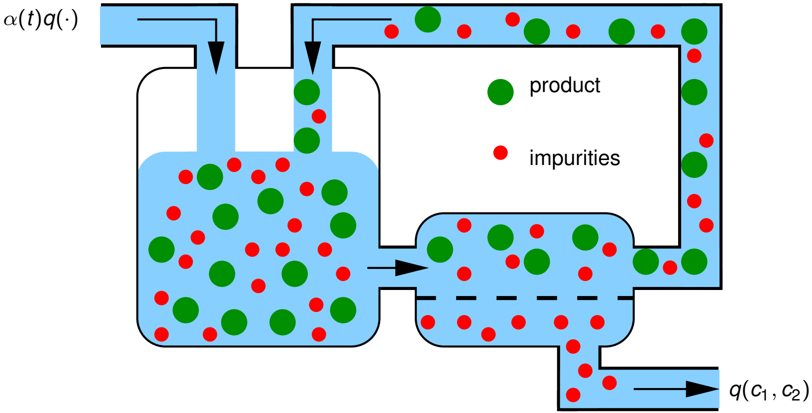
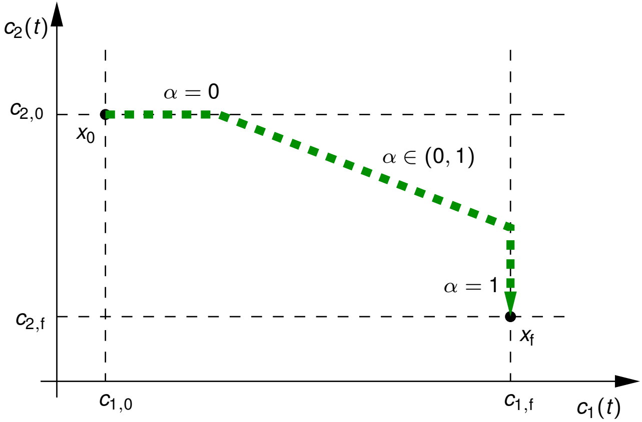


– constant volume diafiltration: $\alpha(t) = 1$ $c_1 \approx \text{const.}$ $c_2 \downarrow$

Operation mode



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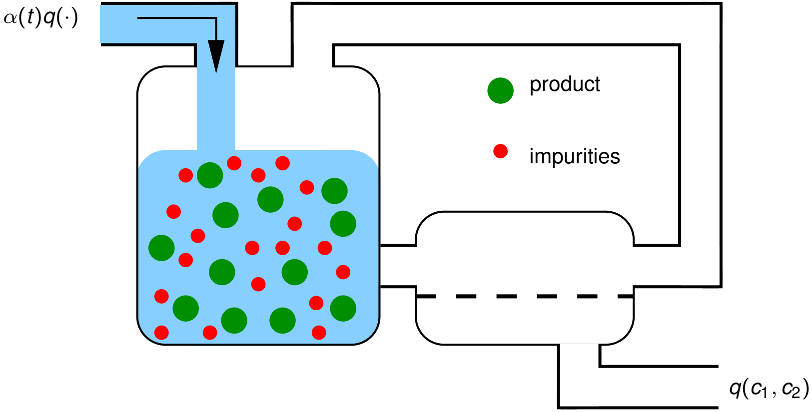
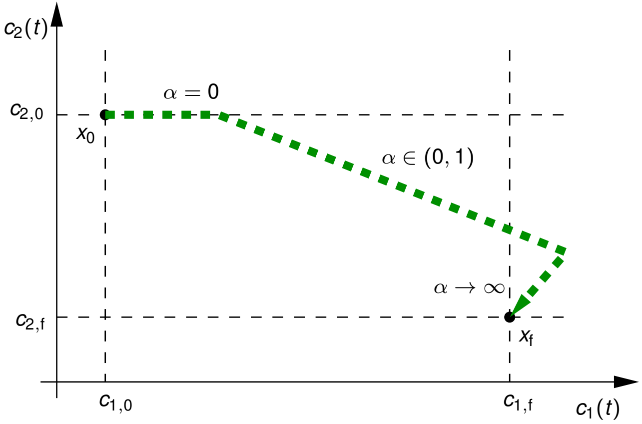


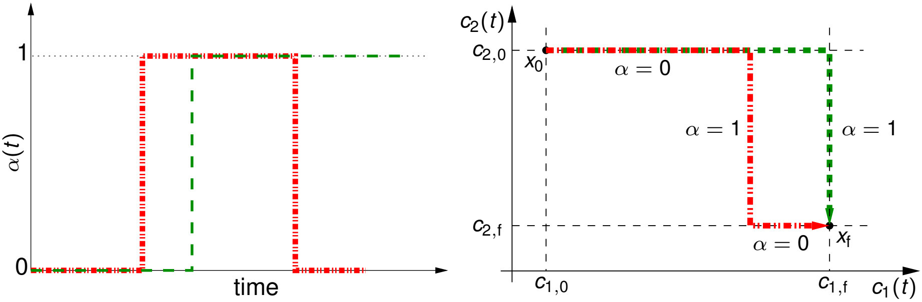
– dilution mode: $\alpha(t) \to \infty$ $\quad c_1 \downarrow \quad c_2 \downarrow \quad \frac{c_1(t)}{c_2(t)} = \text{const.}$

Operation modes

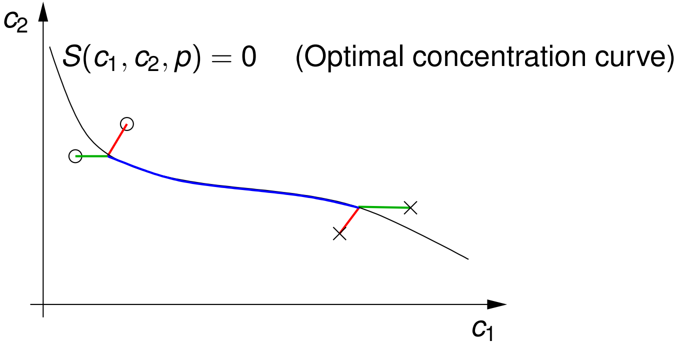


– dilution mode: $\alpha(t) \to \infty$ $\quad c_1 \downarrow \; c_2 \downarrow \; \frac{c_1(t)}{c_2(t)} = \text{const.}$

Traditional industrial diafiltration $\alpha(t) = \{0, 1\}$ or $\{0, 1, 0\}$



$$\alpha(t) = \begin{cases} 0 & (\text{if } S(c_{1,0}, c_{2,0}, p) < 0, S(c_{1,f}, c_{2,f}, p) > 0) \\ f(c_1, c_2, p) & \text{if } S(c_1, c_2, p) = 0 \\ \infty & (\text{if } S(c_{1,0}, c_{2,0}, p) > 0, S(c_{1,f}, c_{2,f}, p) < 0) \end{cases}$$



Paulen and Fikar, Optimal Operation of Batch Membrane Processes, *Springer*, 2016.

Two candidate models:

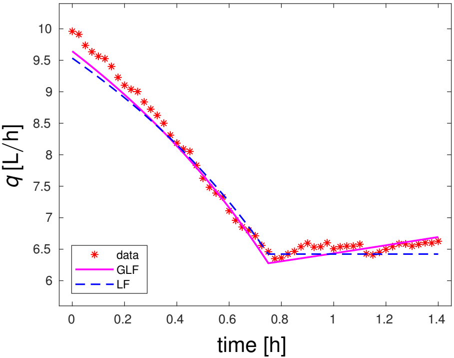
- Generalized limiting flux model (GLF)

$$q = p_1 \ln\left(\frac{p_2}{c_1\, c_2^{p_3}}\right)$$

- Limiting flux model (LF)

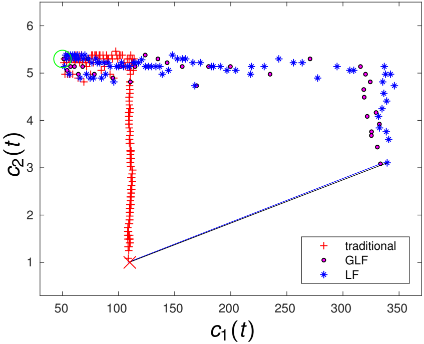
$$q = p_1 \ln\left(\frac{p_2}{c_1}\right)$$

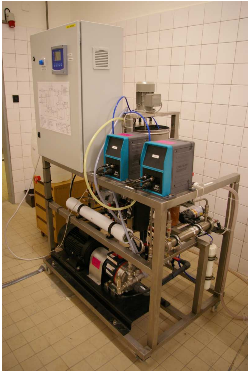
Data fit with operation $\alpha = \{0, 1\}$



Fitting of parameters to the experimental data done using least-squares estimation with dynamic data reconciliation.

- Traditional approach: $\alpha = \{0, 1\}$ t_f =4.28 h
- Time minimization (LF model): $\alpha = \{0, 1, \infty\}$ t_f =3.85 h
- Time minimization (GLF model): $\alpha = \{0, 0.91, \infty\}$ t_f =3.74 h





Conclusions

- Optimal operation of diafiltration using analytical approach
- Traditional approaches are mostly suboptimal
- Successfully validated in laboratory conditions
- Seamless realization of the optimal strategy at the existing hardware
- Extensions to explicit consideration of economic (multi-objective) operation
- Extensions to explicit consideration of membrane fouling
- Robust approaches currently studied