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# Minimizing specific energy consumption using digital twins

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**Abstract:** Buffer capacity in water treatment provides an opportunity to optimize production costs in response to time-of-use electricity charges. A pilot-scale physical twin employing closed-circuit reverse osmosis (CCRO) developed by the University of California-Irvine (UCI) and deployed at the Orange County Water District (OCWD) is used to generate rich experimental data for training a digital twin. This calibrated digital twin is then used to find time varying process setpoints that minimize the specific energy consumption (SEC) of the pilot over a two-day time window. The calibration/optimization is repeated at regular intervals to minimize SEC while adapting to changes in the physical pilot. Our results show that the optimization we propose can reduce the SEC from its worst-case value by 56.3%.

**Keywords**: digital twin; optimization; closed-circuit reverse osmosis; pilot; specific energy consumption

## 1. INTRODUCTION

Digital twins that can predict the transient behaviour of a water treatment plant combined with buffer capacity provide an opportunity to reduce the SEC in response to variations in time-of-use electricity costs. A digital twin's accuracy is dependent on the *richness* of the data used to train it. However, there is limited ability to experiment with changes to process setpoints in a production scale facility due to water quality compliance and output requirements. To bridge this gap, UCI developed a heavily instrumented CCRO physical twin of the OCWD plant. Experiments can be run on the physical twin over a large range of process parameters to develop the rich data set needed to accurately train the digital twin. Then the digital twin can be trained using the *sparse* data from the plant scale system to predict how changes to the process parameters affect the water quality, energy usage, membrane fouling, etc.

In our research, we develop a method to train the digital twin using a rich experimental data set collected from the physical twin. Then we use the digital twin to find a time series of process parameters that minimize the SEC over a two-day interval based on a time-of-use electricity cost schedule. To simplify the exposition in this work we do not consider water quality, membrane lifetime, brine disposal, and other operational factors in the optimization. In practice, these will be included in the optimization cost function and constraints. Finally, even in the absence of time-of-use electricity pricing, it is unclear what CCRO process parameters settings correspond to optimal operation. This work also solves that problem and is generally applicable to other treatment methods.

## 2. METHODS

To train the digital twin, first experiments are run on the pilot system that vary the feed flow, recovery ratio, and recirculation ratio over multiple combinations of values that produce a rich data set. The digital twin was developed in the commercial water treatment modelling software SUMO which is used to calculate the power consumption and permeate flow. The digital twin is calibrated using the experimental data from the physical twin by adjusting the pump efficiencies in the SUMO model to minimize the difference between the measured power and the predicted power in a least squares sense.

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To optimize the SEC, the digital twin is given a vector of decision variables, the feed flow rate $Q$, the permeate recirculation percent $B$, and recovery percentage $R$ in the advanced RO system. The optimization is over a set of $N$ intervals and the vector of decision variables is denoted by $x = \{Q, \mathrm{B}, \mathrm{R}\}$ where $Q \in \mathbb{R}^N, \mathrm{B} \in \mathbb{R}^N$ and $R \in \mathbb{R}^N$. Each interval spans a one hour period of operation to match the hourly change in the OCWD price signal denoted by $C \in \mathbb{R}^N$. For a specific $x$, the SUMO model calculates the power $P \in \mathbb{R}^M$ and recovery flow $Q^r \in \mathbb{R}^M$ at a chosen time interval $dt_s$. We require that $dt_s \leq dt_c$ guaranteeing that $M \geq N$. The power consumed over a specific interval $j$ is $P(jdt_s)$ which we shorten to $P_j$. The interval recovery volumes are denoted similarly. The interval energy consumption for each data interval is then calculated by $E_j = P_j dt_s$. Similarly, the recovery volume is given by $V_j = Q_j^r dt_s$. To calculate the data interval $SEC_j$, the cost $C_i$ is interpolated to the cost $C_j$ where $C_j = C_i$ when $idt_c \leq jdt_s < (i+1)dt_c$. The recovery volumes $V_j$ are obtained directly from the SUMO model. For each data interval the $SEC_j$ is calculated using

$$SEC_j = \frac{E_j C_j}{V_j}.$$

Now the optimization problem is expressed as

$$\min_{x \in \{Q,B,R\}} J = \frac{1}{M} \sum_{j=0}^{M-1} SEC_j + \kappa \left[ \sum_{i=0}^{N-2} \frac{(Q_{i+1} - Q_i)^2}{Q_{max}} + (\mathrm{B}_{i+1} - \mathrm{B}_i)^2 + (R_{i+1} - R_i)^2 \right]$$

subject to

$$Q_{min} \leq Q_i \leq Q_{max},$$
$$0 \leq B_i \leq 1,$$
$$0 \leq R_i \leq 1.$$

The first term is designed to minimize the average SEC over the optimization time interval. The second term is a regularization term that penalizes abrupt changes in the feed flow rate, recirculation percent, and recovery percent. Since $B_i \in [0,1]$ and $R_i \in [0,1]$, the feed flow rate is normalized with the maximum allowable flow rate $Q_{max}$ so that all parts of the regularization term are similar in amplitude. The regularization scaling term $\kappa \geq 0$ determines amount of smoothing. In addition to optimizing the SEC, another optimization was run to maximize the cost function $J$ with $\kappa = 0$. This is the worst-case scenario and allows a better assessment of the amount of SEC reduction that is achievable since the initial conditions are arbitrary. Table 2.1 show the results of the optimizations and Figure 2.1 shows the best and worst SEC.

**Table 2.1** The results from the three optimizations, maximum SEC without regularization, minimum SEC with $\kappa = 1$, and initial conditions.

| **Scenario** | **Total Energy [kWh]** | **Total Volume [$m^3$]** | **Total Cost [$]** | **SEC [$/$m^3$]** |
|---|---|---|---|---|
| Maximum | 111.0 | 25.2 | 14.91 | 67.33 |
| Minimum | 140.8 | 62.2 | 19.05 | 29.41 |
| Initial | 135.9 | 49.0 | 18.38 | 35.97 |

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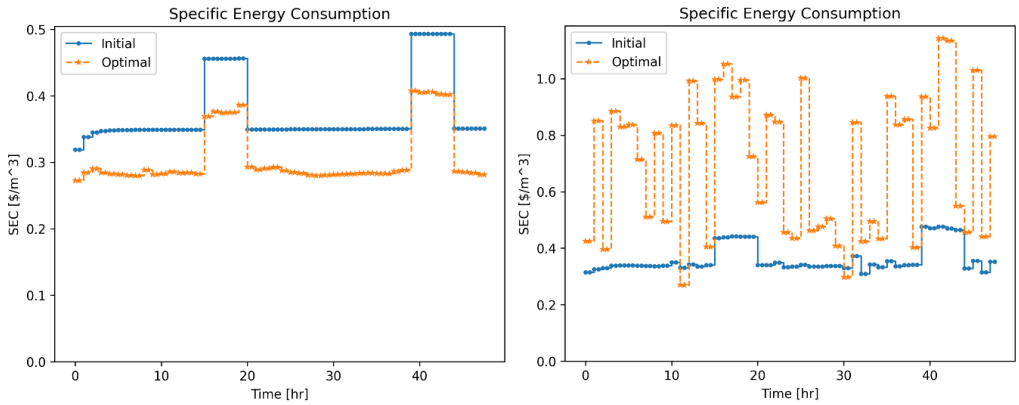


**Figure 2.1** (Left) Optimal SEC for the pilot-scale physical twin. (Right) Worst case SEC.

## 3. CONCLUSIONS

Comparing the worst-case operating setpoints to the optimal operating setpoints, a 56.3% reduction in the SEC is achievable. The initial conditions were based on operator experience. While the initial conditions proved to be close to the optimal setpoints, the reduction in SEC achieved was 18.2%.

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