Multi-objective optimization of a two-stage membrane process with metaheuristics

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The purpose of this paper is to present a study of optimizing a two-stage separation process. A similar process has been earlier studied for example, by Noronha from a single-objective point of view (Noronha, Mavrov & Chmiel 2002). We formulate the optimization as a genuine multi-objective problem and compare different solution alternatives from a practical engineering point-of-view.

The studied process flowsheet is depicted in Figure 1.

![Figure 1. Process flowsheet.](image)

In our study the optimization problem is multi-objective in nature, as the goals are to maximize the recovered permeate amount, to minimize permeate impurity content and to minimize pumping energy consumption simultaneously. Clearly the objectives are conflicting making the problem genuinely multi-objective. Mathematically the objectives can be stated as:

\[
\begin{align*}
    f_1 &= \max_0^T \rho(t)Q(t)dt \\
    f_2 &= \min_0^T c_{\text{perm}}(t)Q(t)dt \\
    f_3 &= \sum_{i}^T P_i(t)dt
\end{align*}
\]

where \( \rho \) is the permeate density (kg/m³), \( Q(t) \) is the flow rate of the permeate (m³/s), \( c_{\text{perm}}(t) \) is the impurity concentration of the permeate (mass fract.) and \( P_i(t) \) is the power consumption of pump \( i \) (kW).

We search for an optimal washing schedule for the two filters and optimal rotation speeds of the pumps over an eight hour time horizon, i.e. \( T = 480 \text{min} \). Thus, the optimization decides how many times and when each filter is washed as well as at what speed each of the four pumps is run. More formally, the decision variables are written as:
1. Rotation speeds of pump P1-P4 (constant over T): \( i \), with \( 0 \leq i \leq 100\% \), \( i = 1, \ldots, 4 \).

2. Time instants when filter \( j \) is washed, \( t_{j,k} \), with \( j = \{1, 2\} \) and \( 0 \leq t_{j,k} < T \).

The integer index \( k \) refers to the fact that a filter can be washed several times over the time horizon \([0, T]\). Since \( T = 480\text{min} \) and one wash cycle takes \( T_{\text{wash}} = 10\text{min} \) we have bounds on the length of the decision vector \( t_{j,k} \): \( 0 \leq k \leq 48 \), with \( k \) integer. In other words \( t_{j,k} \) is a vector of length \( k \). All the decision variables \( t_{j,k} \) are continuous. This results in a mixture of discrete and continuous decision variables. Finally, a constraint on the washings is set: when filter \( j \) is being washed, a new wash cannot be started on the same filter \( j \). Mathematically this translates to a constraint:

\[
t_{j,k+1} - t_{j,k} > T_{\text{wash}}, \forall j, k
\]

The process is modelled with generic process simulation software, Apros®, which utilizes dynamic conservation equations for mass, momentum and energy to model the process flow lines and the equipment. Fouling of the membrane units is modelled with simplistic pressure loss model. This pressure loss model is:

\[
\xi_{\text{feed}}(t) = a_i \int_0^t \xi_{\text{feed},i}(\tau) d\tau
\]

where \( a_i \) is a filter specific constant coefficient (\( i = 1, 2 \)), \( \xi_{\text{feed},i} \) is the pressure loss coefficient of filter \( i \)'s permeate flow line. In other words, the pressure loss increases as the cumulative amount of impurities imping on the membrane increases.

The process is first optimized using a conventional weighting coefficient method for the three objectives to produce a reference solution. Next, two advanced multi-objective solution methods, namely a Particle Swarm Optimization (PSO) and an Evolutionary Algorithms (EA) are utilized to compare with the reference solution. In this part we also experiment with different parameters for the algorithms to further evaluate their performance in the separation process optimization.

We reflect the different algorithms performances from a practical separation engineering point of view. The results obtained from PSO and EA are compared with the conventional weighting coefficient method to evaluate the usefulness of these methods. Secondly, the computational effort needed for the algorithms is reflected upon. Finally, we discuss the relative manual work load between modelling and optimization. Furthermore, we discuss how the results provide feedback for software development in the area of simulation-based optimization. This relates the presented work to a wider scope of integration of different simulators, optimization algorithms and other related tools to produce an integrated engineering platform.

References


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