Industrial Water Reuse Network Synthesis by Metaheuristic Approach

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This paper presents an optimization model for the synthesis of water networks. A superstructure presenting all the available candidates is proposed and the model is solved using Particle Swarm Optimization (PSO). The objective function aims the primary water consumption minimization. The concepts of Pinch Analysis were used as a initial point to limit the solution space. The optimal reuse network presents the minimum flowrates of the primary water, reuse, wastewater and the maximum concentration of the inlets and outputs of the system. The global PSO was codified in Maple 14® and a literature example was used to test the model applicability. Results were compared with the solutions obtained using GAMS, showing the flexibility and efficiency of the metaheuristic approach in solving water network reuse synthesis problems.

1. Introduction

In the last decades some methodologies for solving the process integration problem has been proposed, based on Pinch Analysis or Mathematical Programming or based on a combinations of both (Bagajewicz et al., 2000; El-Halwagi, et al., 2003; Tan et al., 2007; Liu et al., 2010, Iancu et al., 2010). Generally such formulations result in non-convex models, in the form of Non Linear Programming (NLP) problems. These models, frequently, when solved using Mathematical Programming, can be trapped in local minima. Meta-heuristic algorithms, like Genetic Algorithms, Tabu Search and PSO can solve this kind of problem. Although there are not definitive proves of convergence, these algorithms can achieve global optima, and can be considered global optimization methods. The great difficulties in using meta-heuristic methods are the high computational effort. Good initial estimative are fundamental for the solution of the problem in a shorter time. Because of the stochastic behavior PSO has been applied to search for the globally optimized variable values, which correspond to a set of non-linear models that represent the superstructure of reutilization network.
2. Problem definition and model formulation

The problem consists in designing a mass exchange network that minimizes the primary water demand in the industrial plant. The proposed superstructure has all the possible configurations of mass transfer between the streams of water and the process streams as well as all the possibilities of water reuse. It can be considered that each water stream with low concentration of pollutants transfer mass in countercurrent with the rich stream in pollutants and can be achieved in the supply \((N-1)\) unities of process. It is not allowed the direct reuse between the process unities. It means that the water stream leaving a process unity cannot supply it again. Splitting and mixing nodes are considered in the entrance and in the exit of each process unity, respectively, resulting in \(N(N-1)\) streams of water reuse candidates to the design of the network. In this way the inlet flowrate of the unity \(i\) \((f_{\text{in}}^i)\), corresponds to the flowrate of fresh water \((f_{\text{freshwater}}^i)\) combined with the possible reuse flowrates \((f_{\text{reuse}}^i)\) from the other \(k\) unities. The unity \(i\) outlet flowrate \((f_{\text{out}}^i)\) is split in effluent flowrate \((f_{\text{wastewater}}^i)\), and in the possible reuse flowrates \((f_{\text{reuse}}^i)\) that could supply the unities \(k\). For each process unity \(i\) it is considered the fixed pollutant mass transferred and the maximum concentrations of pollutants established in the entrance and in the exit, respectively. Known these parameters, it can be calculated, according to Equation (1), the maximum water flowrate \((f_{\text{max}}^i)\) without mass transfer violations in the process and the necessary water in each process unity \((C_j^m=0)\) corresponds to the supply minimum water profile.

\[
f_i = \frac{m_i}{(C_{\text{in}}^m - C_{\text{out}}^m)}
\]  

(1)

The water mass balance is given by Equation (2). Individual mass balances are defined for the process unities, according to Equations (3), (4) and (5). Pollutants mass balances are given by Equations (6) and (7).

\[
\sum_{j=1}^{N} f_{\text{freshwater}}^i + \sum_{j=1}^{N} \sum_{j=1}^{J} m_{i,j} - \sum_{j=1}^{N} f_{\text{wastewater}}^i = 0
\]  

(2)

\[
f_{\text{in}}^i - f_{\text{out}}^i - \sum_{j=1}^{J} m_{i,j} = 0 \quad \forall \, i \in N
\]  

(3)

\[
f_{\text{freshwater}}^i + \sum_{k=1}^{K} f_{\text{reuse}}^i - f_{\text{in}}^i = 0 \quad \forall \, i \in N
\]  

(4)

\[
f_{\text{wastewater}}^i + \sum_{k=1}^{K} f_{\text{reuse}}^i - f_{\text{out}}^i = 0 \quad \forall \, i \in N
\]  

(5)

\[
f_{\text{freshwater}}^j C_{\text{in}}^j + \sum_{k=1}^{K} f_{\text{reuse}}^j C_{\text{in}}^j - f_{\text{in}}^j C_{\text{in}}^j = 0 \quad \forall \, i \in N; \forall \, j \in J
\]  

(6)

\[
f_{\text{in}}^i C_{\text{in}}^i + m_{i,j} - f_{\text{out}}^i C_{\text{in}}^i = 0 \quad \forall \, i \in N; \forall \, j \in J
\]  

(7)

Process unities inlet and outlet concentrations must be given in function of the constraints of the maximum permissible inlet and outlet concentrations of pollutants, according to inequalities (8) and (9):
Equation (10) can be defined as the maximum allowable flowrate constraint:

\[ f_{i}^\text{in} - f_{i}^\text{out} \leq 0 \quad \forall i \in N \]  

Pinch Analysis can achieve the minimum water flowrate target. So, the constraint of freshwater flowrate must be satisfied according to Equation (11):

\[ \sum_{i=1}^{N} f_{i}^\text{freshwater} - f_{\text{Pinch}} \leq 0 \]  

The other constraints are:

\[ f_{i}^\text{freshwater}, f_{i}^\text{pasteurizer}, f_{i}^\text{inlet}, f_{i}^\text{outlet}, f_{i}^\text{inlet} \geq 0 \quad \forall i \in N \]  

Finely, the proposed optimization problem consists in the minimization of the objective function \( z \), subject to the constraints presented in Equations (2) to (17).

\[ \text{Min} \quad z = \sum_{i=1}^{N} f_{i}^\text{freshwater} \]  

This formulation resulted in a NLP problem, due to the bilinearities between flowrate and concentration, in the pollutants mass balance. Nonlinear models can be nonconvex and the solution can be trapped in local optima. In the case of linear models, the global optimum is always assured. To achieve the problem solution the search space for the variables water flowrate was reduced by applying Pinch Analysis. The inferior limit is fixed by the profile of minimum supply and the superior limit is established by the limit water profile. The variable minimum target of the freshwater flowrate in the industrial plant was also obtained by Pinch Analysis. Using the maximum outlet concentration the bilinearity was eliminated and the NLP models were transformed in LP models, considering a necessary optimality condition proposed by Savelski and Bagajewicz (2000). This condition says that the solution of a problem of water allocation is optimum if the outlet water stream in the process unities achieves its maximum allowable. This condition for the outlet concentrations was manipulated in the search space by fixing in the inferior and superior limits the correspondent maximum allowable values.

To avoid nonviable solutions due to the violation of the inequalities constraints the objective function was penalized by adding a criterion to be minimized referring to the violated constraints. If the constraints are violated the objective function is penalized by adding the correspondent residues to such violated constraints. So, the nonviable solutions obtained interactively were penalized according to Equations (19) to (21):

\[ z_p = z + \sum_{i=1}^{n} b_i G_i + \sum_{j=1}^{m} c_j H_j \]  

\[ G(x) = \begin{cases} g(x) & \text{se } g(x) > 0 \\ 0 & \text{se } g(x) \leq 0 \end{cases} \]  

\[ H(x) = \begin{cases} h(x) & \text{se } h(x) - \varepsilon > 0 \\ 0 & \text{se } h(x) - \varepsilon \leq 0 \end{cases} \]
3. Case Study

Table 1 presents the limit data for a mono-component system with 10 process that use water. The model formulation to this problem resulted in 83 equations (the constraints and the objective function) and 161 continuous variables to be determined. Using the strategies described the number of unknown variables is reduced from 161 to 120. The PSO algorithm was used to synthesize the network with the following parameters: \( \omega_{\text{init}} = 0.9 \), \( \omega_{\text{end}} = 0.4 \), \( c_1 = c_2 = 1.5 \). Preliminary tests showed also that a good convergence can be achieved when 300 particles and 25 iterations are used. Table 2 and Figure 2a present the results. This problem was also solved using GAMS (the solver used was CONOPT) and the results are presented in Table 3 and Figure 2b.

Table 1: Problem data - Bagajewicz and Savelski (2001)

<table>
<thead>
<tr>
<th>Process</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{i0} ) (ppm)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>50</td>
<td>50</td>
<td>400</td>
<td>400</td>
<td>0</td>
<td>50</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>( C_{i0}^{\text{out}} ) (ppm)</td>
<td>80</td>
<td>90</td>
<td>200</td>
<td>100</td>
<td>800</td>
<td>800</td>
<td>100</td>
<td>300</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( m_i ) (g/h)</td>
<td>2e3</td>
<td>2.8e3</td>
<td>4e3</td>
<td>3e3</td>
<td>3e4</td>
<td>5e3</td>
<td>2e3</td>
<td>1e3</td>
<td>2e4</td>
<td>6.5e3</td>
<td></td>
</tr>
<tr>
<td>( f_i^{\text{max}} ) (ton/h)</td>
<td>25.0</td>
<td>32.0</td>
<td>20.0</td>
<td>30.0</td>
<td>37.5</td>
<td>6.3</td>
<td>3.3</td>
<td>10.0</td>
<td>66.7</td>
<td>21.7</td>
<td>252.4</td>
</tr>
<tr>
<td>( f_i^{\text{min}} ) (ton/h)</td>
<td>36.3</td>
<td>44.3</td>
<td>22.9</td>
<td>60.0</td>
<td>40.0</td>
<td>12.5</td>
<td>10.0</td>
<td>10.0</td>
<td>80.0</td>
<td>43.3</td>
<td>359.3</td>
</tr>
</tbody>
</table>

Table 2: Results for the reuse water network synthesis with PSO

<table>
<thead>
<tr>
<th>Process</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_i^{\text{freshwater}} ) (t/h)</td>
<td>25.0</td>
<td>32.0</td>
<td>15.70</td>
<td>26.80</td>
<td>20.10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>36.70</td>
<td>0</td>
</tr>
<tr>
<td>( f_i ) (t/h)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>152.32</td>
<td></td>
</tr>
<tr>
<td>( f_i^{\text{wastewater}} ) (t/h)</td>
<td>25.0</td>
<td>32.0</td>
<td>44.54</td>
<td>40</td>
<td>10.55</td>
<td>10</td>
<td>10</td>
<td>80</td>
<td>43.34</td>
<td>318.28</td>
<td></td>
</tr>
<tr>
<td>( C_{i0} ) (ppm)</td>
<td>0</td>
<td>0</td>
<td>25.02</td>
<td>31.84</td>
<td>49.72</td>
<td>312.0</td>
<td>250.0</td>
<td>0</td>
<td>50.0</td>
<td>141.4</td>
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</tr>
<tr>
<td>( C_{i0}^{\text{out}} ) (ppm)</td>
<td>80</td>
<td>90</td>
<td>31.84</td>
<td>49.72</td>
<td>312.0</td>
<td>250.0</td>
<td>0</td>
<td>50.0</td>
<td>141.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Results for the reuse water network synthesis with GAMS

<table>
<thead>
<tr>
<th>Process</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_i^{\text{freshwater}} ) (t/h)</td>
<td>25.0</td>
<td>32.0</td>
<td>17.14</td>
<td>27.75</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>39</td>
<td>0</td>
</tr>
<tr>
<td>( f_i ) (t/h)</td>
<td>0</td>
<td>0</td>
<td>5.70</td>
<td>22.50</td>
<td>24.98</td>
<td>4.09</td>
<td>2</td>
<td>2</td>
<td>9.5</td>
<td>18.77</td>
<td>154.8</td>
</tr>
<tr>
<td>( f_i^{\text{wastewater}} ) (t/h)</td>
<td>25.0</td>
<td>32.0</td>
<td>50.25</td>
<td>40</td>
<td>8.80</td>
<td>10</td>
<td>10</td>
<td>79.95</td>
<td>41.89</td>
<td>320.7</td>
<td></td>
</tr>
<tr>
<td>( C_{i0} ) (ppm)</td>
<td>0</td>
<td>0</td>
<td>24.99</td>
<td>40.29</td>
<td>49.96</td>
<td>255.46</td>
<td>399.76</td>
<td>0</td>
<td>49.99</td>
<td>144.79</td>
<td></td>
</tr>
<tr>
<td>( C_{i0}^{\text{out}} ) (ppm)</td>
<td>80</td>
<td>90</td>
<td>40.29</td>
<td>49.96</td>
<td>255.46</td>
<td>399.76</td>
<td>599.64</td>
<td>100</td>
<td>299.91</td>
<td>299.91</td>
<td></td>
</tr>
</tbody>
</table>

Both networks can be considered optimal from the environmental point of view, considering that the minimum freshwater flowrate of 165.9 t/h is assured. The network
obtained with the PSO algorithm presented 11 reuse streams, 7 freshwater streams and 5 wastewater streams, totalizing 23 water streams. The network obtained with GAMS presented 12 reuse streams, 7 freshwater streams and 5 wastewater streams totalizing 24 water streams.

4. Conclusions
In this paper a metaheuristic (PSO algorithm) approach was studied in the problem of reuse water networks. The optimality conditions and concepts of process integration were applied in the procedure of models optimization. A superstructure containing all the possible reuse water configurations in the industrial plant was proposed. The nonconvex model was transformed in a convex model, assuring the global optimum. A criterion of penalization in the objective function was used to avoid nonviable solutions. An example from the literature was used to test the applicability of the developed model. The results were compared with the solution obtained with GAMS, and the metaheuristic approach shown flexibility and efficiency in solving reuse water networks synthesis problems. Adequate manipulation of the model constraints jointly with Pinch Analysis concepts can achieve good solutions for the problem.

Figure 2: Reuse network synthesis: (a) PSO; (b) GAMS.

References


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