OPTIMIZATION OF WATER CONSUMPTION IN PROCESS INDUSTRY

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Optimization of water consumption in the process industry represents one of the important research challenges for process engineers. The main goal is to reduce the freshwater consumption and to satisfy the strict environmental regulations on the industrial effluents. In this work we use the general superstructure and the global optimization model proposed recently by the authors for the design of integrated process water networks in order to solve water network problems of different types and complexity. The optimization model is formulated as a non-convex NLP and a MINLP problem, which are solved to global optimality.

Keywords: optimization, water network, NLP and MINLP model.

Introduction

Global freshwater consumption has quadrupled over the last 50 years\(^1\). By the year 2050, it is predicted that at least a quarter of the world’s population will be living with chronic or regular water shortages\(^2\). Increasing pollution of surface and ground water is intensifying the water crisis and will have negative consequences on the environment. Water has already become synonymous with the terms “liquid gold”, “the oil of the 21st Century” and “blue gold”\(^3\). These facts are key drivers for better water management and sustainability. In general, about 70 percent of global freshwater is used in agriculture, 20 percent in industry and 10 percent for domestic users. However, it depends of industrialization and urbanization and is different for developed and developing countries. In some countries such as Canada industrial freshwater use is 80 percent, domestic use 11 percent and agricultural use 9 percent\(^1\).

In the process industries freshwater is used for different purposes such as process water, water for cooling, power and steam generation, cleaning, washing, transporting a product etc. In these processes wastewater is generated and should be treated before discharge to the environment. Industrial users of freshwater are under increasing pressure to reduce freshwater consumption and wastewater generation, so in dustrial water management plays an important role in our future life and is one of the main research challenges for process engineers. To systematically address to this issue the water pinch technology\(^4\)-\(^16\) based on engineering heuristics, and mathematical programming\(^17\)-\(^32\) based on superstructure optimization are used.

In this paper we solve the water network problems of different types and complexity using the general superstructure and global optimization model proposed recently by authors\(^31\). In the first example both classes of water network problems (fixed and variable flowrates through water-using units) are solved to global optimality. In the second one the non-convex MINLP model taking into account the cost of piping as well as choice of different technologies for treatment units is solved to global optimality. The outline of the paper is as follows. First, we present the problem. Then the general superstructure and brief description of the mathematical model is given. We then discuss the solution of different examples. Finally, in the last section we present general conclusions.
Problem statement

Given is a set of freshwater sources with corresponding contaminant concentrations, a set of water-using units and wastewater treatment operations. The problem consists in obtaining a water network where a chosen objective function is globally optimized as well as the maximum contaminant concentrations in the discharge effluent to the environment is satisfied.

Superstructure

The superstructure of the integrated water network proposed by Ahmetović and Grossmann (2010) is given in Figure 1. It consists of one or multiple sources of water, water-using processes, and wastewater treatment operations. The unique feature is that all feasible connections are considered between them, including water re-use, water regeneration and reuse, water regeneration recycling, local recycling around process and treatment units and pretreatment of feed water streams. The superstructure can be used to represent separate subsystems as well as an integrated system. Furthermore, it enables modeling different types of water network optimization problems.

Figure 1. Generalized superstructure for the design of integrated process water networks.
Model

The model of integrated process water networks consists of mass balance equations for water and the contaminants for every unit in the network. The model is formulated as a non-convex nonlinear programming (NLP), and as a non-convex mixed-integer nonlinear programming (MINLP) [31]. The nonlinearities in the models appear in the mass balance equations in the form of bilinear terms (concentration times flowrate). In addition to this, nonlinearities appear in the objective function as concave terms of the cost functions for the water-treatment operations. Tight variable bounds as well as the cut by Karuppiah and Grossmann (2006) are added to tighten the lower bound of the global optimum.

We extended the non-convex NLP optimization model given by Ahmetović and Grossmann (2010) and formulate a non-convex MI NLP problem to allow choice of different technologies for each treatment unit. For example, if one treatment unit consists of two different technologies (TU_1 and TU_2) (see Figure 2) the objective function of the MINLP problem for integrated water network will be defined as follows:

$$
\min Z = H \cdot \sum_{s \in \text{SW}} FW_s \cdot CFW_s + AR \cdot \sum_{i \in \text{TU}_i} IC_i \cdot y_i \cdot (FTU_i)^2 + H \cdot \sum_{i \in \text{TU}_i} OC_i \cdot FTU_i
$$

(1)

Figure 2. Example of choice of two different technologies for one treatment unit.

where \(y_t\) is binary variable. Binary variable is equal to one if treatment technology \(t\) is chosen for treatment unit or zero if treatment technology \(t\) is not selected for treatment unit. As in Figure 2 we have two treatment technologies for one treatment unit, the maximum one treatment technology can be chosen for treatment unit (see constraint (2)). The upper bound constraint for the flowrate of wastewater in treatment technology \(t\) is given by equation (3).

$$
\sum_{i \in \text{TU}_i} y_t \leq 1
$$

(2)

$$
FTU_i \leq FTU_i^U \cdot y_t
$$

(3)

In the similar way, the non-convex MINLP model given by Ahmetović and Grossmann (2010) can be extended to allow choice of different technologies for each treatment unit. In this case, the MINLP model takes into account the cost of piping as well as choice of different technologies for treatment. We use the same solution method to solve the proposed models in this paper as given by Ahmetović and Grossmann (2010).

Examples

We use two examples to address to water network problems of different types and complexity. Both examples were implemented in GAMS33 and solved on a on a Toshiba Satellite Notebook with 4 GB RAM memory, and Intel Core Duo 2 processor. The general purpose global optimization solver BARON34 is used for solving the examples to global optimality. In all the cases the tolerance selected for optimization was 0.01.
Example 1

In this example, we consider a network with three process units (PU), three treatment units (TU) and two contaminants (A, B). Data for example are given in Tables 1 and 2, respectively and are taken from Karuppiah and Grossmann (2006). Treatment unit TU₂ can remove both contaminants and TU₁ and TU₃ only one (A or B). The environmental discharge limit for contaminant A and contaminant B is 10 ppm. The freshwater cost is assumed to be $1/ton, the annualized factor for investment is taken to be 0.1, and the total time for the network plant operation in a year is assumed to be 8000 h. Superstructure for this example is given in Figure 3.

Table 1. Data for process units with fixed water flowrates for Example 1.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Flowrate (t/h)</th>
<th>Discharge load (kg/h)</th>
<th>Maximum inlet concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>PU₁</td>
<td>40</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>PU₂</td>
<td>50</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PU₃</td>
<td>60</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2. Data for treatment units for Example 1.

<table>
<thead>
<tr>
<th>Unit</th>
<th>% removal of contaminant</th>
<th>IC (Investment cost coefficient)</th>
<th>OC (Operating cost coefficient)</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>16800</td>
<td>1</td>
</tr>
<tr>
<td>TU₁</td>
<td>95</td>
<td>0</td>
<td>24000</td>
<td>0.033</td>
</tr>
<tr>
<td>TU₂</td>
<td>80</td>
<td>90</td>
<td>12600</td>
<td>0.0067</td>
</tr>
</tbody>
</table>

Figure 3. Superstructure for Example 1.

The problem is first formulated as the non-convex NLP where the objective function is to minimize the total network cost consists of the freshwater cost and the costs of treatment units. In the first case we solve the problem when the flowrates through the process units are fixed. The NLP model consists of 92 continuous variables and 62 constraints. The global solution is obtained in 0.37 CPUs and is the same ($381751.35/year) as proposed by Karuppiah and Grossmann (2006).
We solve the same NLP problem for the case when flowrates through the process units are continuous variables to be determined by the optimization. Data for process units and limiting water flowrate are given in Table 3. Treatment unit data and the environmental discharge limit for contaminants are the same as given for the problem with the fixed flowrates. The NLP model consists of 95 continuous variables and 62 constraints. The global solution ($381751.35/year) is obtained in 0.57 CPUs and is the same as for the problem with fixed flowrates. In both cases only TU$_2$ is selected by the optimization.

Table 3. Data for process units with variable flowrates for Example 1.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Discharge load (kg/h)</th>
<th>Maximum inlet concentration (ppm)</th>
<th>Maximum outlet concentration (ppm)</th>
<th>Limiting water flowrate (t/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>PU$_1$</td>
<td>1</td>
<td>1.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PU$_2$</td>
<td>1</td>
<td>1</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>PU$_3$</td>
<td>1</td>
<td>1</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

In addition to this, we solved the same problem as the MINLP for the case when the investment cost for piping and the operating cost for pumping water are included in the objective function. The fixed cost pertaining to the pipes is assumed to be $6, the variable cost for each individual pipe $100, and operating cost coefficient for pumping water $0.006/ton$^{35}$. The model consists of 134 continuous variables, 42 discrete variables, and 147 constraints. The global optimum solution of water network given in Figure 4 is $394617.64/year.$

Figure 4. Optimal solution for water network with the fixed flowrates through the process units.

The MINLP model for variable flowrates through the process units consists of 137 continuous variables, 42 discrete variables, and 147 constraints. The obtained global solution for this case (Figure 5) is $391219.80/year. In both cases (fixed and variable flowrates) the global solution is obtained in less than 1.6 CPUs, the water network consists of 8 removable connections (connections which can be deleted from the superstructure) and the freshwater consumption was the same (40 t/h). However, the total network cost in the case of variable flowrates (Figure 5) was smaller than in the case of fixed flowrates due to smaller flowrates through the process units and smaller operating cost for pumping water.
Example 2

In this example we consider a network with four process units (PU), two treatment units (TU) and two contaminants (A, B). Each treatment unit consist of two different treatment technologies differ in their investment and operating cost as well as the percent removal of each contaminant. Data for example are given in Tables 4 and 5, respectively and are taken from Karuppiah and Grossmann (2006). The environmental discharge limit for contaminants, the freshwater cost, the annualized factor for investment, the total time for the network plant operation, the fixed cost pertaining to the pipes, the variable cost for each individual pipe, and operating cost coefficient for pumping water is the same as in Example 1. Superstructure allowing selection of technologies for treatment units is given in Figure 6.
Table 4. Data for process units with fixed water flowrates for Example 2.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Flowrate (t/h)</th>
<th>Discharge load (kg/h)</th>
<th>Maximum inlet concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>PU₁</td>
<td>40</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>PU₂</td>
<td>50</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PU₃</td>
<td>60</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PU₄</td>
<td>70</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5. Data for treatment units for Example 2.

<table>
<thead>
<tr>
<th>Treatment unit</th>
<th>Treatment technology</th>
<th>% removal of contaminant</th>
<th>IC (Investment cost coefficient)</th>
<th>OC (Operating cost coefficient)</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>TU₁</td>
<td>TU₁₁</td>
<td>95</td>
<td>0</td>
<td>16800</td>
<td>1</td>
</tr>
<tr>
<td>TU₁</td>
<td>TU₁₂</td>
<td>90</td>
<td>0</td>
<td>4800</td>
<td>0.5</td>
</tr>
<tr>
<td>TU₂</td>
<td>TU₂₁</td>
<td>0</td>
<td>90</td>
<td>12600</td>
<td>0.0067</td>
</tr>
<tr>
<td>TU₂</td>
<td>TU₂₂</td>
<td>0</td>
<td>95</td>
<td>36000</td>
<td>0.067</td>
</tr>
</tbody>
</table>

Karuppian and Grossmann (2006) modeled the network problem for this example as a GDP (General Disjunctive Programming) problem by allowing a choice of different treatment technologies for each treatment unit. They reformulated this GDP as a non-convex MINLP using the convex hull representation method. Using their proposed algorithm the global solution ($619205.4/year) is found by DICOPT in 1.44 CPUs. In addition, they reported the same global solution ($619205.4/year) obtained by BARON in much longer time (17541 CPUs).

We solved the same network problem using the MINLP model as given in the previous section of this paper. The MINLP model consists of 141 continuous variables, 4 discrete variables and 86 constraints. The global solution $619205.4/year is obtained by BARON in 1.25 CPUs and is the same as the solution proposed by Karupppian and Grossmann (2006). However, it is worth pointing out that using our proposed method takes much less time (1.25 CPUs) to solve the same network problem by BARON compared to the time reported by the authors (17541 CPUs). This is due to the tighter variable bounds and the special cut.

The non-convex MINLP model of water network problem which take into account the cost of piping as well as choice of different technologies for treatment consist of 213 continuous variables, 76 discrete variables and 231 constraints. The global optimum solution $639244.45/year is obtained in 155 CPUs and the optimal network design with 14 removable connections is given in Figure 7.
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Figure 7. Optimal solution of water network problem taking into account the cost of piping as well as choice of different technologies for treatment units.

Conclusion

In this paper, we have presented that the proposed NLP and MINLP models can be used to address to both classes of water network problems (fixed and variable flowrates through water-using units). The non-convex NLP optimization model is extended and formulated as a non-convex MINLP problem to allow choice of different technologies for treatment units. The non-convex MINLP model given by Ahmetović and Grossmann (2010) is extended and takes into account the cost of piping as well as choice of different technologies for treatment units. The examples in the paper are solved to global optimality.

References


