Minimizing Water and Energy Consumptions in Industrial Water Networks

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This study gives a MILP framework for solving a heat and water allocation problem. Both energy and water consumptions are taken into account for proposing numerous optimal solutions for a fixed number of connections between processes in the network. Results are represented on Pareto fronts for each number of connections. Networks proposed are optimal in terms of energy and water consumptions and can easily be applied at industrial scale because they involve low flow rates and their complexity is also topologically limited. In previous studies, the optimal network reaches the fresh water target but it is not always an optimal choice, as shows the economical study carried out here. A low increase in fresh water consumption leading to a significant decrease in energy consumption allows designing a cheaper network.

1. Introduction

Based on recent International Agencies reports, freshwater and world energy demands will considerably increase during the 21st century, mainly because of an unceasing industrial growth. However, water and energy are central elements in process industry; consequently, all efforts made to reduce them contribute to environmental advances. During the last decade, a lot of attention has been paid to the development of new techniques allowing the minimization of both water and energy consumption. These researches were conducted by means of two main strategies, either graphical techniques associated to the concept of water pinch or mathematical methods lying on mathematical programming approaches. The environmental impact induced by the process industry is linked both to the high volumes involved and to the diversity of toxic products generated along the process chain. So, a real need to define optimized water networks thus reducing the impact of contaminants on the environment, has recently emerged. This study aims at defining a general methodology for taking into account the single contaminant case.

Since the 1980's, numerous methods have been applied to design water allocation-heat exchange networks for industrial purposes. In a lot of studies, the water allocation problem and the heat exchanger network design are sequentially considered (Bagajewicz et al., 2002; Kim et al., 2009). The same techniques as those used for the design of water allocation problem, when heat exchangers are integrated into the network, can be applied. Insight-based pinch strategies are the most commonly used;

they first consist in targeting freshwater and then, in designing the energy network (Foo, 2009). In order to handle more complex problems, mathematical programming approaches have been developed (Feng et al., 2009; Chen et al., 2010), based on a non linear formulation since they involve bilinearities due to products between concentrations and flow rates.

For the design of water allocation networks, optimization problems can be solved either linearly (MILP) or nonlinearly (MINLP). The linear case is generally restricted to simple water networks involving only one contaminant, while the nonlinear one can theoretically be applied to more complex networks.

As it was already shown in Boix et al. (2010), a water allocation problem can be solved with a linear programming procedure (MILP) as it satisfies the conditions of optimality demonstrated by Savelski and Bagajewicz (2000) when fresh water flow rate is minimized. In this study, the same approach as for the water allocation problem is used: a linear formulation coupled with an epsilon-constraint-based optimization strategy is implemented to propose a lot of theoretical solutions to a case study. Consequently, with this method, energy, water and the number of connections are taken into account simultaneously. Finally, an engineering and economical analysis allows extracting the best industrial solution from the set of theoretical ones.

2. Mathematical Formulation

2.1 Problem statement

A set of processes, each requiring a specific water composition at a fixed temperature, is involved in a single-contaminant network. Heat exchangers can be placed, if necessary, both at the inlet and discharge of each process because of environmental restrictions on discharge temperature. The heat exchanger allocation in the network will be carried out during the optimization phase. All possible connections between units can exist and the problem can be formulated as follows: how can we link all units while respecting their input requests (on concentrations and temperatures) so as to minimize several objectives? The aim is to find a network with a minimum number of connections between processes and a minimum fresh water and energy consumptions.

2.2 Modeling equations

In most of previous works, the heat and water allocation problem is generally solved either with sequential pinch techniques or with MINLP optimization. Indeed, the model contains bilinear terms due to products in mass balances for contaminants. These bilinearities are caused by multiplying concentrations and flow rates. However, as it was already shown by Boix et al. (2010), the problem can become linear by using partial flow rates instead of total flow rates while achieving the necessary conditions of optimality enounced by Savelski and Bagajewicz (2000).The following nomenclature is used in the balance equations:

w_1^j fresh water flow rate going to the process j (T/h)

$wp_i^{j \rightarrow k}$ partial flow rate of the component i between two processes j and k (T/h)

wd_i^j discharged partial mass flow of the component i from the process j (T/h)

M_i^j amount of contaminant i generated by the process j (g/l)

$C\max_j^{in}$ maximal concentration at the input of the process j (g/h)

$C\max_j^{out}$ maximal concentration at the output of the process j (g/h)

T_w, Tp_j and Td respective temperatures of fresh water, process j and discharge (°C)

M_i^j amount of contaminant i generated by the process j (g/s)

Qp_j, Qn_j energy necessary for respectively heating or cooling the process j (kW)

$$\sum_k wp_1^{k \to j} + w_1^j = wd_1^j + \sum_k wp_1^{j \to k} \tag{1}$$

$$\sum_k wp_{i>1}^{k \to j} + M_{i>1}^j = wd_{i>1}^j + \sum_k wp_{i>1}^{j \to k} \tag{2}$$

$$\sum_j wd_1^j = \sum_j w_1^j \tag{3}$$

$$\sum_j wd_{i>1}^j = \sum_j M_{i>1}^j \tag{4}$$

$$w_1^j \times T_w + \sum_i wp_1^{i \to j} \times TP_i + Qp_j - Qn_j = Tp_j \times \left(\sum_i wp_1^{j \to i} + wd_1^j \right) \tag{5}$$

$$\sum_j wd_1^j \times TP_j + Qpd - Qnd = Td \times \sum_j w_1^j \tag{6}$$

With equations (5) and (6), the energy necessary to heat is counted as positive and negative for cooling. The final energy consumption is the sum of absolute values of energies (at processes and discharge), expressed in kW.

Constraints on concentrations are represented by inequalities (7) and (8). Using the condition of optimality proved by Savelski and Bagajewicz (2000), the outlet concentrations can be fixed at their maximum value:

$$wp_{in,i>1}^j \leq C\max_j^{in} \times wp_{in,1}^j \tag{7}$$

$$wp_{out,i>1}^j \leq C\max_j^{out} \times wp_{out,1}^j \tag{8}$$

$$wp_{i>1}^{j \to i} = C\max_j^{out} \times wp_1^{j \to i} \tag{9}$$

2.3 Optimization procedure

In a first step, mono-objective optimizations are carried out to identify the different targets for each objective. For the example presented below, the number of interconnections in the network is defined in the reduced integer range [8-64], which corresponds respectively to the minimum and maximum number of connections allowable in the network; the methodology consists in solving the biobjective problem (fresh water consumption versus energy consumption) parameterized by the number of interconnections. A lexicographic optimization based on the epsilon-constraint strategy

is implemented (Mavrotas, 2009). For a fixed interconnection number, and for given ranges of energy, fresh water is minimized. So, for each particular value of the number of interconnections, a Pareto front can be generated.

3. A Case Study

3.1 Problem data
The didactic case taken from Bagajewicz et al. (2002) has been recently revisited by Feng et al. (2009). It involves 8 process units with a fresh water source at 20°C. Furthermore, wastewater must be discharged at 30°C. The bounds on data are displayed in Table 1. This optimization problem is solved within GAMS environment (General Algebraic Modelling Systems) with CPLEX solver.

Table 1: Data range values for the case study (from Feng et al., 2009).

Processes	$C_{\max j}^{in}$	$C_{\max j}^{out}$	M_j	T_j
1	25	80	2000	40
2	25	90	2880	100
3	25	200	4000	80
4	50	100	3000	60
5	50	800	30000	50
6	400	800	5000	90
7	400	600	2000	70
8	0	100	1000	50

3.2 Results
Results for mono-objective optimization are given in Table 2. The method is validated as the same fresh water target 125.94 T/h than Bagajewicz et al. (2002) and Feng et al. (2009), is obtained. The energy consumption target is 31943 kW and the minimum number of interconnections for the network considered is 8. Let us recall that energy consumption includes energy for heating and for cooling.

Table 2: Mono-objective results for the case study. Numbers in bold are results for the minimized criterion whereas the two others are kept free.

	Fresh water (T/h)	Connections number	Energy (kW)
Fresh water (T/h)	*125,94*	64	40638
Connections number	160,75	*8*	43639
Energy (kW)	134,02	64	*31943*

After this preliminary step, biobjective optimizations are carried out in order to estimate the interconnection number. Hence, the minimum values for fresh water flow rate and energy consumption are displayed in figure 1 for a fixed number of connections. It is worth noting that the fresh water target (125.94 T/h) is obtained when the network contains 11 connections, whereas the energy target (31943 kW) is available for 12.
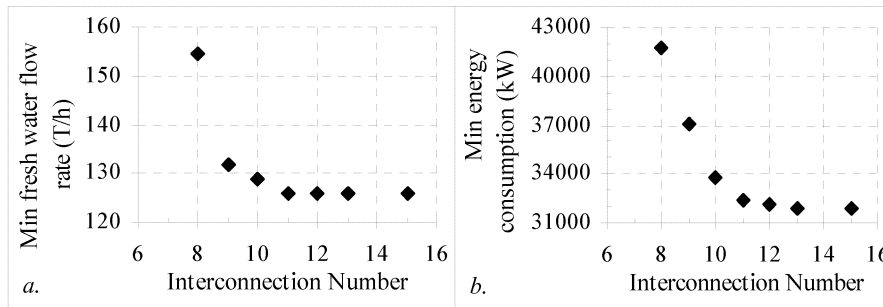
Figure 1: Results for biobjective optimizations. Figure 1a: Minimum fresh water flow rate (T/h). Figure 1.b: Minimum of energy consumption (kW) vs. interconnection number.

For giving a complete overview of available solutions, figure 2 shows all the possible solutions found from 8 to 12 connections. It must be highlighted that minimizing energy consumption can be effective but to the detriment of fresh water consumption and of the number of connections.
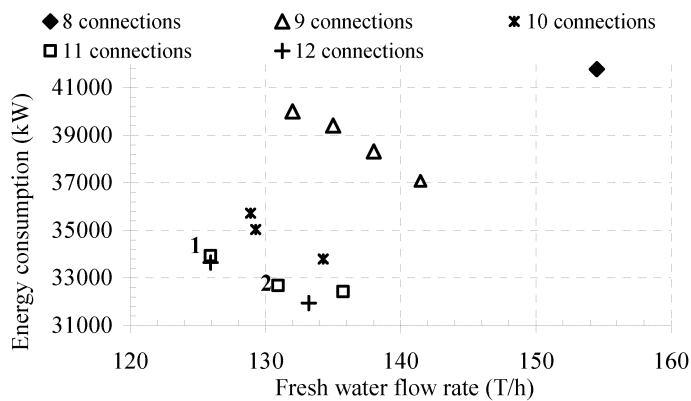

Figure 2: Numerical results for the case study.

4. Discussion and Conclusion

In previous studies (Feng et al., 2009), energy consumption is always minimized when the fresh water target is reached. However, when taking into account some costs given in literature, it is worth pointing out this network (noted 2 in Figure 2) is not optimal in terms of cost. The network noted 1 in Figure 2 might be a better choice for a practitioner. For instance, assuming that orders of magnitude for fresh water and energy are respectively about 0.45€/ton (Kim et al., 2009) and 0.095€/kWh (http://www.energy.eu/#Industrial). If the network 1 is chosen instead of the network 2, a loss of 5 T/h of fresh water against a gain of 1000kW (an hour) allows the industry to

make an hourly benefit of about 7%. Figure 3 shows the flow sheet for the considered network considered.
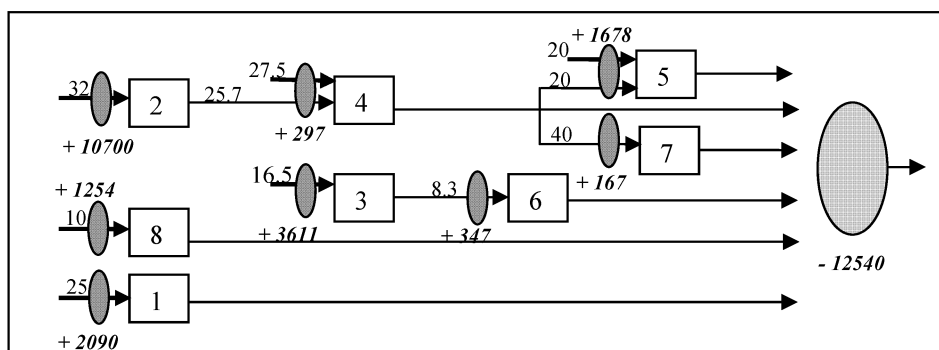

Figure 3: Flow sheet for the network chosen. Broad arrows are fresh water entrances, numbers in italic are flow rates (T/h) and numbers in bold represent utility duty (kW).

To conclude, this study leads to optimize a water and heat allocation network by the use of a MILP program. This allows dealing with more complex problems (with regeneration step for instance) and designing simple networks minimizing simultaneously water and heat consumptions.

References

Bagajewicz M., Rodera H., Savelski M., 2002, Energy efficient water utilization systems in process plants, Computers and Chemical Engineering, 26, 59-79.

Boix M., Montastruc L., Pibouleau L., Azzaro C., Domenech S., 2010, Multiobjective optimisation of water networks with contaminant, Computer Aided Chemical Engineering, 28, 859-864.

Chen C., Liao H., Jia, X., Ciou Y., Lee J., 2010, Synthesis of heat-integrated water-using networks in process plants, Journal of the Taiwan Institute of Chemical Engineers, 41, 512-521.

Feng X., Li Y., Shen R., 2009, A new approach to design energy efficient water allocation networks, Applied Thermal Engineering, 29, 2302-2307.

Foo D. C. Y., 2009, A state-of-the-art review of pinch analysis techniques for water network synthesis, Industrial and Engineering Chemistry Research, 48, 5125-5159.

Kim J., Kim J., Kim J., Yoo C., Moon I., 2009, A simultaneous optimization approach for the design of wastewater and heat exchange networks based on cost estimation, Journal of Cleaner Production, 17, 162-171.

Mavrotas, G., 2009. Effective implementation of the ε-constraint method in multi-objective mathematical programming problems. Ap. Math. Comp. 213, 455-465.

Savelski M. and Bagajewicz M., 2000. On the optimality conditions of water utilization systems in process plants with single contaminant, Chemical Engineering Science, 55, 5035-5048.