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Minimizing water and energy consumptions in water and heat exchange networks

Marianne Boix, Luc Pibouleau*, Ludovic Montastruc, Catherine Azzaro-Pantel, Serge Domenech

Laboratoire de Génie Chimique, U.M.R. 5503 CNRS/INP/UPS, Université de Toulouse, 4, Allée Emile Monso, 31432 Toulouse Cedex 4, France

This study presents a mathematical programming formulation for the design of water and heat exchangers networks based on a two-step methodology. First, an MILP (mixed integer linear programming) procedure is used to solve the water and energy allocation problem regarding several objectives. The first step of the design method involves four criteria to be taken into account., ie, fresh water consumption (F_1), energy consumption (F_2), interconnection number (F_3) and number of heat exchangers (F_4). The multiobjective optimization Min [F_1, F_2] is solved by the so-called ε-constraint method and leads to several Pareto fronts for fixed numbers of connections and heat exchangers. The second step consists in improving the best results of the first phase with energy integration into the water network. This stage is solved by an MINLP procedure in order to minimize an objective cost function. Two examples reported in the dedicated literature serve as test bench cases to apply the proposed two-step approach. The results show that the simultaneous consideration of the abovementioned objectives is more realistic than the only minimization of fresh water consumption. Indeed, the optimal network does not necessarily correspond to the structure that reaches the fresh water target. For a real paper mill plant, energy consumption decreases of almost 20% as compared with previous studies.

Keywords:
Water networks
Energy integration
Multiobjective optimization
MILP
MINLP

1. Introduction

Current anthropogenic activities are of great concern due to their strong impact on environment. During the last thirty years, industrial activities have increased by 30%, leading to an alarming depletion of natural resources [1]. Process industries are among the most important consumers of water in various fields such as petrochemical plants and refineries, steel industries or food processing. In addition, the great majority of involved processes need water with a given quality at a fixed temperature. Hence, huge amounts of energy are also used in order to cool and/or heat water to reach operating temperatures by means of cold and heat utilities. There is thus a critical need in reducing both rejects of contaminants and the consumption of primary resources such as water and energy. Moreover, the respect of environmental guidelines is closely associated with a decrease in industry profitability. This paradoxical situation can typically be tackled by means of multiobjective optimization where a good solution has to be defined under a set of constraints. This solution can be approached by an ecological industrial network, that must be economically viable and topologically simple as possible with reduced water and energy consumption. Despite this situation, it must be emphasized that Water Allocation Networks (WAN) design and Heat Exchanger Networks (HEN) optimization have been tackled separately for a long time.

One of the first study of WAN is the innovative work of Takama et al. [2] introducing the concept of superstructure to solve a problem applied to a petroleum refinery by means of mathematical programming. Numerous mathematical models have been developed following their ideas in order to minimize water consumption in industrial networks [3–10]. This issue has also been studied with more conceptual design techniques including “water pinch technology” [11–16] since the application of this concept by Wang and Smith [17] to the specific problem of water allocation. Several other techniques such as stochastic methods or genetic algorithms have also been used recently [18,19].

Generally, the design of HEN is tackled similarly to WAN with mathematical programming [20–24] and insight-based approaches [25–28]. Energy consumption or annualized costs are the two main objective functions to minimize in this kind of problem. Recently, evolutionary procedures such as genetic algorithms [29–31] or simulating annealing [32] have also been implemented.

Nomenclature

$\mathrm{Cmax}_j^{\mathrm{in}}$	Maximal concentration of contaminant at the input of the process j (ppm)
$\mathrm{Cmax}_j^{\mathrm{out}}$	Maximal concentration of contaminant at the output of the process j (ppm)
Cr_m^{out}	User-fixed outlet concentration of contaminant for regeneration unit m (ppm)
DAF	Dissolved Air Flotation
HEN	Heat Exchangers Network
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer NonLinear Programming
M_i^j	Mass load of contaminant i generated by process j ($\mathrm{g\ h^{-1}}$)
NLP	NonLinear Programming
Qpd, Qnd	Energy required for heating (respectively cooling) before the discharge (kW)
Qp_j, Qn_j	Energy required for heating (respectively cooling) the process j (kW)
Qrp_m, Qrn_m	Energy required for heating (respectively cooling) the regeneration m (kW)
zuc(i), zuh(j)	Binary variables for the existence of a heat exchanger between hot stream i and a cold utility and between cold stream j and a hot utility
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
T_w	Temperature of fresh water(°C)
Tp_j	Temperature of process j (°C)
Td	Discharge temperature (°C)
WAHEN	Water Allocation and Heat Exchange Networks
wd_i^j	Discharged flow rate from process j ($\mathrm{T\ h^{-1}}$)
wmax_j	Maximal water flow rate at the inlet of the process j ($\mathrm{T\ h^{-1}}$)
$\mathrm{wp}_i^{j\rightarrow k}$	Flow rate between two processes j and k ($\mathrm{T\ h^{-1}}$)
$\mathrm{wp}_{\mathrm{in},i}^j$	Total flow rate at the inlet of the process j ($\mathrm{T\ h^{-1}}$)
$\mathrm{wp}_{\mathrm{out},i}^j$	Total flow rate at the outlet of the process j ($\mathrm{T\ h^{-1}}$)
$\mathrm{wpr}_i^{j\rightarrow m}$	Flow rate going from process j to regeneration unit m ($\mathrm{T\ h^{-1}}$)
$\mathrm{wr}_i^{m\rightarrow n}$	Flow rate between two regeneration units m and n ($\mathrm{T\ h^{-1}}$)
wrd_i^m	Discharged flow rate from regeneration unit m ($\mathrm{T\ h^{-1}}$)
wrmax_m	Maximal water flow rate at the inlet of the regeneration unit m ($\mathrm{T\ h^{-1}}$)
$\mathrm{wrp}_i^{m\rightarrow j}$	Flow rate going from regeneration unit m to process j ($\mathrm{T\ h^{-1}}$)
$\mathrm{wr}_{\mathrm{in},i}^m$	Total flow rate at the inlet of the regeneration unit m ($\mathrm{T\ h^{-1}}$)
$\mathrm{wr}_{\mathrm{out},i}^m$	Total flow rate at the outlet of the regeneration unit m ($\mathrm{T\ h^{-1}}$)
w_1^j	Fresh water flow rate used by a process ($\mathrm{T\ h^{-1}}$)
$\mathrm{yp}_i^{j\rightarrow k}$	Binary variable of the existence of the water flow rate going from the process j to the process k
$yc(i, i^o, k)$	Binary variable of the existence of the cool stream i at the stage k.
$yh(j, ji^o, k)$	Binary variable of the existence of the cool stream j at the stage k.
Big-U	U is a large number, arbitrarily fixed at 10^4

Subscripts and superscripts

i	Refers to water when it is equal to 1 and to contaminants when: $i > 1$
j, k	Indices for process units, with $j \neq k$
m, n	Indices for regeneration units, with $m \neq n$
in	Inlet
out	Outlet

During the last decade, some studies that deal with both WAN and HEN have emerged, leading to the design of Water Allocation and Heat-Exchange Networks (WAHEN). Conceptual design approaches and mathematical programming remain the main techniques to design energy efficient water allocation networks. The former was first introduced by Savulescu and Smith [33], by considering water and energy consumptions separately and solving the problem sequentially. They improved their previous work by setting up the so-called "two dimensional grid diagram" [34,35] some years later, by simultaneously minimizing water and energy. However, graphical techniques are restricted to mono-contaminant networks, and cannot guarantee optimality. Mathematical models have also been developed to optimize WAHEN; they can be divided into two main types either sequential [36,37] or simultaneous [38–42]. The former approach aims at finding the water consumption target to design the water network in a first step and minimum energy consumption is then achieved for the network chosen. In this case, the WAN problem is often solved with a nonlinear programming (NLP) whereas the HEN one is tackled with a mixed integer nonlinear programming (MINLP). The simultaneous resolution of both models is carried out with MINLP [39]: the problem is yet hard to solve due to the large number of variables. Finally, some hybrid models involving pinch technology and mathematical programming [43], genetic algorithms coupled with adaptive simulated annealing (GA/SA) [44] or temperature–concentrations diagrams [45] have also been developed. Some reviews of process integration tools for water and energy savings can also be found in Klemeš et al. [46,47].

The aim of this study is to design an energy efficient water network considering several objectives. Indeed, in all the mentioned previous works, objectives are always water and energy consumptions. Even if these two objectives are of great environmental concern, other criteria can affect the final decision of an industrial practitioner. In fact, the number of streams, of heat exchangers, or the gain provided by regenerating polluted water represents also relevant objectives. Consequently, we propose to design an efficient water/energy allocation network regarding several objectives solved with an MILP procedure. One optimal network is selected from the Pareto front and improved in term of energy consumption by heat integration through an MINLP procedure. The latter is a variant of the work of Yee et al. [20] and does not take into account stream mixing, as it was already done by Bogataj and Bagajewicz [39]. A comparison of our results with two examples from the literature [15,40] is carried out and illustrates the proposed method. Finally, the effects of mixing streams and the impact of choosing an optimal network before heat integration are discussed.

2. Resolution strategy

2.1. Problem statement and superstructure definition

In the superstructure all the connections are possible between:

- any pair of process units, each one requiring a specific water composition and operating at a fixed temperature,

- any pair of regeneration units, each one operating with fixed outlet concentration and running temperature,
- any process unit and any regeneration unit

Recycle loops to the same process or regeneration unit are forbidden.

Cold and heat utilities and heat exchangers are available to satisfy temperature constraints. The design of the WAHEN consists in a two-step optimization:

(1) At the first design step, heat exchangers can be placed both at the inlet of each process and regeneration units and the inlet of the discharge to environment. The heat exchanger allocation in the network will be carried out during the second optimization phase. The first problem can be formulated as follows: how all units can be linked while respecting their input requests (on concentrations and temperatures) so as to minimize several objectives? At the end of this step, a Pareto front is plotted in order to make a preliminary choice of the water network.
(2) The second step consists in improving the design of the first stage by the implementation of heat integration to obtain a cost optimal network. For this purpose, the addition of cold and heat utilities, as well as heat exchangers is possible. The objective of this second step can be expressed as follows: how utilities and heat exchangers can be located so as to minimize the total cost of the network?

The first step aims at designing a water and heat allocation network and is based on the superstructure depicted in Fig. 1. In order to define a generic formulation, the physical or chemical operation (reaction, separation …) performed in each process j is not taken into account. However, a process j generates a mass of contaminant due to its operating mode. This contamination is expressed in g/h and noted:M_i^j for each contaminant i; this value imposed by the process itself, has to be fixed by the user. After the first stage, hot and cold streams are identified in the corresponding network to carry through the heat integration of the second step. Several classical assumptions are made to simplify the problem:

- process units operate isothermally,
- no water and heat losses or gains are considered,
- streams have a constant heat capacity ($C_p = 4.18$ kJ/(kg .°C)),
- heat exchangers are of countercurrent type,
- heat integration only concerns stream water and hot/cold utilities; any other stream is excluded.

The Fig. 1 shows a superstructure including j process units and m regeneration units:

- the water feeds for a process unit (j) can be: fresh water, water from other process units (named k, with $j \neq k$) and/or water from regeneration units (m). A regeneration unit (m) is fed by water going from process units (j) and water from other regeneration uits (named n, with $n \neq m$).
- water leaving a process unit (j) can be distributed either to other process units (named k, with $j \neq k$), or to regeneration units (m) or can be directly discharged. In the same way, water leaving a regeneration unit can go either to other regeneration units (named n, with $n \neq m$) or to process units (j).

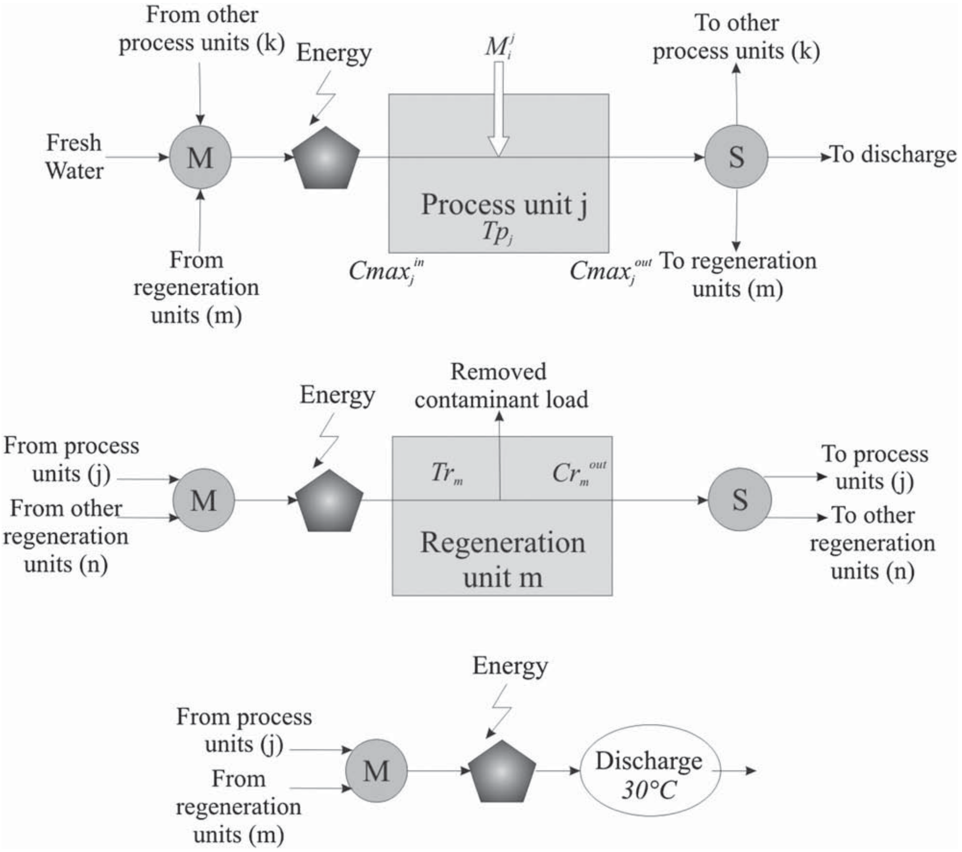

Fig. 1. Superstructure of the heat and water allocation network. M and S respectively refer to mixer and splitter, notations in italic represent operating constraints for each unit.

2.2. Multiobjective optimization

In the first step of the optimization phase, several objectives are taken into account to determine an optimal design for the considered network. They involve environmental, economical or topological issues that are likely to influence the final decision of the practitioner. They are relative to:

- fresh water consumption:

$$\mathrm{Min}\left(\sum\nolimits_j w_1^j\right) \tag{1}$$

- energy consumption:

$$\mathrm{Min}\left((\mathrm{Qpd}+\mathrm{Qnd})+\sum\nolimits_j\left(\mathrm{Qp}_j+\mathrm{Qn}_j\right)+\sum\nolimits_m(\mathrm{Qrp}_m+\mathrm{Qrn}_m)\right) \tag{2}$$

- water stream interconnections,
- number of heat exchangers.

The methodology for dealing with these four objectives is as follows. First, mono-objective optimizations are carried out to identify the different targets for each objective. Objective functions are represented by equations (1) and (2). Then the methodology consists in solving the biobjective problem (fresh water consumption versus energy consumption) parameterized by the number of interconnections and the number of heat exchangers. A lexicographic optimization based on the epsilon-constraint strategy is implemented [48] from which a Pareto front can thus be generated:

- let us recall that one Pareto front is generated for one value of the number of heat exchangers. Consequently, in order to build a front, the number of heat exchangers is fixed at an arbitrary value (included between its minimal and its maximal values);
- then, biobjective optimizations between the other pair of criteria, namely fresh water and energy consumptions, are carried out. To reach this step, the objective of energy consumption is bounded between two values while fresh water consumption is minimized by the numerical program. This operation is repeated until the validity domain of the values for energy consumption has been entirely explored;
- Pareto fronts are constructed when all the values of exchanger numbers have been evaluated.

Pareto fronts lead us to explore several solutions instead of only minimizing fresh water flow rate. The networks obtained in order to choose the better compromise for the following step of the optimization are then ranked according to a TOPSIS procedure.

In the second step of the optimization procedure, when the network is designed and streams are allocated, a monobjective optimization is carried out. Only heat exchangers and cold or/and heat utilities are placed by minimizing a cost objective function.

2.3. MILP formulation for heat and water allocation network

The traditional model [5,40,10] for water allocation network design usually 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. [49], the problem can be expressed in a linear form by using partial flow rates instead of total flow rates, while achieving the necessary conditions of optimality [50]. All the flow rates (either water or contaminant) or expressed with w with an index $i=1$ when it is referred to water and $i>1$ when it is expressed for a contaminant. As they are partial contaminant flow rates, they represent contaminant concentration (ppm) multiplied with water flow rates (T h^{-1}) leading to the same unit as mass loads: g h^{-1}.

2.3.1. Flow rate mass balances

- For a given process j, the inlet water ($i=1$) flow rate is equal to the outlet water flow rate, $j\neq k$:

$$w_1^j+\sum\nolimits_k \mathrm{wp}_1^{k\to j}+\sum\nolimits_m \mathrm{wrp}_1^{m\to j} = \mathrm{wd}_1^j+\sum\nolimits_k \mathrm{wp}_1^{j\to k} +\sum\nolimits_m \mathrm{wpr}_1^{j\to m} \tag{3}$$

- For a given regeneration unit m, the inlet water flow rate is equal to the outlet water flow rate, $m\neq n$:

$$\sum\nolimits_n \mathrm{wr}_1^{n\to m}+\sum\nolimits_j \mathrm{wpr}_1^{j\to m} = \sum\nolimits_j \mathrm{wrp}_1^{m\to j}+\sum\nolimits_n \mathrm{wr}_1^{m\to n} \tag{4}$$

- The overall fresh water flow rate is equal to the total discharged water flow rate:

$$\sum\nolimits_m \mathrm{wrd}_1^m+\sum\nolimits_j \mathrm{wd}_1^j = \sum\nolimits_j w_1^j \tag{5}$$

2.3.2. Contaminant mass load balances

- For a given process j, the inlet contaminant ($i>1$) partial flow rate plus the contaminant mass load is equal to the outlet contaminant flow rate, $j\neq k$:

$$\sum\nolimits_k \mathrm{wp}_{i>1}^{k\to j}+\sum\nolimits_m \mathrm{wrp}_{i>1}^{m\to j}+M_i^j=\mathrm{wd}_{i>1}^j+\sum\nolimits_k \mathrm{wp}_{i>1}^{j\to k} +\sum\nolimits_m \mathrm{wpr}_{i>1}^{j\to m} \tag{6}$$

- For a given regeneration unit m, the inlet contaminant partial flow rate is equal to the outlet contaminant partial flow rate, $m\neq n$:

$$\sum\nolimits_n \mathrm{wr}_{i>1}^{n\to m}+\sum\nolimits_j \mathrm{wpr}_{i>1}^{j\to m} = \mathrm{wrd}_{i>1}^m+\sum\nolimits_j \mathrm{wrp}_{i>1}^{m\to j} +\sum\nolimits_n \mathrm{wr}_{i>1}^{m\to n} \tag{7}$$

- As the only source of contaminant in the network is generated by process units themselves, the total discharged contaminant partial flow rate is equal to the sum of contaminant mass loads of each process j:

$$\sum\nolimits_m \mathrm{wrd}_{i>1}^m+\sum\nolimits_j \mathrm{wd}_{i>1}^j = \sum\nolimits_j M_{i>1}^j \tag{8}$$

2.3.3. Energy balances

With equations (9), (10), and (11), the energy necessary to heat is considered as positive, and negative for cooling. The global energy consumption is the sum of absolute values of energy (at processes and discharge), expressed in kW.

- For a given process unit j, inlet energy on the mixer plus a heating (Qp_j) or a cooling (Qn_j) utility is equal to the outlet energy of the splitter:

$$\left(w_1^j \times T_w + \sum\nolimits_k wp_1^{k\to j} \times Tp_k + \sum\nolimits_m wrp_1^{m\to j} \times Tr_m\right) + \left(Qp_j - Qn_j\right)\Big/C_p = Tp_j \times \left(\sum\nolimits_k wp_1^{j\to k} + wd_1^j + \sum\nolimits_m wpr_1^{j\to m}\right)(9) \tag{9}$$

- For a given regeneration unit m, inlet energy on the mixer plus a heating (Qrp_m) or a cooling (Qrn_m) utility is equal to the outlet energy of the splitter:

$$\left(\sum\nolimits_j wpr_1^{j\to m} \times Tp_j + \sum\nolimits_n wr_1^{n\to m} \times Tr_n\right) + (Qrp_m - Qrn_m)/C_p = Tr_m \times \left(\sum\nolimits_j wrp_1^{m\to j} + wrd_1^m + \sum\nolimits_n wr_1^{m\to n}\right) \tag{10}$$

- The energy discharged plus a heating (Qpd) or a cooling (Qnd) utility is equal to the total energy released into the environment:

$$\sum\nolimits_j wd_1^j \times Tp_j + \sum\nolimits_m wrd_1^m \times Tr_m + (Qpd - Qnd)/C_p = Td \times \left(\sum\nolimits_j w_1^j + \sum\nolimits_m wrd_1^m\right) \tag{11}$$

2.3.4. *Constraints*

Given the set of mass balances equations, constraints on contaminant concentrations are added to the mathematical problem. They are represented by inequalities (12), (13) and (14). Using the condition of optimality proved by Savelski and Bagajewicz [50], the outlet concentrations can be fixed at their maximum value:

$$wp_{in,i>1}^j \le Cmax_j^{in} \times wp_{in,1}^j \tag{12}$$

$$wp_{out,i>1}^j \le Cmax_j^{out} \times wp_{out,1}^j \tag{13}$$

$$wr_{out,i>1}^m = Cr_m^{out} \times wr_{out,1}^m \tag{14}$$

2.3.5. *Binary variables*

At this stage of the modelling process, the problem is linear and can be solved with a Linear Programming (LP) algorithm. Nevertheless, in order to evaluate the network complexity, a binary variable is allocated to each flow, thus transforming the problem into an MILP formulation. These variables $yp^{j\to k}$ are added into the model by using a so-called Big-U constraint (U has to be bigger than any water flow rate of the plant):

$$Wp_1^{j\to k} \le yp^{j\to k} \times U \tag{15}$$

Moreover, binary variables are also introduced for representing the number of exchangers in the network.

2.4. *MINLP formulation for superstructure integration*

As mentioned above, the design of a WAHEN is carried out by implementing a two-step procedure:

- the first step consists of the biobjective optimization (fresh water consumption versus energy consumption) parameterized by the number of interconnections and the number of heat exchangers, carried out by implementing a MILP procedure. The main difference with previous works in which monobjective problems were solved giving only a single WAN, is the generated Pareto front which offers a set of “good” WANs to the practitioner.
- the selection of the WAN among the solutions proposed in the Pareto front is carried out with the TOPSIS procedure. After selecting a WAN among the Pareto front, the heat integration is carried out in the second step. The network is decomposed into hot and cold streams characterized by their inlet and outlet temperatures in the network and also by the water flow rate.

The physical process modelling, based of the work of Yee et al. [20],, is used to design a HEN while minimizing a given objective (cost or energy consumption) and satisfying given demands of heating and cooling. The model is derived from the superstructure shown in Fig. 2.

Once the WAN to be integrated is defined, the hot and cold streams must be identified so as to know their inlet and outlet temperatures as well as the associated calorific flow rate. The number k of steps of the superstructure is set to the greatest number of hot or cold streams, plus one. With i hot streams, j cold streams and k steps in the superstructure, the modelling variables are the following ones:

- th(i,k) and tc(j,k): temperatures of hot stream i and cold stream j at the inlet of step k;
- q(i,j,k): exchanged energy between i and j at step k;
- qh(j) and qc(i): exchanged energy between the hot stream i and a cold utility and between the cold stream j and a hot utility;
- dt(i,j,k): temperature difference between hot stream i and cold stream j at step k;
- dtuh(i) and dtuc(j): temperature differences between hot stream i and a cold utility and between cold stream j and a hot utility;
- *A*_int(i,j,k): exchange area for matching streams i and j at step k;
- *A*_uhc(i) and *A*_uch(j): exchange areas for the matching hot stream i and a cold utility and cold stream j and a hot utility.

Finally binary variables linked to the existence of heat exchangers are defined:

- z(i,j,k): existence of a heat exchanger between hot stream i and cold stream j at step k;
- zuc(i) and zuh(j): existence of a heat exchanger between hot stream i and a cold utility and between cold stream j and a hot utility.

The data required for integrating a WAN are listed in Table 1. It represents all the fixed parameters necessary for heat integration (variables are not represented in this table).

The modelling equations are based on energy balances and heat exchange area computations:

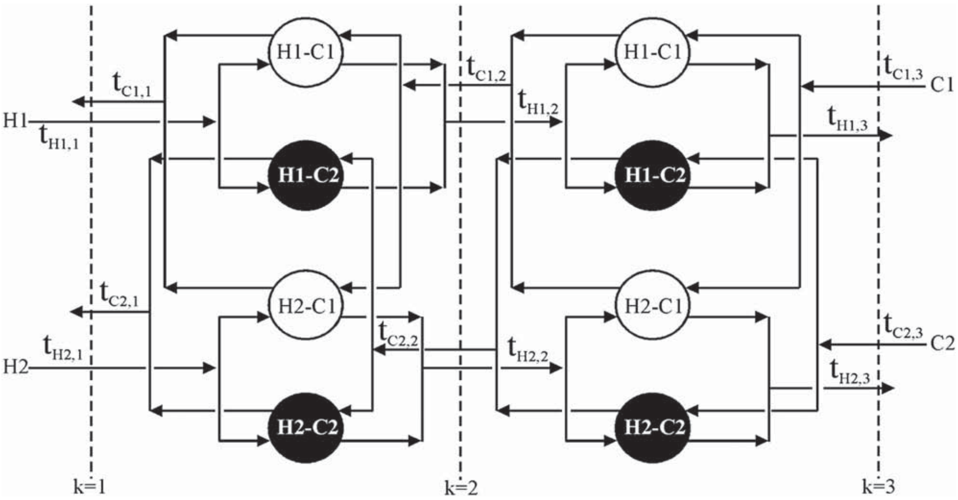

Fig. 2. HEN superstructure (from Yee et al. [21],).

- Energy balances for hot streams *i* and cold streams *j* are given by:

$$\mathrm{Fh}(i) \times (\mathrm{th}(i,k) - \mathrm{th}(i,k+1)) = \sum\nolimits_j q(i,j,k) \tag{16}$$

$$\mathrm{Fc}(j) \times (\mathrm{tc}(j,k) - \mathrm{tc}(j,k+1)) = \sum\nolimits_i q(i,j,k) \tag{17}$$

- In the same way, energy balances of hot stream *i* and a cold utility and between a cold stream *j* and a hot utility are written as:

$$\mathrm{Fh}(i) \times (\mathrm{th}(i,k) - \mathrm{thout}(i)) = \mathrm{qc}(i) \tag{18}$$

$$\mathrm{Fc}(j) \times (\mathrm{tcout}(j) - \mathrm{tc}(j,k)) = \mathrm{qh}(j) \tag{19}$$

- In order to assign inlet temperatures for hot and cold streams, equations (20) and (21) are introduced:

$$\mathrm{thin}(i) = \mathrm{th}(i,k) \tag{20}$$

$$\mathrm{tcin}(j) = \mathrm{tc}(j,k) \tag{21}$$

- At step *k*, exchange areas for matching a hot and cold stream *i* and *j*, a hot stream *i* with a cold utility and a cold stream *j* with a hot utility are expressed as follows:)
- Finally, binary variables *z* are introduced into logical constraints defining the existence of heat exchangers and utilities:

$$A_{\mathrm{Int}(i,j,k)} = \frac{q(i,j,k) \times \left(\frac{1}{\mathrm{hh}(i)} + \frac{1}{\mathrm{hc}(j)}\right)}{\left(\mathrm{dt}(i,j,k) \times \mathrm{dt}(i,j,k+1) \times \frac{\mathrm{dt}(i,j,k) + \mathrm{dt}(i,j,k+1)}{2}\right)^{\frac{1}{3}}} \tag{22}$$

$$A_{\mathrm{uch}(j)} = \frac{\mathrm{qh}(j) \times \left(\frac{1}{\mathrm{hc}(j)} + \frac{1}{\mathrm{huh}}\right)}{\left((\mathrm{tuhin} - \mathrm{tucout}(j)) \times \mathrm{dtuh}(j) \times \frac{(\mathrm{tuhin} - \mathrm{tucout}(j)) + \mathrm{dtuh}(j)}{2}\right)^{\frac{1}{3}}} \tag{23}$$

$$A_{\mathrm{uhc}(i)} = \frac{\mathrm{qc}(i) \times \left(\frac{1}{\mathrm{hh}(i)} + \frac{1}{\mathrm{huc}}\right)}{\left((\mathrm{thout}(i) - \mathrm{tucin}) \times \mathrm{dtuc}(i) \times \frac{(\mathrm{thout}(i) - \mathrm{tucin}) + \mathrm{dtuc}(i)}{2}\right)^{\frac{1}{3}}} \tag{24}$$

Table 1
Data for heat integration.

Design parameter	Corresponding element	Notation	Unit
Calorific flow-rate	Hot and cold streams	Fh(*i*), Fc(j)	kW/°C
Inlet temperature	Hot and cold streams	thin(*i*), tcin(j)	°C
Outlet temperature	Hot and cold streams	thout(*i*), tcout(j)	°C
Inlet temperature	Hot (vapour) and cold (water)	tuhin, tucin	°C
Outlet temperature	Hot (vapour) and cold (water)	tuhout, tucout	°C
Heat transfer coefficient	Hot and cold sides	hh(*i*), hc(j)	kW/m^2 °C
Heat transfer coefficient	Hot (vapour) and cold (water)	huh, huc	kW/m^2 °C
Amount of heat exchanged	Hot and cold streams	Qtot_h(*i*), Qtot_c(j)	kW

- Finally, binary variables z are introduced into logical constraints defining the existence of heat exchangers and utilities:

$$q(i,j,k) - \min\left(\mathrm{Qtot}_{h(i)}, \mathrm{Qtot}_{c(j)}\right) \times z(i,j,k) \leq 0 \tag{25}$$

$$\mathrm{qc}(i) - \mathrm{Qtot}_{h(i)} \times \mathrm{zuc}(i) \leq 0 \tag{26}$$

3. Illustrative examples

3.1. Example of Dong et al. [40]

This example used to validate the two-step approach was first proposed by Bagajewicz et al. [36] and more recently by Dong et al. [40]. It involves three process units without any regeneration process. Fresh water feeds the network at a temperature of 20 °C and pollute water is discharged to the waste at 30 °C. The corresponding data are listed in Table 2, where $W\mathrm{max}_j$ refers to the maximum flow rate for process j.

3.1.1. Water network optimization without energy integration

As abovementioned, in a first step each one of the three objectives listed in Table 3 was optimized separately (monobjective optimization) to provide problem targets represented by bold numbers in Table 3. Then considering the pair [Fresh water, Energy consumption], the corresponding MILP problem parameterized by the number of connections (3 and 5), provides only three (one for three connections and two for five connections) non dominated solutions shown in Fig. 3. Only three objectives are taken into account for this first case study because the number of solutions is very limited and thus, adding another objective would have constrained the problem too much. Note that in this study the connections going to the waste are not taken into account.

For three connections (network 1), the water consumption is 87.5 kg/s, for an energy requirement of 47,025 kW/h. By adding two connections, either the minimum of fresh water consumption is reached (77.27 kg/s) for the network 2, or the minimum for energy (46,930 kW/h) is obtained for the network 3. In all the previous works [39,40,51], only the network corresponding to the minimum of fresh water consumption is obtained. However, as it is shown on this example, this solution does not lead necessarily to the minimum of energy consumption.

Table 2
Date for the example of Dong et al. [40].

Process	$C\mathrm{max}_j^{\mathrm{in}}$ (ppm)	$C\mathrm{max}_j^{\mathrm{out}}$ (ppm)	M_j (kg/s)	Tp_j(°C)	$W\mathrm{max}_j$(Kg/s)
1	50	100	5000	100	100
2	50	800	30,000	75	40
3	800	1000	50,000	100	166.7

Table 3
Results for mono-objective optimizations.

Objective	Fresh water (kg/s)	Connection number	Total energy (MW)
Minimal value	77.27	3	46.93

3.1.2. Improvement of solutions by heat integration

In order to select the best solution among the three networks, a cost objective function related to heat integration is introduced. Each network is characterized by a set of hot (cold) streams with given calorific flow rates and fixed inlet and outlet temperatures. For comparison purposes the total cost function for the network already defined in the papers of Bogataj and Bagajewicz [39], and Dong et al. [40], is used. This nonlinear cost function is expressed by equation (27).

$$\begin{aligned}\mathrm{Cost} = {} & \sum_i \sum_j \sum_k C_{\mathrm{HE}}(i,j) \times z(i,j,k) + \sum_i C_{\mathrm{HE}}(i) \times \mathrm{zuc}(i) + \sum_j C_{\mathrm{HE}}(j) \times \mathrm{zuh}(j) + \sum_i \sum_j \sum_k C_A(i,j) \times A_{\mathrm{Int}}(i,j,k)^{\beta} \\ & + \sum_i C_A(i) \times A_{\mathrm{uch}}(i)^{\beta} + \sum_j C_A(j) \times A_{\mathrm{uhc}}(j)^{\beta} + fa\left(\sum_i C_{\mathrm{uc}}(i) \times \mathrm{qc}(i) + \sum_j C_{\mathrm{uh}}(j) \times \mathrm{qh}(j)\right) + \sum_j W_1^j \times C_{\mathrm{FW}} \\ & + C_{\mathrm{Con}}\left(\sum_i \sum_{i^\circ \neq i} \sum_k \mathrm{yc}(i,i^\circ,k) + \sum_j \sum_{j^\circ \neq j} \sum_k \mathrm{yh}(j,j^\circ,k)\right)\end{aligned} \tag{27}$$

This complex function takes into account of the following items:

- The investment cost of heat exchangers:

$$\begin{aligned}& \sum_i \sum_j \sum_k C_{\mathrm{HE}}(i,j) \times z(i,j,k) + \sum_i C_{\mathrm{HE}}(i) \times \mathrm{zuc}(i) \\ & + \sum_j C_{\mathrm{HE}}(j) \times \mathrm{zuh}(j) + \sum_i \sum_j \sum_k C_A(i,j) \times A_{\mathrm{Int}}(i,j,k)^{\beta} \\ & + \sum_i C_A(i) \times A_{\mathrm{uch}}(i)^{\beta} + \sum_j C_A(j) \times A_{\mathrm{uhc}}(j)^{\beta}\end{aligned} \tag{28}$$

- The investment cost of connections:

$$C_{\mathrm{Con}}\left(\sum_i \sum_{i^\circ \neq i} \sum_k \mathrm{yc}(i,i^\circ,k) + \sum_j \sum_{j^\circ \neq j} \sum_k \mathrm{yh}(j,j^\circ,k)\right) \tag{29}$$

- The annual cost for energy consumption:

$$\mathrm{fa}\left(\sum_i C_{\mathrm{uc}}(i) \times \mathrm{qc}(i) + \sum_j C_{\mathrm{uh}}(j) \times \mathrm{qh}(j)\right) \tag{30}$$

- Consumed fresh water cost:

$$\sum_j W_1^j \times C_{\mathrm{FW}} \tag{31}$$

The notations and the values used in equations (27)–(31) are defined in Table 4. These values are taken from Dong et al. [40] and the cost of connection is extracted from the study of Bogataj and

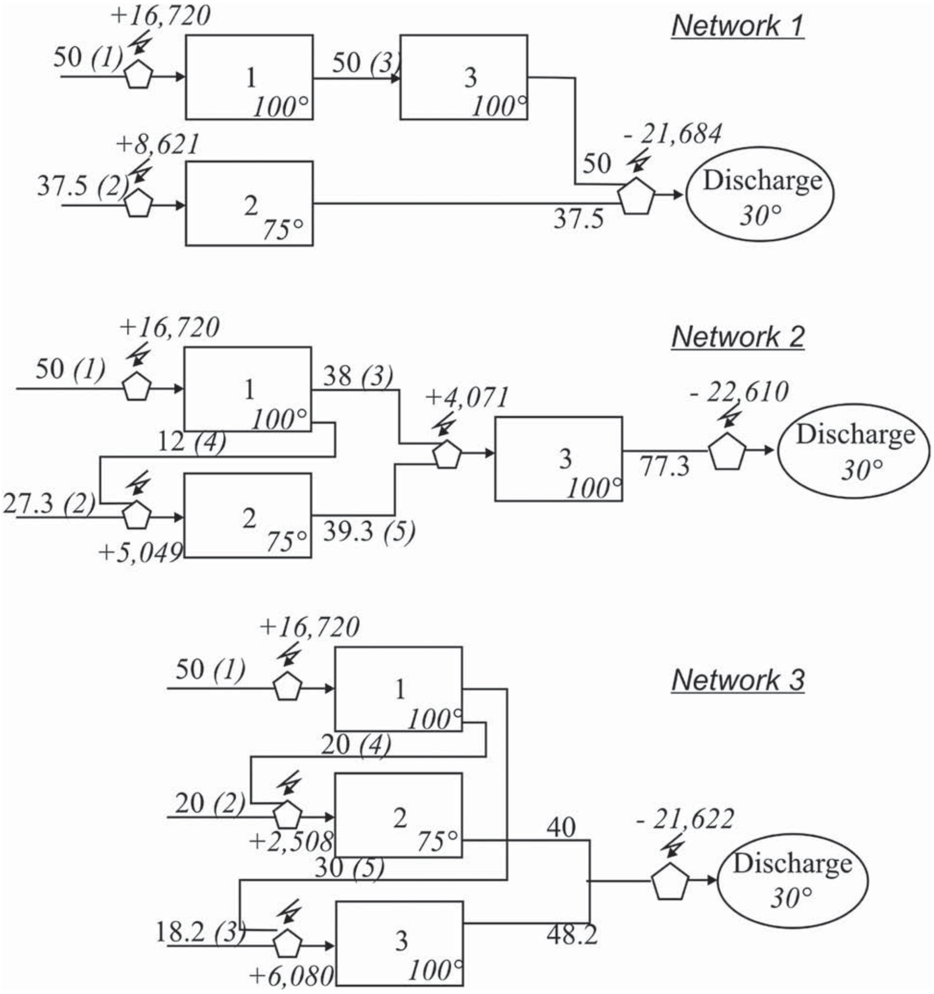

Fig. 3. Representation of the three networks Flow rate are in kg/s; energy, written in italic, in kW/h; a cooling (heating) corresponds to a negative (positive) energy; the connection number is in brackets.

Bagajewicz [39]. The plant is assumed to operate continuously 8000 h per year. Furthermore, the cost is calculated annualy on the base of a life time of 10 years.

For the three networks identified in the previous subsection, heat integration is carried out by means of the MINLP solver COIN-COUENNE of the GAMS package. The initialization phase is automatically performed by the solver. For analysis purposes, the total cost of equation (27) is decomposed into two terms: the investment cost (*IC*) and the annual operating cost (*AOC*).

- The investment cost is obtained by merging equations (28) and (29):

$$\begin{aligned}\mathrm{IC} = & \sum_i \sum_j \sum_k C_{\mathrm{HE}}(i,j) \times z(i,j,k) + \sum_i C_{\mathrm{HE}}(i) \times \mathrm{zuc}(i) \\ & + \sum_j C_{\mathrm{HE}}(j) \times \mathrm{zuh}(j) + \sum_i \sum_j \sum_k C_A(i,j) \times A_{\mathrm{Int}}(i,j,k)^{\beta} \\ & + \sum_i C_A(i) \times A_{\mathrm{uch}}(i)^{\beta} + \sum_j C_A(j) \times A_{\mathrm{uhc}}(j)^{\beta} \\ & + C_{\mathrm{Con}} \left(\sum_i \sum_{i^\circ \neq i} \sum_k \mathrm{yc}(i,i^\circ,k) + \sum_j \sum_{j^\circ \neq j} \sum_k \mathrm{yh}(j,j^\circ,k) \right)\end{aligned} \tag{34}$$

- The annual operating cost is given by adding equations (30) and (31):

$$\mathrm{AOC} = \mathrm{fa}\left(\sum_i C_{\mathrm{uc}}(i) \times \mathrm{qc}(i) + \sum_j C_{\mathrm{uh}}(j) \times \mathrm{qh}(j) \right) + \sum_j W_1^j \times C_{\mathrm{FW}} \tag{35}$$

3.1.3. *Discussion*

Table 5 gives the main characteristics and the optimization results for the three networks. The Table contains also the results published by Dong et al. [40]. Let us recall that in this last study, the heat integration was performed only on the network giving the minimum of fresh water consumption. However, the heat integration of network 2 (giving also the minimum of fresh water consumption) leads to a total cost of 4.31 M$, while Dong et al. [40] obtained 2.94 M$ for the same network. The difference comes from the initial MINLP formulation which excludes stream splitting for simplification purposes; consequently a MINLP optimization was also performed on this network by allowing stream splitting; the same value (2.94 M$) for the total cost as in the paper of Dong et al. [40] is found again. In the two last lines of Table 5, investment and operating costs are different because the networks of this study and the one of Dong et al. [40] are structurally different, but they give

Table 4
Notations and numerical parameters used in cost functions (27) to (31).

Symbol	Meaning	Value	Unit
C_{HE}	Investment cost of a heat exchanger	8000	\$/y
C_A	Pre-exponent term for area cost	1200	\$/y
C_{uc}	Cost of cold utility	189	\$/kW
C_{uh}	Cost of hot utility	377	\$/kW
C_{FW}	Cost of fresh water	0.45	\$/T
C_{con}	Investment cost of a connection	3000	\$
B	Exponent for area cost	0.6	
f_a	Annual operating time ratio	0.91	
tuhin, tuhout	Inlet and outlet vapour temperatures for heating	120	°C
tucin, tucout	Inlet and outlet water temperatures for cooling	10, 20	°C
huh, huc, hh, hc	Heat transfer coefficients	0.5	kW/m^2 °C
Tmapp	Minimal approach temperature	10	°C

Table 5
Results for heat integration.

Network	Characteristics	IC (M\$)	AOC (M\$)	Total cost (M\$)
Network 1 (Min connections)	- 2 cold streams - 2 hot streams	0.46	2.40	2.86
Network 2 (Min fresh water)	- 3 cold streams - 2 hot streams	0.57	3.74	4.31
Network 3 (Min energy)	- 3 cold streams - 3 hot streams	0.60	3.15	3.75
Dong et al. (2008)	- 4 cold streams - 3 hot streams	0.31	2.63	2.94
Network 2 (stream splitting)	- 4 cold streams - 3 hot streams	0.57	2.37	2.94

the same minimal total cost. So it can be noted that the same optimal solution in terms of total cost may correspond to several solutions in terms of network internal structures.

From Table 5, the best total cost is provided by network 1, which was ranked in an intermediate position concerning as well as water consumption and energy in the first design study without energy integration. This shows all the interest of the first step multi-objective approach, which provides several solutions among which that of minimal total cost can be identified; this solution does not necessarily corresponds to the one giving the minimum of water consumption (i.e. network 2) in the preliminary optimization phase.

3.2. Example of Manan et al. [43]

3.2.1. Problem formulation

This new example is related to an existing Malaysian paper mill plant shown in Fig. 4. Manan et al. [43] optimized this plant by means of the pinch method; in a first step they minimized the fresh water consumption and energy integration was carried out in a second step.

In this plant, the paper machine involves forming and pressing sections. The pulp, also called stock, is treated in the forming section in order to elaborate the paper sheet which is then sent towards the pressing station. The paper machine can receive water either from regeneration units, or from clarified water tower, or from the deculator process. This water is used for eliminating remaining fibres in the forming and pressing sections, then the water is removed from the stock and sent towards the saveall disc filters to remove wood fibres. It may also be sent towards the de-inking process or the DAF (dissolved air flotation). The deculator, used for removing pollutants heavier than fibres, needs also fresh water as well as the unit of chemical preparation. The four regeneration units are constituted by the three saveall disc filters for trapping the solid pollutant and the DAF to remove the suspending particles.

Some pieces of the plant are decomposed into several units (see Fig. 5): for example the pressing station is made up of three processes having each one particular characteristic. After this decomposition the plant is constituted of 12 process units and four regeneration ones. In Fig. 5, four mixers have been added in order to obtain more realistic temperatures. For example, the two outlet streams of forming units with their respective flow rates and temperatures are mixed. However, these mixers can only receive water from their immediate predecessors.

The pollutant is the total quantity of suspending solids expressed in ppm and includes different pollutant types transported by the water; however the problem is assumed to be reduced to a mono-pollutant one. Furthermore some outlet concentrations resulting from stream mixing are given. For example the five outlet streams of forming and pressing stations are mixed to produce a stream of concentration 3750 ppm. The contaminant mass load M_i^j of each unit is deduced from this global concentration value by means of the relation:

$$M_i^j = C\max_j^{out} \times Wp_{in,1}^j - C\max_j^{in} \times Wp_{in,1}^j \qquad (36)$$

The optimization procedure needs some data related to each process and concerning the maximal inlet/outlet concentrations,

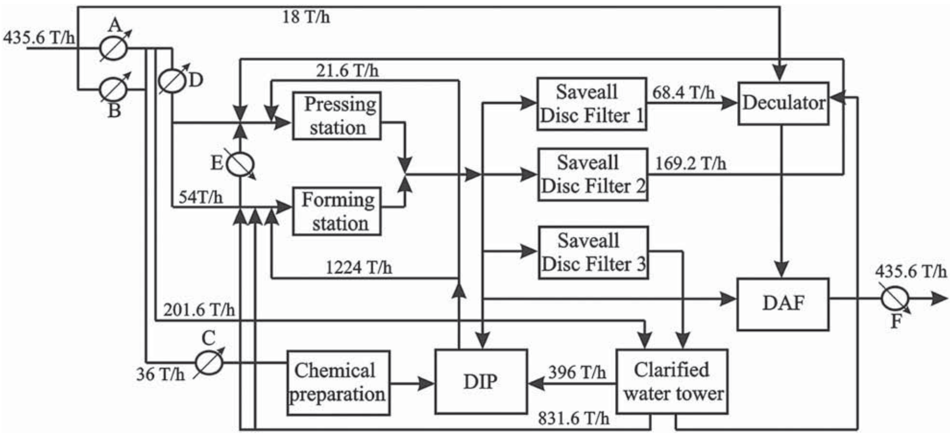

Fig. 4. Paper mill plant (modified from Manan et al. [41]).

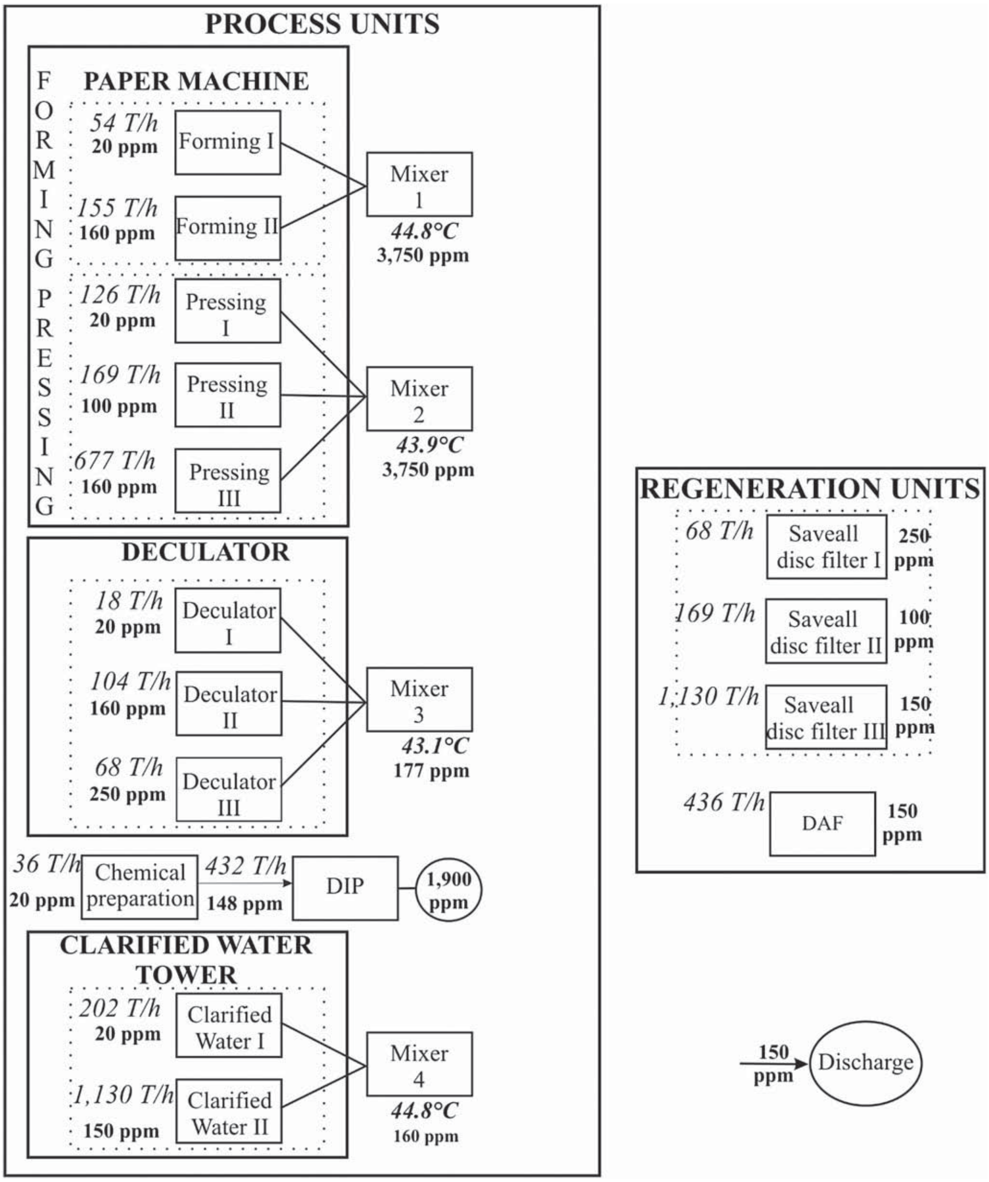

Fig. 5. New flowsheet of the plant involving 12 process units and four regeneration ones.

Table 6
Data for the paper mill plant.

Process	Type	$W\max_j$ (T/h)	$C\max_j^{\text{in}}$ (ppm)	M_i^j (kg/s)	Tp_j (°C)
1	Forming I	54	20	201,420	50
2	Forming II	155	160	556,450	43
3	Pressing I	126	20	469,980	50
4	Pressing II	169	100	616,850	43
5	Pressing III	677	160	2,430,430	43
6	Deculator I	18	20	2826	38
7	Deculator II	104	160	1775	46
8	Deculator III	68	250	−4993	40
9	Chemical preparation	36	20	0	81
10	De-inking process	432	148	756,720	49
11	Clarified water I	202	20	28,224	38
12	Clarified water II	1130	150	11,304	46
Regeneration unit	Type	$Wrmax_m$(T/h)	Cr_m^{out}(ppm)		Tr_m(°C)
1	Saveall disc filter I	169	250	–	40
2	Saveall disc filter II	436	100	–	43
3	Saveall disc III	1130	150	–	46
4	DAF	832	150	–	48

Table 7
Results for mono-objective optimizations.

Objective	Fresh water Flow rate (T/h)	Total energy (kW)	Number of heat exchangers	Number of connections
Minimal value	377.5	36,621	8	27

operating temperature and the maximal water flow rate; these data are listed in Table 6. According to Manan et al. [43], fresh water temperature is set at 30 °C and water must be discharged to the waste at 35 °C maximum.

3.2.2. *Water network optimization without energy integration*

As it can be observed in Fig. 4, the industrial process involves six heat exchangers. In this study a heat exchanger can be placed at the inlet of each unit for cooling or heating its inlet stream, that is to say 17 potential exchangers (12 for process units, four for regeneration units, and one for the waste). However for investment purposes, the number of heat exchangers has to be minimized, requiring new binary variables. The set of objectives is then the fresh water flow rate, the energy consumption, the number of connections and the number of heat exchangers.

3.2.2.1. Preliminary monobjective optimizations. The bounds for the problem are deduced from the monobjective optimization of each one of the four criteria (see Table 7). For fresh water flow rate, the same value (377.5 T/h) as in Manan et al. [43] is found. The number of connections depends on the number of heat exchangers in the process and increases when the number of heat exchangers decreases. The minimum number of connections vs. the number of heat exchangers is plotted in Fig. 6. For simplifying purposes in the following studies, when the number of heat exchangers is fixed, the number of connections is assumed to vary between the minimum value and the minimum value plus 2 (arbitrarily chosen in order to obtain networks with a reduced number of connections).

3.2.2.2. Multiobjective optimization. For fixed numbers of heat exchangers the biobjective optimization [Fresh water, Energy consumption] gives the Pareto front of Fig. 7 involving only 8 non dominated solutions. With 8 exchangers, the minimum of fresh water is 406.8 T/h, while 13 exchangers give 377.5 T/h. The minimal energy consumption is obtained for 10 exchangers, and it increases for 9, 8, 11, 12 and 13 exchangers. The following trends can be deduced from Fig. 7:

- fresh water consumption decreases when the number of exchangers increases.
- the variations of energy consumption are quite different: the minimum is reached for 10 exchangers and this value increases when exchangers are added or suppressed.
- for a given number of heat exchangers, the minimum fresh water and minimum energy vary in opposite sense, showing their antagonist nature.

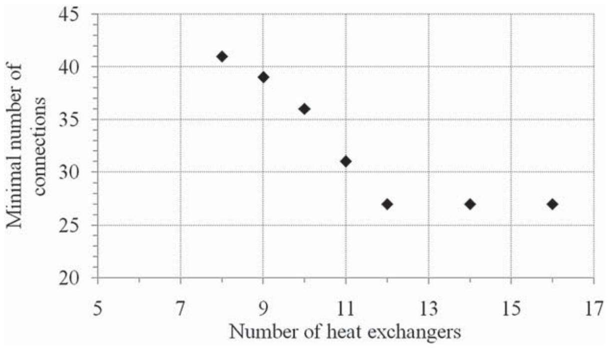

Fig. 6. Minimal number of connections vs. The number of heat exchangers.

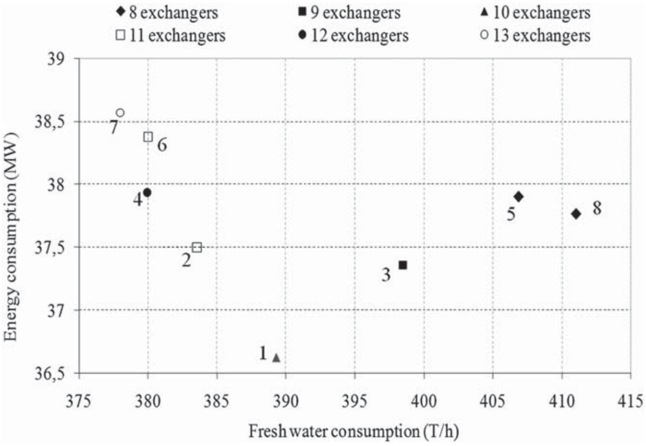

Fig. 7. Pareto fronts for fixed numbers of heat exchangers.

3.2.3. *Network selection*

The selection of a given network among the solutions of the Pareto front can be performed by implementing the TOPSIS procedure [52]. TOPSIS is a classical MCDM method (Multiple Criteria Decision Making) and, its fundamental concept is the comparison of Euclidian distances to choose the best alternative. The TOPSIS procedure calculates the distance between available solutions and the optimized ideal reference point (here, it is the point where all the objectives are at their minimal values). Assuming the same weight for the three objectives (equal to 1 for each one), the solution ranking is displayed in Table 8 and represented by the numbers in Fig. 7.

The network with 10 exchangers is ranked in first position; hence, this solution is retained for further considerations. The GAMS solver indicates that heat exchangers must be located before units 1, 2, 3, 5, 6, 7, 8, 10 and 12, and before the waste. In order to minimize exchange area, it must be decided on what inlet stream the exchangers must be placed. For example, considering unit 1, two inlet streams with different temperatures and flow rates arrive at the process mixer as it is shown in Fig. 8. The heat exchanger area is computed from the temperature difference between its inlet and outlet streams according to classical relations (37)–(38). In order to minimize heat exchanger area, the heat exchanger must be placed on the stream corresponding to the most important difference

Table 8
TOPSIS ranking of the solutions reported in Fig. 7.

TOPSIS ranking	Number of exchangers	Energy consumption (MW)	Fresh water consumption (T/h)
1	10	36.62	389.3
2	11	37.49	383.5
3	9	37.36	398.5
4	12	37.93	379.3
5	8	37.90	406.9
6	11	38.38	383.8
7	13	38.57	377.5
8	8	37.76	411.0

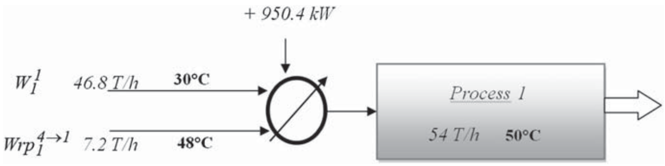

Fig. 8. Process 1 with two inlet streams.

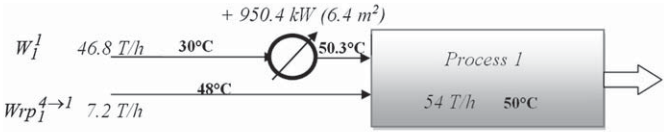

Fig. 9. Process 1 with its heat exchanger.

between its temperature and the target one; the fresh water stream is chosen in Fig. 8.

$$A = \frac{Q}{\Delta T \times U} \tag{37}$$

$$Q = m \times \mathrm{Cp} \times \varDelta T \tag{38}$$

where A is the exchange area (m^2), Q, the amount of heat provided (J), U, the mass transfer coefficient equal to 5678 $\mathrm{W/m^2K}$ from Manan et al. [43], Cp, the specific heat of water (1 cal/kg°C) and $\varDelta T$ is the difference of temperatures.

The first step of the computational procedure consists in calculating the temperature T of the colder stream submitted to the amount Q of heat from Equation (38) and using Equation (40). The heat exchanger area is then computed in the second step by means of Equation (37). For the example shown in Fig. 8, we obtain $T = 50.31$ °C and $A = 6.4$ m^2. The heat exchanger is now designed and placed on process 1 as indicated in Fig. 9.

$$T = \frac{Q}{m \times C_p} + T_1 \tag{40}$$

Once units involving heat exchangers have been identified, this simple procedure allows choosing the inlet stream to position the heat exchanger in order to minimize its area. This method can also be implemented for retrofitting existing networks. As in the previous example, another approach for choosing an efficient network among the eight ones of the Pareto front is to perform heat integration based on economic objective.

Table 9
Results for the heat integration of the eight networks.

Network	FW (T/h)	Number of connections	Hot streams	Cold streams	Energy before (MW)	Energy after (MW)	Cost (M$)
1	389.3	34	1	5	36.6	14.19	3.82
2	383.5	31	2	5	37.5	14.49	3.77
3	398.5	39	2	7	37.4	14.47	3.95
4	379.3	29	2	5	37.9	14.69	3.72
5	406.9	40	1	6	37.9	14.33	4.01
6	383.8	30	2	5	38.4	14.15	3.64
7	377.5	27	2	4	38.6	14.74	3.72
8	411.0	40	1	7	37.8	14.07	4.07

3.2.4. Heat integration

In this section, heat integration is performed on the eight networks identified in part 3.2.2 and shown in Fig. 7. The same procedure as in the previous example is implemented, and the cost function presented in Equation (29) with the data of Table 4 are used. The minimization of this cost function gives the results displayed in Fig. 10, where the solution given by Manan et al. [43] is also reported. The energy consumption lies in the range [14.07, 14.74] MW, while without energy integration (Fig. 7) this range was [36.5, 38.5] MW, demonstrating the efficiency of energy integration. Considering energy consumption, the solutions displayed in Fig. 10 are better than the one (17.22 MW) proposed by Manan et al. [43].

The main features of the eight networks optimized with the MINLP procedure of the GAMS package are displayed in Table 9, where a bold value represents the minimal value for the considered item. For example, network 1 was ranked first before energy integration, whereas network 8 became the best one regarding energy consumption after energy integration. According to previous studies which always propose to choose the network giving the minimum fresh water consumption for performing energy integration, network 7 would be selected, while network 8 would be chosen after energy integration in order to minimize energy consumption. However, this network involves an important

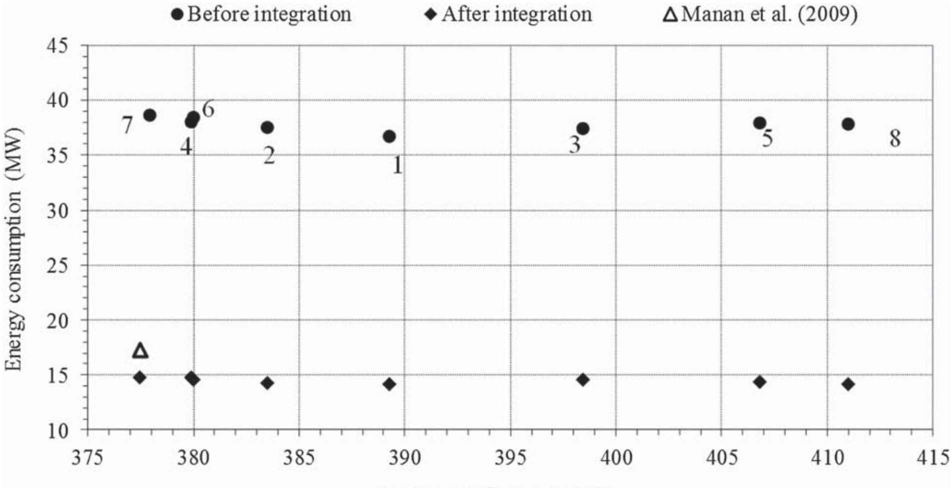

Fig. 10. Heat integration of the eight networks.

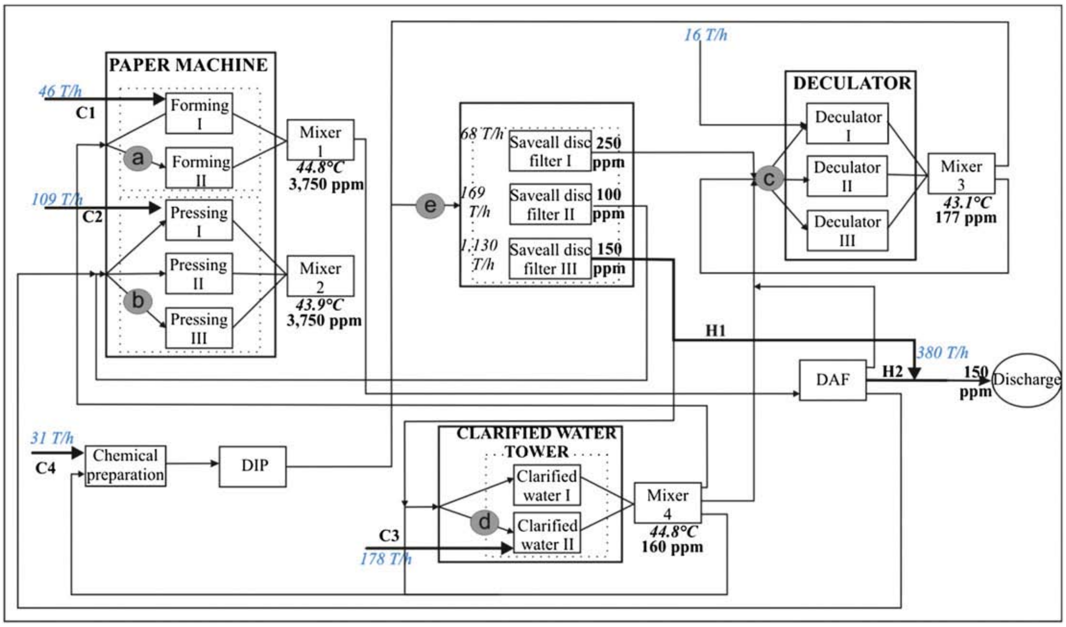

Fig. 11. Best water network with the five heat exchangers not considered for heat integration. C1 to C4 and H1, H2 are the five considered in Fig. 12 for heat integration.

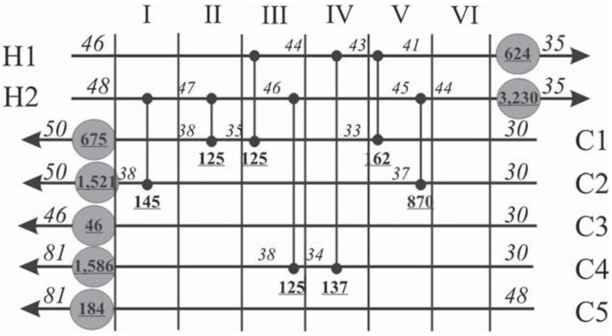

Fig. 12. Heat exchanger network for the solution of Fig. 11. Numbers in italic represent temperatures in °C whereas underlined numbers are enthalpy utilities expressed in kW.

number of connections leading to an increase in cost. Considering the cost including all items (fresh water, energy, heat exchangers and connections), network 6 turns out to be the most efficient. The corresponding water network is shown in Fig. 11 and the heat exchanger network is displayed in Fig. 12. Fig. 11 shows the water network with 5 heat exchangers noted a, b, c, d, e. These exchangers were not taken into account in the integration step because the difference between the temperature of inlet and outlet flows is smaller than 10 °C (minimal temperature approach). The enthalpy values associated with each heat exchanger of Fig. 11 are presented in Table 10 and the five flows considered for heat integration are represented in the Fig. 12. The total energy consumption in MW can be calculated by adding the enthalpy utilities of the five exchangers of Fig. 11 and the different utilities of Fig. 12. This sum reaches a total energy consumption of 14.07 MW for the network considered.

Table 10
Cold or hot utility for each heat exchanger of Fig. 11 (a to e).

Heat exchangers (cf. Fig. 11)	a	b	c	d	e
Hot (+) or cold (−) utilities (kW)	−217	−1211	+114	+1129	+1844

4. Conclusion

In this study, industrial water networks involving only one contaminant are optimized according to several objectives. This multiobjective optimization method is innovative when compared to previous works because different and better solutions with regard to the chosen objectives can be identified. To our knowledge, the works reported in the dedicated literature consider only one solution (generally corresponding to the minimum of fresh water consumption) for performing heat integration: by generating several non dominated solutions, the multiobjective approach proposed in this work provides several good compromise solutions for heat exchanger network design.

Considering the pair of criteria (fresh water, energy consumption) to be minimized, the corresponding MILP problem parameterized by the number of heat exchangers and connections, provides a set of non dominated solutions (trade-off solutions) with very reduced CPU times. A first procedure allows the allocation and design of heat exchangers on the various networks of the Pareto front. Finally, energy consumption is improved by performing heat integration on these networks, by minimizing a cost function by means of an MINLP procedure. This procedure was applied to an existing Malaysian paper mill plant and heat integration provides a gain of 21% as compared to the recent study of Manan et al. [43].

References

[1] OECD, Organisation for Economic Co-operation and Development. OECD Environmental Outlook to 2030, Paris, 2008.
[2] N. Takama, T. Kuriyama, K. Shiroko, T. Umeda, Optimal water allocation in a petroleum refinery, Comput. Chem. Eng. 4 (1980) 251–258.
[3] M.M. El-Halwagi, V. Manousiouthakis, Automatic synthesis of mass-exchange networks with single-component targets, Chem. Eng. Sci. 45 (1990) 2813–2831.
[4] A. Alva-Argaez, A. Kokossis, R. Smith, Wastewater minimization of industrial system using an integrated approach, Comput. Chem. Eng. 22 (suppl.) (1998) 741–744.
[5] C.H. Huang, C.T. Chang, H.C. Ling, C.C. Chang, A mathematical programming model for water usage and treatment network design. Ind, Eng. Chem. Res. 38 (1999) 2666–2679.
[6] A. Koppol, M. Bagajewicz, B. Dericks, M. Savelski, On zero water discharge solutions in the process industry, Ad. Environ. Res. 8 (2004) 151–171.

[7] M. Savelski, M. Bagajewicz, On the necessary conditions of optimality of water utilization systems in process plants with multiple contaminants, Chem. Eng. Sci. 58 (2003) 5349–5362.

[8] R. Karuppiah, I.E. Grossmann, Global optimization for the synthesis of integrated water systems in chemical processes, Comput. Chem. Eng. 30 (2006) 650–673.

[9] M. Boix, L. Montastruc, L. Pibouleau, C. Azzaro-Pantel, S. Domenech, A multiobjective optimization framework for multicontaminant industrial water network design, J. Environ. Manag. 92 (2011) 1802–1808.

[10] X. Feng, J. Bai, H. Wang, X. Zheng, Grass-roots design of regeneration recycling water networks, Comput. Chem. Eng. 32 (2008) 1892–1907.

[11] V.R. Dhole, N. Ramchandani, R.A. Tainsh, M. Wasilewski, Make your process water pay for itself, Chem. Eng. Sci. 103 (1996) 100–103.

[12] N. Hallale, A new graphical targeting method for water minimisation, Adv. Environ. Res. 6 (2002) 377–390.

[13] J. Jacob, C. Viviant, H.F. Houle, J. Paris, Analysis and optimization of water networkds in pulp and paper manufacturing: pinch technology, in French, Pulp Pap. Can. 103 (2002) 24–27.

[14] R.F. Dunn, M.M. El-Halwagi, Process integration technology review: background and applications in the chemical process industry, J. Chem. Technol. Biotechnol. 78 (2003) 1011–1021.

[15] Z.A. Manan, S.R. Wan Alwi, Z. Ujang, Water pinch analysis for an urban system: a case study on the Sultan Ismail Mosque at the Universiti Teknologi Malaysia (UTM), Desalination 194 (2006) 52–68.

[16] D. Ng, Y. Foo, R.R. Tan, Y. Tan, Ultimate flowrate targeting with regeneration placement, Chem. Eng. Res. Des 85 (2007) 1253–1267.

[17] Y.P. Wang, R. Smith, Wastewater minimization, Chem. Eng. Sci. 49 (1994) 981–1006.

[18] V. Lavric, P. Iancu, V. Plesu, Genetic algorithm optimisation of water consumption and wastewater network topology, J. Clean. Prod. 13 (2005) 1405–1415.

[19] D. Cao, X. Feng, X. Duan, Design of water network with internal mains for multi-contaminant wastewater regeneration recycle, Chem. Eng. Res. Des 82 (2004) 1331–1336.

[20] T.F. Yee, I.E. Grossmann, Z. Kravanja, Simultaneous optimization models for heat integration – I. Area and energy targeting and modelling of multi-stream exchangers, Comput. Chem. Eng. 14 (1990) 1151–1164.

[21] C.L. Chen, P.S. Hung, Simultaneous synthesis of flexible heat-exchange networks with uncertain source-stream temperatures and flow rates, Ind. Eng. Chem. Res. 43 (2004) 5916–5928.

[22] W. Verheyen, N. Zhang, Design of flexible heat exchanger network for multiperiod operation, Chem. Eng. Sci. 61 (2006) 7730–7753.

[23] A.J. Isafiade, D.M. Fraser, Interval-based MINLP superstructure synthesis of heat exchanger networks, Chem. Eng. Res. Des 86 (2008) 245–257.

[24] L.A. López-Maldonado, J.M. Ponce-Ortega, J.G. Segovia-Hernández, Multiobjective synthesis of heat exchanger networks minimizing the total annual cost and the environmental impact, Appl. Therm. Eng. 31 (2011) 1099–1113.

[25] E.C. Hohmann, Optimum networks for heat exchange, Ph.D. Thesis, University of Southern California, 1971.

[26] B. Linnhoff, D.W. Townsend, D. Boland, G.F. Hewitt, B.E.A. Thomas, A.R. Guy, R.H. Marsland, A User Guide on Process Integration for the Efficient Use of Energy, second ed. The Institution of Chemical Engineers, Rugby, UK, 1994.

[27] R. Smith, Chemical Process Design and Integration. Wiley, New York, USA, 2005.

[28] M.M. El-Halwagi, Process Integration. Elsevier, Amsterdam, 2006.

[29] M. Ravagnani, A. Silva, P. Arroyo, A. Constantino, Heat exchanger network synthesis and optimisation using genetic algorithm, App. Therm. Eng. 25 (2005) 1003–1017.

[30] B. Allen, L. Sarvard-Goguen, L. Gosselin, Optimization of heat exchanger networks with genetic algorithms designing each heat exchanger including condensers, App. Therm. Eng. 16 (2009) 3437–3444.

[31] M. Gorji-Bandpy, H. Yahyazadeh-Jelodar, M. Khalili, Optimization of heat exchanger network, Appl. Therm. Eng. 31 (2011) 779–784.

[32] D.R. Lewin, A generalized method for HEN synthesis using stochastic optimization – II. The synthesis of cost-optimal networks, Comput. Chem. Eng. 22 (1998) 1387–1405.

[33] L.E. Savulescu, R. Smith, Simultaneous Energy and Water Minimization. AIChE Annual Meeting, Miami, 1998.

[34] L.E. Savulescu, J.K. Kim, R. Smith, Studies on energy and water minimization – Part I: systems with no water re-use, Chem. Eng. Sci. 60 (2005a) 3279–3290.

[35] L.E. Savulescu, J.K. Kim, R. Smith, Studies on energy and water minimization – Part II: systems with maximum re-use of water, Chem. Eng. Sci. 60 (2005b) 3291–3308.

[36] M. Bagajewicz, H. Rodera, M. Savelski, Energy efficient water utilization systems in process plants, Comput. Chem. Eng. 26 (2002) 59–79.

[37] P. Zheng, X. Feng, F. Qian, D. Cao, Water system integration of a chemical plant, Ener. Convers. Manag. 47 (2006) 2470–2478.

[38] X. Zheng, X. Feng, D. Cao, Design water allocation network with minimum fresh water and energy consumption, Comput. Aided Chem. Eng. 15 (2003) 388–393.

[39] M. Bogataj, M. Bagajewicz, Synthesis of non-isothermal heat integrated water networks in chemical processes, Comput. Chem. Eng. 32 (2008) 3130–3142.

[40] H.G. Dong, C.Y. Lin, C.T. Chang, Simultaneous optimization approach for integrated water-allocation and heat-exchange networks, Chem. Eng. Sci. 63 (2008) 3664–3678.

[41] B. Leewongtanawit, J.K. Kim, Synthesis and optimization of heat-integrated multiple-contaminant water systems, Chem. Eng. Process 47 (2008) 670–694.

[42] G.T. Polley, M. Picón-Núñez, J.J. López-Maciel, Design of water and heat recovery networks for the simultaneous minimization of water and energy consumption, Appl. Therm. Eng. 30 (2010) 2290–2299.

[43] Z.A. Manan, S.Y. Tea, S.R. Wan Alwi, A new technique for simultaneous water and energy minimisation in process plant, Chem. Eng. Res. Des 87 (2009) 1509–1519.

[44] J. Du, X.Q. Meng, H.B. Du, H.M. Yu, X.S. Fan, P.J. Yao, Optimal design of water utilization network with energy integration in process industries, Chin. J. Chem. Eng. 12 (2004) 247–255.

[45] J. Martínez-Patiño, M. Picón-Núñez, L.M. Serra, V. Verda, Design of water and energy networks using temperature–concentration diagrams, Energy 36 (2011) 3888–3896.

[46] J.J. Klemeš, P.S. Varbanov, S. Pierucci, Process integration for energy and water saving, increasing efficiency and reducing environmental impact, Appl. Therm. Eng. 30 (2010) 2265–2269.

[47] J.J. Klemeš, F. Friedler, I. Bulatov, P.S. Varbanov, Sustainability in the Process Industry – Integration and Optimization. McGraw-Hill, New-York, 2010.

[48] G. Mavrotas, Effective implementation of the ε-constraint method in multi-objective mathematical programming problems, Appl. Math. Comput. 213 (2009) 455–465.

[49] M. Boix, L. Montastruc, L. Pibouleau, C. Azzaro-Pantel, S. Domenech, Multi-objective optimization of industrial water networks with contaminants, Comput. Aided Chem. Eng. 28 (2010) 859–864.

[50] M. Savelski, M. Bagajewicz, On the optimality conditions of water utilization systems in process plants with single contaminants, Chem. Eng. Sci. 55 (2000) 5035–5048.

[51] X. Feng, Y. Li, R. Shen, A new approach to design energy efficient water allocation networks, Appl. Therm. Eng. 29 (2009) 2302–2307.

[52] L. Ren, Y. Zhang, Y. Wang, Z. Sun, Comparative analysis of a novel M-TOPSIS method and TOPSIS, Appl. Math. Res. 1 (2007).