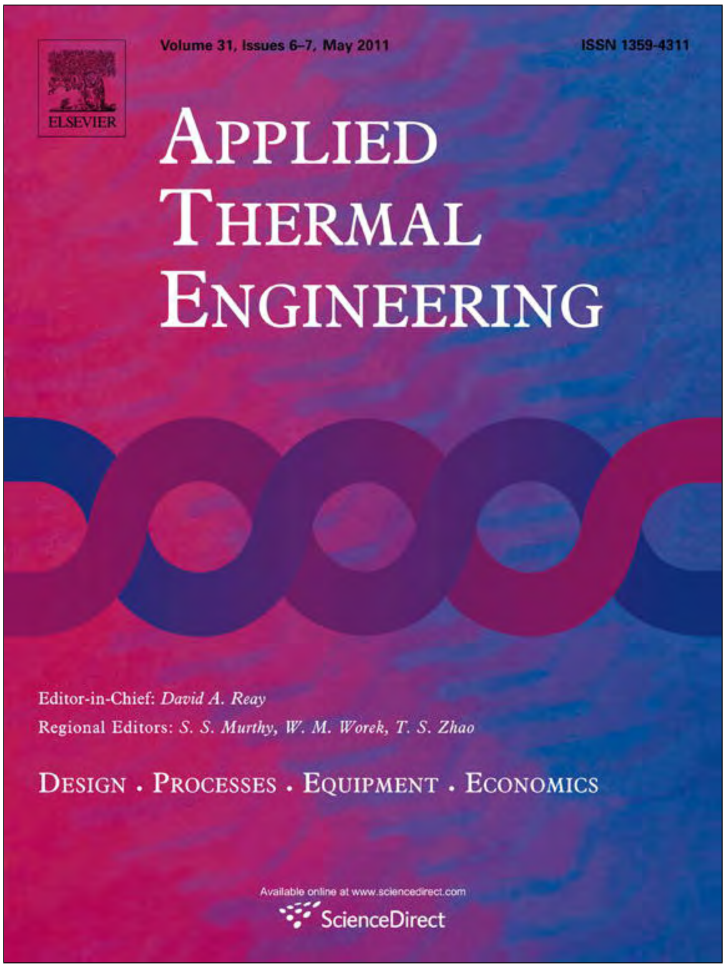
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Multiobjective synthesis of heat exchanger networks minimizing the total annual cost and the environmental impact

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ABSTRACT

This paper presents a mathematical programming formulation for the synthesis of heat exchanger networks minimizing simultaneously the total annual cost and the environmental impact. The proposed model consists of a Multiobjective Mixed Integer Non-Linear programming problem that considers the optimal location and use of different types of hot and cold utilities available through disjunctive formulations. The total annual cost objective function considers the minimization of the cost for the utilities and capital for the heat exchanger units, whereas the environmental impact objective function is calculated through the eco-indicator 99 for the different types of utilities using the life cycle analysis methodology. Three example problems are presented to show the applicability of the proposed methodology without numerical complications.

1. Introduction

The energy integration through heat exchanger networks (HENs) has produced significant economical and environmental benefits to the industry. Several papers reviews have been reported in different times for the methodologies to solve the HEN synthesis problem [1–4]. The most common methods to solve the synthesis of HEN can be classified as sequential [5–10] and simultaneous [11,12].

Most of the methodologies reported to solve the synthesis of HEN problem have considered exclusively one type of hot and one type of cold utilities, and these are placed at the extremes of the cold and hot process streams, respectively. However, in the industrial practice usually there are available several types of utilities (for example, hot oil, furnace fuel gas, high-pressure steam, medium-pressure steam, low-pressure steam, cooling water, air cooling, refrigerants, etc.) with different temperature levels, physical properties and unitary costs associated. Therefore, the optimal selection and location for the allowable utilities are decisions that must be taken into account during the synthesis of HEN. In this context, Costa and Quiroz [13] proposed a targeting approach for problems with different utilities by maximizing the use of the cheapest utilities, whereas Jezowski and Friedler [14] proposed basic algorithms for problems with multiple utilities and forbidden matches. Shethna et al. [15] reported an MILP model to predict the trade-offs between capital and utility costs for problems with multiple utilities. Shenoy et al. [16] proposed a targeting approach to determine the cost-optimal loads for multiple utilities. Isafiade and Fraser [17] formulated the problem of synthesis of HEN including multiple utilities as an MINLP problem, and Ponce-Ortega et al. [18] reformulate the model by Ponce-Ortega et al. [19] to include the optimal location of multiple utilities and isothermal process streams.

Recently, other methodologies have been proposed to solve the synthesis of HEN problem based on stochastic methods such as simulating annealing [20,21], genetic algorithms [22–26] and other stochastic methods [27–29] to avoid get trapped in local solutions.

In addition to the economical concerns, nowadays the environmental problems have become a priority, due to the environmental degradation produced by the industrial practice. The installation of a HEN yields by itself environmental benefits because this reduces the external consumption of utilities; however, for the case when several utilities are considered, the economic aspects must be considered simultaneously with the environmental impact that their use produces over their entire life cycle. Sometimes, the best economical solution may yield the worst environmental impact. Recently, several methodologies to track the environmental impact that any process, product or service produces over the entire life have been reported,

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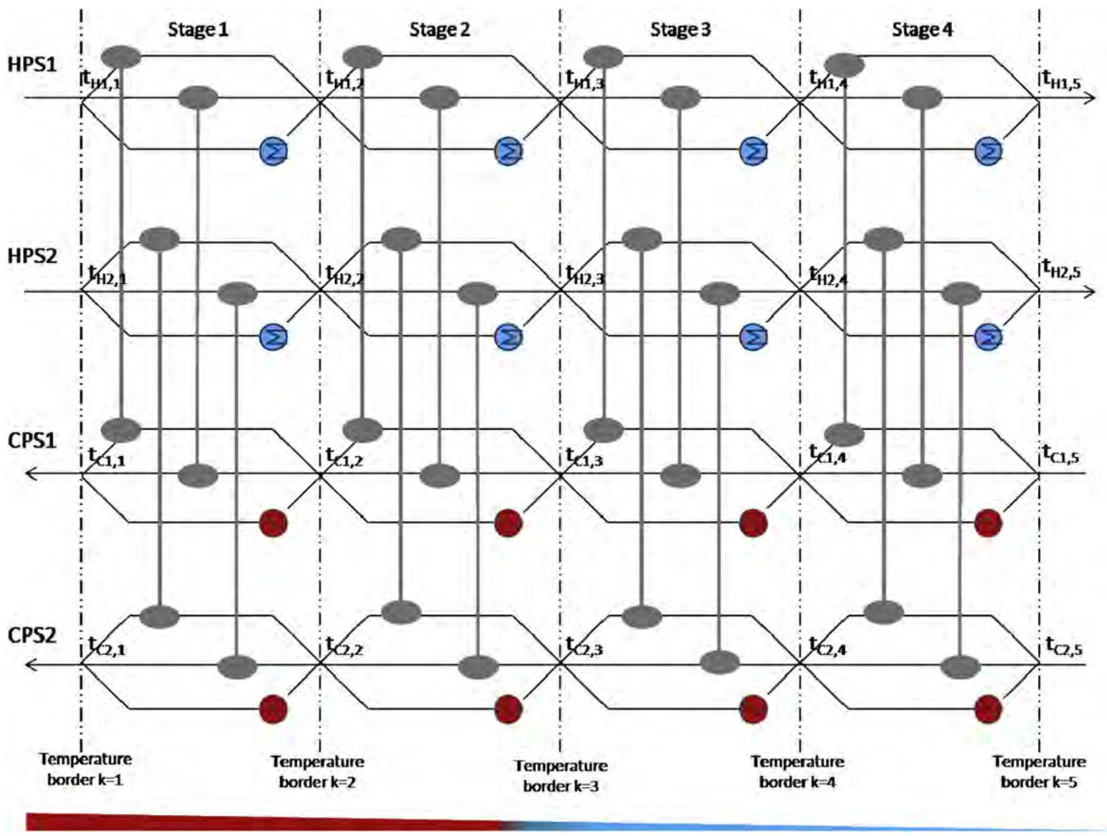

Fig. 1. Superstructure for the HEN synthesis.

one of these methodologies is the eco-indicator 99 that is based on the life cycle analysis (LCA) methodology [30]. Some applications of the LCA methodology to quantify the environmental impact in the process design have been reported by Azapagic and Clift [31], Alexander et al. [32], Hoffmann et al. [33], Chen and Shonnard [34], Hugo and Pistikopoulos [35], Guillén-Gosalbez et al. [36], Gebreslassie et al. [37], and others. In addition, Guillén-Gosalbez and Grossmann [38] have presented models for the design of supply chains involving the LCA methodology. Chen et al. [39] proposed a design procedure for the HEN design considering simultaneously economic and environmental aspects, and Wen and Shonnard [40] presented a methodology to determine the targets for the synthesis of HEN considering environmental and economic assessments; however, these two approaches are based on sequential formulations and they do not consider simultaneously the capital and operational costs of the network yielding suboptimal solutions.

This paper presents a multiobjective mixed integer non-linear programming problem (moMINLP) for the synthesis of HEN considering simultaneously the minimization of the total annual cost and the environmental impact. The total annual cost considers the utility cost as well as the capital cost for the heat exchanger units. The model also considers the optimal selection and location in the network of the different types of utilities available, and the environmental impact is measured trough the eco-indicator 99 associated to each type of the utilities selected. This paper is organized as follows; Section 2 presents the definition of the problem addressed in this paper, Section 3 presents the model formulation, Section 4 presents the methodology proposed to solve the moMINLP problem, the application to three cases of study of the proposed model is presented in Section 5; and finally, the conclusions are presented in Section 6.

2. Problem statement

Given a set of hot process streams (HPS) with their heat capacity flowrates that require to be cooled from their supply to their target temperatures as well as a set of cold process streams (CPS) with their heat capacity flowrates that require to be heated from their supply to their target temperatures. There are available a set of hot and cold utilities (HU and CU, respectively) to satisfy the heating and cooling requirements. Given also is the cost information for the different types of hot and cold utilities as well as the capital cost data for the heat exchangers units, in addition to the unitary environmental impacts associated to each type of utility calculated through the eco-indicator 99 methodology, considering the entirely life cycle for these utilities. The problem then consists of determining the heat exchanger network that minimizes simultaneously the total annual cost and the overall environmental impact.

3. Model formulation

The model formulation is based on the superstructure shown in Fig. 1, which is an extension of the superstructure by Yee and Grossmann [12,41]. In this case, the problem is divided into stages; in each stage any match of process streams is allowed; in addition, there exist the possibility to use any cold/hot utility available for the hot/cold process streams. The selection for the type of the external utilities is an optimization decision. The temperatures for the frontiers of the superstructure are optimization variables; and to avoid numerical complications, the isothermal mixing of the streams at the exit of any stage is considered (this way, there is only required the heat balance in each stage of the superstructure to determine the temperature of the frontier for each process stream and because the total flowrate for each stream is known previous to the optimization process, this balance is a linear relationship as can be seen in Eqs. (5) and (6)).

Before presenting the model formulation, the following sets are defined. HPS, CPS and ST represent the sets for the hot process streams, cold process streams and the number of stages in the superstructure. HPS1 and HPS2 are subsets for the nonisothermal and isothermal hot process streams, respectively. Whereas, CPS1 and CPS2 are subsets for the nonisothermal and isothermal cold process streams, respectively. The indexes i, j are used for the hot and cold process streams, whereas the index k is used for the stages in the superstructure. HU and CU are sets for the hot and cold utilities, and the indexes n and m are used for the hot and cold utilities, respectively. All the symbols used for the model formulation are presented in the Nomenclature section.

The constraints for the model include the mass and energy balances for the superstructure shown in Fig. 1, as well as the logical constraints for the existence of the heat exchanger units in the network and the selection for the type of utilities used, in addition to the objective functions for the total annual cost and the environmental impact. The model then is constituted for the following constraints.

(a) Total energy balances for the process streams

The total energy balance for a hot process stream i is equal to the sum of the energy exchanged with any cold process stream j in any stage of the superstructure, plus the heat exchanged with any cold utility m in any stage of the superstructure.

For nonisothermal hot process streams, the energy balance is stated as follows:

$$\left(T_{\mathrm{IN}_i} - T_{\mathrm{OUT}_i}\right)\mathrm{FCp}_i = \sum_{k\in \mathrm{ST}}\sum_{j\in \mathrm{CPS}} q_{i,j,k} + \sum_{k\in \mathrm{ST}}\sum_{m\in \mathrm{CU}} q_{\mathrm{cu}^m_{i,k}}, \quad i\in \mathrm{HPS1} \tag{1}$$

Whereas for the isothermal hot process streams:

$$F\lambda_i^{\mathrm{cond}} = \sum_{k\in \mathrm{ST}}\sum_{j\in \mathrm{CPS}} q_{i,j,k} + \sum_{k\in \mathrm{ST}}\sum_{m\in \mathrm{CU}} q_{\mathrm{cu}^m_{i,k}}, \quad i\in \mathrm{HPS2} \tag{2}$$

Furthermore, the total energy balance for any cold process stream j is equal to the sum of the energy exchanged with any hot process stream i in any stage of the superstructure, plus the heat exchanged with any cold utility n in any stage of the superstructure.

For nonisothermal cold process streams:

$$\left(T_{\mathrm{OUT}_j} - T_{\mathrm{IN}_j}\right)\mathrm{FCp}_j = \sum_{k\in \mathrm{ST}}\sum_{i\in \mathrm{HPS}} q_{i,j,k} + \sum_{k\in \mathrm{ST}}\sum_{n\in \mathrm{HU}} q_{\mathrm{hu}^n_{j,k}}, \quad j\in \mathrm{CPS} \tag{3}$$

And for the isothermal cold process streams:

$$F\lambda_j^{\mathrm{evap}} = \sum_{k\in \mathrm{ST}}\sum_{i\in \mathrm{HCPS}} q_{i,j,k} + \sum_{k\in \mathrm{ST}}\sum_{n\in \mathrm{HU}} q_{\mathrm{hu}^n_{j,k}}, \quad j\in \mathrm{CPS2} \tag{4}$$

(b) Energy balance for each stage of the superstructure

An energy balance for each hot and cold process stream in each stage of the superstructure is required to calculate the temperature at the border of each stage.

For the hot process streams, the energy exchanged in the stage k is equal to the energy exchanged with any cold process stream plus the energy exchanged with any cold utility.

$$\left(t_{i,k} - t_{i,k+1}\right)\mathrm{FCp}_i = \sum_{j\in \mathrm{CPS}} q_{i,j,k} + \sum_{m\in \mathrm{CU}} q_{\mathrm{cu}^m_{i,k}}, \quad k\in \mathrm{ST},\ i\in \mathrm{HPS1} \tag{5}$$

For the cold process streams, the energy exchanged in any stage k is equal to the energy exchanged with any hot process stream plus the energy exchanged with any hot utility.

$$\left(t_{j,k} - t_{j,k+1}\right)\mathrm{FCp}_j = \sum_{i\in \mathrm{HPS}} q_{i,j,k} + \sum_{n\in \mathrm{HU}} q_{\mathrm{hu}^n_{j,k}}, \quad k\in \mathrm{ST},\ j\in \mathrm{CPS1} \tag{6}$$

Notice here that the optimization variables are the temperatures for the frontiers of the stages of the superstructure ($t_{i,k}$) and that FCp_i is a known parameter; therefore, Eqs. (5) and (6) are convex linear relationships. If the isothermal mixing is not considered, there is required an energy balance around each exchanger and also the individual flowrate and the outlet temperature from each exchanger become into optimization variables, this yields non-convex relationships because the bilinear terms for the individual flowrate times outlet temperature (these non-convex terms are hard to solve and can easily get trapped in local suboptimal solutions).

(c) Assignment of the temperatures for the extreme borders for the superstructure

The supply temperatures for the hot and cold process streams correspond to the temperatures for the first border and last border of the superstructure, respectively.

$$T_{\mathrm{IN}_i} = t_{i,1}, \quad i\in \mathrm{HPS} \tag{7}$$

$$T_{\mathrm{IN}_j} = t_{j,\mathrm{NOK}+1}, \quad j\in \mathrm{CPS} \tag{8}$$

Whereas, the target temperatures for the hot and cold process streams correspond to the last and first border of temperatures for the superstructure, respectively.

$$T_{\mathrm{OUT}_i} = t_{i,\mathrm{NOK}+1}, \quad i\in \mathrm{HPS} \tag{9}$$

$$T_{\mathrm{OUT}_j} = t_{j,1}, \quad j\in \mathrm{CPS} \tag{10}$$

(d) Constraints for the feasibility of the temperatures in the superstructure

To ensure a monotonically decrease for the temperatures from the left side to the right side of the superstructure the following constraints must be included.

$$t_{i,k} \ge t_{i,k+1}, \quad k\in \mathrm{ST},\ i\in \mathrm{HPS1} \tag{11}$$

$$t_{i,k} = T_{\mathrm{IN},i}, \quad k\in \mathrm{ST},\ i\in \mathrm{HPS2} \tag{12}$$

$$t_{j,k} \ge t_{j,k+1}, \quad k\in \mathrm{ST},\ j\in \mathrm{CPS1} \tag{13}$$

$$t_{j,k} = T_{\mathrm{IN},j}, \quad k\in \mathrm{ST},\ j\in \mathrm{CPS2} \tag{14}$$

(e) Definition for the heat exchanger units

Following relationships are used to active the binary variables z when these exchange a given amount of heat (i.e., when the heat exchanged is greater than zero, the associated binary variable must be one). These relationships are stated for the heat exchanger units between process streams, and cold and hot utilities.

$$q_{i,j,k} - Q_{i,j}^{\max} z_{i,j,k} \le 0, \quad i\in \mathrm{HPS},\ j\in \mathrm{CPS},\ k\in \mathrm{ST} \tag{15}$$

$$q_{\mathrm{cu}^m_{i,k}} - Q_i^{\max} z_{\mathrm{cu}^m_{i,k}} \le 0, \quad i\in \mathrm{HPS},\ k\in \mathrm{ST},\ m\in \mathrm{CU} \tag{16}$$

$$q_{\mathrm{hu}^n_{j,k}} - Q_k^{\max} z_{\mathrm{hu}^n_{j,k}} \le 0, \quad j\in \mathrm{CPS},\ k\in \mathrm{ST},\ n\in \mathrm{HU} \tag{17}$$

(f) Feasibilities for the temperature differences

When the heat exchanger units exist, it is required that the difference between the temperatures for the hot and cold process

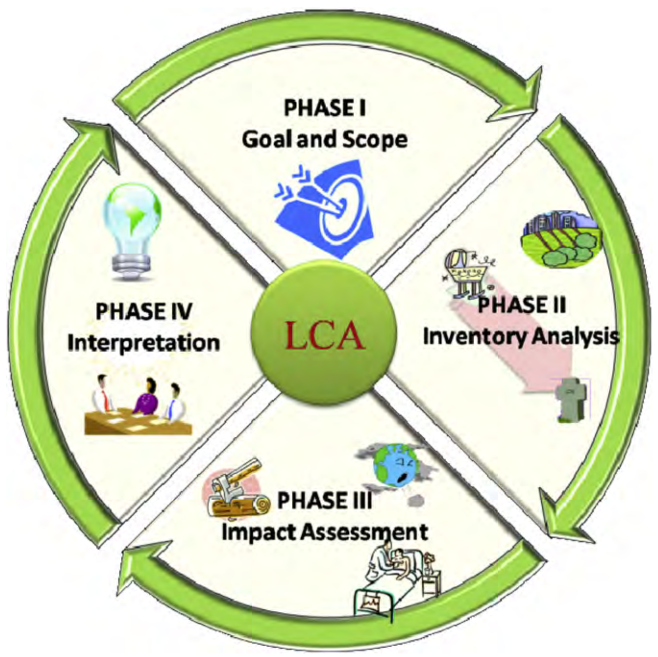

Fig. 2. Phases of the LCA methodology.

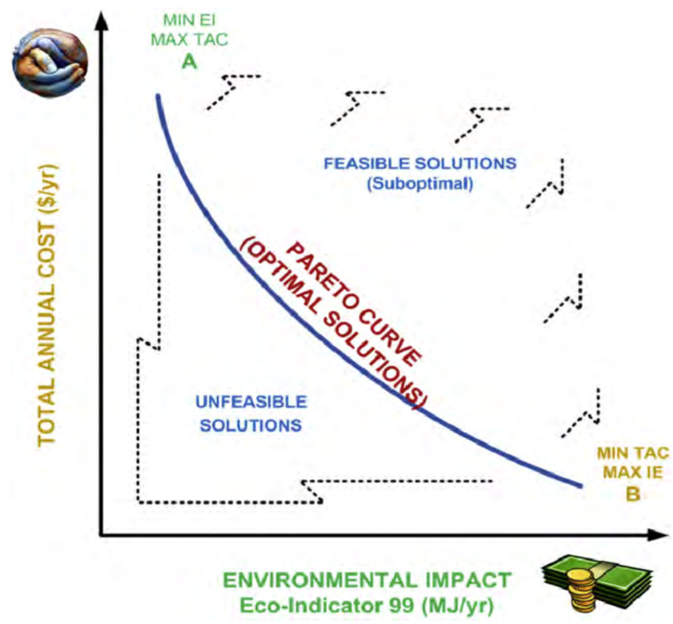

Fig. 3. Pareto frontier optimal solutions.

streams must be greater than the minimum temperature difference allowed. Therefore, the difference of temperatures for the frontiers of the superstructure must be calculated only when the heat exchanger exists as follows.

$$dt_{i,j,k} \le t_{i,k} - t_{j,k} + \Delta T^{max}_{i,j}\left(1 - z_{i,j,k}\right), \quad i \in HPS,\ j \in CPS,\ k \in ST \tag{18}$$

$$dt_{i,j,k+1} \le t_{i,k+1} - t_{j,k+1} + \Delta T^{max}_{i,j}\left(1 - z_{i,j,k}\right), \quad i \in HPS,\ j \in CPS,\ k \in ST \tag{19}$$

Similarly for the coolers

$$dt_{cu_{i,k}} \le t_{i,k} - T_{OUT_{cu_{i,k}}} + \Delta T^{max}_{cu_i}\left(1 - z_{cu_{i,k}}\right), \quad i \in HPS,\ k \in ST \tag{20}$$

$$\left[\begin{array}{c} Z_{cu_{i,k}} \\ \left[\begin{array}{c} Z_{cu^1_{i,k}} \\ \left[\begin{array}{c} T_{OUT,cu_{i,k}} = T_{OUT,cu^1} \\ T_{IN,cu_{i,k}} = T_{IN,cu^1} \end{array}\right] \end{array}\right] \vee \left[\begin{array}{c} Z_{cu^2_{i,k}} \\ T_{OUT,cu_{i,k}} = T_{OUT,cu^2} \\ T_{IN,cu_{i,k}} = T_{IN,cu^2} \end{array}\right] \vee \ldots \vee \left[\begin{array}{c} Z_{cu^{NCU}_{i,k}} \\ T_{OUT,cu_{i,k}} = T_{OUT,cu^{NCU}} \\ T_{IN,cu_{i,k}} = T_{IN,cu^{NCU}} \end{array}\right] \end{array}\right] \vee \left[\begin{array}{c} \neg Z_{cu_{i,k}} \\ \left[\begin{array}{c} T_{OUT,cu_{i,k}} = 0 \\ T_{IN,cu_{i,k}} = 0 \end{array}\right] \end{array}\right], i \in HPS,\ k \in ST \tag{28}$$

$$dt_{cu_{i,k+1}} \le t_{i,k+1} - T_{IN_{cu_{i,k}}} + \Delta T^{max}_{cu_i}\left(1 - z_{cu_{i,k}}\right), \ i \in HPS,\ k \in ST \tag{21}$$

And finally for the heaters

$$dt_{hu_{j,k}} \le T_{IN_{hu_{j,k}}} - t_{j,k} + \Delta T^{max}_{hu_j}\left(1 - z_{hu_{j,k}}\right), \quad j \in CPS,\ k \in ST \tag{22}$$

$$dthu_{j,k+1} \le T_{OUT_{hu_{j,k}}} - t_{j,k+1} + \Delta T^{max}_{hu_j}\left(1 - zhu_{j,k}\right), \ j \in CPS,\ k \in ST \tag{23}$$

where the parameters $\Delta T^{max}_{i,j}$, $\Delta T^{max}_{cu_i}$ and $\Delta T^{max}_{hu_i}$, are calculated as follows.

$$\begin{array}{ll} \text{if} & \begin{array}{l} T_{IIN,i} - T_{JIN,j} < \Delta T_{MIN} \\ \Delta T^{max}_{i,j} = abs\left[T_{IIN,i} - T_{JIN,j}\right] + \Delta T_{MIN} \end{array} \\ \text{else} & \Delta T^{max}_{i,j} = \max\left\{0, T_{IIN,i} - T_{JIN,j}, T_{JOUT,j} - T_{IOUT,i}\right\} \end{array} \tag{24}$$

Therefore, to ensure a feasible heat exchange, the following constraints must be included.

$$\Delta T_{min} \le dt_{i,j,k}, \quad i \in HPS,\ j \in CPS,\ k \in ST \tag{25}$$

$$\Delta T_{min} \le dt_{cu_{i,k}}, \quad i \in HPS,\ k \in ST \tag{26}$$

$$\Delta T_{min} \le dt_{hu_{j,k}}, \quad j \in CPS,\ k \in ST \tag{27}$$

(g) Selection for the type of cold utility

When a cooler exists for a specific location of the superstructure, it is required to select the type of cold utility used and therefore the associated inlet and outlet temperatures as follows.

Previous disjunction implies that when the Boolean variable $Z_{cu_{i,k}}$ is true, then one of the Boolean variables $z^1_{cu_{i,k}}, z^2_{cu_{i,k}}, z^{NCU}_{cu_{i,k}}$ must be true, and the associated temperature must be calculated according to it. When the Boolean variable $z_{cu_{i,k}}$ is false, the temperature for the cold utility are set as zero because the unit does

Table 1
Stream data for Example 1.

Stream	T_{in} (°C)	T_{out} (°C)	FCp (kW/°C)	h (kW/m^2 °C)	Cost ($/yr)	Eco-indicator 99 (1/kJ)
H1	105	25	10.0	0.5	–	–
H2	185	35	5.0	0.5	–	–
C1	25	185	7.5	0.5	–	–
HPS[a]	210	209	–	5.0	160	8.7058E–03
MPS[b]	160	159	–	5.0	110	8.8656E–03
LPS[c]	130	129	–	5.0	50	9.1278E–03
CW[d]	5	6	–	2.6	10	2.0219E–05

[a] High-pressure steam.
[b] Medium-pressure steam.
[c] Low-pressure steam.
[d] Cooling water.

Table 2
Results for Example 1.

Designs	Total area (m^2)	Utilities cost ($/yr)	Capital cost ($/yr)	Total annual cost ($/yr)	Environmental impact (1/yr)
Minimum TAC solution B	184.239	53,157.173	43,922.66	97,079.84	4,084.39
Minimum EIA solution A	5,755.919	28,150.000	1,372,210.67	1,400,400.00	2,427.99
Goal solution	218.064	49,335.778	51,986.37	101,320.00	3,350.00

not exist. This disjunction is modeled using the convex hull reformulation as follows [42,43].

$$z_{\mathrm{cu}_{i,k}} = \sum_{m \in \mathrm{CU}} z_{\mathrm{cu}^m_{i,k}}, \quad i \in \mathrm{HPS}, \; k \in \mathrm{ST} \tag{29}$$

$$T_{\mathrm{OUT,cu}_{i,k}} = \sum_{m \in \mathrm{CU}} t_{\mathrm{out,cu}^m_{i,k}}, \quad i \in \mathrm{HPS}, \; k \in \mathrm{ST} \tag{30}$$

$$T_{\mathrm{IN,cu}_{i,k}} = \sum_{m \in \mathrm{CU}} t_{\mathrm{in,cu}^m_{i,k}}, \quad i \in \mathrm{HPS}, \; k \in \mathrm{ST} \tag{31}$$

$$t_{\mathrm{out,cu}^m_{i,k}} = T_{\mathrm{OUT,cu}^m} z_{\mathrm{cu}^m_{i,k}}, \quad i \in \mathrm{HPS}, \; k \in \mathrm{ST}, \; m \in \mathrm{CU} \tag{32}$$

$$t_{\mathrm{in,cu}^m_{i,k}} = T_{\mathrm{IN,cu}^m_{i,k}} z_{\mathrm{cu}^m_{i,k}}, \quad i \in \mathrm{HPS}, \; k \in \mathrm{ST}, \; m \in \mathrm{CU} \tag{33}$$

(h) Selection for the type of hot utility

Similarly for the heaters, it is required to select the type of hot utility; in the next disjunction, if the Boolean variable $z_{\mathrm{hu}_{j,k}}$ is true, the inlet and outlet temperatures associated are assigned. However, if Boolean variable $z_{\mathrm{hu}_{j,k}}$ is false, the inlet and outlet temperatures for the hot utility are set as zero, because that unit does not exist.

Previous disjunction is modeled using the convex hull reformulation yielding the following equations:

$$z_{\mathrm{hu}_{j,k}} = \sum_{n \in \mathrm{HU}} z_{\mathrm{hu}^n_{j,k}}, \quad j \in \mathrm{CPS}, \; k \in \mathrm{ST} \tag{35}$$

$$T_{\mathrm{OUT,hu}_{j,k}} = \sum_{n \in \mathrm{HU}} t_{\mathrm{out,hu}^n_{j,k}}, \quad j \in \mathrm{CPS}, \; k \in \mathrm{ST} \tag{36}$$

$$T_{\mathrm{IN,hu}_{j,k}} = \sum_{n \in \mathrm{HU}} t_{\mathrm{in,hu}^n_{j,k}}, \quad j \in \mathrm{CPS}, \; k \in \mathrm{ST} \tag{37}$$

$$t_{\mathrm{out,hu}^n_{j,k}} = T_{\mathrm{OUT,hu}^n_{j,k}} z_{\mathrm{hu}^n_{j,k}}, \quad j \in \mathrm{CPS}, \; k \in \mathrm{ST}, \; n \in \mathrm{HU} \tag{38}$$

$$t_{\mathrm{in,hu}^n_{j,k}} = T_{\mathrm{IN,hu}^n_{j,k}} z_{\mathrm{hu}^n_{j,k}}, \quad j \in \mathrm{CPS}, \; k \in \mathrm{ST}, \; n \in \mathrm{HU} \tag{39}$$

(i) Objective function

The objective function consists of the simultaneous minimization of the total annual cost and the environmental impact. These objectives are stated as follows:

$$\min Z = \{\mathrm{TAC}; \mathrm{EI}\} \tag{40}$$

where TAC is the total annual cost associated to the synthesis of the HEN, and EI is the global environmental impact due to the operation for the new HEN. Notice that these two objectives contradict each other. The formulations for these two objectives are presented as follows.

$$\left[\left[\begin{array}{c} Z_{\mathrm{hu}^1_{j,k}} \\ T_{\mathrm{OUT,hu}_{j,k}} = T_{\mathrm{OUT,hu}^1} \\ T_{\mathrm{IN,hu}_{j,k}} = T_{\mathrm{IN,hu}^1} \end{array}\right] \vee \left[\begin{array}{c} Z_{\mathrm{hu}_{j,k}} \\ Z_{\mathrm{hu}^2_{j,k}} \\ T_{\mathrm{OUT,hu}_{j,k}} = T_{\mathrm{OUT,hu}^2} \\ T_{\mathrm{IN,hu}_{j,k}} = T_{\mathrm{IN,hu}^2} \end{array}\right] \vee \ldots \vee \left[\begin{array}{c} Z_{\mathrm{cu}^{\mathrm{NHU}}_{j,k}} \\ T_{\mathrm{OUT,hu}_{j,k}} = T_{\mathrm{OUT,hu}^{\mathrm{NHU}}} \\ T_{\mathrm{IN,hu}_{j,k}} = T_{\mathrm{IN,hu}^{\mathrm{NHU}}} \end{array}\right]\right] \vee \left[\begin{array}{c} \neg Z_{\mathrm{hu}_{j,k}} \\ T_{\mathrm{OUT,hu}_{j,k}} = 0 \\ T_{\mathrm{IN,hu}_{j,k}} = 0 \end{array}\right], \quad j \in \mathrm{CPS}, \; k \in \mathrm{ST} \tag{34}$$

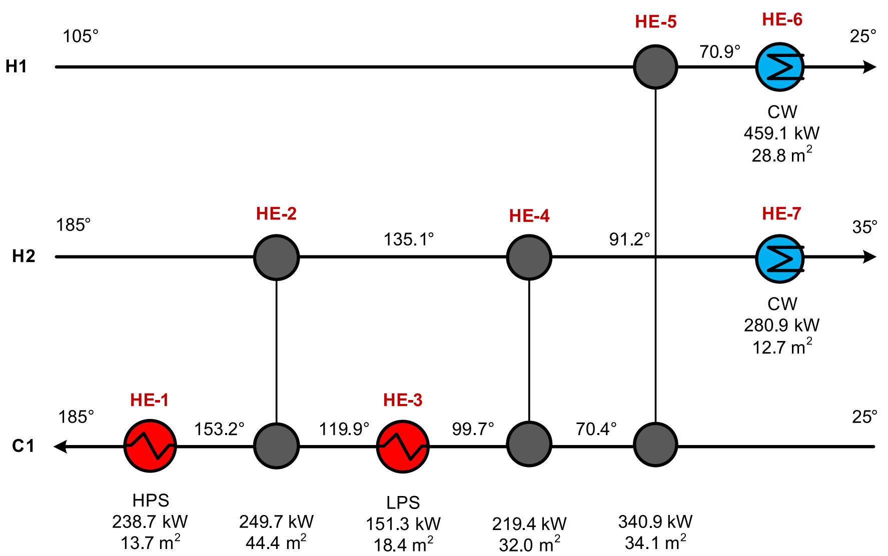

Fig. 4. Network with the minimum TAC for the Example 1.

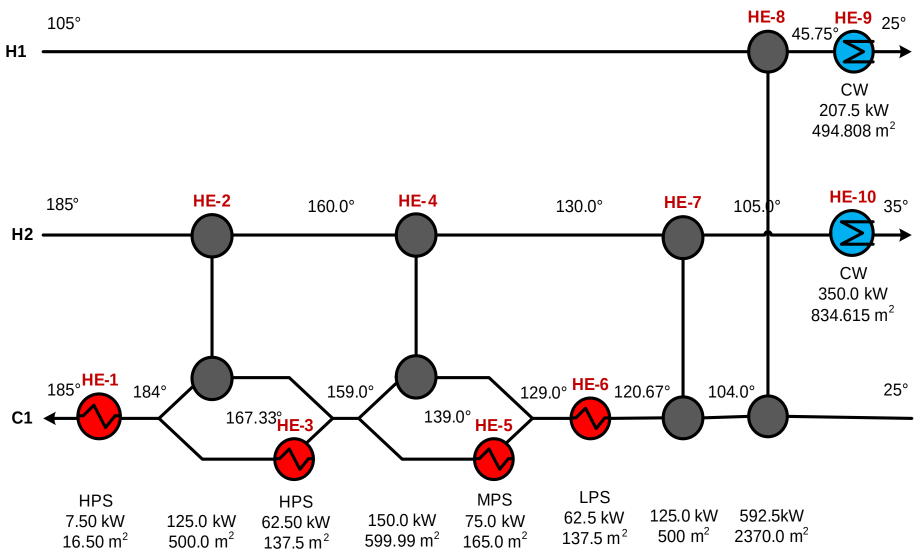

Fig. 5. Network with minimum EI for Example 1.

3.1. *Total annual cost objective function*

The objective function for the total annual cost includes the operation cost for hot and cold utilities and capital cost due to the heat exchanger area for each transfer unit, as well as the fixed cost for the exchangers, coolers and heaters. Chen [44] approximation is used to calculate the LMTD for the heat exchanger units to avoid the use of logarithmic terms in the optimization model. Therefore, the problem is formulated as the minimization of the total annual cost as follows:

$$
\begin{aligned}
\min \mathrm{TAC} = {} & \sum_{i\in \mathrm{HPS}}\sum_{k\in \mathrm{ST}}\sum_{m\in \mathrm{CU}} C_{\mathrm{CU}^m} q_{\mathrm{cu}^m_{i,k}} + \sum_{j\in \mathrm{CPS}}\sum_{k\in \mathrm{ST}}\sum_{n\in \mathrm{HU}} C_{\mathrm{HU}^n} q_{\mathrm{hu}^n_{j,k}} \\
& + \mathrm{AN_F}\Bigg[\sum_{i\in \mathrm{HPS}}\sum_{j\in \mathrm{CPS}}\sum_{k\in \mathrm{ST}} C_{F_{i,j}} z_{j,k} + \sum_{i\in \mathrm{HPS}}\sum_{k\in \mathrm{ST}} C_{F_{i,\mathrm{cu}}} z_{\mathrm{cu}_{i,k}} + \sum_{j\in \mathrm{CPS}}\sum_{k\in \mathrm{ST}} C_{F_{\mathrm{cu},j}} z_{\mathrm{hu}_{j,k}} \\
& + \sum_{i\in \mathrm{HPS}}\sum_{j\in \mathrm{CPS}}\sum_{k\in \mathrm{ST}} C_{i,j} \left\{ \frac{q_{i,j,k}\left(\frac{1}{h_{i,k}}+\frac{1}{h_{j,k}}\right)}{\left[\left(dt_{i,j,k}\right)\left(dt_{i,j,k+1}\right)\left(\frac{dt_{i,j,k}+dt_{i,j,k+1}}{2}\right)+\Delta\right]^{1/3}} \right\}^{\beta} \\
& + \sum_{i\in \mathrm{HPS}}\sum_{k\in \mathrm{ST}} C_{i,\mathrm{cu}} \left\{ \frac{\sum_{m\in \mathrm{CU}} q_{\mathrm{cu}^m_{i,k}}\left(\frac{1}{h_i}+\frac{1}{h^m_{\mathrm{cu}}}\right)}{\left[\left(dt_{\mathrm{cu}_{i,k}}\right)\left(dt_{\mathrm{cu}_{i,k+1}}\right)\left(\frac{dt_{\mathrm{cu}_{i,k}}+dt_{\mathrm{cu}_{i,k+1}}}{2}\right)+\Delta\right]^{1/3}} \right\}^{\beta} \\
& + \sum_{j\in \mathrm{CPS}}\sum_{k\in \mathrm{ST}} C_{\mathrm{hu},j} \left\{ \frac{\sum_{n\in \mathrm{HU}} q_{\mathrm{hu}^n_{j,k}}\left(\frac{1}{h^n_{\mathrm{hu}}}+\frac{1}{h_j}\right)}{\left[\left(dt_{\mathrm{hu}_{j,k}}\right)\left(dt_{\mathrm{hu}_{j,k+1}}\right)\left(\frac{dt_{\mathrm{hu}_{j,k}}+dt_{\mathrm{hu}_{i,k+1}}}{2}\right)+\Delta\right]^{1/3}} \right\}^{\beta} \Bigg]
\end{aligned} \tag{41}
$$

The parameter Δ is used to avoid infeasibilities in previous equation, and $\mathrm{AN_F}$ is an annualization factor for the capital costs. C_{CU^m} and C_{HU^n} are the unitary cold and hot utility costs, respectively. C_F is the fixed charge for the capital cost for the heat exchanger units, whereas C and β are coefficients for the capital cost functions.

It is worth notice here that the film heat transfer coefficients for the streams are considered constants, known previous to the optimization process, based on the physical properties of the streams and the experience of the designer. To calculate adequately the film heat transfer coefficients, the highly non-convex formulations by Serna-González et al. [45], Mizutani et al. [46], Ponce-Ortega et al. [43], Ravagnani and Caballero [47] can be used. However, these relationships do not guarantee optimal solutions and they are very difficult to solve using deterministic optimization approaches. In this context, using good assumed values for the film heat transfer coefficients based on the experience, the heat exchangers detailed design can be done after the synthesis of the HEN manipulating the exchangers geometry and the pressures drops as optimization variables to determine the real film heat transfer coefficients as it is usually done in most of the previously reported methodologies [1–4], avoiding this way numerical complications in the synthesis of the HEN.

3.2. *Environmental impact objective function*

The eco-indicator 99 was used to quantify the environmental impact, which uses the life cycle analysis (LCA) methodology. The LCA is an approach for analysis and evaluation of the environmental impact associated to a product, process or activity. Fig. 2 shows the main stages of the LCA to obtain the eco-indicator 99 [30,48].

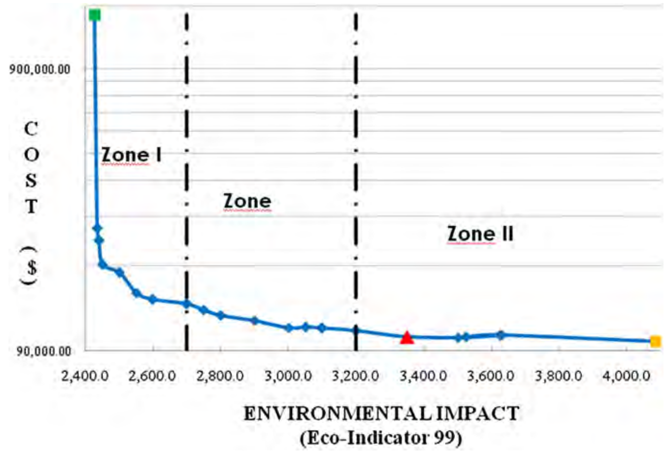

Fig. 6. Pareto frontier for Example 1.

Three impact categories are identified in the eco-indicator 99: (1) damage to the human health, which is measured in DAYLY's per kg of emission (Disability Adjusted Life Years; that means that one life year of one individual is lost, or one person suffers four years from a disability with a weight of 0.25); (2) damage to the ecosystem quality, which is measured in PDF per kg release or kg of emission to air (Potentially Disappeared Fraction of Species; i.e., all species disappear from 1 m^2 during one year, or 10% percent of all species disappear from 10 m^2 during one year); and finally (3) damage to the resources, which is measured in MJ surplus energy per kg of extracted material, or kg of extracted fuel, or per m^3 of extracted gas, or per MJ extracted energy; (i.e., a damage of 1 means that due to a certain extraction, further extraction of this resources in the future will require one additional MJ of energy, due to the lower resource concentration, or other unfavorable characteristics of the remaining reserves).

These three categories are subdivided into 11 subcategories as follows.

1. Carcinogenic effects on humans.
2. Respiratory effects on humans that are caused by organic substances.
3. Respiratory effects on humans that are caused by inorganic substances.
4. Damage to human health that is caused by climate change.
5. Human health effects that are cause by ionizing radiations.
6. Human health effects that are caused by ozone layer depletion.
7. Damage to ecosystem quality that is caused by ecosystem toxics emissions.
8. Damage to ecosystem quality that is caused by combined effect of acidification and eutrophication.
9. Damage to ecosystem quality that is caused by land occupation and land conversion.
10. Damage to resources caused by the extraction of minerals.
11. Damage to resources caused by extraction of fossil fuels.

The Eq. (42) can be used to calculate the eco-indicator 99:

$$\text{EcoIndicator} = \sum_{d} \sum_{b \in I(d)} \delta_d \omega_d \theta_b \tag{42}$$

$$\theta_i = \sum_{b} \beta_b \alpha_{bi} \tag{43}$$

where θ_b is the damage category that is calculated from the environmental burdens of the chemical process, β_b is associated with

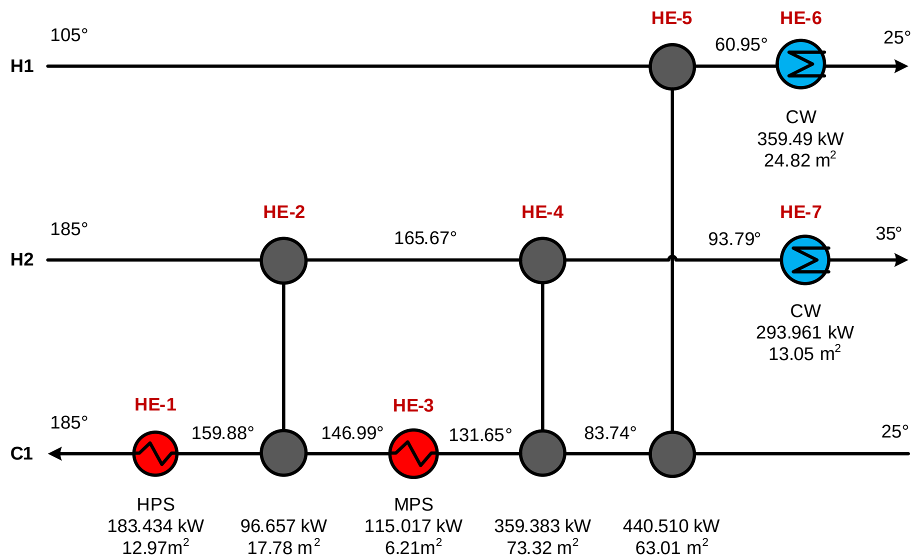

Fig. 7. Optimal solution obtained for the Goal method for Example 1.

Table 3
Stream data for Example 2.

Stream	T_{in} (°C)	T_{out} (°C)	FCp (kW/°C)	h (kW/m^2 °C)	Cost ($/yr)	Eco-indicator 99 (1/kJ)
H1	155	85	150.0	0.5	–	–
H2	230	40	85.0	0.5	–	–
C1	115	210	140	0.5	–	–
C2	50	180	55	0.5	–	–
C3	60	175	60	0.5	–	–
HPS[a]	255	254	–	0.5	70	8.7058E–03
MPS[b]	205	204	–	0.5	50	8.8656E–03
LPS[c]	150	149	–	0.5	20	9.1278E–03
CW[d]	30	40	–	0.5	10	2.0219E–05
CA[e]	40	65	–	0.5	5	2.9044E–06

[a] High-pressure steam.
[b] Medium-pressure steam.
[c] Low-pressure steam.
[d] Cooling water.
[e] Cooling air.

Table 4
Results for Example 2.

Designs	Total area (m^2)	Utilities cost ($/yr)	Capital cost ($/yr)	Total annual cost ($/yr)	Environmental impact (1/yr)
Minimum TAC solution B	6,780.75	495,917.16	724,308.54	1,220,225.70	78,012.00
Minimum EI solution A	98,182.07	249,450.00	6,662,527.40	6,911,977.40	41,138.08
Goal solution	8,368.58	378,264.97	958,303.58	1,336,568.55	58,821.00

the direct emissions, the energy generation and the production of raw materials, and α_{bi} is the damage factor associated to each damage category d.

The eco-indicator 99 uses the normalization and weighting factors δ_d and ω_d, respectively. In this work, the Hierarchist perspective is used for the LCA methodology [48].

Present work considers the environmental impact that is generated by the entirely life, since production to final disposal for the hot and cold utilities. Notice that the model allows the optimal selection of different types of utilities, for heating different steams (high-, medium- and low-pressure steam) are considered, whereas for cooling, cooling water, air cooling and different types of refrigerants are considered. The aspects considered for the calculations for the eco-indicator 99 for these utilities are the energy required for their production, resources extractions, consumption of fossil fuels, as well as the extraction of raw materials and the emission of pollutants to the environment.

The objective function for the environmental impact is formulated as the product of the eco-indicator 99 for each heating utility and the total load of each hot utility used, plus the eco-indicator 99 for each cold utility times their corresponding total load of cold utilities, in all stages of the superstructure. The objective function is annualized as well as the function for the total annual cost as follows.

$$\min \mathrm{EI} = H_Y\left[\sum_{i\in HPS}\sum_{k\in ST}\sum_{n\in HU}\left(q_{hu^n_{i,k}}\right)\left(\mathrm{EcoIndicator}_{hu^n}\right) + \sum_{j\in CPS}\sum_{k\in ST}\sum_{m\in CU}\left(q_{cu^m_{j,k}}\right)\left(\mathrm{EcoIndicator}_{cu^m}\right)\right] \quad (44)$$

Finally, the optimization formulation minimizes (41) and (44) subject to the constraints given by Eqs. (1)–(39) yielding a moMINLP model. Next section explains the way to solve adequately this problem.

4. Solution strategy

Several methodologies have been reported to solve moMINLP optimization problems (see [49]), in the present paper the constraint and goal methods are used.

4.1. Constraint method

In the constraint method, one of the objectives is transformed as a limit, and the problem consists of minimizing the other objective yielding a single objective problem as it is shown in the following equation.

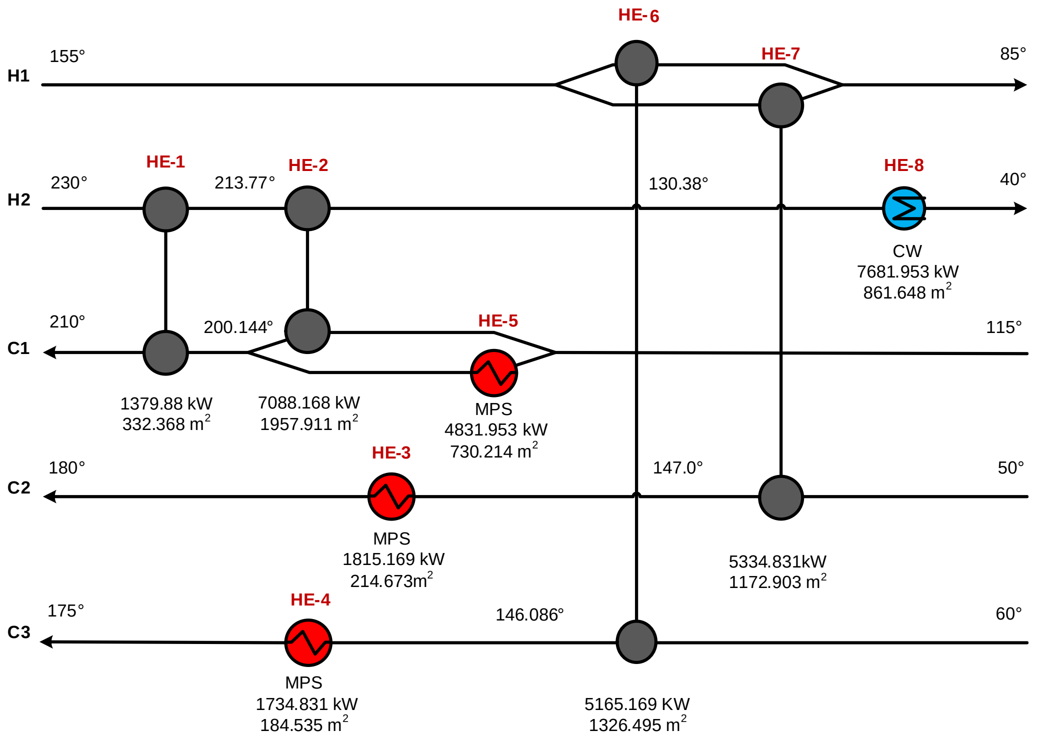

Fig. 8. Network with minimum TAC for the Example 2.

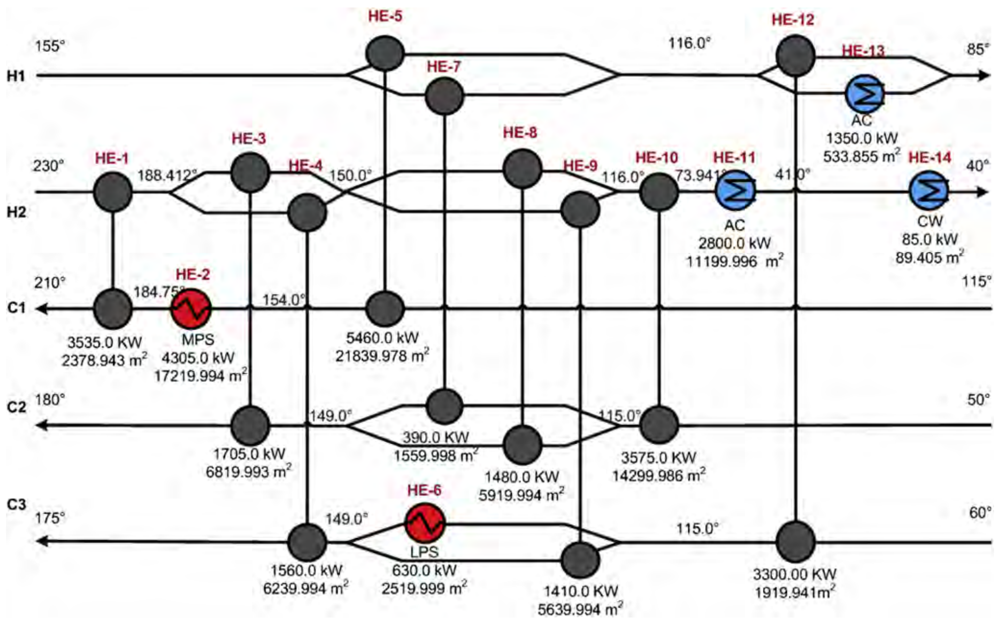

Fig. 9. Network with minimum EI for Example 2.

$$
\begin{aligned}
& \min\ Z_{\text{mult}} = \text{TAC} \\
& s.t. \\
& \quad \min\ \text{EI}_j \le \varepsilon_j \quad j = 1,2..,k; \\
& \quad \text{Eqs. } (1)-(41) \text{ and } (43)
\end{aligned}
\tag{45}
$$

where, ε is a parameter that imposes a limit for the EI objective function. Different values for the minimum TAC will correspond to different values for ε. Therefore, it is possible to determine the minimum value for ε and the maximum value for ε. The minimum feasible value for ε corresponds to the problem that minimizes the EI without taken into account the TAC; on the other hand, the maximum feasible environmental impact is obtained for the problem that minimizes the TAC without considering the EI. These two extreme points are identified as solution A and solution B in Fig. 3. Notice in Fig. 3 that a set of solutions between points A and B can be obtained for different values of ε, this set of solutions is called a Pareto set of optimal solutions that can be obtained solving the problem given by equations for values of ε between min EI (solution A) and maximum TAC (solution B). Above the Pareto curve there are identified suboptimal solutions, whereas below the Pareto curve the solutions are infeasible. The constraint method consists of obtaining the Pareto set of optimal solutions, and then the designer has to make the decision of which objective is dominant.

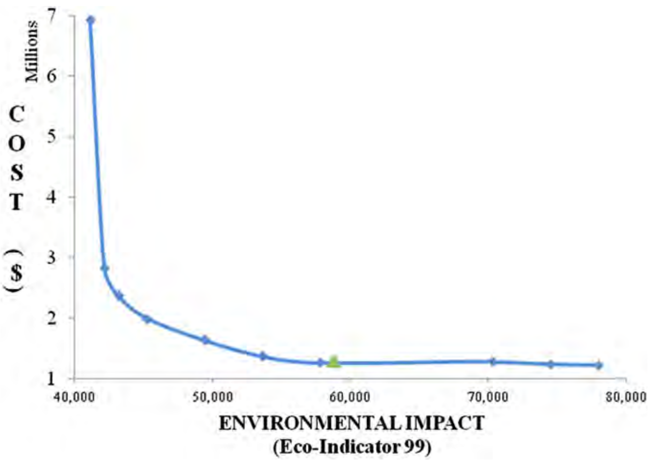

Fig. 10. Pareto frontier for Example 2.

4.2. Goal method

In the goal method, to solve the multiobjective optimization problems, first the target for the minimum total annual cost (TAC_{min}) is obtained from solution B identified previously from Fig. 3, whereas the target for the minimum environmental impact (EI_{min}) is obtained from solution A identified in Fig. 3. In the goal formulation, the problem is transformed into a single objective problem where the objective is to minimize the deviation from two targets for the two objectives subjects to the constraints given by the original problem. Therefore, the multiobjective problem for the goal method is formulated as follows:

$$
\begin{aligned}
& \min_{x,\delta_i^+,\delta_i^-} Z_{\text{goal}} = \delta_{\text{TAC}}^+ + \delta_{\text{TAC}}^- + \delta_{\text{EI}}^+ + \delta_{\text{EI}}^- \\
& s.t. \\
& \quad Z_{\text{TAC}} - \text{TAC}_{\min} = \delta_{\text{TAC}}^+ - \delta_{\text{TAC}}^- \\
& \quad Z_{\text{EI}} - \text{EI}_{\min} = \delta_{\text{EI}}^+ - \delta_{\text{EI}}^- \\
& \quad \delta_i^+ \ge 0;\ \delta_i^- \ge 0 \\
& \quad \text{Eqs. } (1)-(41) \text{ and } (43)
\end{aligned}
\tag{46}
$$

where, $\delta_{\text{TAC}}^+, \delta_{\text{TAC}}^-, \delta_{\text{EI}}^+, \delta_{\text{EI}}^-$ are positive and negative deviations for the two objectives. Notice that these positive and negative deviations are restricted to have positive values.

5. Results and discussion

This section presents three example problems to show the applicability of the proposed methodology. For all example problems, the solver DICOPT in conjunction with the solvers CONOPT and CPLEX implemented in the General Algebraic Modeling System (GAMS) [50] were used.

For all cases analyzed in this paper, the eco-indicators 99 for the utilities available were calculated following the life cycle analysis [30,48]. The parameter H_Y used in all examples was 8000 h/year.

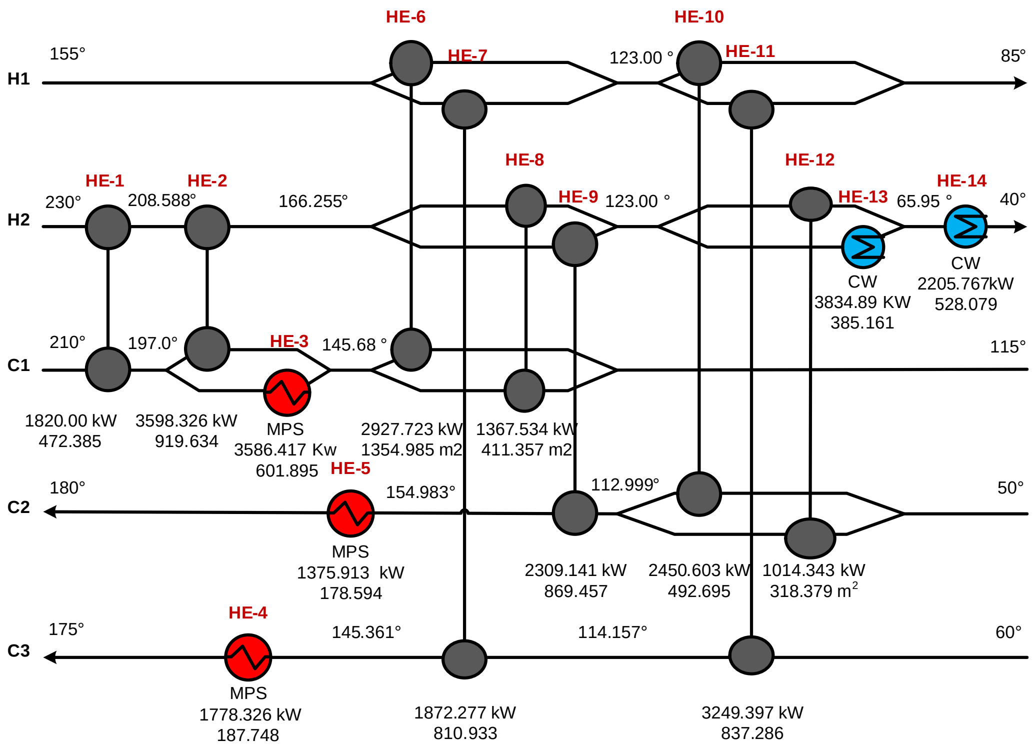

Fig. 11. Optimal solution obtained for the goal method for Example 2.

5.1. Example 1

This example was previously reported by Isafiade and Fraser [17]. This problem consists of two hot and one cold process streams and the streams data are shown in Table 1. There are available high-, medium- and low-pressure steams to satisfy heating requirements, and there is available cooling water for the cooling requirements. The capital costs for the heat exchanger units for this example are calculated using the model $C_{exc} = 800[\text{Area}(m^2)]$ and the annualization factor used is 0.298/year.

The use of each utility has associated a specific cost and their inlet and outlet temperatures as well as their film heat transfer coefficients, as can be seen in Table 1. Additionally, each type of utility has an overall environmental damage obtained from its entirely life and it is quantified in the eco-indicator 99 per unit of kJ of the type of utility and shown in Table 1.

Table 2 shows the results obtained for Example 1, including the minimum total annual cost and the minimum environmental impact, as well as the solution with the goal method.

The solution for the Example 1 without considering the environmental impact concerns (solution B) yields the network shown in Fig. 4. This network has three heat exchanger units between process streams, in addition to two coolers and two heaters. Notice that the heater 3 for the process stream C1 is between the heat exchanger units 2 and 4. Heaters 1 and 3 use 238.7 kW of high and 151.3 kW of low-pressure steams, respectively. Notice that this solution consumes the cheapest utilities when it is possible (even that the cheapest utilities are the most polluted). The minimum total annual cost for this example is $97,079/year, whereas its corresponding environmental impact measured through the eco-indicator 99 (i.e., the maximum EI allowed) is 4084. This extreme solution corresponds to the one obtained by the approach by Ponce-Ortega et al. [18] that considers multiple utilities and minimize exclusively the TAC.

The solution for Example 1 for the case that minimizes the EI without considering the TAC is shown in Fig. 5 (solution A). This network has four heat exchanger units between process streams, and two coolers and four heaters. Notice that heaters 3, 5 and 6 are between process exchangers. The minimum environmental impact for this problem is 2428, whereas its corresponding total annual cost is $1,400,400/year. Notice that this solution A corresponds to the maximum energy recovery and at the same time the minimum utilities requirements consuming the cleanest utilities (even that the cleanest utilities are the most expensive). It is worth of notice that solution A has several heat exchangers more than the minimum because the environmental impact is dominated by the use of utilities; this is, the solution for the minimum EI corresponds to the solution to the minimum utilities consumption (including the optimal selection for the cleanest utilities) without considering the capital costs for the heat transfer units.

Table 5
Stream data for Example 3.

Stream	T_{in} (C)	T_{out} (C)	FCp (kW/C)	h (kW/m^2 °C)	Cost ($/yr)	Eco-indicator 99 (1/kJ)
H1	340	340	1900.0	1.52	–	–
H2	390	390	1493.1	1.63	–	–
H3	420	420	2594.4	1.75	–	–
H4	475	475	1999.1	1.58	–	–
C1	350	350	992.5	1.81	–	–
C2	375	375	1801.2	1.72	–	–
C3	400	400	4361.6	1.64	–	–
HPS[a]	627	627	–	2.5	100	8.7058E–03
MPS[b]	473	473	–	2.0	50	8.8656E–03
LPS[c]	423	423	–	1.5	20	9.1278E–03
CW[d]	303	303	–	1.0	10	2.0219E–05
AC[e]	313	313	–	0.5	5	2.9044E–06

[a] High-pressure steam.
[b] Medium-pressure steam.
[c] Low-pressure steam.
[d] Cooling water.
[e] Cooling air.

Table 6
Results for Example 3.

Designs	Total area (m^2)	Utilities cost ($/yr)	Capital cost ($/yr)	Total annual cost ($/yr)	Environmental impact (1/yr)
Minimum TAC solution B	388.10	52,889.00	33,626.34	86,515.34	16,268.51
Minimum EIA solution A	6,908.90	30,874.00	220,597.43	251,471.43	10,347.11
Goal solution	674.641	40,374.00	46,141.34	86,515.34	12,104.93

In addition, notice that solution A has three heat exchanger units more than solution B, the heat transfer area for solution A is 3024.2% greater than solution B. On the other hand, solution B has a total utility cost 89% greater than solution A. As a results, solution A has a total annual cost 1342.5% greater than the minimum given by solution B, whereas solution B has an environmental impact 68% greater than the minimum given by solution A.

It is noteworthy that solutions A and B are extreme solutions that could be impractical for many situations, and this way the proposed methodology is very useful to determine the set of optimal solutions that compensate simultaneously the minimum EI (solution A) and the minimum TAC (solution B). Applying the solution strategy for the constraint method, the Pareto frontier can be obtained to provide the information that the decision maker requires. Fig. 6 shows the Pareto frontier for Example 1, three zones can be identified. Zone I represents optimal designs where the environmental impact is the dominant, in zone II the dominant is the total annual cost and in zone III two objectives are considered. In zone I the environmental impact is 11.2% bigger than the minimum given by solution A, however, the cost is 41% greater than the minimum given by solution B. In zone II, the total annual cost is 9.4% bigger respect to the minimum given by solution B, while the environmental impact is 32% greater than the minimum given by solution A. The main advantage of the proposed methodology is that it allows to select the optimal solution from the Pareto curve the one that compensates both objectives and best fits to the designer criteria.

Fig. 7 shows the optimal solution obtained with the goal method, where the TAC is 4.37% greater than the minimum and the EI is 37.97% greater than the minimum. Notice that the network configuration for the goal solution is similar to the solution B; however, the heat exchanger units are different to reduce the utilities consumption.

5.2. Example 2

This example was also reported by Shenoy et al. [16] and by Isafiade and Fraser [17]. The problem consists of cooling two hot process streams and heating three cold process streams; there are available three different types of steam (i.e., high, medium and low pressure steams) and two cold utilities (i.e., water and air cooling). The capital costs for the heat exchanger units for this example are calculated using the following equation $C_{exc} = 13{,}000 + 1000[\text{Area}(m^2)]^{0.83}$ and the annualization factor used is 0.322/year. The stream data for this example are shown in Table 3, including the eco-indicators 99 for the different types of utilities used in this problem.

Table 4 presents the results obtained for the Example 2, for the cases for minimum total annual cost (TAC), minimum environmental impact (EI), and the goal solution.

Fig. 8 presents the solution for the Example 2 minimizing the total annual cost without considering the environmental impact concerns (solution B). Notice that the solution identifies two sub-networks; a sub-network between streams H1, C2 and C3; and

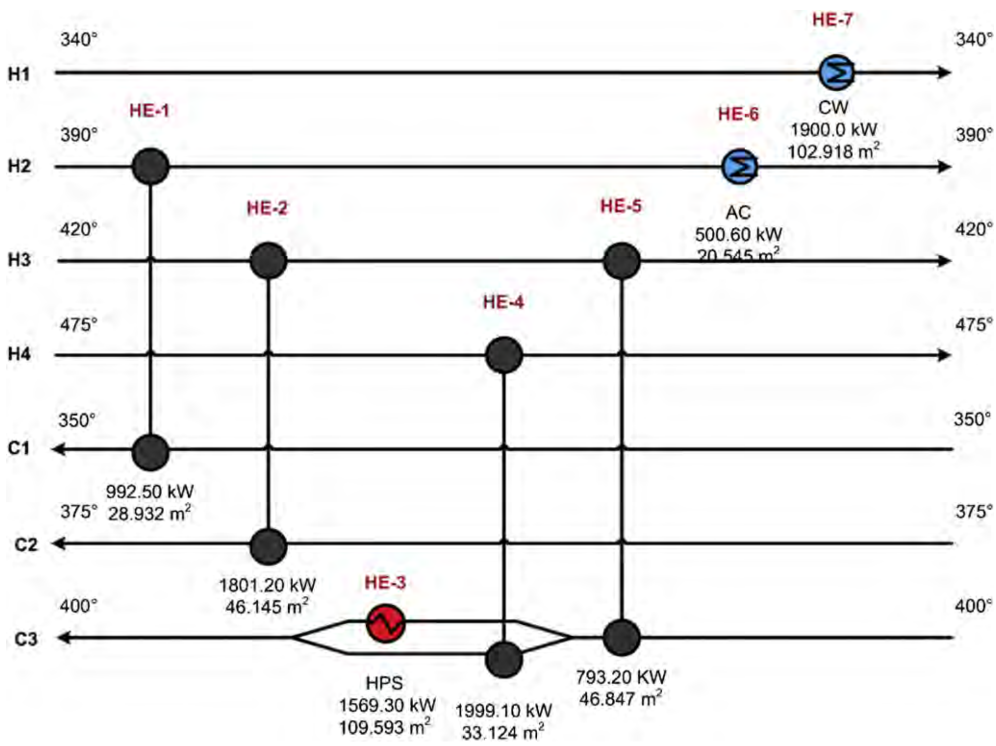

Fig. 12. Network with minimum TAC for the Example 3.

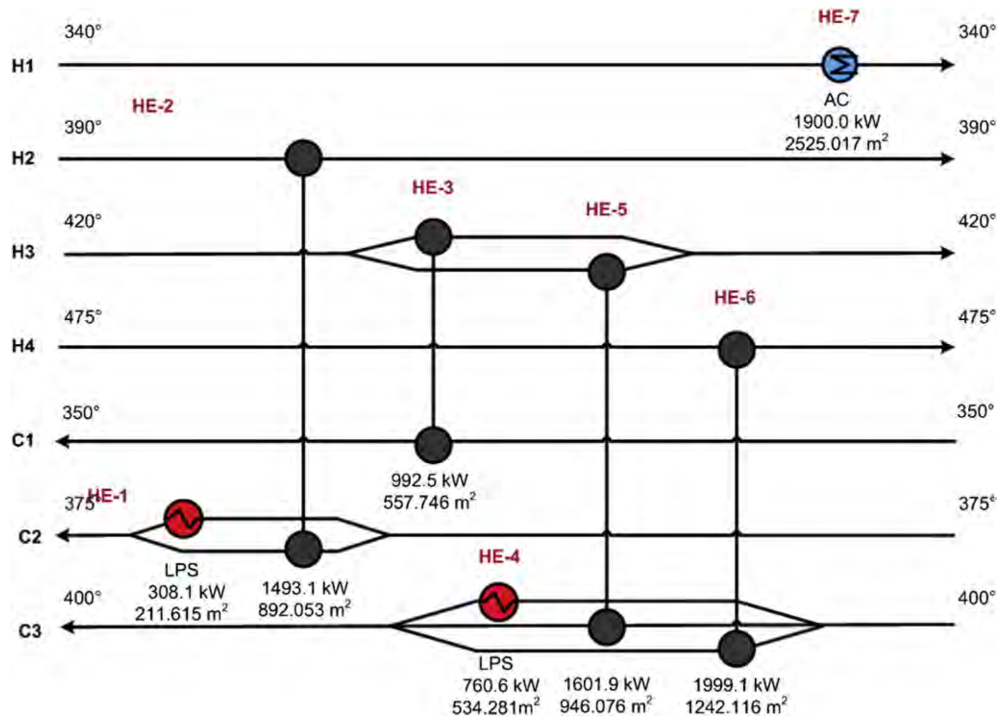

Fig. 13. Network with minimum EI for the Example 3.

other sub-network between streams H2 and C1. This solution has four heat exchanger units between process streams, in addition to one cooler and three heaters. For this example the utilities services are in the extreme of the network. The units HE-3, HE-4 and HE-5 are heaters and use 1815.169 kW, 1734.831 kW, and 4831.953 kW of medium-pressure steam, respectively. The minimum total annual cost for this example is $1,220,225.70/year, with a value of 78,012/year for the environmental impact measured through the eco-indicator 99; this solution represents the maximum EI at minimum cost. Previously reported methodologies usually produce HEN that minimize the TAC; however, one of the advantages of the proposed methodology is that it takes into account the possibility to include heaters and coolers between process exchangers (i.e., in positions different than at the extreme of the superstructure), as it is the case of heater HE-5 of Fig. 8.

For Example 2 where the EI is minimized without considering the TAC is shown in Fig. 9 (solution A). This network has nine heat exchanger units between process streams, and three coolers and two heaters. Notice that heaters 2, 6 and cooler 11 are between process exchangers. The minimum environmental impact for this problem is 41,138.08/year, whereas its corresponding total annual cost is $6,911,977.4/year. Solution for minimum EI has several exchanger units more than the minimum number of units, and this HEN could represent serious operational problems. Therefore, the main objective of the proposed methodology is to find the HEN that compensates both objectives simultaneously.

Notice that the network with minimum EI has six units more than the network with minimum TAC with larger area. There are two coolers more with 2800 kW and 1350 kW of air cooling and other of 85.0 kW of cooling water. There are two heaters with 4305.0 kW and 6300 kW of medium- and low-pressure steam, respectively. The total utility cost for solution B is 98.8% greater than solution A and the capital cost for solution A is 466.45% greater than solution B; therefore, the total annual cost for solution A is 466.45% greater than solution B, while solution B has an environmental impact 89.6% greater than the minimum given by solution A.

Therefore, the solution using the constraint method is shown in Fig. 10; where are observed different designs, as well as, the network with minimum total annual cost and the minimum environmental impact for this example. The main idea of the proposed methodology is that it allows the designer to select the optimal solution from this Pareto curve that best fits the specific requirements; it is noteworthy that this Pareto curve represents a set of optimal solutions that compensate both objectives simultaneously.

The optimal solution obtained for the goal method is presented in Fig. 11, where the TAC is 9.53% greater than the minimum and the EI is 42.98% greater than the minimum. This goal solution has several heat transfer units more than the minimum; therefore, for the case when this represents operational problems, the designer can select a different solution from the Pareto curve shown in Fig. 10. It is worth of notice that the solutions in the right hand side of Fig. 10 present a lower number of heat transfer units (i.e., they are easier to operate) but at the expense of a higher environmental impact.

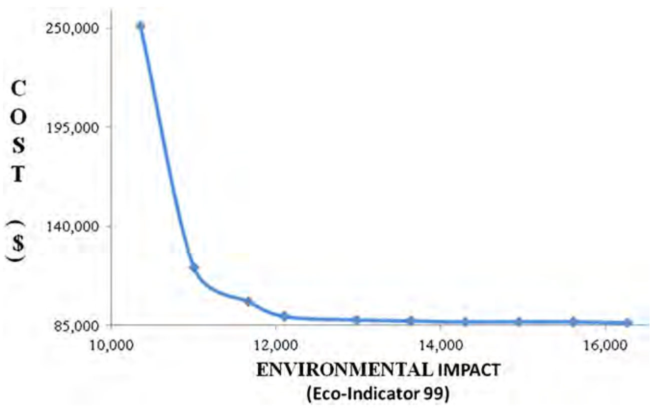

Fig. 14. Pareto Frontier for Example 3.

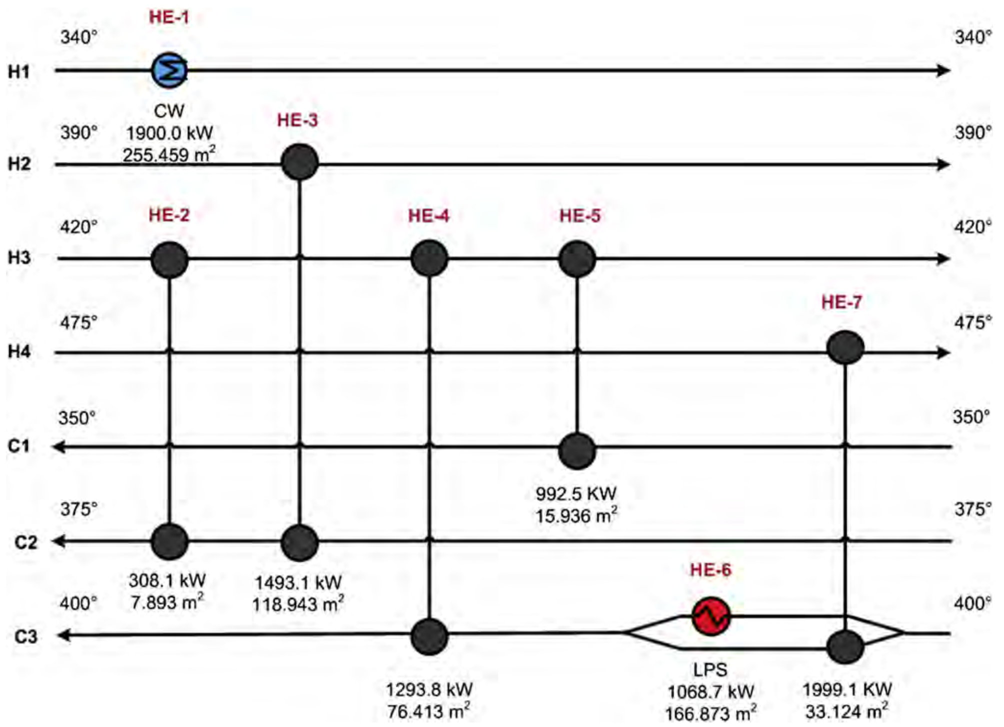

Fig. 15. Optimal solution obtained for the goal method for Example 3.

5.3. *Example 3*

This example considers the use of isothermal process streams and it was previously reported by Ponce-Ortega et al. [18]. The problem consists of four hot process streams and three cold process streams, there are three available different types of steams (i.e., high-, medium- and low-pressure steams) and two cold utilities (i.e., water and air cooling). The capital costs for the heat exchanger units for this example are calculated using the following equation $C_{exc} = 1650[\text{Area}(m^2)]^{0.65}$ and the annualization factor used is 0.23/year. The stream data for this example are shown in Table 5, including the eco-indicators 99 for the different types of utilities used in this problem.

The results for the Example 3 are present in the Table 6, for the cases for minimum total annual cost (TAC), minimum environmental impact (EI), and goal solution.

Fig. 12 represents the solution for the minimum total annual cost without considering the environmental impact concerns. This network has four heat exchanger units between process streams, in addition to two coolers and one heater. The heater 3 uses 1569.30 kW of high-pressure steam, and it is located in parallel with the heat exchanger 4. The minimum total annual cost for this example is $86,515.34/year, whereas its corresponding environmental impact measured through the eco-indicator 99 (i.e., the maximum EI allowed) is 16,268.51/year. This solution is the one that can be obtained using previous methodologies that only minimizes the TAC; however, one of the advantages of the solution reported in Fig. 12 is that it considers the arrangements in parallel of heaters and coolers like is the case for HE-3 and HE-4 for cold process stream C3.

On the other hand, solution A of Example 3 represents the solution for the case that minimizes the EI without considering the TAC, and it is shown in Fig. 13. This network has four heat exchanger units between process streams, and one cooler and two heaters. The minimum environmental impact for this problem is 10,347.11/year, whereas its corresponding total annual cost is $25,470.00/year. Notice that in this case, solutions A and B have the same number of heat transfer units; however, solution A only uses AC as cold utility and LPS as hot utility, whereas solution B uses AC and CW for cold utility and HPS as hot utility. Also, notice that solution of Fig. 13 has two heaters in parallel with process exchangers for cold streams C2 and C3, situation that usually is not considered by previous methodologies.

In this example, the solutions A and B have seven heat exchanger units; however, the heat transfer area for solution A is 1680.18 times greater than solution B. On the other hand, solution B has a total utility cost 71.3% greater than solution A, and the solution A has a capital cost 556.03% greater than the minimum given by solution B. As a result, solution A has a total annual cost 190.7% greater than the minimum given by solution B, whereas solution B has an environmental impact 57.23% greater than the minimum given by solution A.

Fig. 14 presents the set of solutions obtained with the constraint method, considering simultaneously the total annual cost and environmental impact.

The optimal solution obtained for the goal method is present in Fig. 15, where the TAC is the same for the minimum TAC, and the EI is 17% greater than the minimum. This solution has seven heat transfer units, and it uses the cheapest hot utility and the most expensive cold utility.

Finally, Table 7 shows the problem size and the computation time in an Intel® Core™2 Duo at 2.00 GHz with a 4.00 GB of RAM. No

Table 7
Problem size for the three examples.

Example	Constraints	Binary variables	Continuous variables	CPU time [s]
Example 1	515	120	507	4.125
Example 2	843	216	878	7.266
Example 3	535	144	589	2.156

numerical complications were observed in the solution of the examples presented and the CPU time consumed was relatively small.

6. Conclusions

This paper presented a new mathematical programming model for the synthesis of HEN considering simultaneously the minimization of the total annual cost and the environmental impact. The total annual cost considers the capital and utility cost and it takes into account the optimal selection and location of different utilities allowable, whereas the environmental impact objective function considers the entire environmental impact measured though the life cycle analysis methodology using the eco-indicator 99 for different utilities allowable. Results show that these two objectives contradict each other, and that the multiobjective solution procedure presented in this paper is suitable to solve adequately these problems. No numerical complications were observed during the solution of the problem addressed.

The model uses constant film transfer coefficients for each stream based on the physical properties, allowable pressure drops and the typical exchanger geometry, the real film heat transfer coefficients are obtained after the synthesis stage during the heat exchanger detailed design adjusting the exchanger geometry and the pressure drops for the streams. The purpose of using constant film transfer coefficients is to avoid non-convex relationships that are very difficult to solve in the optimization process and to avoid the possibility to get trapped in a local optimal solution.

It is worth of notice that the assumption of isothermal mixing at the exit of the stages of the superstructure avoids the non-linear balances to determine the outlet temperature from any stage, and therefore it is only required an energy balance for each stage for each process stream. This way, all the constraints for the model are linear and the non-linear terms are only in the objective function, this is a very useful characteristic of the model to avoid numerical complications.

Nomenclature

A heat transfer area
AN_F annualization factor
C area cost coefficient
C_{CU^m} unitary cost of cold utility
C_{HU^n} unitary cost of hot utility
$C_{F_{i,j}}$ fixed charge for exchangers
Cp specific heat capacity
CPS $\{j|j$ is a cold process stream$\}$
CPS1 $\{j|j$ is a non isothermal cold process stream$\}$
CPS2 $\{j|j$ is an isothermal cold process stream$\}$
CU cold utility
$dt_{i,j,k}$ temperature approach difference for match (i, j) at temperature location k
$dt_{cu_{i,k}}$ temperature approach difference for match between hot stream i and a cold utility at the temperature location k
$dt_{hu_{j,k}}$ temperature approach difference for match between cold stream j and a hot utility at the temperature location k
$EcoIndicator_{hu^n}$ eco-indicator 99 for the type n of hot utilities in the network
$EcoIndicator_{cu^m}$ eco-indicator 99 for the type m of cold utilities in the network
EI environmental impact
EI_{min} minimum environmental impact allowed
F flowrate
FCp heat capacity flowrate
h film heat transfer coefficient
HPS $\{i|i$ is a hot process stream$\}$
HPS1 $\{i|i$ is a non isothermal hot process stream$\}$
HPS2 $\{i|i$ is an isothermal hot process stream$\}$
HU hot utility
NOK total number of stages
$q_{i,j,k}$ heat exchanged between hot process stream i and cold process stream j in stage k
$q_{cu^m_{i,k}}$ heat exchanged between cold utility m and hot stream i in stage k
$q_{hu^n_{j,k}}$ heat exchanged between hot utility n and cold stream j in stage k
Q^{max} upper bound for heat exchanged
ST $\{k|k$ is a stage in the superstructure, $k = 1,\ldots,$NOK$\}$
$t_{i,k}$ temperature of hot stream i at the hot end of stage k
$t_{j,k}$ temperature of cold stream j at the hot end of stage k
TAC total annual cost
TAC_{min} minimum total annual cost allowed
T_{IN_i} inlet temperature of stream i
T_{OUT_i} outlet temperature of stream i
$T_{OUT_{cu_{i,k}}}$ outlet temperature for cold utility in stage k
$T_{IN_{cu_{i,k}}}$ inlet temperature for cold utility in stage k
T_{OUT,cu^m} parameter for the outlet temperature for cold utility m
$T_{IN,cu^m_{i,k}}$ parameter for the inlet temperature for cold utility m
$t_{out,cu^m_{i,k}}$ disaggregated variables for the outlet temperature for cold utility m
$t_{in,cu^m_{i,k}}$ disaggregated variables for the inlet temperature for cold utility m
$T_{OUT_{hu_{j,k}}}$ outlet temperature for hot utility in stage k
$T_{IN_{hu_{j,k}}}$ inlet temperature for hot utility in stage k
$T_{OUT,hu^n_{j,k}}$ parameter for the outlet temperature for hot utility n
$T_{IN,hu^n_{j,k}}$ parameter for the inlet temperature for hot utility n
$t_{out,hu^n_{j,k}}$ disaggregated variables for the outlet temperature for hot utility n
$t_{in,hu^n_{j,k}}$ disaggregated variables for the inlet temperature for hot utility n
ΔT^{max} upper bound for temperature difference
ΔT_{MIN} minimum approach temperature difference
Z Boolean variables used to model disjunctions
$z_{i,j,k}$ binary variables for match (i, j) in stage k
$z_{cu^m_{i,k}}$ binary variables for match between cold utility m and hot stream i
$z_{hu^n_{j,k}}$ binary variables for match between hot utility n and cold stream j
Z_{goal} total objective function for the goals
Z_{mult} multiobjective function
Z_{TAC} total annual cost objective function
Z_{EI} objective function for the environmental impact

Greek symbols

α_{bi} damage factor caused by each damage category.
β exponent for area in cost equation
β_b burdens of process of hot and cold utilities in the network
Δ small number
δ_d normalization factors for the damage category d
δ^+_{EI} positive deviation for objective function of environmental impact
δ^-_{EI} negative deviation for objective function of environmental impact
δ^+_{TAC} positive deviation for objective function of total annual cost
δ^-_{TAC} negative deviation for objective function of total annual cost
ε_j parameter of the interval between TAC_{min} and EI_{min} for the constraint method
$F\lambda^{cond}_i$ condensation heat load for hot stream i

$F\lambda_j^{evap}$ evaporation heat load for cold stream j
θ_i damage category
ω_d weighting factors for the damage category

Subscripts and superscripts
i hot process stream
j cold process stream
k index for stage (1,…,NOK) and temperature location (1,…,NOK + 1)
m cold utility
n hot utility

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