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Heat exchanger network synthesis and optimisation using genetic algorithm

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Abstract

In the last few decades, several papers were published on heat exchanger network synthesis. Most of them present techniques using mathematical programming for the synthesis and optimisation tasks. Recent developments in heat exchanger networks synthesis present some heurist methods, such as genetic algorithm (GA) and simulated annealing. In this paper, a strategy for the synthesis and optimisation of heat exchanger networks was developed using GA. First of all, the ΔT_{min} is optimised using GA jointly with the problem table, from the Pinch Analysis. By using the optimum ΔT_{min}, found in the previous stage, the problem is divided in two different regions, below and above the pinch. Thus, using GA, the optimal networks above and below the pinch are obtained, considering stream splitting as well. Some examples from the literature were solved with the proposed systematic, and results show heat exchanger networks with lower costs than those ones presented in the literature for the cases studied.

Keywords: Optimisation; Heat exchanger networks; Genetic algorithms

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1. Introduction

One of the most frequent problems in industrial plants is the excessive energy consumption. It represents the most important contribution to the composition of the global cost of industrialised products. Although heat recovery systems are frequently studied in synthesis problems, great attention was drawn after the first energetic world crisis, during the seventies. Therefore, the study of alternatives to minimize the consumption of energy produced by burnt combustibles has increased.

In industrial processes there are streams that need heating and streams that need cooling, usually achieved by using hot and cold utilities, respectively. Heat exchanger network (HEN) synthesis is a mean to obtain heating and cooling by process streams energetic integration, by using heat streams to heat cold streams and cold streams to cool hot streams. In this way, it is possible to reduce the amount of hot and cold utilities. Besides the utilities consumption reduction, it is important to use a small number of heat transfer equipment, decreasing the fixed cost of the final network.

According to Ravagnani et al. [1], several kinds of studies were done aiming to develop methodologies to obtain optimal HEN, to reach these goals. Research was concentrated in two important areas, Pinch Analysis, which uses thermodynamic concepts and heuristics and Mathematical Programming, as Linear, Non-Linear and Mixed Integer Linear and Non-Linear Programming. Recently heuristic methods of optimisation have also been used to solve linear and non-linear models.

Essentially, the HEN synthesis task consists of finding a practical sequence of equipment combining pairs of streams, in a way that the network is optimal in relation to the global cost. The great complexity of the problem is its combinatorial nature. For a fixed number of streams, there are a great number of possibilities of combinations. Nevertheless, the number of HEN configurations that satisfies the minimum utilities consumption is smaller than the total number of possible configurations. The satisfaction of this restriction implies in finding a HEN with the minimum utilities consumption to a given minimum temperature of approach ($\Delta T_{\min}$). The presented methods to the HEN synthesis aims to find the optimum or near optimum among all the network configurations.

The first stage of heat exchanger network synthesis is to find the minimum utility demand, the minimum number of heat transfer equipment, the minimum heat transfer area and the minimum global annual cost. This stage is known as pre-analysis. To achieve this goal, it is necessary to find the optimum $\Delta T_{\min}$ for each case in study. During the second stage, heat exchangers are allocated and the practical sequence between the equipment is found, aiming the goals fixed in the first stage.

Most of papers published in literature present the heat exchanger network synthesis without taking into account $\Delta T_{\min}$ optimisation. This step is essential to the network optimisation. Bad choices to the $\Delta T_{\min}$ can bring bad heat exchanger networks, considering the aspects of energy consumption and equipment costs.

Thus, the objectives of this paper are to synthesize optimal heat exchangers networks, relative to energy consumption, minimum number of heat transfer equipment and minimum global annual cost, considering the $\Delta T_{\min}$ optimisation stage. The proposed methodology uses Pinch Analysis, together with genetic algorithms.

2. Pinch analysis

As can be seen in Ravagnani [2], to obtain an optimal heat exchanger network using Pinch Analysis, three steps must be followed. The first one consists of finding the minimum energy demand, the minimum number of heat exchangers and the minimum global annual cost. The second step consists of the heat exchangers network synthesis, or the definition of the streams that must exchange heat, as well as the best sequence of the equipments, to achieve the objectives defined in the first stage. In the third step, the network is evolved by identifying and breaking loops.

Some tools were developed, based in the First and in the Second Laws of Thermodynamics, to establish the objectives in the first stage. One of these tools is the Problem Table Algorithm, according to Smith [3]. This algorithm allows finding the minimum hot and cold utilities demand and the location of the pinch point, for a given $\Delta T_{\min}$. It is based in the division of the problem in temperature intervals. For each interval, energy balances has to be done. A cascade of energy is built, and the values of minimum energy demand and the pinch point are identified. The pinch point represents the degree of heat integration in the process, and acts as a bottleneck of energy. Thus, the problem is divided in two different regions, above and below the pinch. Above the pinch, just hot utilities are allowed and below, only cold utilities.

2.1. ΔT_{min} optimisation

The behaviour of energy consumption as function of $\Delta T_{\min}$ is well known. As $\Delta T_{\min}$ is increased, energy demand is increased too. However, heat exchange area decreases. The global cost is obtained by summing the two curves in a diagram, Cost X $\Delta T_{\min}$.

The cost of heat exchange area is related to $\Delta T_{\min}$ in a non-linear way, and the energy cost in a linear way. To find the optimum value of $\Delta T_{\min}$ a trade off between energy, area and their costs must be done.

2.2. Heat exchangers network synthesis

To achieve the minimum global cost in a heat exchangers network, energy and capital costs must be decreased. The number of equipment in the network influences the capital cost. It is because the cost of each heat exchanger involves also founding, piping, valves, etc.

The Minimum number of equipment is obtained by the $N - 1$ rule, where N is the number of hot and cold streams, including hot and cold utilities.

For the synthesis task, Linnhoff and Hindmarsh [4] presented the Pinch Design Method. It guarantees to obtain heat exchangers networks with the minimum energy demand, as calculated in the Problem Table Algorithm, by using some heuristics proposed in the method to choose the streams that must be matched.

3. Optimisation

Optimisation is an area of computational science whose main objective is to find the best solution for problems in which the quality of the response can be measured by a number. To solve problems like these, it is important to consider two components. The first one to be considered is the search space. In this space, all the possibilities of solution are considered. The second one is the objective function, which is a mathematical function that associates each point in the solutions space to a real number, making possible to evaluate all the members of the search space.

The solution of problems with a high degree of computational complexities has been a constant challenge. Problems with combinatorial nature, whose optimal solution in many cases is very difficult to find, are very common in Engineering. Traditional methods of exact optimisation are characterised by the stiffness of its mathematical models, making the representation of real situations difficult, more and more dynamic and complex. The introduction of optimisation techniques based in Artificial Intelligence, as the heuristic search based ones, associated to the conventional optimisation techniques, reduced the problem of stiffness.

3.1. Heuristic methods of optimisation

Heuristic rules can be defined as practical rules, derived from the experience and observation of behaviour tendencies of the system in analysis. They are applicable to all kinds of problems, as in the day by day actions and decisions as well as in the optimisation of problems that presents situations of uncertainty, as well as in the necessity of decisions based in insufficient information, situations with a great number of alternatives, reducing the number of attempts, in problems of great dimensions or large number of restrictions, reducing the amount of calculus.

During the 50s, by using analogies with nature, some heuristic algorithms were proposed, trying to simulate biological phenomena. These algorithms, called Natural Optimisation Methods, have some features in common. The most important thing is their random characteristic, trying to simulate the fortune that apparently governs distinct processes in nature, from the evolution of species to the social behaviour of animals.

During the 80s, with the crescent use of computers, the use of these algorithms to the optimisation of functions and processes became viable, when traditional methods were not successful, such as problems of combinatorial optimisation, problems where the objective function cannot be expressed mathematically or problems with a great number of local minima.

Some heuristic methods seemed motivated by these algorithms, as Simulated Annealing, Swarm Algorithms, Ant Colony Optimisation an genetic algorithms.

3.2. Genetic algorithms

Genetic algorithms are relatively recent methods. They do not use any information of derivate, and because of this, present good chances of escape from local minimum. Their application in practical problems generally brings to global optimal, or, at least, to solutions more satisfactory than those ones obtained by other methods.

They use a direct analogy of the evolution phenomena in nature, in such a way that each individual represents a possible solution to a given problem. The individuals are randomly determined from the search space. The 'fitness' of the solutions, which is the result of the variable that is to be optimised, is determined subsequently from the fitness function. The individual that generates the best fitness within the population has the highest chance to return in the next *generation*, with the opportunity to reproduce by crossover, with another individual, producing decedents with both

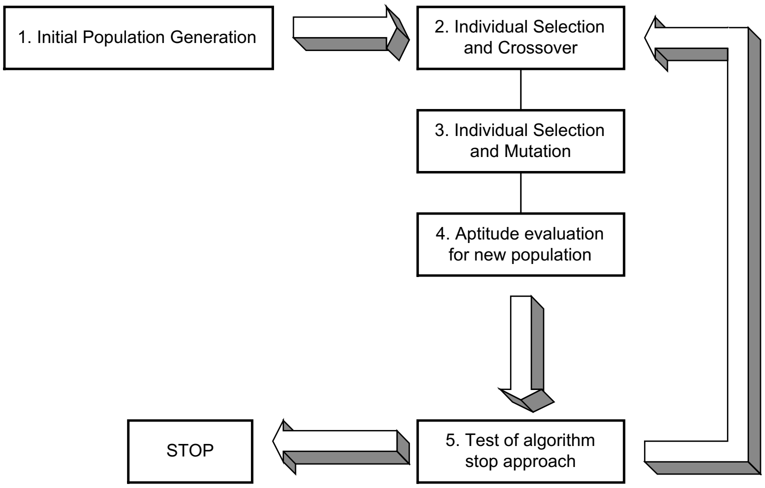

Fig. 1. Genetic operations for each generation.

characteristics. If a genetic algorithm is developed correctly, the population (group of possible solutions) will converge to an optimal solution for the proposed problem. The processes that have more contribution to the evolution are the crossover, based in the selection and reproduction and the mutation.

Genetic algorithms are different from the traditional methods of search and optimisation, specially because they work with a codification of the group of parameters and not with the parameters, and they use a population, and not just a point.

Fig. 1 shows the beginning of the algorithm and the genetic operations necessary for each iteration.

Besides of genetic operators, it is also important to analyse the influence of some parameters in the behaviour and in the performance of the genetic algorithm, to establish them according to the problem necessities and the available resources. The influence of each parameter in the algorithm performance depends on the class of problems that is being treated. Thus, the determination of an optimised group of values to these parameters will depend on a great number of experiments and tests.

The principal genetic parameters are the size of the population that affects the global performance and the efficiency of the genetic algorithm, the mutation rate that avoids that a given position remains stationary in a value, or that the search becomes essentially random.

4. Methodology

The methodology employed in this paper consists of two distinct stages.

In the first stage, $\Delta T_{\min}$ is optimised using a genetic algorithm. The concepts related to the first step from the Pinch Analysis are used as described in Section 2. With the optimum $\Delta T_{\min}$ the hot and cold utilities demand is calculated and the pinch point is found. Pinch location is used to split the problem into two distinct regions, above and below it. For each region, the optimal configuration of the heat exchangers network will be determined in the second stage.

In the next stage, the objective function is proposed, with its restrictions. Being a non-linear function, another genetic algorithm will be used to optimise the objective function, including some thermodynamic concepts to find the best heat exchanger network. The two optimal networks, obtained for the two regions, below and above the pinch must be connected. The final network is optimal relative to the minimum utility demand and to the minimum global annual cost.

4.1. ΔT_{min} optimisation

As presented in Section 2, to find the optimal ΔT_{min} the function global cost is obtained by summing the annual cost of energy and the capital cost. In this stage, the heat exchangers network is not yet synthesised. In this way, the heat transfer area to be used in the cost function is the minimum possible heat transfer area, to the network to be synthesised. This area is found, after the ΔT_{min} optimisation, to a group of heat and cold streams by plotting the composite curves in a diagram Temperature X Enthalpy (TH). This diagram is divided in Enthalpy intervals. The minimum area is found in Eq. (1), proposed in Towsend and Linnhoff [5].

$$A_{\mathrm{min}} = \sum_{j}^{\mathrm{intervals}} \frac{1}{\Delta T_{\mathrm{LM}_j}} \cdot \left(\sum_{i}^{\mathrm{streams}} \frac{q_i}{h_i} \right)_j \tag{1}$$

In this equation, j represents the enthalpy intervals and i the process streams present in each interval. ΔT_{LM} represents the logarithm mean temperature difference to the stream i in the interval j, q_i and h_i are the heat available or necessary and the individual heat transfer coefficient for the stream i in the interval j, respectively.

For each ΔT_{min} fixed, a different value for A_{min} and for hot and cold utilities are found. Consequently, for the function global cost, which depends on these variables, different values will be obtained.

The annual costs of energy, capital and global are represented by Eqs. (2)–(4), respectively.

$$C_{\mathrm{Energy}} = C_{\mathrm{HU}} \cdot \mathrm{HU} + C_{\mathrm{CU}} \cdot \mathrm{CU} \tag{2}$$

$$C_{\mathrm{Capital}} = (a + b \cdot A^{c}_{\mathrm{min}}) \cdot \frac{(1+i)^t}{t} \tag{3}$$

$$C_{\mathrm{Global}} = C_{\mathrm{Energy}} + C_{\mathrm{Capital}} \tag{4}$$

where C_{HU} is the cost of hot utility in \$/kW/year; C_{CU} is the cost of cold utility in \$/kW/year; HU is the hot utility demand, in kW; CU is the cold utility demand, in kW; a, b and c are constants that depends of the kind of the equipment; i is the interest rate; t is the plant lifetime, in years. The costs are in \$/year.

The value of optimum ΔT_{min} is obtained by finding the minimum of Eq. (4), that is the minimum cost of the heat exchangers network. This is, therefore, the objective function to be minimised in the first stage in this work. A genetic algorithm is used to the minimisation of this non-linear function.

The genetic operators used in this stage are *initialisation*, that is the generation of a randomly initial population (parents), being the individuals represented by the value of the variable in study, in this case the ΔT_{min}; the *aptitude calculus*, that is the objective function calculus for each individual in the population, in this case the global cost; the *crossover*, that in this stage was obtained by a linear combination between two parents, as presented in Tang and Wang [6], showed in Eq. (5); the *mutation*, that was achieved by a linear combination between a *child* generated in the crossover and a random number, as can be observed in Eq. (6); and the *selection*, that is the choice of the best individuals to be passed to the next generation.

$$F_i = \alpha \cdot P_j + (1 - \alpha) \cdot P_k \tag{5}$$

$$M_i = \beta \cdot F_j + (1 - \beta) \cdot R \tag{6}$$

In Eq. (5) F represents each *child* generated, i represents the individuals, α is a random number between 0 and 1, P represents the individual parent used to generate the *child*, j and k are the parents positions in the randomly population. In an analogous way, in Eq. (6) M represents the mutated individual, i represents the individuals, β is a random number between 0 and 1, F represents the individual *child* to be mutated, j is the *child* position and R is a random number in the same order of magnitude than F.

The choice of the two parents that will generate a *child* is made by the selection by roulette procedure.

During the mutation stage, not all the *children* are chose to be mutated. To determine if a *child* will or will not be mutated, a random number to each *child* is generated. If this number is less or equal the mutation rate, this *child* will be mutated. If it is greater than the mutation rate, it will be not mutated.

4.2. Synthesis of the optimal HEN

The minimum utilities cost in the HEN is obtained by finding the hot and cold utilities demand, obtained in the step of pre-analysis, to the ΔT_{min} optimised. The minimum capital cost is obtained by finding the matches between streams process that uses heat transfer equipment (heat exchangers, heaters and coolers) with the minor heat exchange area.

To achieve the optimal HEN, four restrictions must be obeyed, as showed below.

- (i) Heat is only transferred from a hot stream to a cold stream, and the hot stream temperature must be hotter than the cold stream temperature, according to Eq. (8).
- (ii) ΔT_{min} value must not be violated in both hot and cold ends of any heat transfer equipment in the network, according to Eq. (9).
- (iii) The minimum utilities demand, fixed in the first step must be assured, according to Eq. (10).
- (iv) The minimum heat transfer equipment must be maintained in each one of the sub-networks of the problem, according to Eq. (11).

The objective function is non-linear and the restrictions are combinations of equalities and inequalities, as shown in (7) to (11).

Minimize:

$$C_{\mathrm{GLOBAL}} = (C_{\mathrm{HU}} \cdot \mathrm{HU} + C_{\mathrm{CU}} \cdot \mathrm{CU}) + \frac{(1+i)^t}{t} \cdot \sum_{k}^{\mathrm{unid}} (a + b \cdot A_k^c) \tag{7}$$

Subject to:

$$\begin{cases} (Th_{\mathrm{in}})_k > (Tc_{\mathrm{out}})_k \\ (Th_{\mathrm{out}})_k > (Tc_{\mathrm{in}})_k \end{cases} \quad k = 1, \ldots, \text{number of heat transfer equipments} \tag{8}$$

$$\begin{cases} |(Th_{\mathrm{in}})_k - (Tc_{\mathrm{out}})_k| \geqslant f \cdot \Delta T_{\mathrm{min}} \\ |(Th_{\mathrm{out}})_k - (Tc_{\mathrm{in}})_k| \geqslant f \cdot \Delta T_{\mathrm{min}} \end{cases} \quad k = 1, \ldots, \text{number of heat transfer equipments} \tag{9}$$

$$\begin{cases} \mathrm{HU} \leqslant \mathrm{HU}_{\mathrm{min}} \\ \mathrm{CU} \leqslant \mathrm{CU}_{\mathrm{min}} \end{cases} \tag{10}$$

$$U_{\mathrm{min}} = N - 1 \tag{11}$$

where C_{HU}, C_{CU}, HU, CU, i, t, a, b and c were defined before; k represents heat exchangers, coolers and heaters; A is the heat transfer area; Th_{in} and Th_{out} are inlet and outlet temperatures of hot stream in the equipment; Tc_{in} and Tc_{out} are inlet and outlet temperatures of cold stream in the equipment; f is a factor to relax the ΔT_{min} restriction; $\mathrm{HU}_{\mathrm{min}}$ and $\mathrm{CU}_{\mathrm{min}}$ are the minimum hot and cold utilities demand; U_{min} is the minimum number of heat transfer equipments; N is the number of streams, included the utilities streams, in each sub-network.

In Eq. (9), f is a parameter used to relax the restriction of ΔT_{min}, i. e., is a measure in perceptual terms of how much this violation can be acceptable. Besides of this violation, minimum approach temperatures in the heat transfer equipment hot and cold ends is guaranteed. This is done to better use of the heat transfer area, by using less heat transfer area. When ΔT_{min} values are bigger (between 20 and 50 °C) it is possible to reduce this value in until 50% without problems in the other restrictions. The value of f is fixed previously, and varies from 0.5 to 1. As smallest is ΔT_{min}, the closer of 1 f is.

Eqs. (8) and (9) were presented separately to emphasize the existence of restrictions of thermodynamics limits and of ΔT_{min}. However, it can be combined, according to Eq. (12).

$$\begin{matrix} (Th_{\mathrm{in}})_k - (Tc_{\mathrm{out}})_k \geqslant \Delta T_{\mathrm{min}} \\ (Th_{\mathrm{out}})_k - (Tc_{\mathrm{in}})_k \geqslant \Delta T_{\mathrm{min}} \end{matrix} \quad k = 1, \ldots, \text{number of equipment} \tag{12}$$

The genetic operators in this stage are the same of the preceding stage, but adapted to the new problem. The *initialisation* generates a randomly initial population (parents), but the individuals, in this case are the HEN configurations.

The choice of the parents that will generate new *children* is made in the same manner that in the previous stage. However, in the crossover, that was made by a linear between two individuals parents combination. In this case, a part of the HEN configuration of a parent is combined with part of the HEN configuration of another parent it is made combining, generating 2 *children*. The position where the parent networks will be divided to form the *child* network is determined randomly. Figs. 2–4 show the step of crossover.

		Heat exhcange combinations						
Parent 1	Hot stream	3	1	5	2	4	6	2
	Cold stream	3	2	4	1	5	2	4

		Heat exchange combinations						
Parent 2	Hot stream	4	6	2	5	1	3	1
	Cold stream	2	5	3	2	4	5	1

Fig. 2. Choosing parents to generate *children*.

		Heat exchange combinations						
Parent 1	Hot stream	3	1	5	2	4	6	2
	Cold stream	3	2	4	1	5	2	4

Division position

		Heat exchange combinations						
Parent 2	Hot stream	4	6	2	5	1	3	1
	Cold stream	2	5	3	2	4	5	1

Division position

Fig. 3. Position of parents division.

		Heat exchange combinations						
Child 1	Hot stream	3	1	5	5	1	3	1
	Cold stream	3	2	4	2	4	5	1

		Heat exchange combination						
Child 2	Hot stream	4	6	2	2	4	6	2
	Cold stream	2	5	3	1	5	2	4

Fig. 4. *Children* generated by selected parents.

To determine whether a *child* will suffer mutation or not a similar procedure to the previous stage is followed. The big difference in this case is in the use a mutation rate that is variable in each generation. The objective of using a variable mutation rate is that it must be dynamic along the generations. In the first generations the difference between the maximum and the minimum

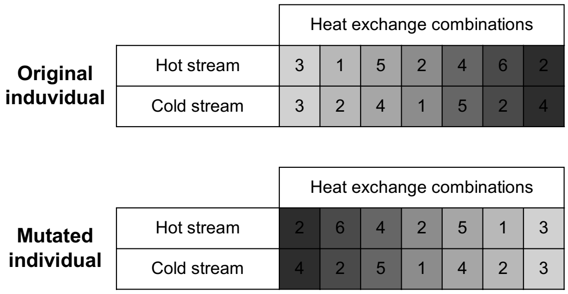

Fig. 5. Mutation step.

value of the objective function is great and the mutation rate is slow, because it exists a great diversity between the individuals. As the values of the objective function are being closer, the differences between the individuals decrease, and to make the appearing of new individuals possible, the mutation rate must be increased. Eq. (13) shows the behaviour of the mutation rate.

In Eq. (13), T is the mutation rate, calculated in each generation. $T_{\min}$ and $T_{\max}$ are the minimum and maximum mutation rate allowed and their values are 10% and 100%, respectively. C_n is the value of the cost of the worst individual and C_1 is the value of the cost of the best one.

The mutation step, in this stage of the study, is developed with all the existent individuals so far, parents and *children*. Differently from the previous step, where mutation was made just with *children* by linear combination, in this stage it occurs by inverting the positions of heat exchange in the network configuration. An example is shown in Fig. 5.

$$T = T_{\min} + (T_{\max} - T_{\min}) \cdot \mathrm{e}^{-10 \cdot \frac{(C_n - C_1)}{C_n}} \tag{13}$$

It is necessary to observe that in all the steps of the proposed methodology in this stage, restrictions must be respected. So, even all parents are generated randomly, not all the *children* and not all the mutated individuals are, necessarily, viable. To assure to achieve a HEN that does not violate any restriction it must be saved just the viable individuals and neglected that one that is not viable, in all the steps of the algorithm.

5. Cases studied

The first case studied is a problem presented by Frausto-Hernández et al. [7]. This problem has 2 hot and 2 cold streams process, a hot utility stream and a cold utility stream. Steam and cold water are hot and cold utility, respectively. The $\Delta T_{\min}$ proposed by the author was 10 °C. Streams data and the heat exchangers cost equation parameters are presented in Table 1. Eq. (14) presents the cost, with C in \$ and A in m^2.

$$C = 1200 \cdot A^{0,57} \tag{14}$$

During the $\Delta T_{\min}$ optimisation, as showed in Fig. 6, a value of 5 °C was found. It was necessary for the genetic algorithm five generations, and the size of the population is 40 individuals. The mutation rate was fixed 30%.

Table 1
Streams data and cost parameters for the first case studied

Stream	Type	T_{in} (°C)	T_{out} (°C)	CP (kW/°C)	h (kW/m^2°C)
H1	Hot	175	45	10	2.615
H2	Hot	125	65	40	1.333
C1	Cold	20	155	20	0.917
C2	Cold	40	112	15	0.166
Vapor	Hot utility	180	179	–	5.000
Água	Cold utility	15	25	–	2.500

Steam cost: 110 $/kW/year
Water cost: 10 $/kW/year

a	*b*	*c*	*i*	*t*
0	1200	0.57	0	1

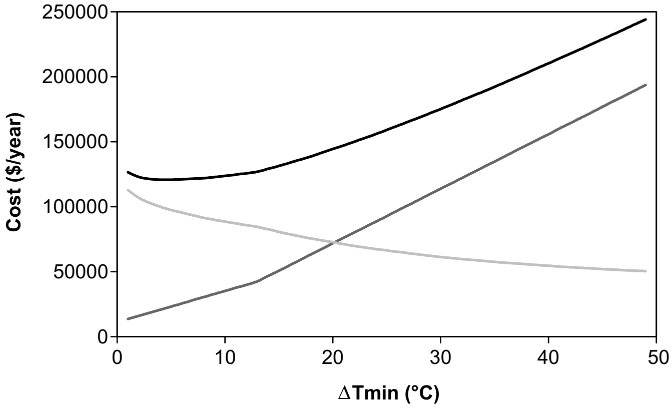

Fig. 6. Behaviour of cost functions for the first case studied.

In a second step, the HEN was synthesised with the optimum value of ΔT_{min}, 5 °C. The problem was divided into two sub-problems, above and below the pinch, and two sub-networks were obtained, with the maximum energy recovery. Fig. 7 shows the final HEN, and the characteristics of each equipment are showed in Table 2. H2a and H2b are the branches resulted of the H2 stream splitting, and C2a and C2b are the branches of the C2 stream splitting. As can be seen in Table 3, the total cost is minor than the value presented in the literature.

It was necessary 28 generations to achieve the minimum value of the objective function, and the value obtained for the global cost was 117.069,34 $/year, with 706.45 m^2 of total heat transfer area. The genetic parameters were 10 individuals as the size of the population, 80% for the maximum mutation rate and 10% for the minimum one. Cost data were the same used in the first step, and a value of 1 was used for the parameter *f*.

The second case studied is a problem presented by Ahmad [8]. The problem has 10 process streams, being 6 hot and 4 cold, a hot utility stream and a cold stream utility. Steam and cold water are hot and cold utility, respectively. The ΔT_{min} proposed by the author was 10 °C. Streams

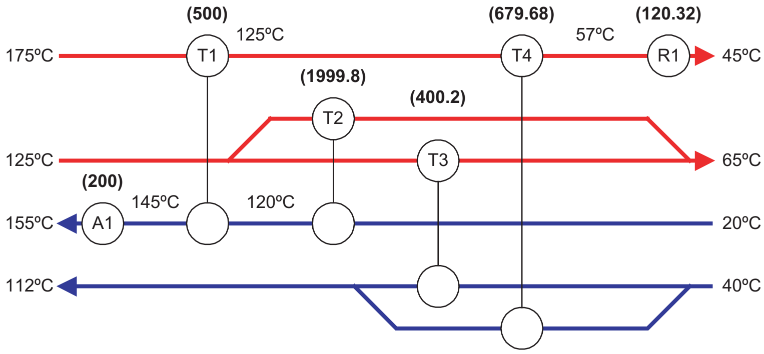

Fig. 7. Optimal HEN configuration for ΔT_{min} of 5 °C to the first case studied.

Table 2
Characteristics of heat transfer equipments

Equipment	Hot stream	Cold stream	Heat exchanged (kW)	Heat transfer area (m^2)	Cost ($)
A1	Steam	C1	200.00	8.85	4159.26
T1	H1	C1	500.00	52.78	11,508.01
T2	H2a	C1	1,999.80	202.23	24,746.57
T3	H2b	C2a	400.20	147.81	20,697.03
T4	H1	C2b	679.68	291.74	30,495.23
R1	H1	Water	120.32	3.04	2,260.04

Table 3
Comparison with the literature

	Frausto-Hernández et al. [7]	This paper
Hot utility (kW)	605.00	200.00
Cold utility (kW)	525.00	120.32
Total area (m^2)	423.26	706.45
Energy cost ($/year)	71,800.00	23,203.20
Capital cost ($/year)	75,553.75	93,866.14
Global cost ($/year)	147,353.75	117,069.34

data and the heat exchangers cost equation parameters are presented in Table 4. Eq. (15) presents the cost equation, with C in $ and A in m^2.

$$C = 60 \cdot A \tag{15}$$

The ΔT_{min} was optimised. Fig. 8 shows the behaviour of the functions energy, capital and global cost for the case studied. It was necessary 57 generations to achieve the minimum value of the objective function, and the optimum ΔT_{min} found was 24 °C. The population size, fixed in 50 individuals and the mutation rate, fixed in 40%, are the genetic parameters used in this first stage.

Table 4
Streams data and cost parameters for the second case studied

Stream	Type	T_{in} (°C)	T_{out} (°C)	CP (kW/°C)	h (kW/m^2 /°C)
H1	Hot	85	45	156.3	0.05
H2	Hot	120	40	50.0	0.05
H3	Hot	125	35	23.9	0.05
H4	Hot	56	46	1250.0	0.05
H5	Hot	90	85	1500.0	0.05
H6	Hot	225	74	50.0	0.05
C1	Cold	40	55	466.7	0.05
C2	Cold	55	65	600.0	0.05
C3	Cold	65	165	195.0	0.05
C4	Cold	10	170	81.3	0.05
Steam	Hot utility	200	199	–	0.05
Water	Cold utility	15	25	–	0.05

Steam cost: 100 $/kW/y
Water cost: 15 $/kW/year

a	*b*	*c*	*i*	*t*
0	300	1	0	5

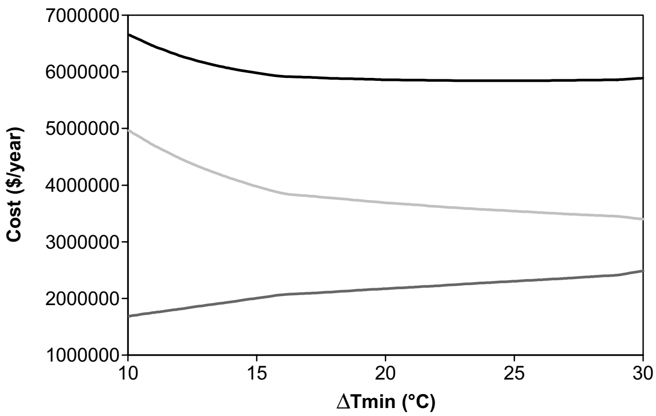

Fig. 8. Behaviour of cost functions for the second case studied.

In the second stage, a HEN was synthesised using the optimum value of ΔT_{min} found in the first stage, 24 °C. The problem was divided into two sub-problems, below and above the pinch. The HEN synthesised is optimal relative to energy and capital costs. The HEN configuration is presented in Fig. 9 and the equipment characteristics are presented in Table 5. Table 6 shows a comparison between the global costs with the literature.

It was necessary eight generations to achieve the minimum value of the objective function. The minimum cost corresponds to 5673 M$/year, with total heat transfer area of 56,600.56 m^2. The population size in the third stage of the proposed methodology to the second case studied was

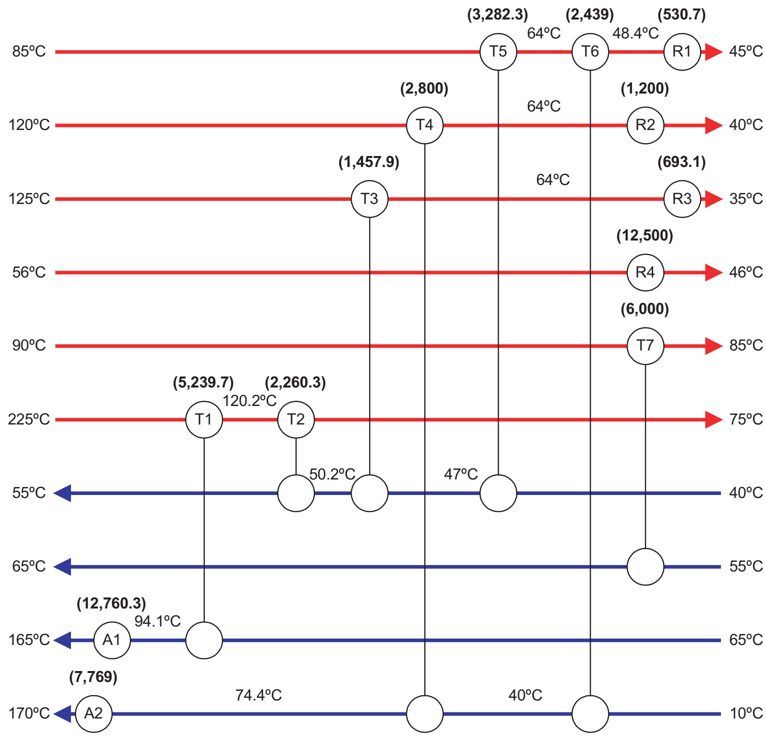

Fig. 9. Optimal HEN configuration for ΔT_{min} of 24 °C for the second case studied.

Table 5
Characteristics of heat transfer equipment

Equipment	Hot stream	Cold stream	Heat exchanged (kW)	Heat transfer area (m^2)	Cost ($)
A1	Steam	C3	12,760.3	8065.75	483,945.0
A2	Steam	C4	7769.0	4716.40	282,984.2
T1	H5	C3	5239.7	2390.65	143,438.9
T2	H5	C1	2260.3	2161.51	129,690.8
T3	H3	C1	1457.9	1495.40	89,724.2
T4	H2	C4	2800.0	3329.76	199,785.7
T5	H1	C1	3282.3	4311.51	258,690.6
T6	H1	C4	2439.0	3184.48	191,068.8
T7	H5	C2	6000.0	8925.74	535,544.6
R1	H1	Water	530.7	727.23	43,633.6
R2	H2	Water	1200.0	1428.16	85,689.7
R3	H3	Water	693.1	910.80	54,648.0
R4	H4	Water	12,500.0	14,953.17	897,190.4

fixed in 20 individuals, the maximum mutation rate was 80% and the minimum was 10%. Cost data are the same used in the previous stage, and the *f* factor was 0.71, for the ΔT_{min}.

Table 6
Comparison with literature

	Ahmad [8]	This paper
Hot utility (kW)	15,400	20,529.3
Cold utility (kW)	9796	14,923.8
Total area (m^2)	–	56,600.56
Energy cost ($/y)	1,686,940	2,276,787
Capital cost ($/y)	5,387,060	3,396,034
Global cost ($/y)	7,074,000	5,672,821

6. Conclusions

This paper presented a new methodology for the optimal HEN synthesis by using Pinch Analysis together with genetic algorithms. Also, the ΔT_{min} optimisation was achieved, contrary to most papers published in literature that consider a previously fixed value. However, a bad choice for ΔT_{min} will result in a bad HEN, relative to energy and capital costs. In the case studied, the value proposed by Ahmad [8] was 10 °C. Using the procedure developed for the ΔT_{min} optimisation, the value found was 24 °C. For the ΔT_{min} proposed in literature, Ahmad [8], the values for the HEN are very different, as can be seen in Table 4. The minimum global cost is achieved for ΔT_{min} of 24 °C. Although the energy cost is grater than the presented in the literature, the capital cost is minor. Because of that, the global annual cost is the minimum, as compared to literature.

In relation to the second stage, results prove the applicability of the developed methodology, in the case studied. Merging Pinch Analysis and genetic algorithms, the procedure is automatic during the synthesis task, and the user does not need to make choices for each match of streams. Also, the optimal HEN is achieved.

Finally, one can conclude that the proposed approach is efficient in the first stage, during the ΔT_{min} optimisation and during the second stage as well. As it was seen in the case studied, the final values are better than that ones presented in literature.

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