AN ALTERNATIVE PROCEDURE TO RETROFIT AN INDUSTRIAL PLANT. A CASE STUDY

F.S. LIPORACE*, F.L.P. PESSOA# and E.M. QUEIROZ#

** CENPES/PDEAB/EBS - Sala 2114 - Petrobras - Cidade Universitária - Q. 7 - Ilha do Fundão*
CEP: 21949-900 - Rio de Janeiro - RJ Tel.: (21) 3865-7027 Fax: (21) 3865-6342
liporace@petrobras.com.br

 # Dept. de Eng. Química - Escola de Química - UFRJ - Cidade Universitária - Ilha do Fundão
CEP: 21949-900 - Rio de Janeiro - RJ
mach@eq.ufrj.br

Abstract **- In this work, an alternative procedure to retrofit an industrial plant is proposed, based on a new heat exchanger network (HEN) synthesis and evolution algorithm. The idea is to consider the retrofitting as a grassroots design, but with match constrains accounted for during the synthesis. First, a lower bound for the HEN total annual cost (TAC) is determined and a new HEN is synthesized. A comparison between this HEN and the actual one is performed to search for structural similarities, forming the set of match constrains. Then, a new HEN keeping those similarities is proposed. The comparison among the three HENs indicate the recommended structural modifications. A Case Study is considered. Results show a reduction on the TAC, indicating the actual HEN is poorly integrated and a retrofit can be performed without many changes on the structure. The automatic HEN synthesis and evolution are performed using the software AtHENS,**

Keywords: **retrofit, automatic synthesis, automatic evolution, industrial plant.**

I. INTRODUCTION

The area of Process Design has evolved a lot for the last two decades since there was an increase on the Energetic Integrated Systems research, particularly on the problem of Heat Exchanger Network (HEN) synthesis (Gundersen and Naess, 1988). Among the various methods so far proposed to solve this problem, the Pinch Design Method, PDM (Linnhoff and Hindmarsh, 1983), can be highlighted. The PDM combines a strong thermodynamics basis and an easy way to synthesize networks near to the pinch point (PP).

On developing processes nowadays, the concepts of energetic integration are already accounted for during the synthesis stage, so the total annual cost (TAC) can be reduced, and hence the energy cost. But, as almost all the older processes did not do this, they frequently present a high-energy consumption. In order to improve it, these processes must go through some structural changes (retrofitting), which represent an increase on the capital cost (new heat transfer area, new piping etc), indicating that there is a trade-off between the operational and capital costs. Works on this issue are published since the 80's (Linnhoff and Withrell (1986), Tjoe and Linnhoff (1986)), the majority of them are based on the thermodynamic approach. In the 90's, some works based on the mathematical programming approach were developed (Ciric and Floudas, 1990), which use the concept of superstructure and an MINLP programming to model the problem and solve it automatically. The great advantage of this approach is that models can be as exact as the designer may wish, incorporating all kind of constrains. The disadvantage is that, in doing so, the problem complexity increases in the same proportion and so the way to solve it, which depends on a good initial point to avoid convergence difficulties and instability. Other works (Asante and Zhu (1996), Briones and Kokossis (1996)) propose methods that combine both mathematical and thermodynamic approaches, decreasing the problem complexity, but they are still dependent on a good initial point.

As the major feature of a good retrofit method is to decrease the energy consumption with the lowest change on the actual HEN structure, this work proposes a retrofit procedure, which combines the idea of incorporating all kind of match constrains from the retrofit procedures based on the mathematical programming approach and the fast and easy way to synthesize grassroots HEN from the design procedures based on the thermodynamic approach. This combination was possible due to the new HEN synthesis and evolution algorithms proposed by Liporace *et al.* (1997,1999) to automatically synthesize and structurally evolve HENs. The performance of these new algorithms have already been compared to the ones reported in the literature and good results were provided (Liporace *et al.*, 2001). Next, some important features of these algorithms are highlighted.

The HEN synthesis stage uses a modified PDM rule to synthesize the HEN near to the PP, namely the relation between the heat capacity flowrates of the incoming and outgoing streams. The traditional PDM rule (Linnhoff and Hindmarsh, 1983) states that the heat capacity flowrate of the incoming stream must be lower than or equal to the heat capacity flowrate of the outgoing stream. For some examples, it was verified that if this rule was blindly used in the synthesis near to the PP, the synthesis away from the PP could not be performed with minima consumption of utilities (MCU). This was overcome by a slightly modification on that rule, i.e., when the heat capacity flowrate of the incoming stream is lower than the heat capacity flowrate of the outgoing, this one is split in order to match the heat capacity flowrate. In doing so, streams with adequate temperature levels remain on the set of streams that is used in the synthesis away from the PP (Liporace *et al.*, 1997). This algorithm generates HEN with more splitters than the normal, but these may disappear during the evolution stage as long as the controllability analysis says so. In the synthesis away from the PP, it is used the heuristic rule of Ponton & Donaldson (Ponton and Donaldson, 1974)).

In the structural optimization stage, the loop identification procedure is based on the determination of the rank of the Incidence Matrix (Pethe *et al.*, 1989) and to restore the minimum temperature difference (MTD) and/or the target temperatures, if both are violated when the loop is broken, it is used the Simulation Matrix (Liporace *et al.*, 1999). The traditional restoration procedure (Linnhoff *et al.*, 1982) finds a path between a hot and a cold utility that passes through the heat exchanger where the MTD violation is taking place. Such search is not always easy to be conducted automatically and, sometimes, the path does not even exist. So, Liporace *et al.* (1999) proposed to represent the HEN structure, with its heat exchangers, heaters, coolers, splitters and mixers, in a form of a matrix (Simulation Matrix) in order to avoid the need for locating the path. Every time a loop is broken, this matrix allows the performance of a steady-state simulation of the HEN in order to verify in which unit the MTD violation is occurring, restore it by decreasing its heat load, and also check if all the process streams reach their target temperature. The Simulation Matrix allowed the automation of the loop-breaking procedure without the user interference. In our point of view, a loop should only be broken if the TAC is decreased, different from the traditional procedures (Trivedi *et al.*, 1990; Zhu,J.Y. *et al.*, 1999), which try to reach the minimum number of units with the lowest energy penalty without accounting for the HEN TAC.

The proposed new procedure to perform a retrofit analysis on an operating industrial site, based only on the thermodynamic approach, consists of 5 steps:

1) identify the process streams and the actual HEN;

2) "supertarget" the process;

3) synthesize a HEN that accomplishes the energy targets and evolve it by identifying and breaking the loops when economically indicated;

4) compare the HEN from (3) with the actual one in order to identify structural similarities and so define a set of match constrains (similarities);

5) synthesize and evolve a HEN containing those similarities, if they exist, obtaining the proposed new HEN.

The first characteristic of this alternative procedure is that a lower bound to the TAC is calculated and, assuming a grassroots design, a completely new HEN is generated (step 3), which would be the best HEN for that set of process streams. This synthesis is preceded by the "supertargetting" stage, which do not account for the existing heat transfer area, since it is considered that the HEN does not exist. The comparison between this new HEN and the actual one indicates how far the later is from the optimum HEN (indicating the need to retrofit or not) and shows structural similarities between them that would be used as constrains to generate a new HEN. Of course, it is up to the designer to select and use those constrains or any other he may wish. The HEN synthesis and evolution algorithms developed by the authors are based only on the thermodynamic approach, so there are no convergence and instability difficulties and, of course, they do not depend on an initial HEN structure. These facts contribute to reduce significantly the computing time to reach a solution, especially when dealing with big size problems, even when the match constrains are accounted for. This lower computing time allows the designer to use his experience without taking too much of his time and he may try several match constrains.

To illustrate the procedure, a Case Study using operational data extracted from an industrial site is considered. It is an Oximation Unit of a Caprolactma Production Plant.

The HEN synthesis and evolution is performed using the software AtHENS (Automatic Heat Exchanger Network Synthesis), developed at Departamento de Engenharia Química from Escola de Química of Universidade Federal do Rio de Janeiro, which is based on the algorithms previously presented.

II. PROCEDURE AND CASE STUDY

A. Identification of the process streams, of the actual HEN and supertargetting the process

The Case Study unit produces oxime, an intermediate reactant for the synthesis of caprolactama. The raw materials used on the synthesis of oxime are ammonia, air, hydrogen and ciclehexanone. The process is called HPO and has 4 stages:

- hydroxilamine (HYAM) synthesis;
- oxime synthesis by reacting HYAM with ciclehexanone using toluene as solvent;
- oxime-toluene separation;

Table 1 - Data on process streams

Stream	T_i	T_o	M.Cp	h	Stream	T_i	T_o	M.Cp	h
1	60.0	50.0	87.6	0.60	*18*	*22.7*	*85.2*	*4.4*	*1.16*
2	100.0	42.0	4.2	1.01	19	43.6	37.7	73.0	0.96
3	42.0	25.0	4.8	1.01	20	42.2	38.1	65.7	0.96
4	100.0	45.0	0.3	1.01	21	47.8	37.8	64.7	0.96
5	100.0	45.0	0.3	1.01	22	50.0	46.8	35.6	0.96
6	59.0	42.0	150.6	1.01	23	57.2	51.3	35.7	0.96
7	42.0	40.0	300.8	1.01	24	63.9	52.8	35.4	0.96
8	100.0	45.0	3.4	1.01	25	63.9	52.4	35.4	0.96
9	100.0	45.0	0.5	1.01	26	117.0	60.0	71.1	0.65
10	*43.0*	*68.0*	*9.1*	*0.10*	*27*	*55.0*	*70.0*	*21.7*	*0.19*
11	106.0	100.0	534.7	1.01	*28*	*70.0*	*90.0*	*113.6*	*0.39*
12	103.0	50.0	10.1	0.77	29	109.0	106.0	675.0	1.01
13	107.0	40.0	7.5	0.74	*30*	*47.0*	*90.0*	*7.4*	*0.40*
14	180.0	70.0	1.7	0.03	31	100.5	99.5	313.3	1.01
15	*20.0*	*237.0*	*10.2*	*0.01*	cu	5.0	15.0	-----	5.45
16	*21.5*	*22.5*	*1,862.4*	*1.16*	hu	400.0	330.0	-----	11.49
17	*22.0*	*49.0*	*1.2*	*2.24*					

T_i - inlet temperature (ºC); **T_o** - outlet temperature (ºC); **M.Cp** - heat capacity flowrate (kW/ºC); **h** - heat transfer coefficient (kW/m^2 ºC); **cu** - cold utility; **hu** - hot utility.

Table 2 - Data on operational and capital cost

	Cost
hot utility (US\$/MW year)	120,410.44
cold utility (US\$/MW year)	7,420.13
heat exchanger (US\$/year)	256.2 . $A^{0.6}$ (A in m^2)

Table 3 - "Supertargetting" results

Optimum MTD (ºC)	5.0
Pinch Point (ºC)	117.0 / 112.0
Minimum Hot Utility Consumption (kW)	1.17×10^3
Actual Hot Utility Consumption (kW)	4.87×10^3
Maximum Reduction (%)	**76.0**
Minimum Cold Utility Consumption (kW)	1.16×10^4
Actual Cold Utility Consumption (kW)	1.52×10^4
Maximum Reduction (%)	**24.0**

- nitrate ions synthesis (used on the HYAM synthesis).

Based on the Process Sheets, 8 cold streams and 23 hot streams were identified. Table 1 shows the necessary data to perform the energetic integration study: inlet (T_i) and outlet temperatures (T_o) of the process streams and their heat capacity flowrate (M.Cp). In this Table, *cu* means cold utility and *hu*, hot utility. Besides, in order to optimize the MTD, the heat transfer coefficient (h) for each process stream must be known. For the streams which data on density, viscosity and thermal conductivity were known, the heat transfer coefficient was estimated using the well known Dittus-Boelter correlation, assuming a 3/4" pipe and a mean fluid flow velocity of 1.5 m/s. For the others streams, this parameter was arbitrated according to the literature (Sinnot, 1993).

Table 2 presents the data on operational (hot and cold utilities) and capital costs. A heat exchanger lifetime of 10.0 years and a linear depreciation (0.0% as the rate of interest) were used (Wells and Rose, 1986).

Using the data presented in Tables 1 and 2, the optimum MTD is 5.0ºC. Table 3 presents the "supertargetting" results and it also shows a comparison among the target utilities consumption and the actual one, pointing a maximum reduction of 76% on the hot utility consumption and of 24% on the cold utility consumption. The great reduction on the hot utility consumption indicates that it is worthwhile to perform some structural and/or parametric changes on the actual HEN.

The actual HEN structure is shown in Fig. 1. Horizontal lines represent the process streams, with hot streams being directed from the left to the right and cold streams from the right to the left. The process-process heat exchangers are the vertical lines. Circles with up-arrows and down-arrows represent the heaters and coolers, respectively. Based on the data presented in Table 2, the actual HEN TAC is \$$7.58 \times 10^5$/year.

Two facts (the first is the most important) are responsible for the high-energy consumption, especially hot utility:

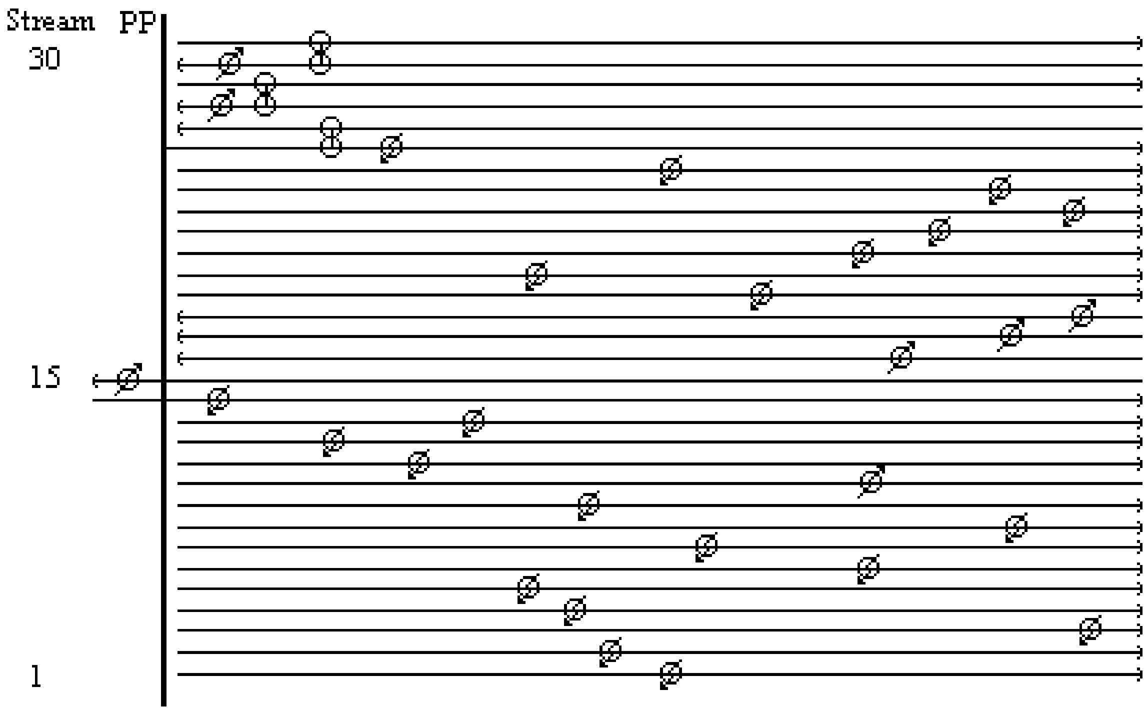

Fig. 1 - Actual HEN (HEN 1)
TAC: \$7.58 x 10^5/year

- use of hot utility below the PP (represented by a full vertical line on Fig. 1) on cold streams 10, 16, 17, 18, 28 and 30;

- poor integration among the process streams (only 3 process-process heat exchangers exist on the actual HEN: hot stream 26 with cold stream 27; cold stream 28 with hot stream 29 and cold stream 30 with hot stream 31).

B. Synthesis and structural evolution of an HEN with MCU - Lower bound

It has already been shown that if only the energy consumption is accounted for, it is worthwhile to care for some structural changes on the actual HEN. In order to verify their amplitude, a lower bound for the HEN should be generated, i.e., a completely new HEN with the lowest TAC. Figure 2 and Table 4 present the initial HEN with MCU. In this Table, *ITH* is the inlet temperature of hot stream, *OTH* is the outlet temperature of hot stream, *ITC* is the inlet temperature of cold stream, *OTC* is the outlet temperature of cold stream, *A* is the heat transfer area. .Splitting of cold stream 15 and hot stream 26 is a consequence of the algorithm proposed by Liporace *et al.* (1997), as already presented. The heat transfer areas were calculated using the heat transfer coefficient from Table 1 and assuming countercurrent configuration and, because of that, they are preliminary results. Of course, in the match where there is a process stream changing phase, the area calculated, as well as the intermediate temperatures, must be seen as rough estimations due to the assumption of constant specific heat made to characterize those streams.

Comparing Figs. 1 and 2, it can be seen an increase on energetic integration among the process streams in the HEN 2 and that the actual process-process heat exchangers do not appear on HEN 2. Besides, it must be noted that, using the same cost parameters from Table 2, the TAC is reduced 47%.

After the synthesis of the HEN with MCU, its structural optimization must be carried out by identifying and breaking the loops that might exist in order to reduce, not the operational cost, but the TAC. Figure 3 presents the first loop identified, which involves the process-process heat exchangers 1-7-8-9 (counted from the left to the right and represented by bold lines). The dashed line represents the heat exchanger with the lowest heat load. Figure 4 shows the HEN after breaking this loop. The appearance of a cooler on hot stream 14 is a consequence of the restoration of the MTD/temperature target. Three additional loops can be identified, but only one is broken, since the others would increase the TAC. Figure 5 presents the final HEN with the lowest TAC. It represents the lower bound for the HEN of this case (HEN 3).

Here, an important fact must be noted. The second loop is composed by 2 process-process heat exchangers and by 2 coolers (heat exchangers 1 and 2 and coolers on hot streams 14 and 26B). Among them, the cooler on hot stream 14 has the lowest heat load. As the loop is broken, eliminating this cooler, and a steady-state simulation is performed to correct any MTD/target

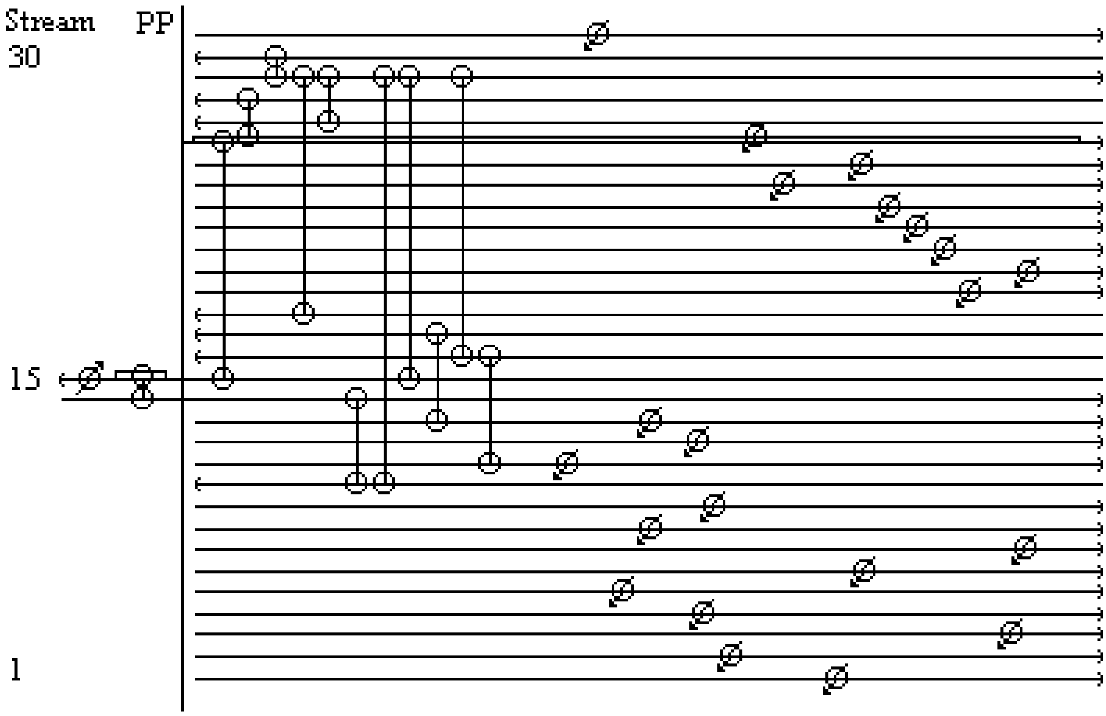

Fig. 2 - HEN with MCU (HEN 2)
TAC: $3.98 x 10^5/year

Table 4 - Data on the HEN presented in Fig. 2 (HEN 2)

Match	ITH	OTH	ITC	OTC	A	Match	ITH	OTH	ITC	OTC	A
hu - 15	400.0	330.0	122.4	237.0	591.4	5 - cu	100.0	45.0	5.0	15.0	0.4
14 - 15A	180.0	117.0	112.0	175.0	2,767.6	8 - cu	100.0	45.0	5.0	15.0	3.7
26A - 15	117.0	60.0	55.0	112.0	11,019.2	9 - cu	100.0	45.0	5.0	15.0	0.6
26B - 28	117.0	79.7	70.0	90.0	547.8	4 - cu	100.0	45.0	5.0	15.0	0.3
29 - 30	109.0	108.5	47.0	90.0	30.7	2 - cu	100.0	42.0	5.0	15.0	5.6
29 - 18	108.5	108.1	22.7	85.2	10.8	26B - cu	79.7	60.0	5.0	15.0	34.6
29 - 27	108.1	107.6	55.0	70.0	44.8	24 - cu	63.9	52.8	5.0	15.0	10.0
14 - 10	117.0	70.0	59.3	68.0	147.1	25 - cu	63.9	52.4	5.0	15.0	10.4
29 - 10	107.6	107.4	43.0	59.3	28.8	1 - cu	60.0	50.0	5.0	15.0	37.3
29 - 15	107.4	106.9	20.0	55.0	493.2	6 - cu	59.0	42.0	5.0	15.0	74.5
13 - 17	107.0	102.7	22.0	49.0	0.9	23 - cu	57.2	51.3	5.0	15.0	5.9
29 - 16	106.9	106.0	22.2	22.5	13.2	22 - cu	50.0	46.8	5.0	15.0	3.7
11 - 16	106.0	103.6	21.5	22.2	28.2	21 - cu	47.8	37.8	5.0	15.0	24.2
11 - cu	103.6	100.0	5.0	15.0	24.9	19 - cu	43.6	37.7	5.0	15.0	17.3
12 - cu	103.0	50.0	5.0	15.0	12.4	20 - cu	42.2	38.1	5.0	15.0	11.0
13 - cu	102.7	40.0	5.0	15.0	12.7	7 - cu	42.0	40.0	5.0	15.0	23.0
31 - cu	100.5	99.5	5.0	15.0	4.1	3 - cu	42.0	25.0	5.0	15.0	4.1

ITH - inlet temperature of hot stream (ºC); **OTH** - outlet temperature of hot stream (ºC);
ITC - inlet temperature of cold stream (ºC); **OTC** - outlet temperature of cold stream (ºC); **A** - heat transfer area (m^2); **hu** - hot utility; **cu** - cold utility.

temperatures violation, there appears the need to include a new cooler in the same place of the eliminated one, but with a different heat load (Fig. 5). Nevertheless, there was a decrease on the HEN TAC. This is because, even keeping the same HEN structure as before and a higher utility consumption, the new HEN has a better heat exchanger heat load / driving force relation, which contributes to decrease the heat transfer areas and, consequently, the capital cost, overcoming the increase on the operational cost. As the structure does not change, the third loop is equal to the second one and the same fact happens. However, now the increase on the operational cost will not be overcome by the decreased on the capital cost, so the loop is not broken. These slightly modifications on the heat exchanger heat load / driving force relation are easily and automatically identified by steady-state simulations performed with the Simulation Matrix (Liporace *et al.*, 1999).

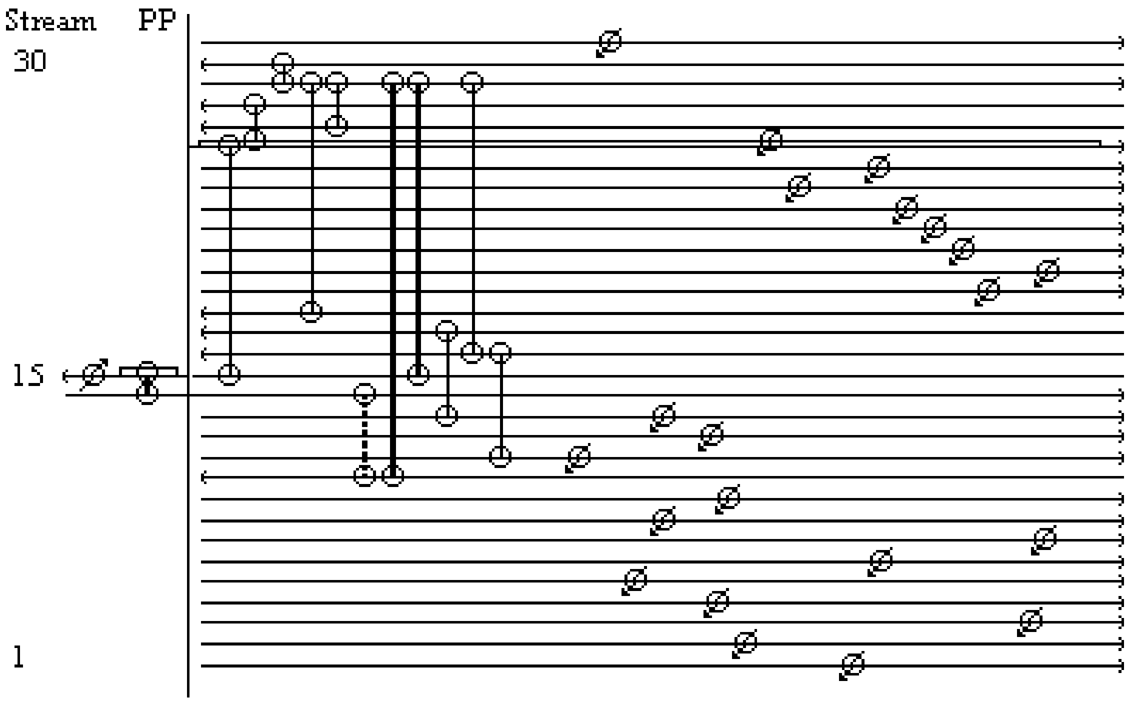

Fig. 3 - First loop identification

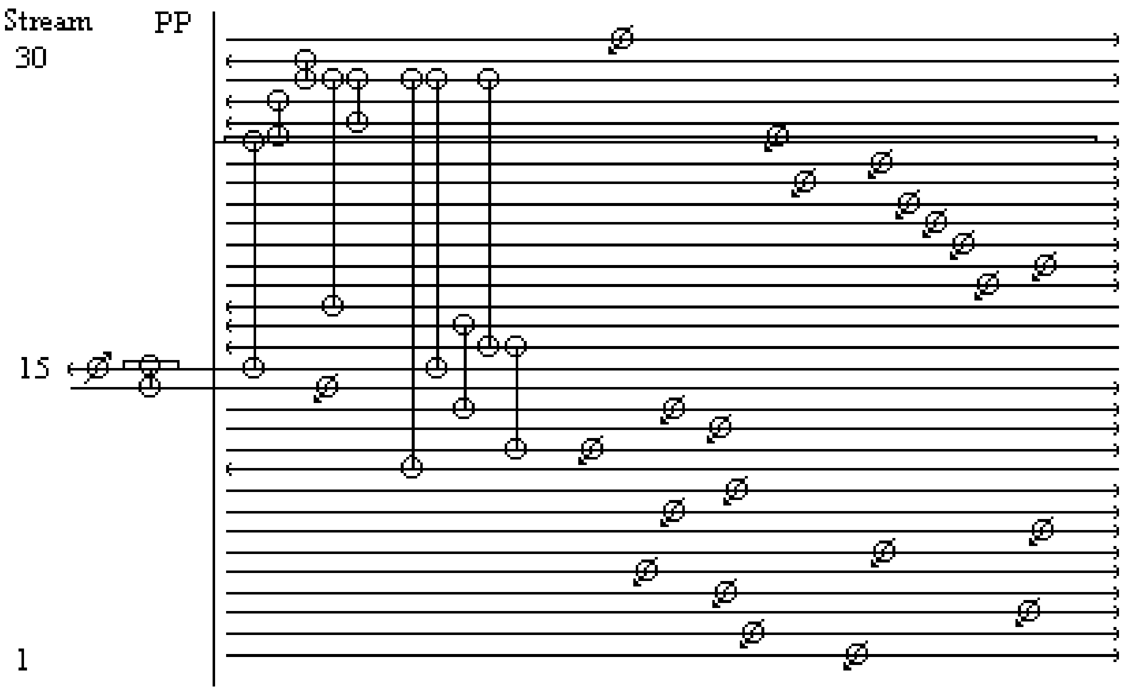

Fig. 4 - HEN after breaking the first loop
TAC: \$3.75 x 10^5/year

Comparing HEN 3 (Fig. 5) and HEN 1 (actual HEN, Fig. 1), it can be seen a great structure similarity in terms of the coolers, but none in terms of the process-process heat exchangers. So the actual HEN is really far from the ideal HEN structure and its TAC. As it was identified a possibility of a great reduction on the TAC, it is worthwhile to proceed with the retrofit analysis, even with poor structural similarities. Also note that there could be a case where, even with different HEN structures, the actual TAC is near to the lower bound and there is no advantage in going on with the retrofit analysis.

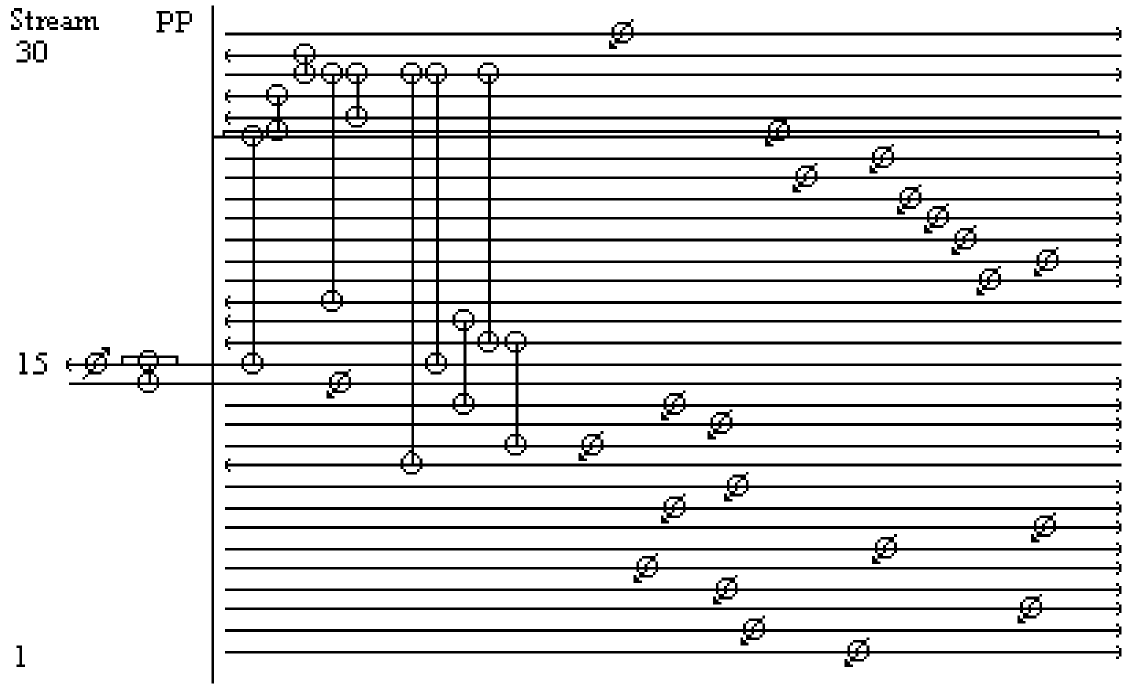

Fig. 5 - Lower bound for HEN structure (HEN 3)
TAC: $3.74 x 10^5/year

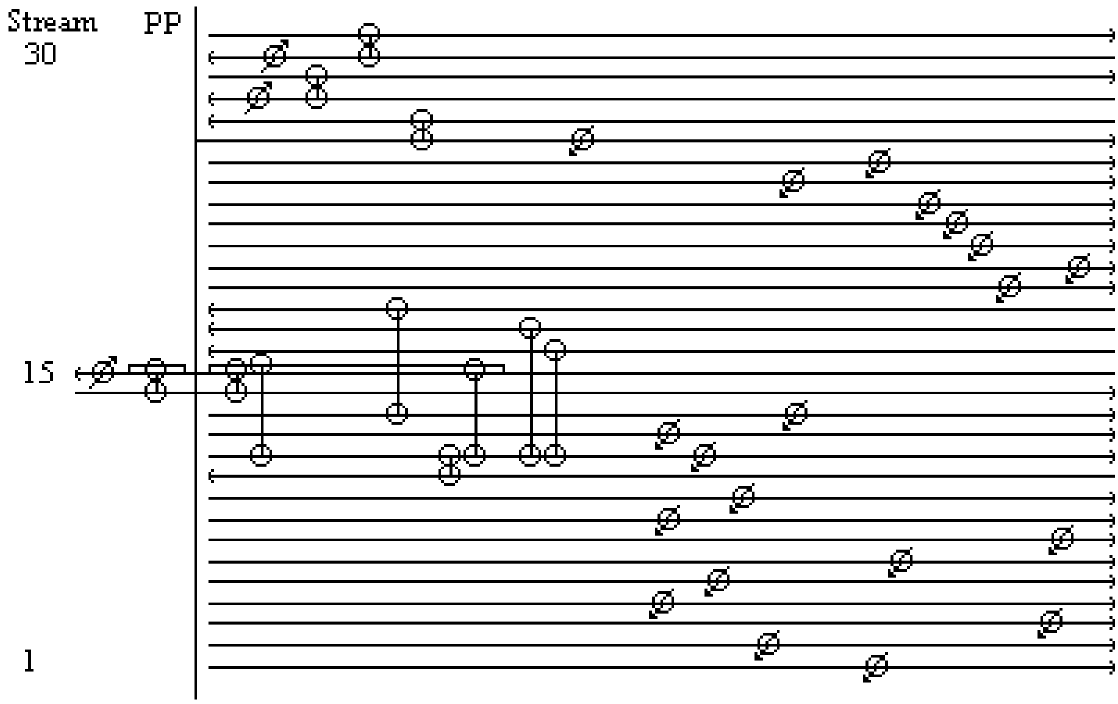

Fig. 6 - HEN with match constrains (HEN 4)
TAC: $3.98 x 10^5/year

C. Proposal of an HEN keeping the existing process-process units and its structural evolution

In this stage, in order to minimize the proposal of structural modifications on the actual HEN structure, it will be designed an HEN that keeps the process streams already integrated, namely: 26-27, 28-29 and 30-31, i.e., in the synthesis stage, it is allowed to the hot stream 26 combine just with the cold stream 27 and/or with cold utility, to the cold stream 27 combine just with

Table 5 - Data on the HEN presented in Fig. 6 (HEN 4)

Match	ITH	OTH	ITC	OTC	A	A*	Match	ITH	OTH	ITC	OTC	A	A*
hu - 15	400.0	330.0	113.3	237.0	624.5	968.7	4 - cu	100.0	45.0	5.0	15.0	0.3	0.3
14 - 15A	180.0	117.0	102.8	165.8	976.0	-----	5 - cu	100.0	45.0	5.0	15.0	0.4	0.4
14 - 15C	117.0	70.0	65.0	112.0	2,067.4	-----	8 - cu	100.0	45.0	5.0	15.0	3.7	3.7
11 - 15D	106.0	104.7	20.0	101.0	2,305.6	-----	9 - cu	100.0	45.0	5.0	15.0	0.6	0.6
hu - 28	400.0	330.0	87.8	90.0	2.4	2.4	2 - cu	100.0	42.0	5.0	15.0	5.6	5.6
29 - 28	109.0	106.0	70.0	87.9	255.6	257.5	13 - cu	70.2	40.0	5.0	15.0	7.9	13.1
hu - 30	400.0	330.0	89.1	90.0	0.1	0.1	24 - cu	63.9	52.8	5.0	15.0	10.0	10.0
31 - 30	100.5	99.5	47.0	89.1	40.5	40.5	25 - cu	63.9	52.4	5.0	15.0	10.4	10.4
13 - 18	107.0	70.2	22.7	85.2	18.6	-----	1 - cu	60.0	50.0	5.0	15.0	37.3	37.3
26 - 27	117.0	112.4	55.0	70.0	42.1	42.1	6 - cu	59.0	42.0	5.0	15.0	74.5	74.5
11 - 10	104.7	104.3	43.0	68.0	51.5	-----	23 - cu	57.2	51.3	5.0	15.0	5.9	5.9
11 - 15C	104.3	104.2	20.0	65.0	121.7	-----	22 - cu	50.0	46.8	5.0	15.0	3.7	3.7
11 - 17	104.2	104.1	22.0	49.0	0.7	-----	21 - cu	47.8	37.8	5.0	15.0	24.2	24.2
11 - 16	104.1	100.6	21.5	22.5	43.0	-----	19 - cu	43.6	37.7	5.0	15.0	17.3	17.3
26 - cu	112.4	60.0	5.0	15.0	86.5	86.5	20 - cu	42.2	38.1	5.0	15.0	11.0	11.0
11 - cu	100.6	100.0	5.0	15.0	4.2	40.5	7 - cu	42.0	40.0	5.0	15.0	23.0	23.0
12 - cu	103.0	50.0	5.0	15.0	12.4	12.4	3 - cu	42.0	25.0	5.0	15.0	4.1	4.1

ITH - inlet temperature of hot stream (ºC); **OTH** - outlet temperature of hot stream (ºC); **ITC** - inlet temperature of cold stream (ºC); **OTC** - outlet temperature of cold stream (ºC); **A** - heat transfer area (m^2); **A*** - existing heat transfer area (m^2); **hu** - hot utility; **cu** - cold utility.

Table 6 - Comparison between HEN 1, HEN 2 and HEN 4

	HEN 1 - (Fig. 1)	HEN 2 - (Fig. 2)	HEN 4 - (Fig. 6)
Hot Utility Consumption (kW)	4.87×10^3	1.17×10^3	1.51×10^3
Reduction on Consumption (%)	-----	76.0	69.0
Cold Utility Consumption (kW)	1.52×10^4	1.16×10^4	1.19×10^4
Reduction on Consumption (%)	-----	24.0	22.0
Total Annual Cost ($/year)	7.58×10^5	3.98×10^5	3.98×10^5
Reduction on the Cost (%)	-----	47.4	47.4

Table 7 - Comparison between HEN 1, HEN 3 and HEN 4

	HEN 1 - (Fig. 1)	HEN 3 - (Fig. 5)	HEN 4 - (Fig. 6)
Hot Utility Consumption (kW)	4.87×10^3	1.29×10^3	1.51×10^3
Reduction on Consumption (%)	-----	74.0	69.0
Cold Utility Consumption (kW)	1.52×10^4	1.17×10^4	1.19×10^4
Reduction on Consumption (%)	-----	23.0	22.0
Total Annual Cost ($/year)	7.58×10^5	3.74×10^5	3.98×10^5
Reduction on the Cost (%)	-----	50.7	47.4

the hot stream 26 and/or with hot utility, to the cold stream 28 combine just with the hot stream 29 and/or with hot utility and so on. These define the set of match constrains to be used in the synthesis stage. As the set of process streams did not change, the MTD, the utilities target, as well as the PP temperature, also did not.

Figure 6 and Table 5 present the HEN with the specified match constrains. Note that, because of them, the HEN structure becomes a little bit less complex than the HEN with MCU (HEN 2), with a lower integration among the process streams and, therefore, a higher utility cost. But the reduction on the TAC, compared with the actual one, is the same (a coincidence) as the one obtained with the HEN with no match constrains and MCU, as shown in Table 6. They are the same because the increase on the operational cost was counterbalanced by the decrease on the capital cost as a consequence of a better heat exchanger heat load / driving force relation among the heat exchangers of the HEN 4.

The loops in HEN 4 are not broken since their elimination do not lead to a decrease on the TAC. Hence, the proposed design of the case with match constrains is HEN 4.

Table 7 shows the comparison between the actual HEN and the two final optimized HENs proposed in this work, one obtained without match constrains (HEN 3) and the other obtained from the HEN with match constrains (HEN 4). Of course, HEN 3 presents better results in terms of reduction on the utility consumption and on the TAC since its initial point is the best one. But, accounting only for the reduction on TAC (this is what really matters to the industry), both HENs show similar performances, with HEN 4 presenting a less complex structure than HEN 3 and more structural similarities, allowing the possibility of using the existing heat exchangers.

Table 5 presents the heat transfer areas of the units proposed in HEN 4 and the respective actual values. Based on the data on capital cost from Table 2, an investment of \$7.90 x 10^5 (only on heat transfer area) must be done to achieve the desired structural changes. As these changes will allow a reduction of \$3.60 x 10^5/year on the TAC, the estimated return of investment is 2.2 years.

The main concern of this procedure is to generate a HEN showing, as much as possible, structural similarities with the actual HEN in order to minimize the proposed changes. On the other hand, the existing retrofit procedures assume the possibility of available heat transfer area redistribution. However, the actual heat transfer area can not be simply redistributed. This goal, in our point of view, should be left to a later step, since, depending on the streams involved and on the changes on the operational conditions of the actual HEN, only a detailed heat exchanger design can effectively indicate the possibility of its use and redistribution.

III. CONCLUSIONS

In this work, an alternative procedure to retrofit HEN is proposed. It is based on a new, fast and automatic grassroots design and evolution algorithms and its main concern is to propose a new HEN with as much structural similarities with the actual HEN as possible in order to minimize the investment on new heat transfer area. These similarities are treated as a set of match constrains, which is used in the initial HEN synthesis stage.

The advantage of this procedure over the existing mathematical programming ones is that it allows the designer to interfere in the synthesis stage using his experience to forbid and/or keep a match depending on the results obtained along the study without taking too much of his time. In the mathematical programming procedures, those constrains must be stated at the beginning and, as said before, the more the constrains the more the problem complexity. Difficulties on convergence and instability are also absent.

To illustrate it, a Case Study, based on an existing and operating site, was considered. According to the proposed procedure, the solution is HEN 4. It repeats the existing match (process-process and coolers), needs few new heat exchangers and presents approximately the same reduction on the TAC as HEN 3, which would be the optimal solution if only the TAC value were taken into account.

This procedure was used on another retrofit study (PETROBRAS refinery) and the results obtained were considered well satisfactory.

At last, AtHENS was fast in solving a big size problem in the HEN synthesis stage (with or without match constrains) as well as in the structural optimization stage, by identifying and breaking the loops. It took AtHENS less than one minute of average computing time (Pentium 166 MHz and 32 MB RAM) to complete the HEN synthesis and evolution.

IV. NOMENCLATURE

A	heat transfer area (m^2)
A*	existing heat transfer area (m^2)
AtHENS	automatic heat exchanger network synthesis
cu	cold utility
h	heat transfer coefficient (W/m^2 ºC)
HEN	heat exchanger network
hu	hot utility
HYAM	hydroxilamine
ITC	inlet temperature of cold stream (ºC)
ITH	inlet temperature of hot stream (ºC)
M.Cp	heat capacity flowrate (W/ºC)
MCU	minima consumption of utilities
MTD	minimum temperature difference (ºC)
OTC	outlet temperature of cold stream (ºC)
OTH	outlet temperature of hot stream (ºC)
PDM	pinch design method
PP	pinch point (ºC)
T_i	inlet temperature (ºC)
T_o	outlet temperature (ºC)

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