Fuzzy Analogical Gates Approach for Heat Exchangers Networks

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ABSTRACT

This paper presents a systematic method for synthesis of heat exchanger networks, the proposed algorithm consists of three sequential steps to select the optimal approach temperature: i) Estimation of normalized minimum approach temperature, normalized minimum hot utility and normalized minimum cold utility. ii) Fuzzy analogical gates network. iii) Selection of the best weight index. Two analogical gates (symmetric and asymmetric) are employed. The symmetric gate (AND gate) inputs are the normalized minimum approach temperature and normalized hot utility. The asymmetric gate (Invoke gate) inputs are the output of the AND gate and the normalized cold utility. The proposed method has been applied for four problems well-known in published literature. The results of these case studies show that the present strategy is both robust and accurate in finding out global optimum in comparison with previous works, characterized by its simplicity and can be implemented by hand calculations.

Keywords
Heat Exchanger Networks, Fuzzy Analogical Gates, Energy saving, Pinch Technology.

1. INTRODUCTION
HEN synthesis subject has been well-studied over the last 40 years. As a research theme, numerous papers have been published focusing distinct methods and techniques of synthesis. Heat recovery systems were always of interest in synthesis studies.

After the first energy crisis, during the 1970s, which can be considered as the driving force of the heat exchanger network synthesis study, as a research area, a considerable increase occurred in the number of papers related to the subject. Industries, universities and research centers had to find solutions to minimize the use of thermal energy from the burn of combustibles, like crude oil. 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 [1].

According to Ravagnani *et al.* [2], several kinds of studies were done aiming to develop methodologies to obtain optimal HEN to reach these goals. Research was concentrated in three important areas, Pinch Analysis, which uses thermodynamic concepts, Heuristics and Mathematical Programming, such as (LP), (NLP), (MILP), and (MINLP). Recently, heuristic methods of optimization have also been used to solve linear and non-linear models.

Gundersen [3] and Furman [1] published complete reviews on HEN synthesis. Important research lines have being proposed, like pinch analysis and mathematical programming.

Pinch Analysis uses thermodynamic concepts and heuristics, as can be seen in the works of Linnhoff and Flower [4], Linnhoff et al. [5, 6, and 7], Linnhoff [8, 9]. In mathematical programming the HEN synthesis is treated as an optimization problem. According to Grossmann et al. [10], a gradual evolution has occurred relative to mathematical programming method utilization, from the sequential approaches, where one aims to obtain the problem solution step by step, as can be seen in the papers of Cerda and Westerberg [11], Colberg and Morari [12], Floudas et al. [13], Gundersen and Grossmann [3] and Papoulias and Grossmann [14], till works using simultaneous optimization, where all of the variables are optimized simultaneously, as can be seen in the papers of Bjork and Westerlund [15], Ciric and Floudas [16], Quesada and Grossmann [17], Yee and Grossmann [18] and Zamora and Grossmann [19].

In this paper a new systematic method for synthesis of heat exchanger networks has been presented, the proposed algorithm consists of three sequential steps to select the optimal approach temperature, the results of case studies show that Fuzzy analogical gates strategy is both robust and accurate in finding out global optimum minimum approach temperature in comparison with previous works, which ensures its economic effectiveness.

2. ANALOGICAL GATES
Analogical gates are of two kinds Badreddin [20]: symmetric and asymmetric. These gates can be regarded as relations on the input set:

$$S = x \times y, x \in [x_{max}, -x_{max}], \ y \ \alpha \ [y_{max}, -y_{max}], \ x, y \ \alpha \ R.$$

Symmetric gates perform operations similar to their logical counter parts such as union (OR), intersection (AND) and exclusion (XOR).They borrow their names from the analogy to Boolean logic-gates on the vertices of the first and third quadrant in the input space.

2.1 Symmetric Gates

In the fuzzy analogical-AND gate as shown in Fig. 1(a), the output grows fastest when both inputs simultaneously grow. Also no output is produced if either input is zero.

The parameters a and b can be obtained by using the boundary conditions and zero derivative on the main axis. In this work the determined values of a, b are 2.28466 and - 0.089817, respectively.
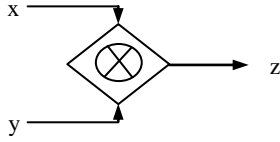

Fig .1(a) Symbols for the analogical (AND) gate.

$$Z = x \otimes y = x[1 - \xi(y,x)] + y[1 - \xi(x,y)] \qquad (1)$$

$$\xi(y,x) = e^{\left[-\frac{ay^2+byx}{y^2+x^2}\right]}, \text{ and } x, y \in R \qquad (2)$$

$$\xi(x,y) = e^{\left[-\frac{ax^2+bxy}{x^2+y^2}\right]}, \text{ and } x, y \in R \qquad (3)$$

2.2 Asymmetric Gates

The invoke gate is characterized such that as the x-input grows, the share of the y-input to the output increases. The absence of the x-input inhibits the output. In the absence of the y-input, the x-input is linearly passed to the output as shown in Fig.1 (b). In prevail gate the x-port is assigned an exceptional prevalence over the y-port. The latter is put-through directly to the output as long as the former is absent. However, once the input is at the prevalent part it strongly dominates the output.
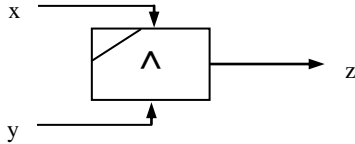

Fig.1 (b) Symbols for the analogical Invoke gate.

$$Z = x \wedge y = x\xi_1(y,x) + y[1 - \xi_2(x,y)] \qquad (4)$$

$$\xi(y,x) = e^{\left[-\frac{a_1y^2+b_1yx}{y^2+x^2}\right]}, \text{ and } x, y \in R \qquad (5)$$

$$\xi(y,x) = e^{\left[-\frac{a_2x^2+b_2xy}{x^2+y^2}\right]}, \text{ and } x, y \in R \qquad (6)$$

Where: $a_1 = 1.4749267$, $b_1 = 0.92870491$,
$a_2 = 2.6317713$, $b_2 = 0.2287955$.

3. FUZZY ANALOGICAL GATES STRATEGY

The algorithm followed in this step is selecting the best weight index as shown in Fig.2 which consists of three sequential steps:

  i.   Estimation of the normalized minimum approach temperature ΔT, normalized hot utility $(Q_H)_{min}$ and normalized cold utility $(Q_C)_{min}$.
  ii.   Fuzzy analogical gates network.

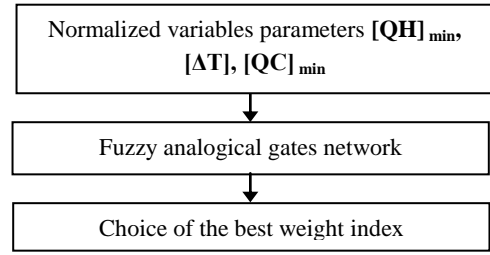 iii.   Selection of the best weight index.

Fig.2. Fuzzy Analogical Gates Strategy

Most of the previous work Aly [21] shows that the synthesis of HEN mostly depends on the minimum heat load (hot and cold), minimum approach temperature difference. Accordingly, in this work these variables have been selected as inputs to the different fuzzy analogical gates.

3.1. Normalized Variables Parameters

Assume different values of minimum approach temperature, get the minimum heating (Q_H) requirement & the minimum cooling (Q_C) requirement from the cascade diagram according to Linnhoff, B., and Hindmarsh [7], for each value of ΔT, $[(Q_H)_{min}, (Q_C)_{min}]$ can be derived by application of a linear programming code, two bounds $(f)_{min}$ & $(f)_{max}$ can be computed, and the normalized variables can be estimated by:

$$\mu = \frac{(f - f_{max})}{(f_{min} - f_{max})}, \text{ Where} \qquad (7)$$

$$\mu = 0 \text{ If } f = f_{max}; \ \mu = 1 \text{ If } f = f_{min}$$

3.2. Fuzzy Analogical Gates Network

Two fuzzy analogical gates will be used sequentially as shown in Fig.3. The first gate is selected to be symmetric and the second gate is asymmetric. A fuzzy analogical - AND gate will be followed by a fuzzy invoke gate.
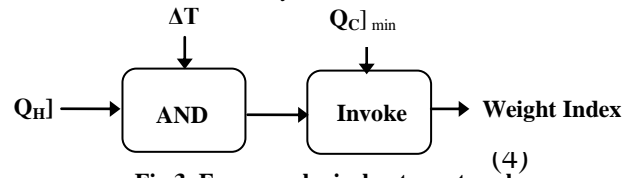
Fig.3. Fuzzy analogical gates network.

The symmetric gate inputs are the normalized heat load $(Q_H)_{min}$ and the normalized temperature difference (ΔT). The asymmetric gate inputs are the output of the symmetric gate and $(Q_C)_{min}$.

3.3. Choice of the Best Weight Index

The final step corresponds to the choice of the best weight Index. The operation is carried out by comparing (W.I) values for all minimum approach temperature and by choosing the greatest one.

$W.I_{optimum} = \max \{W.I_1, W.I_2, W.I_3 \ldots\ldots\} \qquad (8)$

4. PROBLEM STATEMENT

The HEN synthesis problem to be addressed in this paper can be stated as follows: A set of hot streams to be cooled and cold streams to be heated are given which include stream data with inlet and outlet stream temperatures, heat capacity flow

rates and heat transfer coefficients. In addition, a set of hot and cold utilities are specified. The basic objective of the HENS problem is to synthesize a network of heat exchangers, which facilitate the desired heat exchange, while keeping the investment (exchanger area) and operating costs (utilities consumption) to a minimum value. Fuzzy analogical gates strategy is employed in the present work to select the optimal minimum approach temperature which accordingly leads to minimum total annual cost.

5. EXAMPLES
The proposed method will be tested using four case studies reported in the literature, for comparison.

5.1. Example 1 (4SP1)
This is the 4SP1 problem involving two hot and two cold streams, one cold utility and one hot utility stream taken from Shenoy [22]. The overall heat transfer coefficients for all matches are the same. The specifications for all streams, plant data are shown in table 1and 2. The example was solved by MINLP model, Supertarget method as shown in table 3, 4 and Fuzzy analogical gates method to minimize Total Annual Cost (TAC).

5.2. Example 2
This example is taken from Hall [23] involves five hot and four cold streams, one cold utility and one hot utility stream. The overall heat transfer coefficients for all matches are different. The specifications for all streams and plant data are shown in table 7 and 8.The example was solved by MINLP model, Supertarget and Fuzzy analogical gates method to minimize Total Annual Cost (TAC) at EMAT = 20°C. The final optimum network is shown in Fig 5. The annual cost of hot utility and cold utility is ($/Yr 2,584,000). The area requirement is 9680 m^2 and the total capital cost is ($/Yr 1,336,763).

5.3. Example 3
The popular Aromatics plant problem [24] is the subject for this case study. The problem involves finding a cost-optimal network of exchangers for four hot streams and five cold streams one cold utility (Water) and one hot utility stream (Hot Oil) having different heat transfer coefficients. The plant data and specifications of all streams for the aromatics problem are given in Table 11 and 12. The corresponding network structure is shown in Fig. 6. The network obtained in this work has the lowest cost among all the unsplit cases. However, the network obtained by Pettersson [25] using stream splitting has the lowest cost among all the reported solutions as shown in table 14.

5.4. Example 4
This is a 10 stream problem studied first by Ahmed [26]. The problem involves finding a cost-optimal network of exchangers for six hot streams and four cold streams one cold utility and one hot utility stream having the same heat transfer coefficients. The input data for the problem is given in table 15 and 16. The final optimum network is shown in Fig 7. The annual cost of hot utility and cold utility is ($/Yr 2,104,705). The area requirement is 55,513 m^2 and the total capital cost is ($/Yr 3,330,832). The solution obtained by the proposed method is lower than the solution produced by Supertarget, lower than the solution obtained by combination of Pinch & Genetic algorithm and lower than the solution obtained by Differential Evolution Method.

Table 1: Stream and cost data for Example 1.

Stream	T_{in} (°C)	T_{out} (°C)	MCp kW/°C	h kW/m^2°C	Metal Specifications
H1	175	45	10	0.2	SS
H2	125	65	40	0.2	CS
C3	20	155	20	0.2	SS
C4	40	112	15	0.2	CS
HU	180	179	-	0.2	CS
CU	15	25	-	0.2	CS

Table 2: Plant Data.

Utility data	Fuel gas cost	120 ($/kW.yr)
	Cooling water cost	10 ($/kW.yr)
Plant Data	Rate of interest (i)	10 %
	Lifetime (n)	5 years
Capital cost data	A_f : Annualization factor	$(1+i)^n / n$
	Installed unit cost ($)	$30000 + 750(A)^{0.81}$

Table 3: Results of HEN by using MINLP.

Stream	Q (kW)	Area (m^2)	Materials of Construction
1	460.735	171.534	SS/SS
2	519.265	202.273	CS/SS
3	1839.265	712.340	CS/SS
4	560.735	305.547	CS/CS
5	400	119.009	CS/SS
6	320	80.004	CS/SS
Total	**4100**	**1590**	

Table 4: Results of HEN by using Supertarget.

Stream	Q (kW)	Area (m^2)	Materials of Construction
1	460.22	183	SS/SS
2	639.8	377	CS/SS
3	1839.265	972	CS/SS
4	440.2	305.547	CS/CS
5	400	119.009	CS/SS
6	200	59	CS/SS
7	120	26	CS/CS
Total	**4100**	**2041**	

The summary of results of the proposed method is shown in table 5, which confirmed with results obtained, thus the optimum $\Delta T = 25°C$ which give a global cost of ($/Yr 287,875) and a weight index of (0.611), which ensures our strategy.

Table 5. Results of Fuzzy Analogical gates.

ΔT (°C)	μ$_1$	μ$_2$	μ$_3$	W.I
15	0.375	0.926	0.926	0.327
17.5	0.438	0.833	0.832	0.488
20	0.500	0.741	0.739	0.599
25	**0.625**	**0.556**	**0.553**	**0.611**
30	0.750	0.370	0.367	0.376
35	0.875	0.185	0.181	0.093

The final optimum network is shown in Fig 4. The annual cost of hot utility and cold utility is ($/Yr 100,600). The area requirement is 1886.8 m^2 and the total capital cost is ($/Yr 287,875). The solution obtained by the proposed method is lower than the solution produced by MINLP and Supertarget method as shown in table 6.

Table 6: Comparison of results for Example 1.

	Shenoy [22]	Hojjati [28]	Present Work
Method	Supertarget	MINLP	A.G
ΔT (°C)	-	-	25
Hot Utility (kW)	400	400	780
Cold Utility (kW)	320	320	700
Total area (m²)	2041	1590	1886.8
Energy Cost ($/Yr)	51,200	51,200	100,600
Capital Cost ($)	1,031,584	851,602	581,600
Global Cost ($/yr)	383,475	325,502	287,875

Table 7. Stream and cost data for Example 2.

Stream	T_{in} (°C)	T_{out} (°C)	MCp kW/°C	h kW/m²°C	Metal Specifications
H1	120	65	50	0.5	CS
H2	80	50	300	0.25	CS
H3	135	110	290	0.3	SS
H4	220	95	20	0.18	SS
H5	135	105	260	0.25	CS
C6	65	90	150	0.27	SS
C7	75	200	140	0.25	CS
C8	30	210	100	0.15	CS
C9	60	140	50	0.45	SS
HU	250	249	-	0.3	CS
CU	15	25	-	0.2	CS

Table 8: Plant Data

Utility data	Fuel gas cost	120 ($/kW.yr)
	Cooling water cost	10 ($/kW.yr)
Plant Data	Rate of interest (i)	10 %
	Lifetime (n)	5 years
Capital cost data	Af : Annualization factor	(1+i)n / n
	Installed unit cost ($)	$30000 + 750 (A)^{0.81}$

The summary of results of the proposed method is shown in table 9, which confirmed with results obtained, thus the optimum ΔT = 20°C which give a global cost of ($/Yr 3,014,438) and a weight index of (0.684).

Table 9: Results of Fuzzy Analogical gates.

ΔT	μ_1	μ_2	μ_3	W.I
17.5	0.500	1.000	1.000	0.539
20	0.571	0.874	0.874	**0.684**
25	0.714	0.583	0.583	0.651
27.5	0.786	0.437	0.437	0.466
30	0.857	0.291	0.291	0.235

The solution obtained by the proposed method is lower than the solution produced by MINLP and solution obtained by Supertarget method as shown in table 10.

Table 10: Comparison of results for Example 2.

	Hall [23]	Jegede [29]	Hojjati [28]	Present Work
Method	Super-target	MINLP	MINLP	A.G
ΔT (°C)	20	20	20	20
Hot Utility (kW)	20950	20950	20950	20950
Cold Utility (kW)	7000	7000	7000	7000
Total area (m²)	9739	9659	9724	9680
Energy Cost (M$/Yr)	2.584	2.584	2.584	2.584
Capital Cost (M$)	2.971	2.986	2.895	1,.336
Global Cost (M$/yr)	3.540	3.545	3.516	3.014

Table 11. Stream and cost data for Example 3.

Stream	T in (°C)	Tout (°C)	M Cp (kW/°K)	h (kW/m²°K)
H1	327	40	100	0.5
H2	220	160	160	0.25
H3	220	60	60	0.3
H4	160	45	400	0.18
C1	100	300	100	0.25
C2	35	164	70	0.27
C3	85	138	350	0.25
C4	60	170	60	0.15
C5	140	300	200	0.45
Hot Oil	330	250	-	0.3
Water	15	30	-	0.2

Table 12: Plant Data

Utility data	Fuel gas cost	60 (US$/kW.yr)
	Cooling water cost	6 ($/kW.yr)
Plant Data	Rate of interest (i)	0 %
	Lifetime (n)	5 years
Capital cost data	Installed unit cost	10,000 + 350 A ($)

The summary of results of the proposed method is shown in table 13, which confirmed with results obtained, thus the optimum ΔT = 22.5°C with TAC ($/Yr 2,944,998) and a weight index of (0.760).

Table 13: Results of Fuzzy Analogical gates.

ΔT	μ_1	μ_2	μ_3	W.I
20	0.571	1.000	1.000	0.663
22.5	0.643	0.833	0.833	**0.760**
25	0.714	0.667	0.667	0.724
30	0.857	0.333	0.333	0.296

The network obtained in this work has the lowest cost among all the unsplit cases. However, the network obtained by Petterson [25] using stream splitting has the lowest cost among all the reported solutions as shown in table 14.

Table 14: Comparison of results for Example 3.

Authors	Method	Stream Split	Area (m^2)	Q_{Hmin} (MW)	Q_{Cmin} (MW)	TAC (M\$ /Yr)
Linnhoff [30]	S.M	0	17,400	25.31	33.03	2.960
Zhu. O' Neill [31]	NLP	2	16,630	26.22	33.94	2.970
Zhu et al. [31]	NLP	0	16,380	26.83	34.55	2.980
Lewin [32]	GA	2	17,050	25.09	32.81	2.936
Lewin [33]	GA	0	16,880	25.69	33.41	2.946
Petterson [25]	SMR	7	17,473	24.27	31.99	2.905
Krishna [34]	DEM	0	16,536	25.88	33.60	2.942
Azeez [35]	STBS	7	—	—	—	2.922
Present work	A.G	0	15,360	23.08	30.80	2.945

Table 15: Stream and cost data for Example 4.

Stream	T in (°C)	Tout (°C)	M Cp (kW/°K)
H1	85	45	156.3
H2	120	40	50
H3	125	35	23.9
H4	56	46	1250
H5	90	86	1500
H6	225	75	50
C1	40	55	466.7
C2	55	65	600
C3	65	165	180
C4	10	170	81.3
HU	200	198	-
CU	15	25	-

Table 16: Plant Data

Utility data	Fuel gas cost	100 (\$/kW.yr)
	Cooling water cost	15 (\$/kW.yr)
Plant Data	Rate of interest (i)	10 %
	Lifetime (n)	10 years
Capital cost data	A_f : *Annualization factor* Installed unit cost (\$) U (overall heat transfer coefficients)	$\dfrac{i(1+i)^n}{(1+i)^n - 1}$ 60 (A) 0.025 (kW/m^{2}K)

The summary of results of the proposed method is shown in table 17, which confirmed with results obtained, thus the optimum ΔT = 17.5°C with TAC (\$/Yr 2,647,630) and a weight index of (0.575), which ensures our strategy.

Table 17: Results of Fuzzy Analogical gates.

ΔT	μ_1	μ_2	μ_3	W.I
10	0.286	1.000	1.000	0.146
12.5	0.357	0.845	0.845	0.328
15	0.429	0.691	0.691	0.510
17.5	0.500	0.590	0.590	**0.575**
20	0.571	0.525	0.525	0.573
25	0.714	0.395	0.395	0.420
30	0.857	0.265	0.265	0.198

Table 18: Comparison of results of HEN

	Ahmed [26]	Ravagnani [33]	Krishna [19]	This Work
Method	Super target	Pinch + (GA)	(DEM)	A.G
ΔT (°C)	10	24	19.46	17.5
Hot Utility (kW)	15,400	20,529	20,745	19,033
Cold Utility (kW)	9,796	14,923	15,139	13,427
Total area (m^2)	-	56,000	56,085	55,513
Energy Cost (M\$/Yr)	1.686	2.276	2.301	2.104
Capital Cost (M\$)	5.387	3.396	3.365	3.330
Global Cost (M\$/yr)	7.074	5.672	5.666	5.435

The results of the DEM along with those of Ahmad [26] and Ravagnani et al. [27] are presented in Table 18. Ahmad [26] employed a fixed heat recovery approach temperature (HRAT) of 10 °C for synthesizing his network and reported a network cost of \$7,074,000. Ravagnani et al. [27] have obtained a network costing \$5,672,821, for an 'optimized' HRAT of 24 °C. Their work involved finding the optimal value for the minimum approach temperature using a combination of the pinch method and the Genetic Algorithm and subsequently synthesizing a cost-optimal as mentioned earlier, the DEM gives an optimal value for the minimum approach temperature (EMAT), during the simultaneous optimization of the network structure and other parameters. In this case study, it was found that the cost optimal network has a minimum approach temperature of 17.5°C by using Fuzzy Analogical gates method.
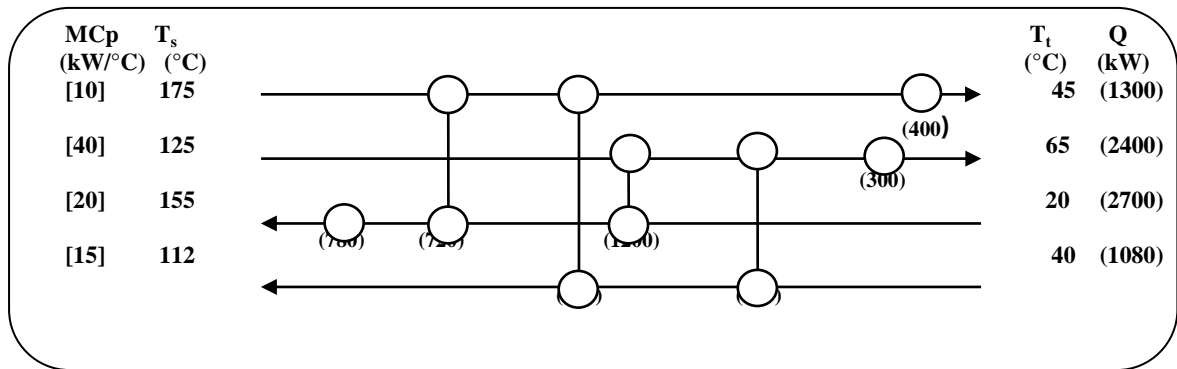
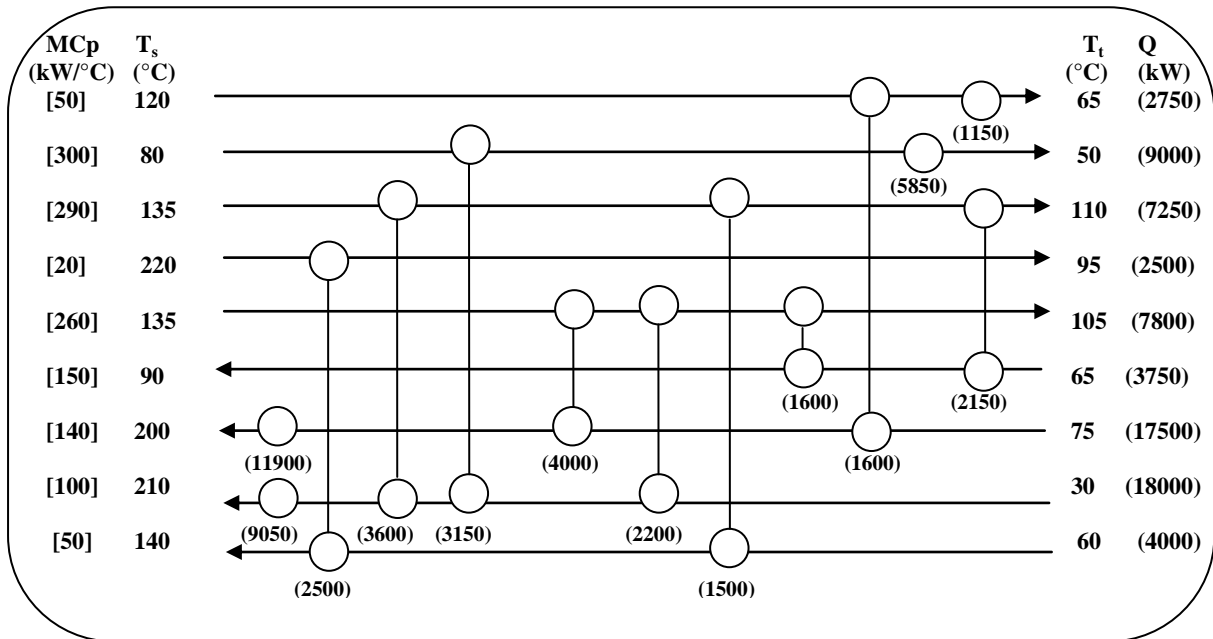**Fig.4. Optimum design for HEN of example 1 at ΔT$_{min}$ = 25°C**

Fig.5. Optimum design for HEN of example 2 at ΔT$_{min}$ = 20°C
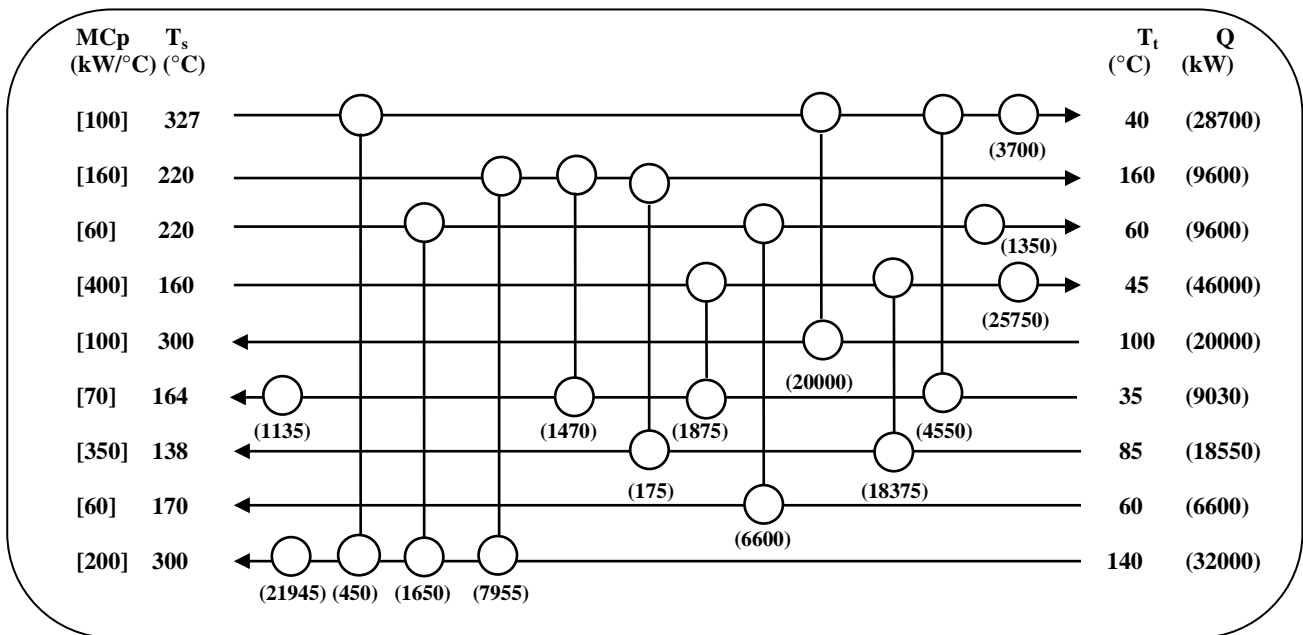
Fig.6. Optimum design for HEN of example 3 at ΔT$_{min}$ = 22.5°C

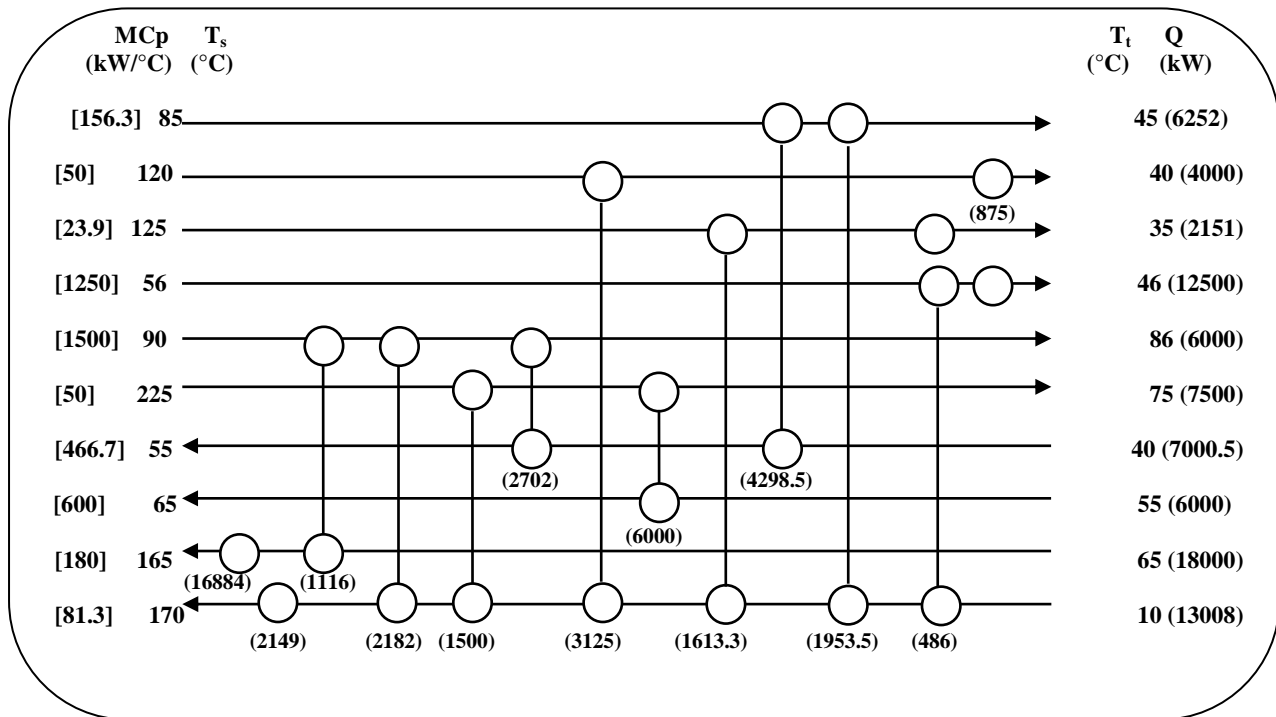| MCp (kW/°C)	T$_s$ (°C)										T$_t$ (°C)	Q (kW)
[156.3]	85										45	(6252)
[50]	120										40	(4000)
[23.9]	125								(875)			35	(2151)
[1250]	56										46	(12500)
[1500]	90										86	(6000)
[50]	225										75	(7500)
[466.7]	55				(2702)		(4298.5)				40	(7000.5)
[600]	65					(6000)					55	(6000)
[180]	165	(16884)	(1116)								65	(18000)
[81.3]	170	(2149)	(2182)	(1500)	(3125)	(1613.3)	(1953.5)	(486)			10	(13008)

Fig.7. Optimum design for HEN at ΔT$_{min}$ = 17.5°C

6. CONCLUSIONS

The present study explores new systematic method for synthesis heat exchanger network. The proposed method when applied to problems previously reported in the literature yielded optimum solutions which are consistent with different approach. It is evident that the performance of the Fuzzy analogical gates is quite encouraging, characterized by its simplicity and can be implemented by hand calculations.

The results of case studies show that the present strategy is both robust and accurate in finding out global optimum cost & optimum minimum approach temperature in comparison with previous works, which ensures its economic effectiveness,

Nomenclature

HENS	Heat Exchanger Networks
LP	Linear Programming
NLP	Non Linear Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non Linear Programming
SS	Stainless Steel
CS	Carbon Steel
W.I	Weight Index
TAC	Total Annualized Cost
EMAT	Exchanger Minimum Approach Temperature
HRAT	Heat Recovery Approach Temperature
SMR	Sequential match reduction
STBS	Supply and Target Based Superstructure
A.G	Analogical Gates
GA	Genetic Algorithm.
DEM	Differential Evolution Method.
S.M	Simple Model
μ_1	Normalized Minimum Approach Temperature
μ_2	Normalized Minimum Hot Utility Requirement
μ_3	Normalized Minimum cold Utility Requirement

7. REFERENCES

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