International Journal of Energy and Environmental Science
2019; 4(1): 18-26
http://www.sciencepublishinggroup.com/j/ijees
doi: 10.11648/j.ijees.20190401.13
ISSN: 2578-9538 (Print); ISSN: 2578-9546 (Online)

Effect of Supertargeting and Non Isothermal Stream Mixing in Heat Exchanger Network Design Using Modified Pinch Analysis

Azeez Oluwatosin Sarafa[1, *], Ogbonnaya Blessing[1], Ekechukwu Onyinye[1], Akande Hassan[2]

[1]Department of Chemical Engineering, Federal University of Technology, Minna, Nigeria
[2]Department of Chemical Engineering, Kaduna Polytechnic, Kaduna, Nigeria

Email address:
tosin.azeez@futminna.edu.ng (A. O. Sarafa)
[*]Corresponding author

To cite this article:
Azeez Oluwatosin Sarafa, Ogbonnaya Blessing, Ekechukwu Onyinye, Akande Hassan. Effect of Supertargeting and Non Isothermal Stream Mixing in Heat Exchanger Network Design Using Modified Pinch Analysis. *International Journal of Energy and Environmental Science.* Vol. 4, No. 1, 2019, pp. 18-26. doi: 10.11648/j.ijees.20190401.13

Received: January 30, 2019; **Accepted**: March 21, 2019; **Published**: May 11, 2019

Abstract: This paper investigated the effect of minimum temperature difference as well as that of non-isothermal stream mixing in heat exchanger networks (HENs) using a modified pinch technique. Supertargeting was carried out to determine the appropriate minimum temperature difference value used to design the HENs. The networks were further optimized to remove the isothermal mixing assumption. In the four case studies used in this work, each shows how these two concepts affect the total annual cost (TAC) of HENs. These were presented in the network comparison tables where the cost of the networks using supertargeting is much lower than the cost of the ones without, and the non-isothermal mixing networks have lower costs than the ones with the isothermal mixing assumption even in the networks designed without supertargeting technique.

Keywords: Supertargeting, Optimization, Non-Isothermal Mixing, Pinch Analysis

1. Introduction

Heat exchanger network synthesis (HENS) can be done with the aim of finding a heat exchanger network (HEN) that provides the minimum total annualized cost for a process. This can be achieved either through a sequential method such as pinch analysis [9], or simultaneously through mathematical programming technique [7, 3, 4], or with a combination of both methods [2, 8].

HENS can be carried out simultaneously using Mathematical programming, which solves the problem as a Mixed Integer Non-Linear Programming (MINLP) by optimizing utility costs, number of units and heat exchanger areas, all simultaneously [4]. Pinch Analysis as a thermodynamic based method of process integration is used in the sequential design of HENs that obey pinch principles and pinch design rules by setting targets, using Composite curves and minimum temperature difference and supertargeting technique [9]. The minimum temperature difference in a heat exchanger network ΔT_{min} is the smallest temperature difference that should exist between hot and cold streams in a heat exchanger for the HEN to be optimal. It is the temperature difference at the pinch point in the composite curves [15].

Supertargeting is the cost optimization tool of pinch analysis, that determines the optimum ΔT_{min} value by considering energy and capital costs tradeoff. The ΔT_{min} value is important in HENS as it directly affects the Energy Target which determines the operating cost and the Heat Exchanger Area Target that controls the capital cost of the network. The smaller the ΔT_{min} value, the lower the energy target but the higher the area target and vice versa. Hence Supertargeting is vital for the design of a globally optimum network [10, 9, 11].

HENS is mostly done with the assumption of isothermal stream mixing between split streams where all split sub streams of a stream exit at the same temperatureand assumed to mix isothermally at the junctions. This assumption was initiated by Yee and Grossmann [13], to eliminate non-linear mixing equations in the constraint equations of the mixers and exchangers, it reduces the problem's dimension and makes it easier to solve. It was used byAzeez et al [3] and compared with non-isothermal stream mixing by Bjork and Westerlund [4]. Thelimitation of this assumption is that it leads to the design of sub optimal networks, as it over-estimates the area cost due to the restriction it places on area trade-offs between the heat exchangers on the split streams [6].

Although the Isothermal mixing assumption makes the HENS more manageable by removing non-linear heat balances in the constraints, it does so at the expense of some important HEN configurations [8]. This can be corrected by the optimization of the designed network using a MINLP formulation that incorporates non-isothermal stream mixing in HENS, while introducing a number of bilinear terms that were excluded by the isothermal mixing assumption [4, 8]. The optimization could be done for the objective function of minimizing area, with split flow ratios and temperatures before mixers as the optimization variables [4] or for the objective function of minimizing total annualized cost (TAC), with split flow ratios and heat exchanger loads as the optimization variables as used by Aspen Energy Analyzer in this paper [1, 2].

Aspen Energy Analyzer is a heat integration software that combines traditional pinch analysis with mathematical programming for the design and optimization of heat exchanger networks (HEN) along with minimum total annual cost (TAC) for a process [12]. It designs the heat exchanger network using either pinch design method [9] or mathematical programming using its Automatic Recommend Design featurethat involves a Linear Programming model and two Mixed Integer Linear Programming (MILP) steps. The software's optimization tool optimizes the designed network considering degrees of freedom, feasibility of heat exchangers, temperatures specifications among other things, with the objective function of either minimizing TAC or the network's area [2].

In this paper, HENs designed using Modified Pinch Analysis on Aspen Energy Analyzer, Version 8.8 was compared with those designed by Bjork and Westerlund [4] in their "global optimization" using the Synheat Model [14]. This research brings to limelight the effect of non-isothermal stream mixing and minimum temperature difference ΔT_{min} on the total cost of HENS.

Problem Statement

There are hot streams in need of cooling and cold streams in need of heating in every plant, these energy needs can be satisfied using external utilities that increase the total cost of production. To achieve minimum total annual cost, the process heat can be conserved through synthesis of a heat exchanger network to exchange heat from the hot streams to heat as much of the cold streams as possible, maximizing process-process heat recovery and at the same time reducing the need for external utilities.

The heat exchange network can easily be synthesized with enough process information; heat capacity flow rates, supply and target temperatures and heat transfer coefficients of the process streams; costs, supply and target temperatures and heat transfer coefficient for the utilities as well as the annual operating time, capital cost index and the annualization factor.

2. Methodology

The modified pinch technique adopted in this research as viewed by the authors is as provided in Aspen Energy Analyzer [1]. It was used to optimize the total annual cost (TAC) of heat exchanger networks discussed in this work. Process data were collected from literature [4], such as the supply and target temperatures, heat transfer coefficients, heat capacity flow rates of the streams, capital cost index and cost of external utilities. Input of the extracted data into the Aspen Energy Analyzer user interface shown in Figure 1.

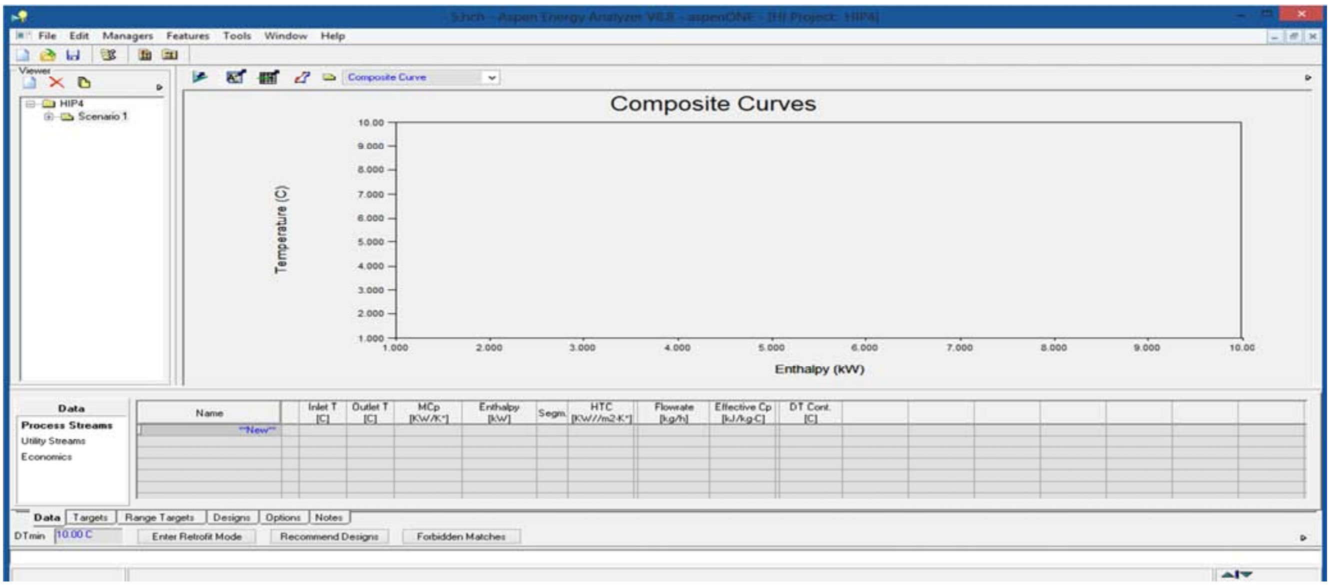


Figure 1. *Aspen Energy Analyzer Version 8.8's user interface.*

Supertargeting was carried out to determine the optimum ΔT_{min} value, by plotting targeted Total Annual Cost against the various values of minimum temperature difference in the heat exchanger network. Then, the heat exchange network was designed in the software's grid diagram using the ΔT_{min} value and pinch design rules [10] under isothermal stream mixing assumption, the designed network was further optimized using the software's optimization tool to remove the isothermal mixing assumption and bring about a non isothermal stream mixing network. Finally, the design process is then repeated at other ΔT_{min} values of to show the effect of ΔT_{min} in HENS.

3. Result and Discussion of Results

Four heat exchanger analysis problems were solved in this work, which focused on the effect of the non isothermal stream mixing assumption and that of the minimum temperature difference ΔT_{min} obtained from supertargeting using Aspen Energy Analyzer.

3.1. Case Study 1

This is a 3-stream problem, whose stream and cost data is shown in Table 1. The supertargeting curve for this problem shown in Figure 2 gives the network'sΔT_{min} as 10℃, the HEN designed using pinch design rules on Aspen Energy Analyzer obtained a total cost of $35,848 (Figure 3). On optimization using the aspen energy analyzer's optimization tool to remove the isothermal stream mixing assumption, the network with non-isothermal stream mixing as in Figure 4 had a total annual cost of $35,051. These networks were compared in Table 2, using total annual cost at different ΔT_{min} values with those designed by Bjork and Westerlund [4] to show the effect of supertargeting on the total annual cost of a network.

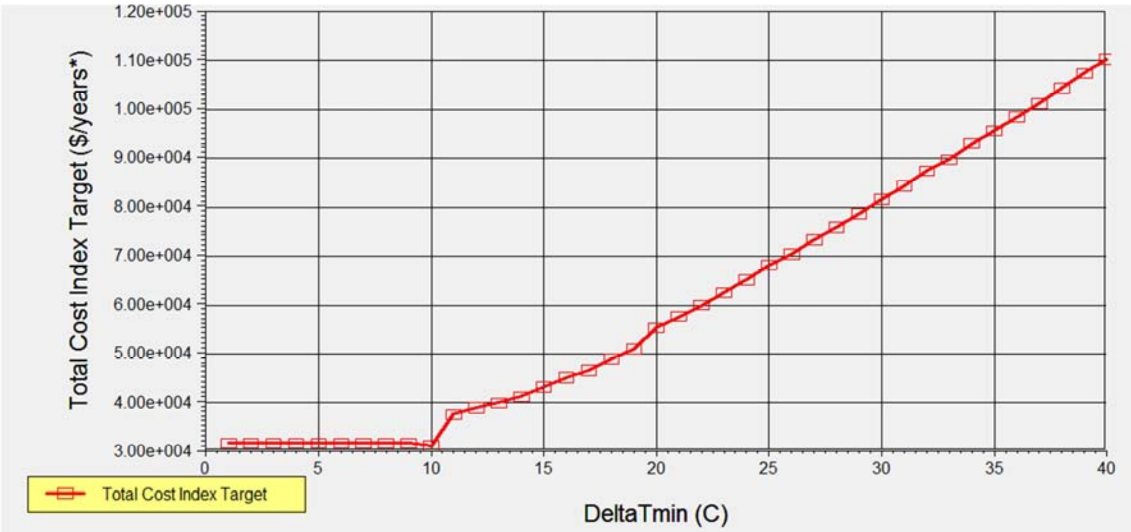


Figure 2. *Supertargeting curve for case study 1.*

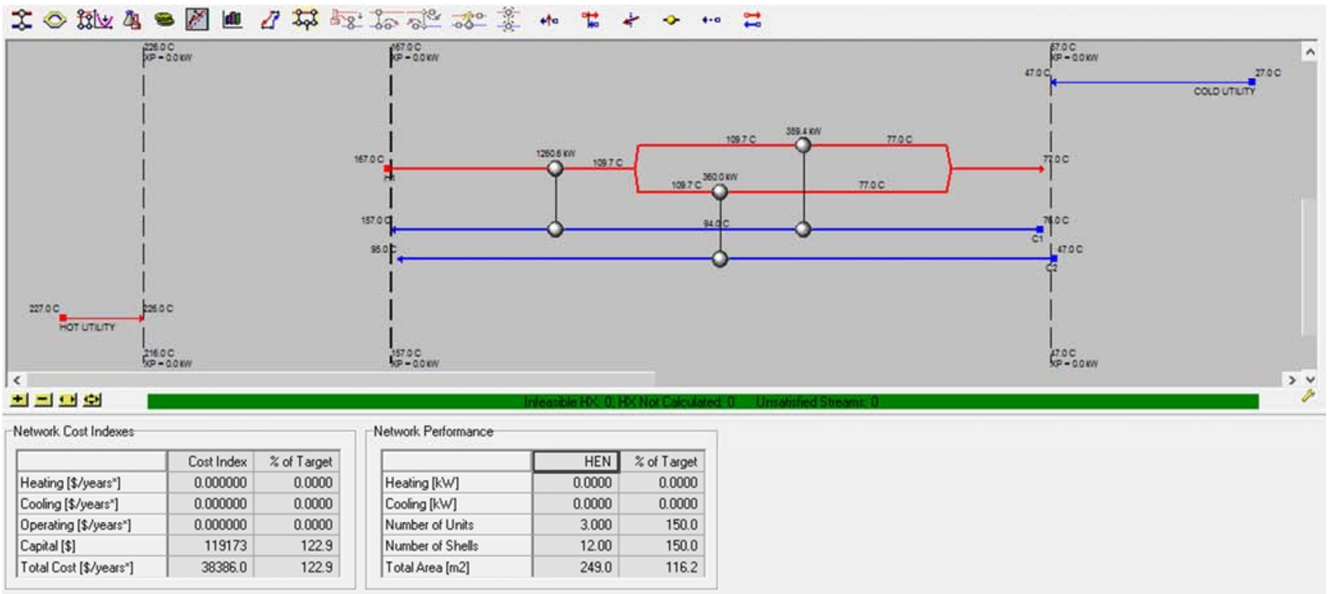


Figure 3. *HEN design with isothermal stream mixing for case study 1.*

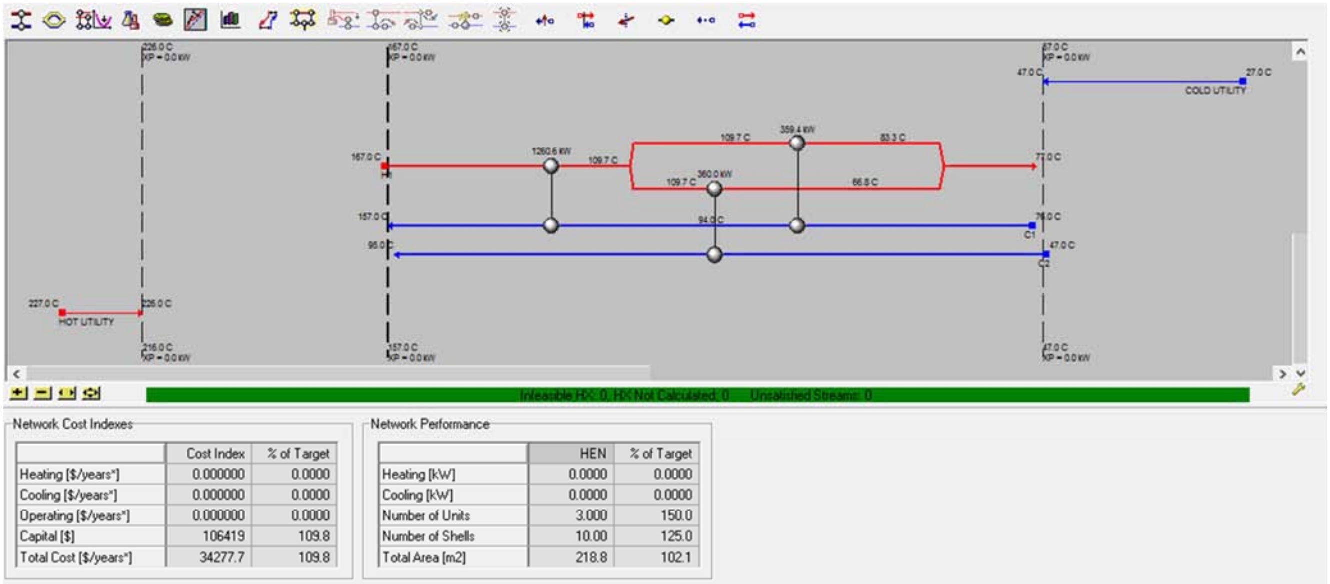


Figure 4. *HEN design with non-isothermal stream mixing for case study 1.*

Table 1. *Stream and Cost data for Case Study 1*

Stream	T_{in}(°C)	T_{out} (°C)	h (kW C^{-1} m^{-2})	FCp(Kw/K)	Cost ($ kw^{-1} yr^{-1})
H1	167	77	2	22	-
C1	76	157	2	20	-
C2	47	95	0.67	7.5	-
HU	227	227	1	-	120
CU	27	47	1	-	20

Heat Exchanger cost = 6600 + 670(area)$^{0.83}$

Table 2. *Network Comparison for Case Study 1.*

Method	ΔT_{min} (°C)	Total Annual Cost (TAC) $/year	
		Isothermal Stream Mixing	Non-Isothermal Stream Mixing
Global Optimization of Bjork and Westerlund, 2002 [4]	Not Stated	76,350	76,330
Modified Pinch Analysis (This work)	10	35,848	35,051
Modified Pinch Analysis	20	58,700	57,923
Modified Pinch Analysis	30	83,866	83,514

3.2. Case Study 2

This case study is based on a three stream problem with a hot utility and a cold utility from Bjork and Westerlund [4], its stream and cost data is given by Table 3. The dependence of the process HEN's total cost on ΔT_{min} is shown by its supertargeting curve in Figure 5, from which the optimum value is obtained as 14 K.

Table 3. *Stream and Cost data for Case Study 2.*

Stream	T_{in}(°C)	T_{out} (°C)	h (kW C^{-1} m^{-2})	FCp(Kw/K)	Cost ($ kw^{-1} yr^{-1})
H1	150	45	2	20	-
C1	60	120	2	11	-
C2	20	120	2	12	-
HU	210	210	1	-	80
CU	5	15	1	-	20

Heat Exchanger cost ($/year) = 4000 + 700(area)$^{0.8}$

The network designed for this problem using modified pinch analysis in Aspen Energy Analyzer shown in Figure 6obtained a TAC of $23, 891 with an area of 120 m^2. On optimization of this network using the Aspen Optimization tool with heat exchanger loads and split stream ratios as the optimization variables, the software obtained a non-isothermal mixing network (Figure 7) with TAC of $23, 439 and area of 118 m^2. These networks were compared with the TAC from other researcher's networks [4] for this problem in Table 4 to depict further the importance of the value of ΔT_{min} in HENS.

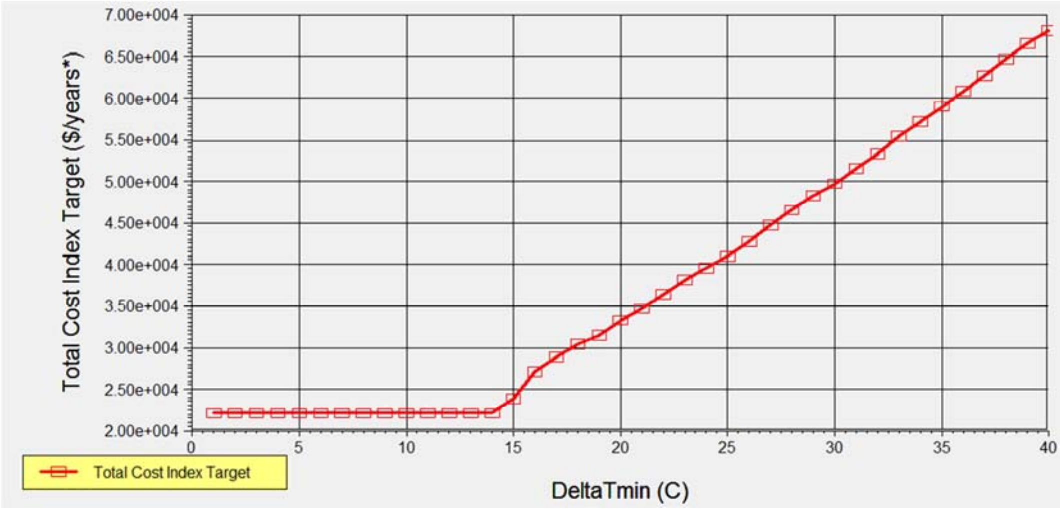
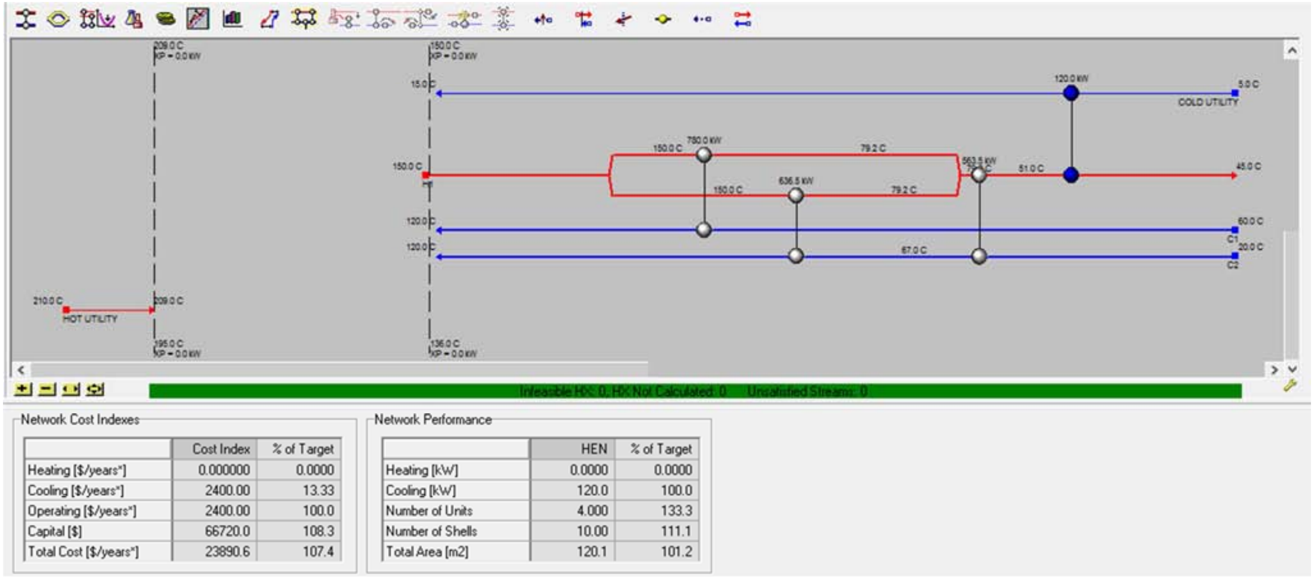


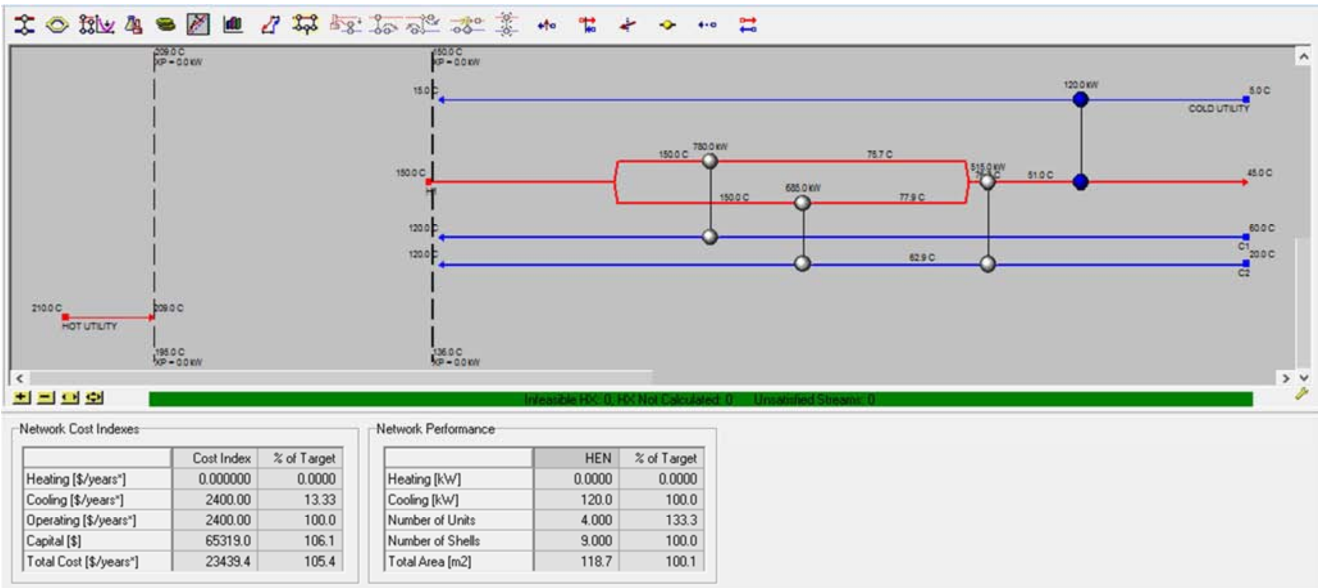
Figure 5. *Supertargeting Curve for Case Study 2.*



	Cost Index	% of Target
Heating [$/years*]	0.000000	0.0000
Cooling [$/years*]	2400.00	13.33
Operating [$/years*]	2400.00	100.0
Capital [$]	66720.0	108.3
Total Cost [$/years*]	23890.6	107.4

	HEN	% of Target
Heating [kW]	0.0000	0.0000
Cooling [kW]	120.0	100.0
Number of Units	4.000	133.3
Number of Shells	10.00	111.1
Total Area [m2]	120.1	101.2

Figure 6. *HEN design with isothermal stream mixing for case study 2.*



	Cost Index	% of Target
Heating [$/years*]	0.000000	0.0000
Cooling [$/years*]	2400.00	13.33
Operating [$/years*]	2400.00	100.0
Capital [$]	65319.0	106.1
Total Cost [$/years*]	23439.4	105.4

	HEN	% of Target
Heating [kW]	0.0000	0.0000
Cooling [kW]	120.0	100.0
Number of Units	4.000	133.3
Number of Shells	9.000	100.0
Total Area [m2]	118.7	100.1

Figure 7. *HEN design with non-isothermal stream mixing for case study 2.*

Table 4. *Cost Comparison for Case Study 2.*

Method	ΔT_{min} (℃)	Total Annual Cost (TAC) $/year	
		Isothermal Stream Mixing	Non-Isothermal Stream Mixing
Global Optimization of Bjork and Westerlund, 2002 [4]	Not Stated	52,429	48,625
Modified Pinch Analysis (This work)	14	23,891	23,439
Modified Pinch Analysis	25	41,733	41,212
Modified Pinch Analysis	35	61,385	60,865

3.3. Case Study 3

Here a HEN was designed for a problem involving 2 hot streams and 2 cold streams using the Aspen Energy Analyzer software, the Stream and Cost data for this problem is displayed in Table 5. Supertargeting was carried out on the problem and a ΔT_{min} value of 3℃ as can be seen in the supertargeting curve on Figure 8, the network designed with the value and the isothermal stream mixing assumption (Figure 9) obtained TAC of $346,471. The removal of the isothermal assumption through optimization of the designed network produced a non-isothermal network (Figure 10) with TAC of $325,328. The networks designed in this work were compared with other works [4, 14] in Table 6, Zamora and Grossmann [14] solved this same problem but without stream splits.

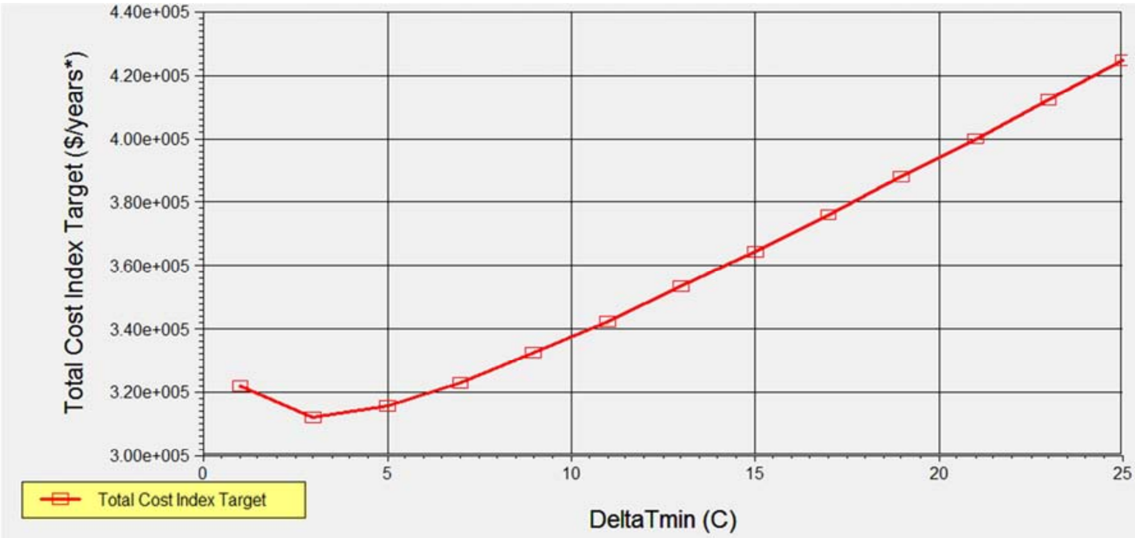


Figure 8. *Supertargeting Curve for Case Study 3.*

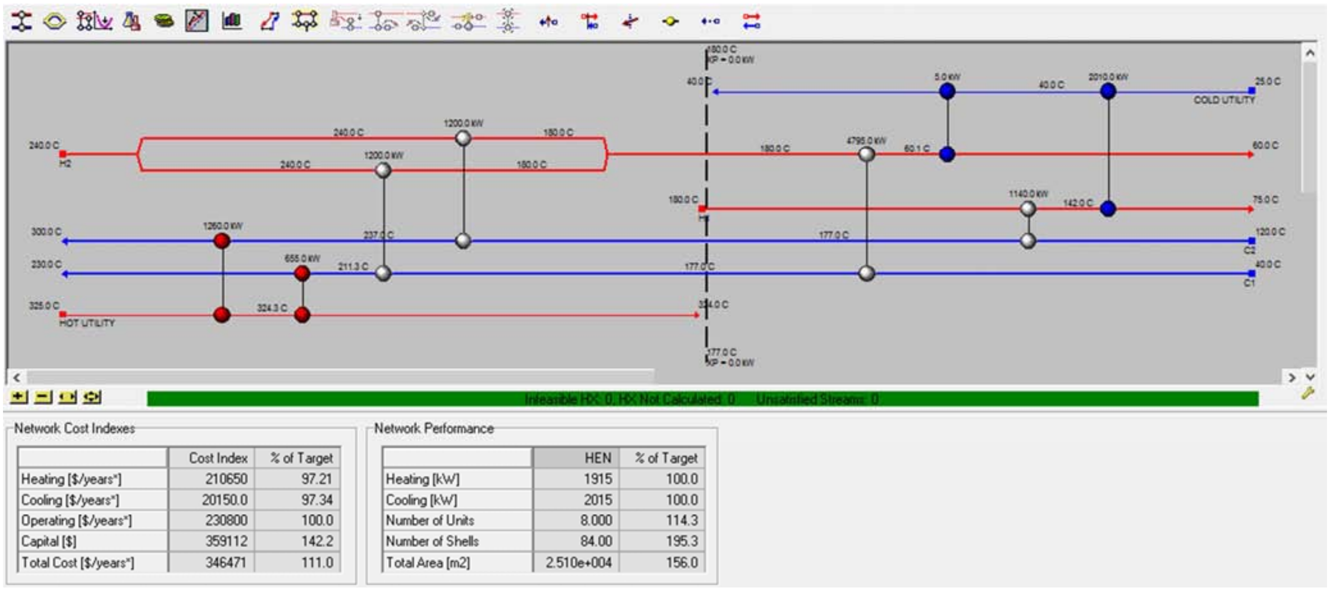


Figure 9. *HEN design with isothermal stream mixing for case study 3.*

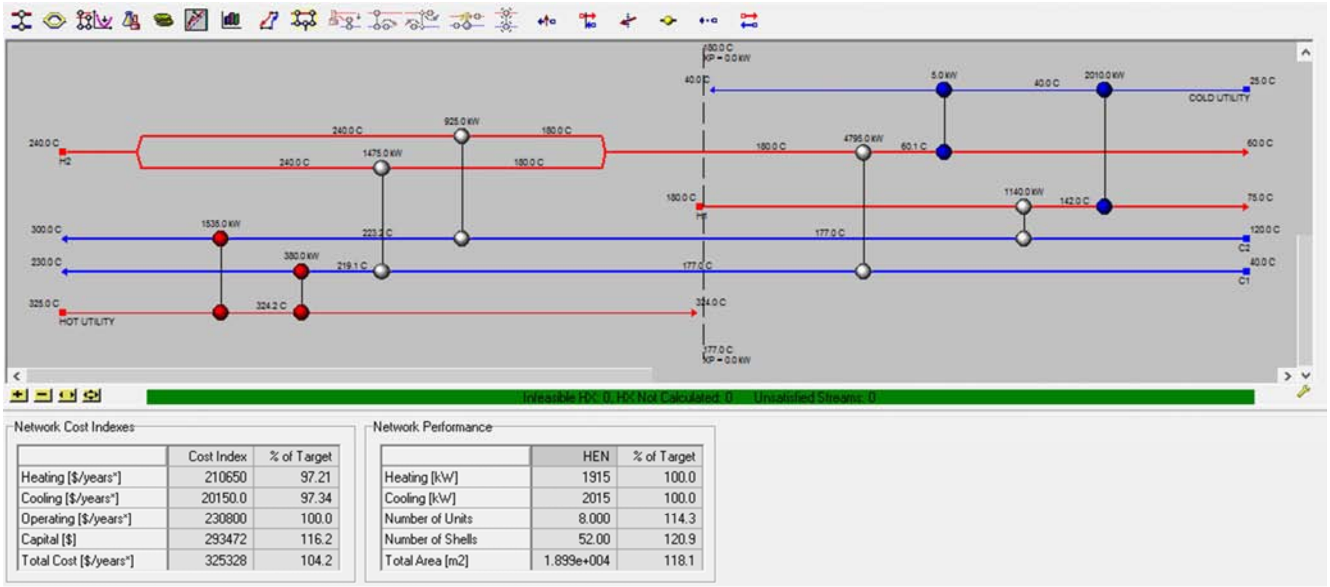


Figure 10. *HEN design with non-isothermal stream mixing for case study 3.*

Table 5. *Stream and Cost data for Case Study 3.*

Stream	T_{in}(°C)	T_{out} (°C)	h (kW C^{-1} m^{-2})	FCp(Kw/K)	Cost (\$ kw^{-1} yr^{-1})
H1	180	75	0.15	30	-
H2	240	60	0.10	40	-
C1	40	230	0.20	35	-
C2	120	300	0.10	20	-
HU	325	325	2	-	110
CU	25	40	0.5	-	10

Heat Exchanger cost = 15,000 + 30(area)$^{0.8}$

Table 6. *Network Comparison for Case Study 3.*

Method	ΔT_{min} (°C)	Isothermal Network Cost ($/year)	Non-Isothermal Network Cost ($/year)
Bolio, 1994 [5]	Not Stated	453,294	-
Zamora and Grossmann, 1998[14]	Not Stated	419,979 (*no stream splits*)	-
Bjork and Westerlund, 2002 [4]	Not Stated	415,189	411,746
This work	3	346,471	325,328
Modified Pinch Analysis	15	374,205	371,720
Modified Pinch Analysis	25	431,806	430,911

3.4. Case Study 4

Here, a 4 stream problem was solved to show the effect of ΔT_{min} and non-isothermal stream mixing, the stream and cost data for this case study are shown in Table 7. The process ΔT_{min} was determined using supertargeting as 5 °C (Figure 11). The HEN designed for this problem (Figure 12) obtained a total annual cost of $49, 774, this network displayed in, on removal of the isothermal mixing assumption using optimization the total cost was reduced to $49,424 as in the optimized network (Figure 13). These networks were compared to isothermal and non-isothermal solutions without the consideration of ΔT_{min} [4] in Table 8.

Table 7. *Stream and Cost data for Case Study 4.*

Stream	T_{in}(°C)	T_{out} (°C)	h (kW C^{-1} m^{-2})	FCp (Kw/K)	Cost (\$ kw^{-1} yr^{-1})
H1	227	147	1.60	6	-
H2	157	57	1.60	6	-
H3	147	67	1.60	7	-
C1	67	227	1.60	10	-
HU	325	325	1.60	-	80
CU	25	40	1.60	-	20

Heat Exchanger cost = 1,000 + 560(area)$^{0.6}$

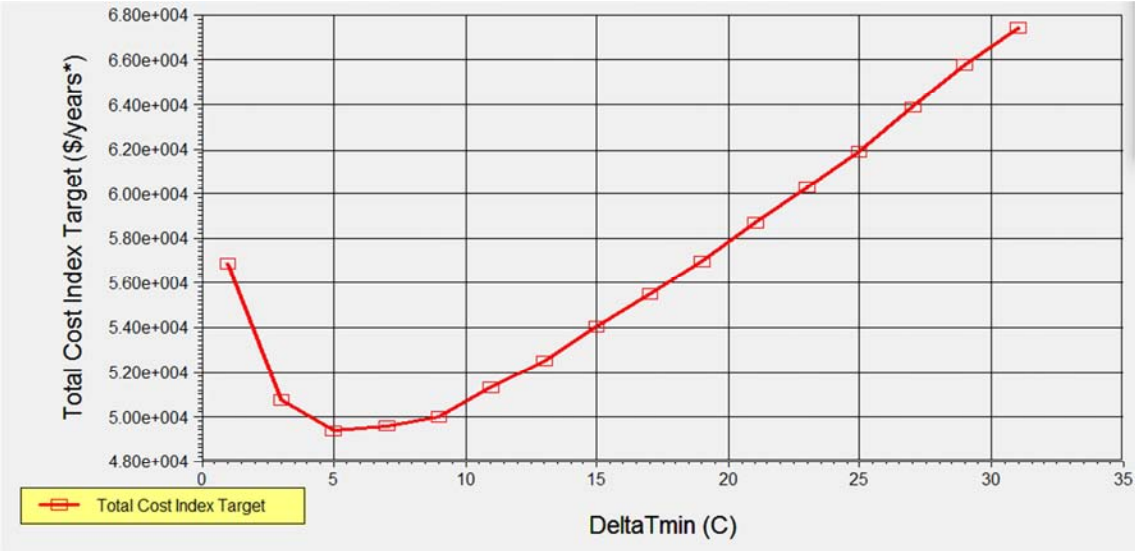


Figure 11. *Supertargeting Curve for Case Study 4.*

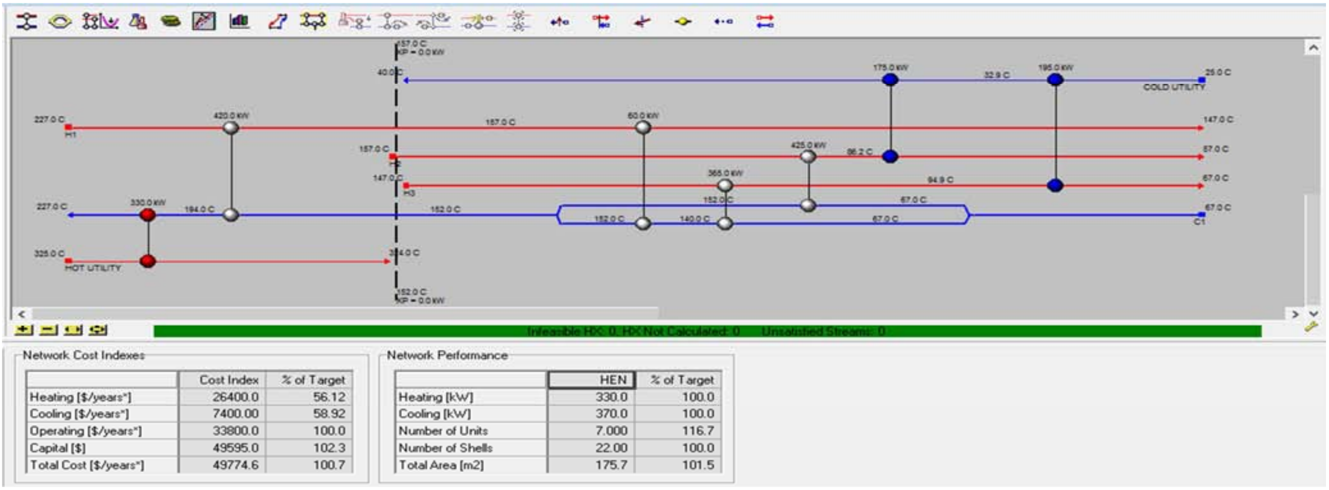


Figure 12. *HEN design with isothermal stream mixing for case study 4.*

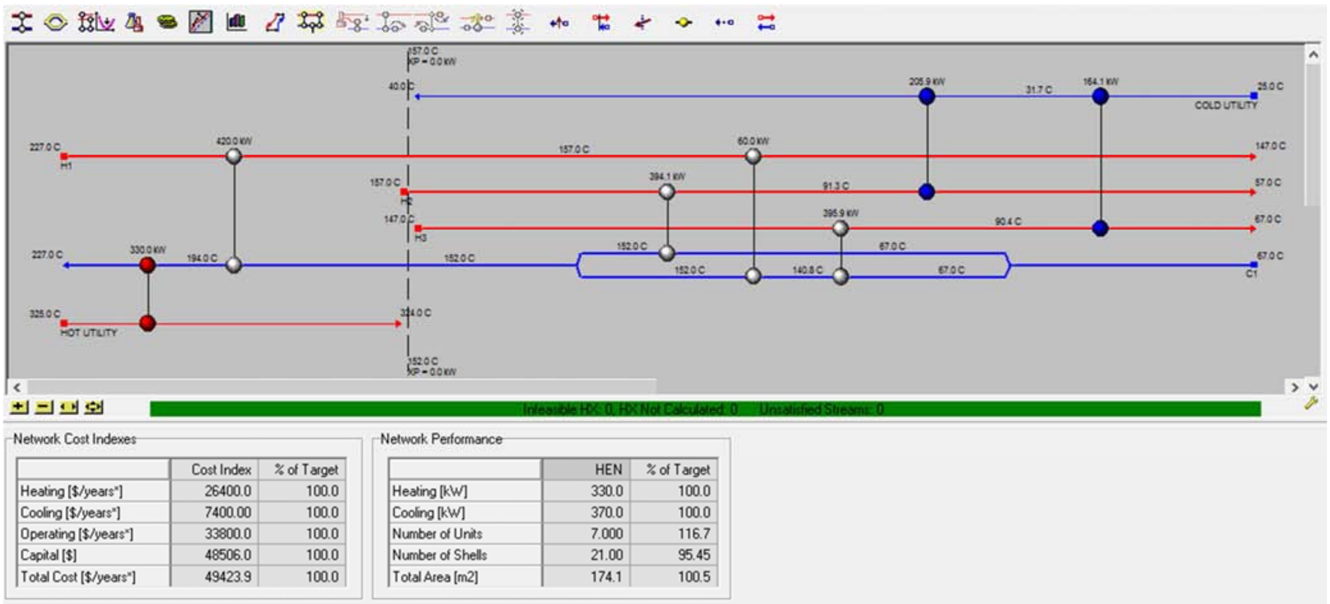


Figure 13. *HEN design with non-isothermal stream mixing for case study 4.*

Table 8. *Network Comparison for Case Study 4.*

Method	ΔT_{min} (°C)	Isothermal Network Cost ($/year)	Non-Isothermal Network Cost ($/year)
Bjork and Westerlund (2002) [4]	Not Stated	61,295	60,842
Modified Pinch Analysis (This Work)	5	49,774	49,424
Modified Pinch Analysis	15	54,041	53,774
Modified Pinch Analysis	25	61,809	61,805

4. Conclusion

In the four case studies considered in this work, the effect of a minimum temperature difference ΔT_{min} can be clearly seen through the network comparison tables. The networks designed using the optimum ΔT_{min} value from supertargeting obtained a lower TAC than those that were designed without considering this, the supertargeting curves for each case study show the range of costs associated with different values of ΔT_{min}. Hence it is necessary to carry out supertargeting to determine ΔT_{min} before HENS for optimum solution. The claim of global optimization will only be valid, if the ΔT_{min} at which the optimization is carried is stated. The trend was confirmed in Network comparison tables of Case Studies 1-4 where TAC varied with ΔT_{min} values.

For all the problems investigated, the TACs for non-isothermal mixing networks were considerably lower than those under the isothermal mixing assumption. This clearly shows that although the isothermal stream mixing assumption makes the HENS problem easier to solve, it does not lead to globally optimal networks and therefore optimization of the designed networks is necessary to remove this assumption and improve the network.

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